Augmented Breathing via Thermal Feedback in the Nose

Jas Brooks
University of Chicago
Chicago, Illinois, USA
jasbrooks@uchicago.edu

Alex Mazursky
University of Chicago
Chicago, Illinois, USA
alexmazursky@uchicago.edu

Janice Hixon
University of Chicago
Chicago, Illinois, USA
jhixon@uchicago.edu

Pedro Lopes
University of Chicago
Chicago, Illinois, USA
pedrolopes@uchicago.edu

Figure 1: (a) We propose a novel nasal interface that augments the perception of breathing via thermal feedback in the nose. By cooling or heating the nasal cavity in sync with inhalations, our device can make the user feel as if they are (b) breathing easier (i.e., inhaling more air) by cooling the inside of the nose or (c) having a harder time breathing (i.e., stuffy room or blocked nose) by heating. Based on study participants' analogies, we demonstrate our method with several applications: (d) a VR game that simulates experiences like breathing dust or fresh air in the outdoors; (e) a meditation app that draws the user's attention to their breathing; and (f) an application that relieves mask-wearers from the perceived air resistance while breathing through the mask filter.

ABSTRACT

We propose, engineer, and study a novel method to augment the feeling of breathing—enabling interactive applications to let users feel like they are inhaling more/less air (perceived nasal airflow). We achieve this effect by cooling or heating the nose in sync with the user's inhalation. Our illusion builds on the physiology of breathing: we perceive our breath predominantly through the cooling of our nasal cavities during inhalation. This is why breathing in a "fresh" cold environment feels easier than in a "stuffy" hot environment, even when the inhaled volume is the same. Our psychophysical study confirmed that our in-nose temperature stimulation significantly influenced breathing perception in both directions: making it feel harder & easier to breathe. Further, we found that ~90 % of the trials were described as a change in perceived airflow/breathing, while only ~8 % as temperature. Following, we engineered a compact device worn across the septum that uses Peltier elements. We illustrate the potential of this augmented breathing in interactive contexts, such as for virtual reality (e.g., rendering ease of breathing crisp air or difficulty breathing with a deteriorated gas mask) and everyday interactions (e.g., in combination with a relaxation application or to alleviate the perceived breathing resistance when wearing a mask).

CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**; • **Hardware** → **Emerging interfaces**.

KEYWORDS

Breathing, Thermal, Trigeminal, Perception, Respiration

ACM Reference Format:
Jas Brooks, Alex Mazursky, Janice Hixon, and Pedro Lopes. 2024. Augmented Breathing via Thermal Feedback in the Nose. In *The 37th Annual ACM Symposium on User Interface Software and Technology (UIST '24), October 13–16, 2024, Pittsburgh, PA, USA.* ACM, New York, NY, USA, 11 pages. https://doi.org/10.1145/3654777.3676438

UIST '24, October 13–16, 2024, Pittsburgh, PA, USA

ACM ISBN 979-8-4007-0628-8/24/10
https://doi.org/10.1145/3654777.3676438

1 INTRODUCTION

Breathing stands out as a unique autonomic function because it is primarily controlled by the brain [38, 39], resulting in a significant impact on human experiences, particularly our comfort and emotional state [16, 36]. Additionally, as it is commonly practiced in everyday life, voluntary deep breathing affects the autonomic nervous system, modulating comfort and stress levels [17].

As such, it is unsurprising that breath-responsive interactive systems and experiences are increasingly popular in human-computer interaction. For instance, a number of games have integrated breath as one of their input modalities [30, 40, 42, 47, 54]. Further, implementing breath as an input has been a common feature in biofeedback systems to support calming interventions, such as promoting stress relief through visual or auditory feedback [28, 31, 32, 48].

While leveraging the user's breathing as an input channel has been explored and can be implemented via a wide range of solutions (e.g., hot-wire [52] or -film [18] sensing, microphones [54], force sensors on the chest [42]), the reverse is not the same—output devices that can alter the user's breathing are very limited.

Output devices for breathing remain non-trivial since, to alter one's breathing, the user's airflow needs to be altered. In fact, interactive devices that can achieve this are extremely rare. One such example is *AirRes Mask*, a mask-based device that uses a servo motor to block the entrance of a tube the user breathes through, thereby physically restricting airflow to enhance virtual reality immersion [46]. This unique example highlights the challenges in engineering a suitable method for altering breath, as to manipulate inhaled airflow, one requires motors, tubes, pumps, and more, making these devices cumbersome and non-practical, which might explain why so few such devices have been proposed.

In this paper, we take a different approach to altering the user's airflow, one that does not require large tubes, pumps, and other mechanical actuators—we alter the user's perceived airflow by cooling down or heating up their nose using Peltier devices, as shown in Figure 1. Our illusion builds on the physiology of breathing: we perceive our breath predominantly through the cooling of our nasal cavities during inhalation. Our user study confirmed that this type of in-nose temperature stimulation significantly influenced breathing perception in both directions: making it feel harder or easier to breathe.

To enable this novel sensation in interactive applications, we engineered a compact device worn across the septum featuring Peltiers and air pressure sensors. Finally, we illustrate the potential of augmented breathing for a range of contexts, from virtual reality to everyday interactions.

2 RELATED WORK

The work presented in this paper builds on the literature on breath-responsive systems and the physiology of breathing.

2.1 Breath as an input modality

The proliferation of breath as an input modality in human-computer interaction (HCI) springs from the abundance of methods available to sense respiratory activity, ranging from hot-wire sensing [18, 52], microphone-based systems [54], force sensors mounted on the chest [42], and emerging approaches like acoustic signal reflections [44]. This plethora of sensing techniques catalyzed a surge in research on integrating breath control into interactive systems.

Examples of breath as input include mapping breathing to navigation in VR [9] or the movements of an amusement ride [30]. Subsequent works incorporated breathing actions, like exhaling with different strengths, to heighten immersion in VR [6, 7, 42, 49]. *Masque* played altered breathing sounds—fast and loud versus light and slow—in synchronization with the user's breath to influence their sense of attraction [28]. Additionally, given the intimate connection of breath with stress relief and relaxation, many systems exist for guided breathing or biofeedback [5, 34, 41].

In comparison, we focus on breath as output—i.e., the interactive device alters the user's perceived breathing. This is conceptually and technically important for "closing the loop" for breathing as an interactive modality.

2.2 Rendering breath to the user via haptics

Several haptic technologies in the form of interactive objects [2, 13, 22, 23, 45] or wearables [11, 12, 15, 20, 27, 33] render breathing in a way that is perceivable–yet external: they do not use haptics to alter breathing; they just *represent* it using haptics. These systems focus on creating *awareness* of breathing rather than altering its perception.

2.3 Altering breathing as an output modality

Unlike research geared towards breathing as input or representing breathing via haptics, there is little research focused on *directly* altering the perception of one's breath. Two systems explored mechanically compressing one's chest to guide breathing [14] and to enhance social connections [33]. Unfortunately, Foo et al.'s participants found that mechanically restricting one's abdominal (lung) expansion can also cause some discomfort [14].

Even more closely aligned with our work is *AirRes Mask* [46], which mechanically restricts breathing by blocking airflow through a gas mask. This allows users to experience progressively harder breathing as the system reduces the air tube's opening diameter, thus constricting airflow.

Compared to prior approaches, our approach stands out since (1) it does not require a large facial coverage (i.e., not a mask form factor as in [46]); (2) non-mechanical actuators are smaller and quieter (e.g., compared to servos [46] or pumps); (3) importantly, it can make users feel it is *both* harder or easier to breathe (which no prior work has achieved); finally, (4) its effect is *perceptual*—there is no risk of mechanical actuators preventing the user from breathing.

3 OUR APPROACH TO REALIZING *AUGMENTED BREATH*

Altering the perception of breathing directly presents a formidable challenge. As described, the only current method to modify breathing requires cumbersome mechanical devices, like motors and tubes, to physically constrict the user's breathing [46]. This approach not only requires mechanical parts but also limits practical applications and introduces safety concerns—it prevents real airflow.

In the study of the nose, nasal patency—the sense of how open or congested one's nose feels—is considered a key aspect of breathing perception. Interestingly, subjective sensations of nasal patency or airflow do not always align with the objective measurements of nasal obstruction [19, 29]. Medical research has revealed that the nasal vestibule (septum) is a critical area for sensing airflow [26], with temperature fluctuations being more pronounced in regions of turbulent airflow, like the mucosa of the turbinates [51]. This cooling of the nose's surfaces, rather than the mere temperature or volume of the inhaled air, triggers the trigeminal sensation influencing the perception of nasal airflow [53]. Medical studies have confirmed that the sensation of airflow is heightened during deep breaths, correlated with larger mucosal temperature changes [3, 50]. Thus, the subjective experience of nasal patency and airflow is closely tied to the changes in intranasal temperature [37].

Building on these physiological insights, we propose and validate a novel approach to realize *augmented* breathing by altering the perception of nasal patency and airflow, allowing users to experience sensations of inhaling more or less air. Our approach utilizes *targeted cooling and heating* in the nose in sync with inhalation, capitalizing on the principle that the perception of breath is primarily influenced by the cooling effect on the nasal mucosa.

It is important to note that we found, in early pilot experiments, that synchronizing the heating/cooling with the inhalation is key to feeling that this effect is about airflow instead of just feeling that one's nose is hot or cold (merely a thermal effect, not our goal). As seen in our study, this synchronized temperature stimulation successfully altered participants' perception of their breathing, with ∼90 % of their remarks focused on perceived airflow or patency.

As a result, our approach offers a compact way to augment breathing that can *both* decrease and increase perceived nasal patency and airflow without requiring physical obstruction.

4 WALKTHROUGH: ALTERING PERCEIVED BREATHING

To illustrate our technique with an application, we designed a virtual reality (VR) experience in which the user navigates through various environments where their sense of breathing is altered. The experience uses our wireless wearable device equipped with Peltier elements and airflow sensors, enabling real-time adjustments to the temperature inside the user's nose, which we found to alter their breathing perception. The design of this application draws upon insights from our user study, specifically leveraging direct quotes and real-world analogies that participants used to describe augmented breathing. These highlight how participants perceived changes in ease of breathing, such as feeling like breathing "more air" or inhaling "through a narrow straw". These augmentations are purely perceptual: the device does not physically restrict airflow. Users maintain constant access to air, experiencing only a *sensation* of altered nasal airflow.

Figure 2: (a) The user opens a room and (b) kicks up dust. Scale depicts perceived nasal airflow for illustration purposes only.

Figure 2 depicts our VR user trying to escape a room where they were being held. As they walk through this old house in search of the door's key, their movements kick dust into the air. In sync with their breathing, our device heats the inside of their nose, creating a brief sense of breathing less due to the dusty and "stuffy room" (quote from Study, by P1).

As depicted in Figure 3, upon finding the key and opening this room's door, the user inadvertently triggers the alarm, releasing smoke—in sync with inhaling, our device increases the nose's temperature to emphasize the feeling of *"smog in the air"* (direct quote from Study, by P8).

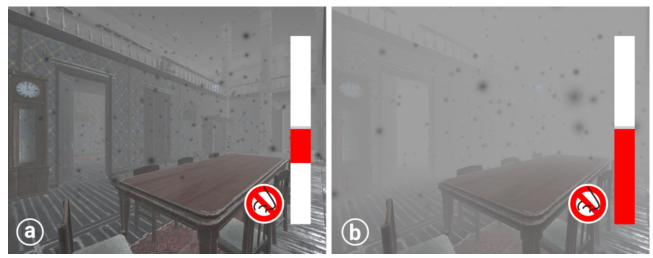

Figure 3: (a) Smoke starts to fill the house with black specks and smog until (b) it feels as if it becomes harder to breathe.

Reacting to the smog, shown in Figure 4, the user finds a gas mask and equips it. Immediately, our device starts to cool off their next inhalations, creating a feeling of *"more air entering my nostrils"* (direct quote from Study, by P6).

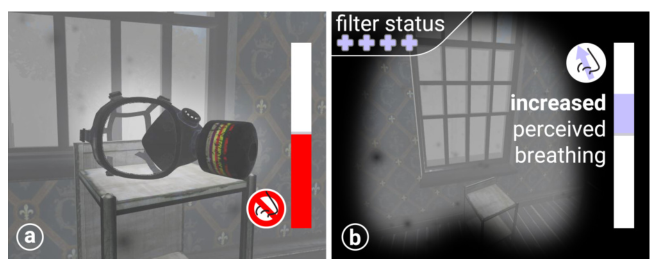

Figure 4: (a) User finds a mask, and (b) equips it, which causes our device to increase their feeling of perceived nasal airflow.

However, as the virtual mask's filter deteriorates, the perceived breathing becomes harder, which can be felt as *"a lot more effort to move air into my lungs"* (direct quote from Study, by P4). As shown in Figure 5, to render this sensation, our device progressively increases the temperature during each inhalation (i.e., fading from cold to hot). As the user finds a new mask and equips it, our device responds by cooling their inhalations and allowing the user to feel like breathing *"more air"* (direct quote from Study, by P3).

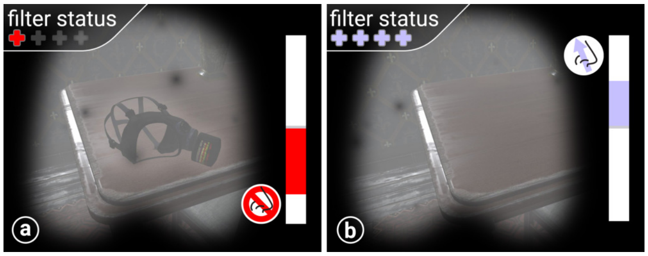

Figure 5: (a) As the mask's filter deteriorates, our device renders a difficulty in inhaling air. (b) With a replacement, our device resets the perceived nasal airflow sensation.

Finally, the user opens the door of the gas-filled room and escapes. As they open the doors (Figure 6), our device pushes through its maximum cooling effect to emphasize the transition from claustrophobic to the relief of *"breathing in an open space"* (direct quote from Study, by P2).

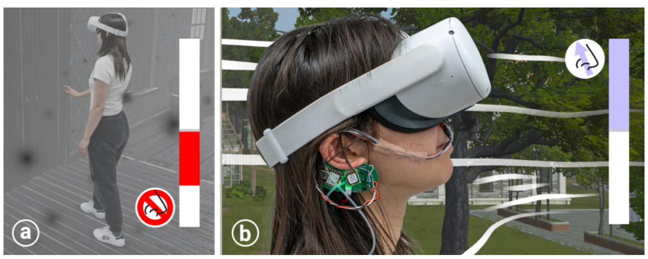

Figure 6: (a) The user opens the final door, leading to an (b) open space where they feel as if they breathe more easily.

5 IMPLEMENTATION

To help readers replicate our design, we provide technical details and an open-source repository.[1] Figure 7 shows our device worn on the nose and around the user's ear.

Circuit design. Our circuit, depicted in Figure 8, was engineered around an ESP32C3 with Bluetooth Low Energy. To change the nose's temperature, we attached two 8 mm × 8 mm Peltiers (*Custom Thermoelectric*, 00711-5L31-03CA-S) paired with thin 10 kΩ thermistors (*TME*, B3950) for temperature monitoring. We also added a 10 kΩ thermistor and a small silicone tube (1 mm ID, 2 mm OD) in one nostril to record the baseline temperature during inhalation, providing a reference point for temperature adjustments. This silicone tube connected to a differential air pressure sensor (*Amphenol All Sensors*, 1 INCH-D1-4V-MINI) within an operating range of −250 Pa to 250 Pa to monitor respiration. Finally, we concentrated most of the components behind the ear (microcontroller, battery, etc.). The in-nose components weighed only 7 g, while the components positioned behind the ear weighed 26 g. This separation balanced functionality with wearability.

Control loop. To regulate the temperature of the Peltiers, we tuned a PID controller, which activates if the temperature is more than 0.25 °C from the set point. The activation of the Peltiers is synchronized with the user's inhalation, capitalizing on the exhalation phase as a natural cooling period that allows the Peltiers to return to the user's baseline body temperature, thus conserving power without the need for active cooling.

[1] https://github.com/humancomputerintegration/augmented-breathing

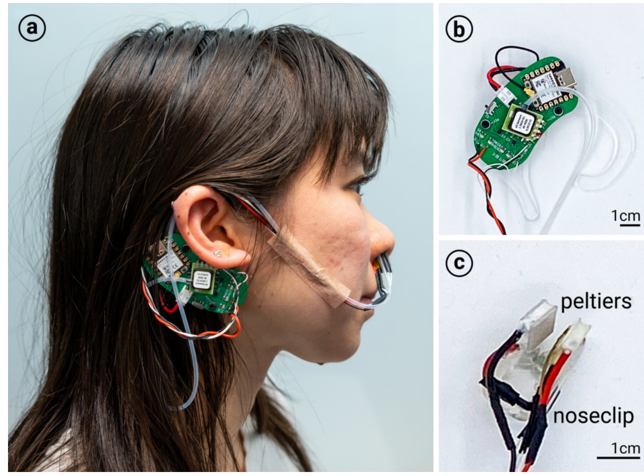

Figure 7: (a) A user wearing our device around the ear and in the nose, comprised of its (b) control unit and (c) nose clip.

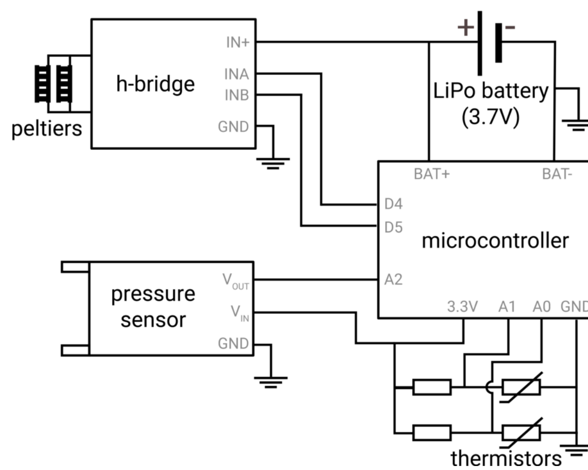

Figure 8: High-level schematic of our device's circuitry.

Inhalation detection. To achieve accurate inhalation detection, our system includes a calibration process. Initially, users hold their breath for two seconds to establish a baseline for the differential air pressure (difference between the pressure measured in the nostril and pressure measured in the room) while not breathing, representing the static noise level of air pressure. The device then records the mean and standard deviation of this baseline pressure. An inhalation is detected when the differential air pressure falls two standard deviations below this mean. Likewise, an exhalation is identified when it rises two standard deviations above.

Latency. To assess system latency, specifically the delay between the temperature peak induced by our device and the peak of inhalation, we analyzed recorded data from all participants. This dataset comprised 3247 breaths, each with temperature stimulation. We found an average latency of 0.21 ± 0.67 s between the onset of the temperature peak (when the Peltier reaches its extreme temperature) and the peak of inhalation (the point of maximum inhalation). Considering that the average inhalation duration was 1.81 ± 0.49 s, a latency of 0.21 s was reasonable for our interactive system. Notably, the temperature peak occurred within the inhalation phase for 91.32 % of the breaths, confirming effective synchronization with the breathing cycle.

Power consumption. Our prototype drew a maximum of 6 W during inhalation. Under a continuous change of perceived airflow only during inhalation, it lasted approximately 22 min with a small 300 mA h Li-Po battery. The device could operate longer with larger batteries, but we noted that 22 min of perceived airflow change was relatively long, considering participants in our studies detected a change in perceived airflow within their first inhalation with our system active.

6 CONTRIBUTION, BENEFITS, & LIMITATIONS

Our key contribution is a novel method to augment a user's breathing, creating the sensation of inhaling more or less air than normal. Moreover, we contribute a device that can realize our approach, which we validated in a user study.

Our approach has four key benefits: (1) our method is the first, to the best of our knowledge, that can *both* decrease and increase perceived airflow (breathing); (2) our device can achieve these sensations without the need for physical obstructions to the user's actual breathing. Unlike previous interactive devices (e.g., [46]) that mechanically restrict the user's breathing to create a feeling of difficulty, our approach has a *perceptual* effect—as such, our device has fewer associated risks than existing approaches that require opening/closing the user's airways; (3) our device can achieve these sensations with small temperature changes as demonstrated in our study, enabling our device to operate on a small battery; finally, (4) our approach is a conceptual and technical step toward "closing-the-loop" for breathing as an interactive modality—while breath as input is fairly popular, breath as an output modality is heavily underexplored.

As the first exploration of this novel idea, it is not without limitations, which reveal future research directions: (1) the limits of our approach to breath augmentation are constrained by the Peltier elements' ability to rapidly achieve the desired temperature during the user's inhalation, namely its speed and power consumption; (2) as with any perceptual illusion, individual physiological differences could affect its efficacy—our study validated its efficacy with people without nasal cavity abnormalities, yet it is not certain if this extends to individuals that had nose surgery or other changes (e.g., nasal septum deviation); (3) our device occupies a portion of the nostril openings, which slightly reduces the baseline nasal patency while wearing the system; finally, (4) while effective, our method only augments nasal breathing, not mouth breathing.

7 USER STUDY: ALTERING PERCEIVED AIRFLOW VIA INTRANASAL TEMPERATURE

Our study sought to characterize the relationship between in-nose thermal stimulation and perceived nasal airflow. We designed a psychophysical study with three tasks: (1) measuring the just-noticeable difference (JND), when participants noticed a change in perceived airflow; (2) measuring the range of comfortable airflow sensations; and (3) understanding the sensations qualitatively.

We hypothesized that cooling/heating the nasal cavity in sync with inhalation would produce a noticeable change in nasal airflow. This study was approved by our Institutional Review Board (24-0416).

7.1 Apparatus

Participants wore our complete setup (including its Peltiers, air pressure sensor, and temperature sensors) as a nose clip with the control unit resting on a table. For maximum sensing and stimulation quality, we added a second air pressure sensor and two thermistors to the other nostril to control the Peltier temperatures independently.

7.2 Calibration

We included an automated calibration at the start of the study to calibrate the system for maximal inhalation sensitivity. This asked participants to hold one breath to record average ambient pressure. Then, we set the inhalation threshold to two standard deviations below the average ambient pressure.

7.3 Procedure

We conducted our study in a lab environment with a consistent temperature of 24.78 ± 0.12 °C and no measurable airflow near participants (measured with an anemometer). Participants wore noise-canceling headphones with white noise. Our device was tested in its two functionalities: cooling and heating, in sync with participants' inhalation. The functionality order was counterbalanced.

7.3.1 Task 1: Measuring the Just Noticeable Difference. The first task measured the Just-Noticeable Difference (JND) in perceived nasal airflow due to temperature changes. This task used a standard psychophysical staircase method. Participants were asked to evaluate if a set of five breaths felt easier to breathe than another set of five breaths (forced choice).

In one of the two sets of breaths participants compared per trial, our device either cooled or heated their nasal septum in sync with inhalation. In the other set of breaths, our device was off. Participants were unaware that two conditions existed—providing a suitable baseline for the study. The set ordering was random. If a participant's answer was "yes", the temperature was adjusted by 0.5 °C increments or decrements based on the tested functionality (cooling or heating)—and the temperature adjustment was reversed for the "no" answer. We selected 0.5 °C given that our PID can maintain a target temperature within a 0.25 °C error margin.

The staircase concluded after reaching four reversals or completing 20 trials. The staircases began at a temperature offset determined from a pilot study: 2 °C for heating and −5 °C for cooling. Finally, after each trial, participants were also invited to voice any sensations that were elicited.

7.3.2 Task 2: Range of Sensation characterization. In our second task, we characterized the range of perceived nasal airflow. Starting with the JND determined from *Task 1* as *level 1*, participants

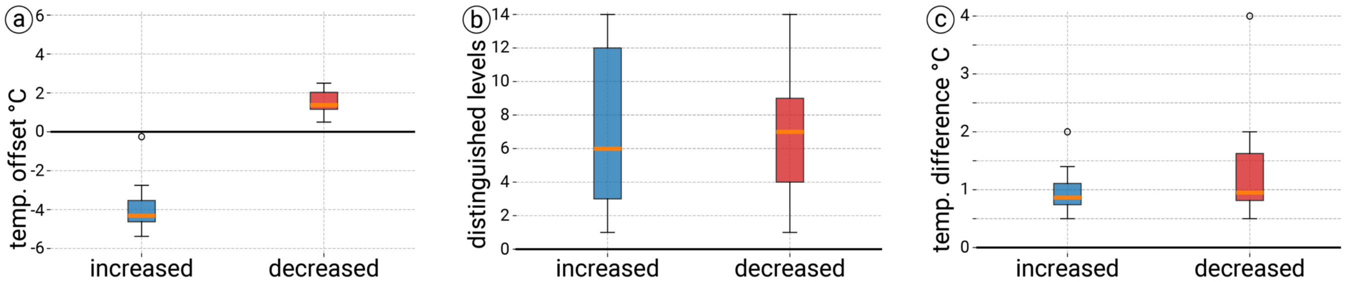

Figure 9: (a) The Just Noticeable Difference values (JNDs) for increased and decreased perceived nasal airflow. (b) On average, participants could distinguish approximately 6 different levels of increased or decreased perceived nasal airflow, but large variance across participants. (c) Still, it typically took, on average, only 1 °C to produce a noticeable new level.

compared their ease of breathing between the current level and a comparative level. If participants did not notice a difference between the two levels, the second level was incremented by 0.5 °C (increasing for heating, decreasing for cooling). If participants indicated that they noticed a difference between levels, the comparative level was then established as a new distinguishable level. The process repeated for 20 trials or until the participant indicated discomfort or pain. Finally, after each trial, participants were also invited to voice any sensations that were elicited.

7.3.3 Task 3: Qualitative exit interview. After completing both tasks, participants engaged in a brief interview. They were asked to describe their experiences during the study and then to compare them to any sensations encountered in real-world situations. Then, participants could provide open feedback about the study experience.

7.4 Participants

We recruited ten participants with an average age of 26.5 years old (SD = 2.72) from our local institution. Four participants identified as men, four as women, and two as non-binary. We did not recruit participants with a deviated septum or a known history of nasal surgery. At the start, participants were given the Nasal Obstruction Symptom Evaluation (NOSE) 5-point Likert Scale [43]. With it, we confirmed that most participants did not have, during the last month, nasal congestion (M = 0.8, SD = 0.79), blockages (M = 0.6, SD = 0.84), trouble breathing (M = 0.4, SD = 0.52), trouble sleeping (M = 1.2, SD = 1.14), or difficulty breathing during exercise (M = 0.1, SD = 0.32). However, two participants disclosed having congestion at the start of the study: P6 reported congestion, and P9 shared that they sometimes experience light congestion. Both stated that they easily perceive differences in their day-to-day ease of breathing (perceived nasal airflow and patency). Participants were compensated with $10 USD for their time.

7.5 Quantitative Results: JND & Perceived levels

In this section, we present the quantitative findings from our study, namely the JND and the number of perceived levels.

7.5.1 Task 1 Results: Just Noticeable Difference. We summarize our results in Figure 9. We found that cooling the septum by an average of −3.9 ± 1.4 °C led to a perceivable increase in perceived nasal airflow (Weber's fraction of 12.11 %) while heating it by 1.5 ± 0.6 °C caused a perceivable decrease (Weber's fraction of 4.71 %).

7.5.2 Task 2 Results: Number of Perceived Airflow Levels. Participants identified an average of 6 different levels of airflow change, with an ability to discern approximately 7 ± 5 levels for increased perceived nasal airflow (cooling effect) and 6 ± 4 levels for decreased (heating). To perceive a new level of sensation, an average temperature change of 1.0 ± 0.4 °C was necessary for increased perceived nasal airflow (cooling) and 1.4 ± 0.9 °C for decreased perceived nasal airflow (heating). The range of sensations explored by participants ranged from −10.5 ± 3.9 °C to 10.6 ± 1.6 °C offsets from their baseline cavity temperature.

7.6 Qualitative Results: What does it feel like?

In this section, we present the qualitative findings from our study, which come from two moments when participants commented: (1) in *Tasks 1 (JND) & 2* after any trial where they felt a difference, and (2) during the exit interview.

Comments were transcribed and analyzed by one author. Each comment was classified as any combination of the following categories: **tactile** (skin sensations like tingling or pain), **temperature**, and **airflow** (any aspects of breathing like patency, airflow, congestion, difficulty or ease in breathing, etc.). Figure 10 depicts a concrete example of how the participants' comments were annotated.

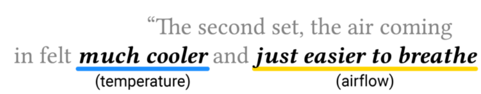

Figure 10: Example response from P6 with annotations.

This qualitative data complements the understanding of our perceptual illusion, providing descriptive insights into how these changes were interpreted.

7.6.1 Does it feel like airflow or temperature? Our analysis revealed that from the 389 descriptors from transcribed comments, an overwhelming majority (89.2 %) pertained to airflow, underscoring this as the prominent aspect of the perceived experience (e.g., P4 saying their nose felt "much more open"or P2's "I could just breathe easier because it was fresher air, versus being stuffy"—to illustrate such comments). In contrast, temperature descriptors accounted for

7.46 % of the comments. Notably, among these temperature-related comments, approximately half (46.7 %) were concurrently associated with airflow (for example, P6 explaining, it's like a "windy day and [you] have a deep breath and you have the cold air rushing into your nostrils"—to illustrate). Finally, only 3.34 % accounted for comments classified as tactile (e.g., P4's "second set felt easier, but the septum felt a little bit tingly this time"—to illustrate).

In other words, participants associated the sensations predominantly with changes in perceived airflow and not temperature or tactile sensations.

7.6.2 Unprompted analogies. Some participants already employed (unprompted) analogies to describe changes in the sensation during *Tasks 1 & 2*. These analogies not only reflect real-world sensations but specifically real-world *breathing* sensations, without any additional context, pointing to their strength.

For **increased airflow**, all ten participants provided unprompted analogies for this airflow sensation. Five participants used analogies relating to the openness of their nose (i.e., nasal patency), such as: "breathing through both nostrils instead of just one" (P2); "clear passage of air through my nostrils" (P6); "decongestion" (P10); or lack of resistance" (P5). Four participants used specific airflow analogies: "there was wind in my nose [...] it was coming through faster" (P9); "more air entering my nostrils" (P6); "more airflow" (P3); "like inhaling more air" (P1). Four participants used air quality analogies such as crisp (P2), clean (P4), fresh (P2, P5), and "good quality" (P8) air. Three participants also likened the increased ease-of-breathing to environmental conditions, such as: "sharp, like breathing in winter" (P9)–though P9 specified that they meant only the sharpness not the cold aspect of winter air in their exit interview–or "windy day and [you] have a deep breath and you have the cold air rushing into your nostrils" (P7).

For **decreased airflow**, seven of ten participants likened it to congestion, clogging, restricted, or high-effort breathing with analogies such as "breathing through narrow straws [...] or a "pinched nose" (P4); "like something was blocking the airflow" (P8); "like [the] breathing equivalent of a weighted blanket" (P9); "scuba diving type breathing" (P8); or even that they "could no longer breathe" (P5). Four participants used air quality analogies: "like smoky [...] breaths felt heavier coming–like the air got thicker" (P9); "felt very, very heavy" (P8); and even like a "smoggy city" (P8). Three participants mentioned air resistance analogies: "[like] wearing a mask" (P8); "a lot more effort to move the air into my lungs" (P4); and "difficulty passing air" (P2).

7.6.3 Task 3 Results: Prompted analogies to real-world experiences. In addition to the unprompted analogies that some participants used to describe sensations in *Tasks 1 & 2*, during the exit interview, participants were specifically prompted to provide real-world analogies to their experiences. Again, these analogies not only reflect real-world sensations but specifically real-world *breathing* sensations, without any additional context, pointing to their strength. These prompted analogies also provided further explanation for how the sensations were described, as participants could provide more information for disambiguation (e.g., P9 disclosing that breathing winter air referred to its sharpness in breath and *not* the air's temperature). Of all prompted analogies, all focused primarily on airflow. We report the specific aspects of breathing altered below.

For **increased airflow**, five of ten participants compared it to moments in life where wind or good air impacted their breathing: "feels like when I do outside and it's windy: [...] like I am breathing in more" (P7); "like stuff was more crisp. Like normal versus really good air [...] the air just felt crisp – not cold" (P2); "like when you're in the wind" (P9); "less thick – the air passing through faster" (P9); "felt like going from an airplane with bad air quality and going outside to a city that has nicer air quality—like I can actually breathe" (P8). Five participants likened the increased inhalation to moments where they were decongested: "much more open" (P4); "using stickers to open your nostrils, but this one is much stronger" (P3); "like inhaling mint [...] when you have a cold. I definitely feel I am breathing more air and fresher air" (P5), which P1 echoed as "like if I were top open a window in a stuffy room, [...] the air I was breathing was fresher". P6, who had some congestion, reported that "there [were] some instances where [my] congestion just went away pretty immediately". Three participants mentioned that the device helped them breathe: "it felt like something was helping me breathe" (P9); "best breathing I've experience in a while – calming" (P2); and "really comfortable, like long breathing [...] it kind of helped me calm down" (P5).

For **decreased airflow**, participants likened the sensation to moments with high-effort breathing: "running or scuba diving, it feels like you are using your lungs more or takes more effort" (P8); "harder to move the air in and out" (P4); "when you're walking up a good amount of stairs, now it's a little harder to breathe" (P2); "as if I was under a blanket" like a "stuffy room" (P1); "it just feels like I cannot breathe in enough air" (P5); or, "it's like being closed in a hot room or smoke [...] I had to work a little harder to get [the air] through" (P9). Four participants likened sensations to real-life moments with nasal blockage: "felt even more congested" and "only felt this when I am really sick" (P6); "when you get a cold, and you try to sleep and you cannot fall asleep, because your nose is clogged" or even "accidentally breathing in water [while swimming]" (P5); "stuffy nose [or] pinching the nose" (P4). Finally, two participants mentioned the decreased airflow reminded them of their breathing during asthma (P4) or anxiety attacks (P5).

8 DISCUSSION

While our study was chiefly aimed at quantitatively characterizing our method's effect, it also captured a remarkably wide range of expressive details from participants. This richness in feedback underscores the depth of personal interaction with the breathing experience and provides a holistic understanding of *what* the effect feels like.

8.1 Device comfort

All participants reported becoming accustomed to the nose clip within the first minute of use. Participants wore the most implemented version of our device for our psychophysical study (sensors for each nostril). Some of their feedback suggested that further reducing the device's weight would improve comfort. Based on their input, we simplified the standalone device by decreasing the number of tubes and sensors to improve comfort.

8.2 Perceived our effect as a change in breathing

Participants primarily framed their experiences in terms of changes in breathing dynamics, such as airflow, blockage, and ease of breathing, rather than temperature sensation. This supports our hypothesis that thermal feedback in the nasal cavity alters one's perception of one's own breathing. These changes were perceived as if their breathing has changed (e.g., "feels like I cannot breathe hard enough") or that they are even being helped to breathe (P9). Moreover, we remind readers that these descriptions and analogies occurred *without any additional context* (e.g., no VR, no visuals, no sound, nothing else). This perception, emerging consistently across responses, validates the notion that thermal feedback can be a powerful modulator of breathing sensation, and our quantitative findings suggest that it only requires a small difference in temperature to produce a noticeable change.

Their analogies also provided further explanation for how the sensations were described, as participants could provide more information (e.g., P9 disclosing that breathing winter air referred to its sharpness in breath and *not* the air's temperature). While there was variation in analogies (i.e., describing changes in airflow, patency, or even effort), participants' descriptions converged on *changes in breathing* that were most akin to *changes in perceived nasal airflow*.

8.3 Secondary effects of augmented breathing

The feedback from some participants, especially P1, P2, and P5, also highlighted that the increase in perceived nasal airflow also had a calming or relaxing effect. Conversely, decreased perceived nasal airflow was reported to induce feelings of anxiety or asthma for two participants. These findings suggest that augmented breathing could also influence both physical states and emotional well-being. This is not surprising given breathing's well-established link to emotion [1, 10, 16], such as controlled breathing enhancing relaxation [4] and reducing pain [21].

8.4 Participant-suggested applications

While *Task 3* was about analogies, two participants also voiced applications for which they would be excited to use the system. P5 felt that the increased perceived nasal airflow "would be really good to help me go to sleep. I imagine if my breath was like that while I was sleeping, I would imagine I would have a better quality of sleep". P8 wanted to use the device to help alleviate the perceived air resistance when wearing a mask is "blocking your airflow, but if you put this device to open it up–it'll feel comfortable"—which we implemented and described in the next section.

9 FURTHER APPLICATIONS

Alongside opportunities for augmented breathing to support future VR experiences, like in our *Walkthrough*, we highlight three potential scenarios where one might find our technique to have further applications. All these additional applications run on an Android mobile phone and communicate to our device using BLE. We implemented these applications in *Java*, using *Processing* and *Android Studio*.

9.1 Relieving the perceived air resistance of masks

The widespread adoption of face masks has been a crucial measure in curbing the transmission of respiratory illnesses, including common colds or COVID-19. However, the success of masking interventions significantly hinges on user compliance. As Koh et al. showed, mask discomfort is the primary source of noncompliance in mask-wearing [24], with a strong correlation between increased air resistance—making breathing *feel* more laborious [35]. Inspired by P8's suggestion that our system could help, we envisioned an application in which our system relieves the perceived increased air resistance. As seen in Figure 11, the user can switch our device's "mask mode" on to counteract the perceived decrease in airflow.

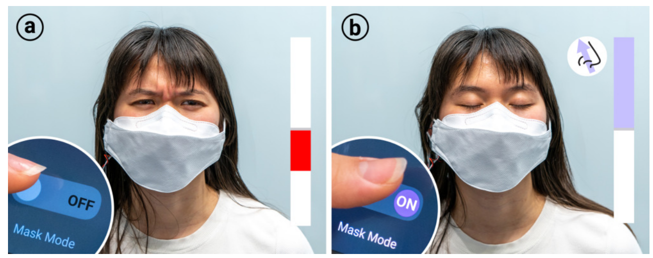

Figure 11: (a) This user finds it hard to breathe with a respirator mask. (b) They use an app to switch on "mask mode", which increases their perceived nasal airflow.

9.2 Meditation and relaxation

Most relaxation & meditation applications require users to actively follow audiovisual guides to reach a specific breathing pattern to achieve stress relief. Here, our approach provides a new output channel for these kinds of applications—by *directly* influencing the aspect that they are focusing on, i.e., their breathing.

This was inspired by comments from participants suggesting our system helped them feel calmer or more relaxed. To this end, we developed a meditation application that makes use of our device to alter the user's perceived airflow in a rhythmic pattern. As depicted in Figure 12, the meditation app increases the perceived airflow of every second breath, making it feel deeper and more pronounced.

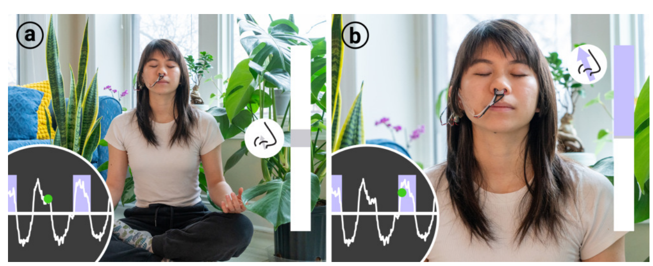

Figure 12: (a) Paired with our meditation app, our device makes every other breath feel deeper. (b) The user relaxes and meditates while experiencing augmented breathing.

9.3 Promoting nasal breathing when helpful

Our system may even offer a novel approach to encourage nasal breathing when helpful, e.g., during physical exercise, leveraging its known benefits for breathing efficiency [8]. Figure 13 envisions this as the example of an application we implemented where our device progressively cools down the user's nose to promote nasal breathing during exercise.

Figure 13: (a) A user does cardio while wearing our device. (b) Normally, they inconsistently breathe through the nose and, instead, breathe through the mouth, but (c) at times, our device encourages nasal breathing by increasing the perceived airflow when they inhale nasally.

9.4 Diving simulator

In addition to applications that increase perceived airflow, we developed an application that leverages the utility of decreased perceived airflow. Inspired by feedback from participant P8, who likened the sensation to the difficulty of breathing while diving, we created a VR diving simulator where our device replicates the "difficulty to breathe" via a scuba air tank and its mask (Figure 14). This simulator allows users to safely acclimate to the sensation of difficult breathing before engaging in actual diving activities.

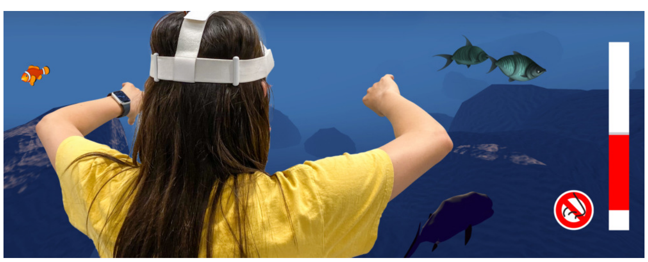

Figure 14: Our device replicates the "difficulty to breathe" via a scuba air tank for a diving simulator.

10 CONCLUSIONS

We introduced a technique for altering the perception of breathing through thermal feedback, using Peltiers to alter the user's sensation of nasal airflow. Unlike existing systems that rely on mechanical parts to restrict breathing, our perceptual approach modulates airflow *perception* and not the actual volume of air that users are inhaling—making it safer than previous devices. Moreover, it is the first approach that enables *both* decreased and increased perceived airflow.

Our study unveiled that our effect can be achieved with small Peltiers and minimal temperature adjustments. This opens potential practical implications for our findings, providing a working method to enrich interactive experiences like virtual reality and apply augmented breathing to everyday contexts.

We envision our work as a foundation for future investigations on how thermal feedback can be harnessed to augment breath perception. Future research may explore altering not only the perception of our inhalation but also our exhalation, developing power-saving strategies, exploring new actuators (e.g., flexible Peltiers [25]), or even investigating its potential impact for therapeutic purposes.

ACKNOWLEDGMENTS

This material is supported by the National Science Foundation Grant No. 2212352. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. We would like to thank Alicia Chun for being a model for our figures.

REFERENCES

[1] Sufyan Ashhad, Kaiwen Kam, Christopher A. Del Negro, and Jack L. Feldman. 2022. Breathing Rhythm and Pattern and Their Influence on Emotion. *Annual Review of Neuroscience* 45, 1 (July 2022), 223–247. https://doi.org/10.1146/annurev-neuro-090121-014424

[2] Ilhan Aslan, Hadrian Burkhardt, Julian Kraus, and Elisabeth André. 2016. Hold my Heart and Breathe with Me: Tangible Somaesthetic Designs. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction*. ACM, Gothenburg Sweden, 1–6. https://doi.org/10.1145/2971485.2996727

[3] Ryan S. Bailey, Kevin P. Casey, Sachin S. Pawar, and Guilherme J. M. Garcia. 2017. Correlation of Nasal Mucosal Temperature With Subjective Nasal Patency in Healthy Individuals. *JAMA Facial Plastic Surgery* 19, 1 (Jan. 2017), 46–52. https://doi.org/10.1001/jamafacial.2016.1445

[4] Richard P. Brown and Patricia L. Gerbarg. 2005. *Sudarshan Kriya* Yogic Breathing in the Treatment of Stress, Anxiety, and Depression: Part II—Clinical Applications and Guidelines. *The Journal of Alternative and Complementary Medicine* 11, 4 (Aug. 2005), 711–717. https://doi.org/10.1089/acm.2005.11.711

[5] Antoinette Bumatay and Jinsil Hwaryoung Seo. 2017. Investigating the Role of Biofeedback and Haptic Stimulation in Mobile Paced Breathing Tools. In *Augmented Cognition. Neurocognition and Machine Learning*, Dylan D. Schmorrow and Cali M. Fidopiastis (Eds.). Vol. 10284. Springer International Publishing, Cham, 287–303. https://doi.org/10.1007/978-3-319-58628-1_23 Series Title: Lecture Notes in Computer Science.

[6] Lisa Anneke Burr, Julius Šula, Julia Mayrhauser, and Alexander Meschtscherjakov. 2023. BREATHTURES: A First Step Towards Breathing Gestures as Distinct Input Modality. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*. ACM, Hamburg Germany, 1–6. https://doi.org/10.1145/3544549.3585787

[7] Yuxuan Chen, Yi Jin, Zhaoning Zeng, Shiyu Chen, Yang Zhou, Xinchi Xu, Jie Liu, and Guihuan Feng. 2023. VisaudiBlow: Fine-grained Blowing Interaction Based on Visual and Auditory Detection. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*. ACM, Hamburg Germany, 1–6. https://doi.org/10.1145/3544549.3585829

[8] George Dallam and Bethany Kies. 2020. The Effect of Nasal Breathing Versus Oral and Oronasal Breathing During Exercise: A Review. *Journal of Sports Research* 7, 1 (2020), 1–10. https://doi.org/10.18488/journal.90.2020.71.1.10

[9] Char Davies and John Harrison. 1996. Osmose: towards broadening the aesthetics of virtual reality. *ACM SIGGRAPH Computer Graphics* 30, 4 (Nov. 1996), 25–28. https://doi.org/10.1145/240806.240808

[10] Christopher A. Del Negro, Gregory D. Funk, and Jack L. Feldman. 2018. Breathing matters. *Nature Reviews Neuroscience* 19, 6 (June 2018), 351–367. https://doi.org/10.1038/s41583-018-0003-6

[11] Esko Dijk and Alina Weffers. 2010. Breathe with the Ocean: a System for Relaxation using Audio, Haptic and Visual Stimuli. In *Proceedings of Haptic and*

Visual Stimuli (Special Symposium at EuroHaptics 2010) (CTIT Workshop Proceedings Series, Vol. 1). University of Twente Centre for Telematics and Information Technology, Amsterdam, The Netherlands, 47–60.
[12] Abdallah El Ali, Ekaterina R. Stepanova, Shalvi Palande, Angelika Mader, Pablo Cesar, and Kaspar Jansen. 2023. BreatheWithMe: Exploring Visual and Vibrotactile Displays for Social Breath Awareness during Colocated, Collaborative Tasks. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*. ACM, Hamburg Germany, 1–8. https://doi.org/10.1145/3544549.3585589
[13] Alexz Farrall, Jordan Taylor, Ben Ainsworth, and Jason Alexander. 2023. Manifesting Breath: Empirical Evidence for the Integration of Shape-changing Biofeedback-based Artefacts within Digital Mental Health Interventions. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. ACM, Hamburg Germany, 1–14. https://doi.org/10.1145/3544548.3581188
[14] Esther Foo, Justin Baker, Crystal Compton, and Brad Holschuh. 2020. Soft Robotic Compression Garment to Assist Novice Meditators. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM, Honolulu HI USA, 1–8. https://doi.org/10.1145/3334480.3382919
[15] Jérémy Frey, May Grabli, Ronit Slyper, and Jessica R. Cauchard. 2018. Breeze: Sharing Biofeedback through Wearable Technologies. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, Montreal QC Canada, 1–12. https://doi.org/10.1145/3173574.3174219
[16] Ikuo Homma and Yuri Masaoka. 2008. Breathing rhythms and emotions. *Experimental Physiology* 93, 9 (Sept. 2008), 1011–1021. https://doi.org/10.1113/expphysiol.2008.042424
[17] Ravinder Jerath, John W. Edry, Vernon A. Barnes, and Vandna Jerath. 2006. Physiology of long pranayamic breathing: Neural respiratory elements may provide a mechanism that explains how slow deep breathing shifts the autonomic nervous system. *Medical Hypotheses* 67, 3 (Jan. 2006), 566–571. https://doi.org/10.1016/j.mehy.2006.02.042
[18] Tao Jiang, Junwen Zhong, Jiaming Liang, Yichuan Wu, Zehui Li, Xiaohao Wang, Liwei Lin, and Xiang Qian. 2019. Wearable Airflow Sensor for Nasal Symmetric Evaluation and Respiration Monitoring. In *2019 IEEE SENSORS*. IEEE, Montreal, QC, Canada, 1–4. https://doi.org/10.1109/SENSORS43011.2019.8956504
[19] A. S. Jones, D. J. Willatt, and L. M. Durham. 1989. Nasal airflow: resistance and sensation. *The Journal of Laryngology & Otology* 103, 10 (Oct. 1989), 909–911. https://doi.org/10.1017/S0022215100110485
[20] Annkatrin Jung, Miquel Alfaras, Pavel Karpashevich, William Primett, and Kristina Höök. 2021. Exploring Awareness of Breathing through Deep Touch Pressure. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. ACM, Yokohama Japan, 1–15. https://doi.org/10.1145/3411764.3445533
[21] Mahin Kamalifard, Mahnaz Shahnazi, Manizheh Sayyah Melli, Shirin Allahverdizadeh, Shiva Toraby, and Atefeh Ghahvechi. 2012. The Efficacy of Massage Therapy and Breathing Techniques on Pain Intensity and Physiological Responses to Labor Pain. *Journal of Caring Sciences* 1, 2 (2012), 73–8. https://doi.org/10.5681/JCS.2012.011 Medium: text/html Publisher: Tabriz University of Medical Sciences.
[22] Pavel Karpashevich, Pedro Sanches, Rachael Garrett, Yoav Luft, Kelsey Cotton, Vasiliki Tsaknaki, and Kristina Höök. 2022. Touching Our Breathing through Shape-Change: Monster, Organic Other, or Twisted Mirror. *ACM Transactions on Computer-Human Interaction* 29, 3 (June 2022), 1–40. https://doi.org/10.1145/3490498
[23] Jina Kim, Young-Woo Park, and Tek-Jin Nam. 2015. BreathingFrame: An Inflatable Frame for Remote Breath Signal Sharing. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, Stanford California USA, 109–112. https://doi.org/10.1145/2677199.2680606
[24] Esther Koh, Mythri Ambatipudi, DaLoria L. Boone, Julia B. W. Luehr, Alena Blaise, Jose Gonzalez, Nishant Sule, David J. Mooney, and Emily M. He. 2022. Quantifying face mask comfort. *Journal of Occupational and Environmental Hygiene* 19, 1 (Jan. 2022), 23–34. https://doi.org/10.1080/15459624.2021.2002342
[25] Jinwoo Lee, Heayoun Sul, Wonha Lee, Kyung Rok Pyun, Inho Ha, Dongkwan Kim, Hyojoon Park, Hyeonjin Eom, Yeosang Yoon, Jinwook Jung, Dongjun Lee, and Seung Hwan Ko. 2020. Stretchable Skin-Like Cooling/Heating Device for Reconstruction of Artificial Thermal Sensation in Virtual Reality. *Advanced Functional Materials* 30, 29 (July 2020), 1909171. https://doi.org/10.1002/adfm.201909171
[26] J. Lindemann, R. Leiacker, G. Rettinger, and T. Keck. 2002. Nasal mucosal temperature during respiration. *Clinical Otolaryngology and Allied Sciences* 27, 3 (June 2002), 135–139. https://doi.org/10.1046/j.1365-2273.2002.00544.x
[27] Sunniva Liu, Jianzhe Gu, Dinesh K Patel, and Lining Yao. 2024. breatHaptics: Enabling Granular Rendering of Breath Signals via Haptics using Shape-Changing Soft Interfaces. In *Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, Cork Ireland, 1–11. https://doi.org/10.1145/3623509.3633372
[28] Xin Liu. 2017. Masque: A Misheard Self. In *Inward to Outward*. Massachusetts Institute of Technology, Cambridge, Massachusetts, USA, 48–63. http://hdl.handle.net/1721.1/114069
[29] Lars Malm. 1997. Measurement of nasal patency. *Allergy* 52 (Dec. 1997), 19–23. https://doi.org/10.1111/j.1398-9995.1997.tb04879.x
[30] Joe Marshall, Duncan Rowland, Stefan Rennick Egglestone, Steve Benford, Brendan Walker, and Derek McAuley. 2011. Breath control of amusement rides. In *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11*. ACM Press, Vancouver, BC, Canada, 73. https://doi.org/10.1145/1978942.1978955
[31] Jelena Mladenović, Jérémy Frey, and Jessica R. Cauchard. 2018. Dišimo: Anchoring Our Breath. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*. ACM Press, Montreal QC, Canada, 1–4. https://doi.org/10.1145/3170427.3186517
[32] Neema Moraveji, Ben Olson, Truc Nguyen, Mahmoud Saadat, Yaser Khalighi, Roy Pea, and Jeffrey Heer. 2011. Peripheral paced respiration: influencing user physiology during information work. In *Proceedings of the 24th annual ACM symposium on User interface software and technology - UIST '11*. ACM Press, Santa Barbara, California, USA, 423. https://doi.org/10.1145/2047196.2047250
[33] Caitlin Morris, Pinyao Liu, Bernhard E. Riecke, and Pattie Maes. 2023. InExChange: Fostering Genuine Social Connection through Embodied Breath Sharing in Mixed Reality. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*. ACM, Hamburg Germany, 1–5. https://doi.org/10.1145/3544549.3583917
[34] Pablo Paredes and Matthew Chan. 2011. CalmMeNow: exploratory research and design of stress mitigating mobile interventions. In *CHI '11 Extended Abstracts on Human Factors in Computing Systems*. ACM, Vancouver BC Canada, 1699–1704. https://doi.org/10.1145/1979742.1979831
[35] Sungmee Park and Sundaresan Jayaraman. 2021. From containment to harm reduction from SARS-CoV-2: a fabric mask for enhanced effectiveness, comfort, and compliance. *The Journal of The Textile Institute* 112, 7 (July 2021), 1144–1158. https://doi.org/10.1080/00405000.2020.1805971
[36] Pierre Philippot, Gaëtane Chapelle, and Sylvie Blairy. 2002. Respiratory feedback in the generation of emotion. *Cognition & Emotion* 16, 5 (Aug. 2002), 605–627. https://doi.org/10.1080/02699930143000392
[37] Jasper Shen, Kevin Hur, Kai Zhao, Donald Leopold, and Bozena Wrobel. 2017. Determinants and Evaluation of Nasal Airflow Perception. *Facial Plastic Surgery* 33, 04 (Aug. 2017), 372–377. https://doi.org/10.1055/s-0037-1603788
[38] Jeffrey C. Smith, Ana P.L. Abdala, Anke Borgmann, Ilya A. Rybak, and Julian F.R. Paton. 2013. Brainstem respiratory networks: building blocks and microcircuits. *Trends in Neurosciences* 36, 3 (March 2013), 152–162. https://doi.org/10.1016/j.tins.2012.11.004
[39] Jeffrey C. Smith, Ana P. L. Abdala, Ilya A. Rybak, and Julian F. R. Paton. 2009. Structural and functional architecture of respiratory networks in the mammalian brainstem. *Philosophical Transactions of the Royal Society B: Biological Sciences* 364, 1529 (Sept. 2009), 2577–2587. https://doi.org/10.1098/rstb.2009.0081
[40] Tobias Sonne and Mads Møller Jensen. 2016. ChillFish: A Respiration Game for Children with ADHD. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction - TEI '16*. ACM Press, Eindhoven, Netherlands, 271–278. https://doi.org/10.1145/2839462.2839480
[41] Florian Soyka, Markus Leyrer, Joe Smallwood, Chris Ferguson, Bernhard E. Riecke, and Betty J. Mohler. 2016. Enhancing stress management techniques using virtual reality. In *Proceedings of the ACM Symposium on Applied Perception*. ACM, Anaheim California, 85–88. https://doi.org/10.1145/2931002.2931017
[42] Misha Sra, Xuhai Xu, and Pattie Maes. 2018. BreathVR: Leveraging Breathing as a Directly Controlled Interface for Virtual Reality Games. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*. ACM Press, Montreal QC, Canada, 1–12. https://doi.org/10.1145/3173574.3173914
[43] Michael G. Stewart, David L. Witsell, Timothy L. Smith, Edward M. Weaver, Bevan Yueh, and Maureen T. Hannley. 2004. Development and Validation of the Nasal Obstruction Symptom Evaluation (NOSE) Scale. *Otolaryngology–Head and Neck Surgery* 130, 2 (Feb. 2004), 157–163. https://doi.org/10.1016/j.otohns.2003.09.016
[44] Rujia Sun, Xiaohe Zhou, Benjamin Steeper, Ruidong Zhang, Sicheng Yin, Ke Li, Shengzhang Wu, Sam Tilsen, Francois Guimbretiere, and Cheng Zhang. 2023. EchoNose: Sensing Mouth, Breathing and Tongue Gestures inside Oral Cavity using a Non-contact Nose Interface. In *Proceedings of the 2023 International Symposium on Wearable Computers*. ACM, Cancun, Quintana Roo Mexico, 22–26. https://doi.org/10.1145/3594738.3611358
[45] Xiaotian Sun and Kiyoshi Tomimatsu. 2017. Breath Is to Be Perceived - Breathing Signal Sharing Involved in Remote Emotional Communication. In *Distributed, Ambient and Pervasive Interactions*, Norbert Streitz and Panos Markopoulos (Eds.). Vol. 10291. Springer International Publishing, Cham, 472–481. https://doi.org/10.1007/978-3-319-58697-7_35 Series Title: Lecture Notes in Computer Science.
[46] Markus Tatzgern, Michael Domhardt, Martin Wolf, Michael Cenger, Gerlinde Emsenhuber, Radomir Dinic, Nathalie Gerner, and Arnulf Hartl. 2022. AirRes Mask: A Precise and Robust Virtual Reality Breathing Interface Utilizing Breathing Resistance as Output Modality. In *CHI Conference on Human Factors in Computing Systems*. ACM, New Orleans LA USA, 1–14. https://doi.org/10.1145/3491102.3502090
[47] Paul Tennent, Duncan Rowland, Joe Marshall, Stefan Rennick Egglestone, Alexander Harrison, Zachary Jaime, Brendan Walker, and Steve Benford. 2011. Breathalising games: understanding the potential of breath control in game interfaces. In *Proceedings of the 8th International Conference on Advances in Computer Entertainment Technology - ACE '11*. ACM Press, Lisbon, Portugal, 1. https:

//doi.org/10.1145/2071423.2071496

[48] Linlin Tu, Chongguang Bi, Tian Hao, and Guoliang Xing. 2018. BreathCoach: A Smart In-home Breathing Training System with Bio-Feedback via VR Game. In *Proceedings of the 2018 ACM International Joint Conference and 2018 International Symposium on Pervasive and Ubiquitous Computing and Wearable Computers - UbiComp '18*. ACM Press, Singapore, Singapore, 468–471. https://doi.org/10.1145/3267305.3267582

[49] Shun-Yu Wang, Chia-Yu Cheng, Shu-Meng Huang, Weng Io Chan, Yu-Hsuan Huang, and Jhih-Wei Lin. 2023. Breathero: Not Another Slow Breathing Game — Exploring Faster-Paced VR Breathing Exercise Games. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*. ACM, Hamburg Germany, 1–7. https://doi.org/10.1145/3544549.3583829

[50] D. J. Willatt and A. S. Jones. 1996. The role of the temperature of the nasal lining in the sensation of nasal patency. *Clinical Otolaryngology* 21, 6 (Dec. 1996), 519–523. https://doi.org/10.1111/j.1365-2273.1996.tb01102.x

[51] Xiaoguang Yan, Susanne Menzel, Kai Zhao, Kanghyun Kim, and Thomas Hummel. 2023. Intranasal trigeminal sensitivity to mechanical stimuli is associated with the perception of nasal patency. *European Archives of Oto-Rhino-Laryngology* 280, 12 (Dec. 2023), 5391–5399. https://doi.org/10.1007/s00405-023-08126-2

[52] I. Yoshiya, T. Nakajima, I. Nagai, and S. Jitsukawa. 1975. A bidirectional respiratory flowmeter using the hot-wire principle. *Journal of Applied Physiology* 38, 2 (Feb. 1975), 360–365. https://doi.org/10.1152/jappl.1975.38.2.360

[53] Kai Zhao, Kara Blacker, Yuehao Luo, Bruce Bryant, and Jianbo Jiang. 2011. Perceiving Nasal Patency through Mucosal Cooling Rather than Air Temperature or Nasal Resistance. *PLoS ONE* 6, 10 (Oct. 2011), e24618. https://doi.org/10.1371/journal.pone.0024618

[54] Daniel Zielasko, Sebastian Freitag, Dominik Rausch, Yuen C. Law, Benjamin Weyers, and Torsten W. Kuhlen. 2015. BlowClick: A Non-Verbal Vocal Input Metaphor for Clicking. In *Proceedings of the 3rd ACM Symposium on Spatial User Interaction - SUI '15*. ACM Press, Los Angeles, California, USA, 20–23. https://doi.org/10.1145/2788940.2788953

Received 20 February 2007; revised 12 March 2009; accepted 5 June 2009