BreatheWithMe: Exploring Visual and Vibrotactile Displays for Social Breath Awareness during Colocated, Collaborative Tasks

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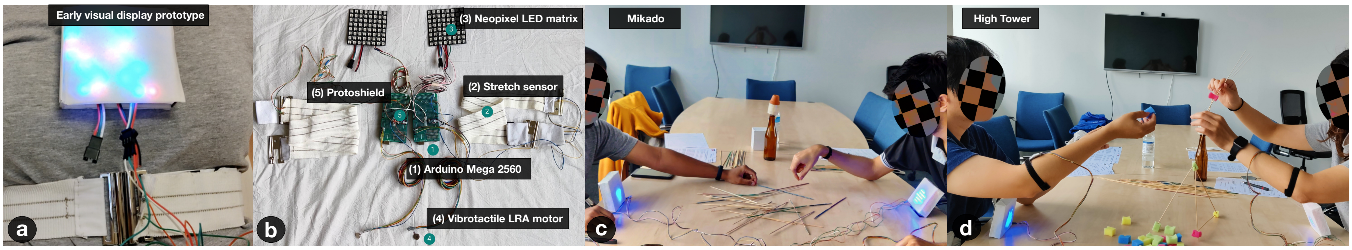

Figure 1: (a) Early chest-worn prototype (b) BreatheWithMe components (c) participants playing Mikado and (d) playing High Tower.

ABSTRACT

Sharing breathing signals has the capacity to provide insights into hidden experiences and enhance interpersonal communication. However, it remains unclear how the modality of breath signals (visual, haptic) is socially interpreted during collaborative tasks. In this mixed-methods study, we design and evaluate BreatheWithMe, a prototype for real-time sharing and receiving of breathing signals through visual, vibrotactile, or visual-vibrotactile modalities. In a within-subjects study (15 pairs), we investigated the effects of modality on breathing synchrony, social presence, and overall user experience. Key findings showed: (a) there were no significant effects of visualization modality on breathing synchrony, only on deliberate music-driven synchronization; (b) visual modality was preferred over vibrotactile feedback, despite no differences across social presence dimensions; (c) BreatheWithMe was perceived to be an insightful window into others, however included data exposure and social acceptability concerns. We contribute insights into the design of multi-modal real-time breathing visualization systems for colocated, collaborative tasks.

CCS CONCEPTS

- **Human-centered computing → Human computer interaction (HCI).**

KEYWORDS

Breathing, respiration, mutltimodal, LED, visual, haptics, awareness, social interactions, collaborative, dyadic

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1 INTRODUCTION

Breathing presents unique opportunities for interaction due to its dual nature as an autonomic process that is also easily controlled by paying attention to it. Breathing patterns are closely connected to our health, emotions, and cognitive state [19, 60], and can also serve as a tacit component of social interaction [33]. Technological advancements in biosensing have made it possible to reveal hidden physiological data (biosignals), which can provide valuable insights into others' emotional and cognitive states [48]. This relates to recent efforts toward sensible human-computer integration [7, 21, 41], where one may sense information that is otherwise difficult to perceive and recognize due to physical or cognitive limitations, or

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otherwise normally hidden during face-to-face interactions. Researchers have found that "expressive" biosignals, when displayed as a social cue, have the potential to enhance interpersonal communication and increase interoceptive awareness [15, 29, 36], which can help us better recognize and express our own and others' emotional and physical states across real [13, 14, 20, 31, 37] and virtual reality environments [22, 27, 52]. While several works have explored a wide-range of breath-responsive systems (cf., [22, 47, 52]), with some works exploring multiple modalities (visual, audio, haptic) [14], it remains unclear how the modality of *social* breath signals can influence collaborative experiences. To address this gap, we sought to explore how the visual and vibrotactile modalities are socially interpreted during dyadic, collaborative tasks, and to what extent they can influence partners' respiration rates and social perceptions.

In this work, we adopt an exploratory, mixed-methods approach that combines a user-centric process [42], qualitative analysis, and statistical methods to better understand, design, and evaluate multimodal real-time breathing visualization systems during collocated, collaborative tasks. We design the BreathWithMe prototype as a design prop to uniquely explore what effects sharing breathing through visual and haptic modalities would have on social interactions in a collaborative context. We ask: **(RQ)** What are the effects of visual and vibrotactile breathing displays on social breath experience during collaborative tasks? In a within-subjects experiment with pairs of users (N=15), we investigate the effect of actuation modality (Visual vs. Vibrotactile vs. VisualVibrotactile) on their breathing synchrony, social presence, and their overall experience of sharing and receiving modality-dependent breathing data. We contribute insights and design considerations for sharing and receiving breathing signals across visual and haptic modalities.

2 RELATED WORK

2.1 Breath-responsive systems for mind, body, and social connection

A large body of works in human-computer interaction, art, and design engages breathing as an interaction mode. Prpa et al. [44] classified breath-responsive systems into 4 frameworks: breathing regulation, mindfulness, somaesthetics, and social. Breathing regulation systems support mental and physical health by promoting a beneficial breathing rate. Mindfulness systems capitalize on breath's capacity to help cultivate our attention. Somaesthetics approach values the full experience of feelings one's breathing in one's body. And the social systems use breathing to augment communication, and promote empathy and connection. Among these, social systems are the least prolific. Yet, recently they have been gaining more popularity. E.g. *JeL* [52], *In the same boat* [47], and *DYNECOM* [22] promote breathing synchronization to stimulate connection. Other systems use breathing to create an ambient presence of a distant loved one[25], or to augment communication by offering an insight into other's state [53]. While these works provide initial insights into the effects of mediating social breathing, they have not explored users' perceptions of different modalities.

2.2 Visualizing human biosignals across modalities

Representing biosignals has numerous benefits, including increasing engagement and reducing stress [16], enhancing engagement and immersion in games [46], improving bodily awareness [55], as well as increasing co-presence [13] and empathy and social connectedness [8, 30, 51]. For more information on the use of biosignals in a social context, see Moge et al.'s review [38]. Howell et al. has also shown that biological signals are open to various interpretations [20], which can affect how they are shared [17] and in what modality they are best represented in [31]. The method of representation often depends on the context and social setting [32]. Researchers have explored various visual and non-visual ways to represent these signals, particularly heart rate, such as through ambient light [29, 50, 58], brightness and frequency [14], and haptic feedback [14, 37, 56]. For an overview of these different representations, the reader can refer to Lux et al.[32]. While these works investigate different representations of biosignals, there is little research comparing these representation methods [29] and how it effects perception and meaning-making. The foregoing served as groundwork for further exploring the role of modalities in social breath awareness systems.

3 BREATHEWITHME PROTOTYPE

3.1 Design considerations

Dagan et al. [9] show that the visual modality easily catches attention given human familiarity with interpreting visual cues through movement, shape, and light. We furthermore draw on Zeagler's [61] functional and technical considerations for on-body wearables. Here, we created a direct mapping (see [44]) between breathing, and visual and vibrotactile actuation. This enables the social portrayal of a person's breathing data on each interacting partner's displays. The vibrotactile motors were tested on the upper arm and forearm [23], also keeping in mind acceptability of social touching on the body [54]. Furthermore, whereas we initially wanted the visual display to be mounted on the chest (Fig. 1(a)), similar to prior work [10], this was abandoned due to the weight of the prototype, and for social acceptability considerations. Due to this, for the visual display, we drew instead on peripheral visual interaction research [4, 35] to provide diffused LED-based breathing biofeedback to users in an ambient manner.

3.2 Hardware and software

We employed a stretch sensor to measure the change in resistance of a conductive yarn during the chest expansion and contraction of a person's inhalation and exhalation. Our final prototype setup consists of two sets of Arduino Mega 2560 microcontrollers, stretch sensors, visual and vibration actuators connected to a single laptop (Macbook Pro: 2 GHz Dual-Core Intel Core i5 Processor). A protoshield was used to fix all the connections of all components (see Fig. 1(b)). To ensure that the wires do not move during the handling of the prototype, wires were fixed onto the protoshield using hot glue. Finally for bidirectional exchange of breathing data, both the microcontrollers were connected with each other using jumper wires. The data logging consisted of a timestamp, raw value of resistance

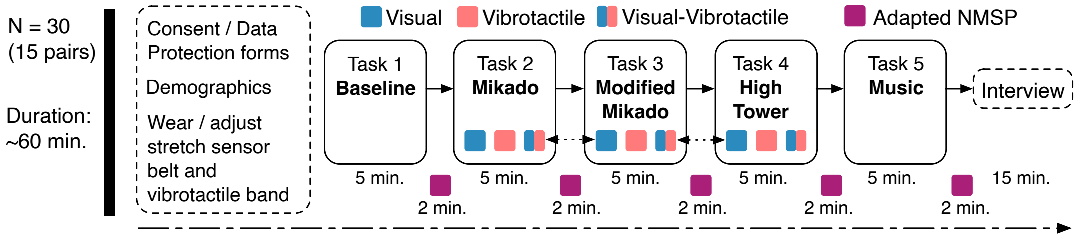

Figure 2: Study procedure.

change, and the type of condition selected. The amplitude, phase and respiration rate calculation was performed retroactively after all the breathing data is collected to keep the time lag for actuation to a minimum. We used the Arduino IDE to read breathing data from sensors, and map the breathing signal to the visual and vibrotactile actuators.

3.2.1 Visual display. We used an 8*8 Neopixel LED matrix, which is configurable for real time analog input displays such as breathing patterns. LEDs were configured to light up depending on the breathing input received from the resistance change of the stretch sensor (see Supplementary Material A (video)). A circular pattern was selected to represent the breathing data, where the expanded circle illustrates inhalation and contracted circle illustrates exhalation. Given little research on mappings between biosignals and color hue, we defaulted on a familiar, less arousing (cold) blue for breath visualization [58, 59] (RGB: (0, 0, 255)). The LED matrix was placed in a plastic container wrapped with a textured fabric paper to diffuse the light intensity. As the display was to be used in a well lit room, the intensity of the matrix was kept at seventy five percent (brightness=100), after preliminary tests. The final prototype was mounted on the desk in front of each participant (see Fig. 1(c,d)).

3.2.2 Vibrotactile actuation. The vibrotactile actuator consisted of an LRA vibration motor attached to a DRV2605L driver. Motor amplitude was modulated as an analog sine wave signal for representing breathing pattern data. We used the haptic effects library, and set the waveform to 67 (Transition Hum 4 – 40%[1]). The motor and driver were secured to a piece of felt fabric, and then covered with plastic and fixed to a velcro strap which can be attached to participants' arms.

3.3 Methods

3.3.1 Study design and measures. Our experiment is a 3 (IV1: Modality: Visual vs. Vibrotactile vs. VisualVibrotactile) x 5 (IV2: Task: Baseline vs. Mikado vs. ModifiedMikado vs. HighTower vs. Music) within-subjects design, tested in a controlled, environment (Figure 1(c,d)). This resulted in 15 conditions, where Baseline and Music were fixed and had no modality feedback. Remainder of conditions were counterbalanced using a Latin Square design. Quantitative measures included: (a) Respiration data from participants (b) Ten items from the Networked Minds Social Presence (NMSP) [5] questionnaire that were adapted to our study (Cronbach's α=0.86), with six questions on mutual attention, two on empathy, and two on dependent action (see Supplementary Material B). For qualitative measures, we ran a paired-participant semi-structured interview. This helped ensure participants' impressions are more directly related to their activities and experiences. The consensually audio-recorded interviews included questions on attention, sharing, and modality preferences (see Supplementary Material B). Our study followed strict guidelines (including approval) from our institute's ethics and data protection committee, including COVID-19 regulations.

3.4 Tasks

We used existing HCI task models [43] based on cooperation and collaboration to explore social respiratory behavior. Participants were requested to play games which focus on balance, concentration, and collaboration between two people. To this end, we chose the pick-up sticks game Mikado[2], and variations of it, which consisted of Mikado sticks, a narrow mouthed bottle, and sponge cubes. All tasks were performed for 5 minutes. The first condition was to collect baseline breathing data during informal conversation, consisting of one or more ice breaking questions taken from [2] (e.g., "Tell us a story of the first time you met"). The second task consisted of playing Mikado, where a set of wooden sticks are randomly placed on the table. The rules of the game are each participant takes a turn to pick up a stick from a pile of sticks without moving the other sticks. The third task was a modified version of Mikado, where each participant had a single stick in their hand, and while holding, both participants had to pick up a third stick and place it in the bottle. Participants could discuss and decide their strategy. The last task was a High Tower task, where using double the number of sticks from the bottle along with the sponge cubes, participants were requested to build a high tower together, that would remain stable for the allotted 5 minutes. The last task was to listen to soothing music together[3] (no actuation) and deliberately synchronize breathing. Detailed task descriptions are in Supplementary Material B.

3.5 Study procedure

Our study procedure is shown in Fig. 2. Participants first read the instructions, signed the consent form, and were explained the procedure. They were then equipped with the stretch sensor on the lower chest and the vibrotactile actuator on the forearm. The experiment consisted of breathing data collection for five conditions starting

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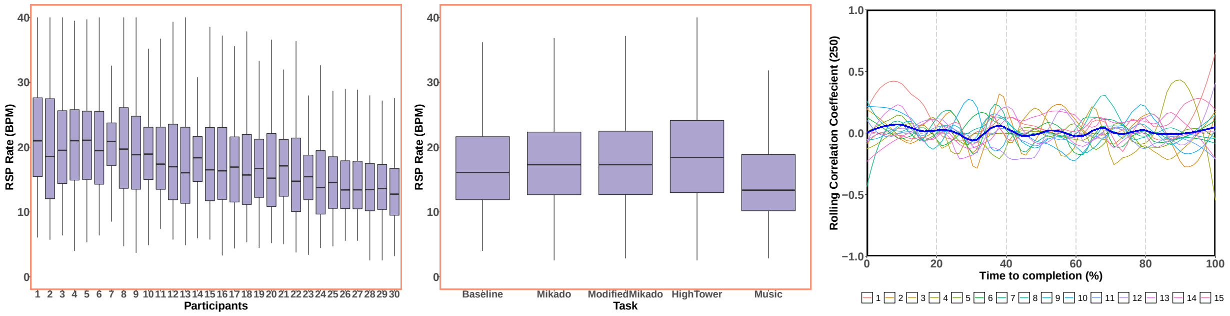
[1] https://www.ti.com/lit/ds/symlink/drv2605.pdf#page=57

[2] https://en.wikipedia.org/wiki/Mikado_(game)

[3] John Ocean - Nature; https://youtu.be/mukMaYNzaOY



(a) Participant respiration rates (ordered).

(b) Respiration rate across tasks.

(c) Synchrony (Pearson rolling correlation coefficient) for all participant pairs over normalized session time. Thick blue line shows the average.

Figure 3:

with baseline data and ending with deliberate breath synchronization. Each condition lasted for approximately five minutes, with a two minute break between conditions, during which participants filled in the adapted NMSP [5]. Lastly, participants underwent a semi-structured interview, and were rewarded with a €10 voucher for participating.

3.5.1 Participants. 30 participants (15 pairs: eleven male-female, three male-male, and one female-female) aged 22-29 ($Md = 25$, $IQR = 2.75$) were recruited[4]. From these fifteen pairs, two pairs were married, four pairs were colleagues, three pairs were classmates, four pairs were housemates, and two pairs were friends. Participants spanned eight nationalities, and all but three pairs knew each other for at least one year.

4 RESULTS

4.1 Preprocessing and data validity

Raw data was recorded with the sampling rate of 50 samples per second. We used Python's Neurokit2 [34] to preprocess the data, and subsequently cleaned, normalized and a Butterworth lowpass filter applied (20Hz; cutoff=2; Nyquist Frequency = 0.4). We used the Khodadad et al. [24] method for signal preprocessing as it uses a fifth order low pass filter, and largely blocks out any high frequencies from the detected data. Our breathing dataset contained 924,086 records. We detected and removed any RSP outliers, by using the Interquartile Range (IQR) method. We removed any values that are 1.1 times the IQR greater than the third quartile or 1.1 times the IQR less than the first quartile. We chose 1.1 instead of the common 1.5 to lower any false positives. This resulted in removal of 7.2% (61,664) records (resulting size = 862,422). We show breaths per minute (BPM) per participant[5] as ordered boxplots in Fig. 3(a), and for tasks in Fig. 3(b).

4.2 Effects of modality and task on breathing synchrony

To assess any potential breathing synchronization, we compute a Pearson rolling cross correlation (with 250 samples), and plot this in Fig. 3(c). Sliding-window correlation measures are common in brain imaging dynamic functional connectivity research [18] as well as in HCI research (e.g., synchrony in EDA measures [49]), though more advanced methods exist (e.g., windowed cross-correlation [45]). To test this, we ran a gaussian Generalized Linear Model for modality as predictor and mean correlation as response variable, $\beta_0 + \beta_1(\text{Modality}) + \varepsilon$, however we did not find any significant effects. We then run a similar model on task, to avoid collinearity effects and test all task conditions, $\beta_0 + \beta_1(\text{Task}) + \varepsilon$, and find a significant effect only for Music (β=0.04, SE=0.02, p<0.05; Odds Ratio = 1.0387353, 95% CI [1.0, 1.08]). Detailed results provided in Supplementary Material C.

4.3 Adapted 10-item NMSP results

We show our adapted NMSP responses as boxplots in Fig. 4. We analyzed the combined effects of Modality (including Baseline and Music) and NMSP question by fitting a full linear mixed-effects model on our data. Since our data distribution here is not normal, we applied the aligned rank transform prior to fitting [57]. Post-hoc contrast tests were performed using ART-C [11]. Analysis of deviance model showed significance for main (Modality=$F_{1,4} = 35.67, p < .001$; NMSP = $F_{1,9} = 5.16, p < .001$) as well as interaction effects ($F_{9,36} = 13.25, p < .001$). Post-hoc contrasts for Modality revealed significant differences at 1% level for all but Vibrotactile-Visual, Vibrotactile-VisualVibro, and Visual-VisualVibro, which shows that each of our tested modalities did not differ from one another with respect to NMSP dimensions. Contrast tests for Modality and NMSP questions are provided in Supplementary Material C.

4.4 Interviews

We analyzed the data with inductive thematic analysis [6]. First we coded it according to evoked topics. Then within each topic we analyzed emerging themes. Pairs are labeled P1-P15 (P#-1 and P#-2 delineating the two participants).

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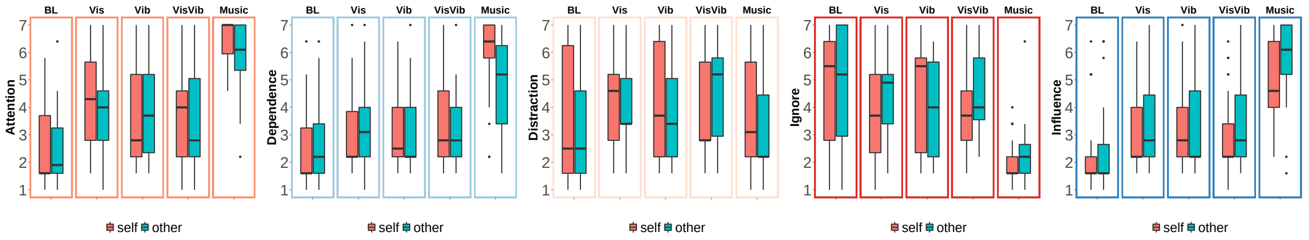
[4] Using G* Power [12], for effect size f=0.25 under α = 0.05 and power (1-β) = 0.9, with 5 repeated measurements within factors, and Task as within-subjects factor, one would need 26 participants.

[5] Participant identifiers have been randomly shuffled for data privacy.



(a) "I / my partner paid close attention to my / partner's breathing pattern."

(b) "My / partner's breathing pattern was often dependent on my / partner's breathing pattern."

(c) "I / my partner was easily distracted from my / partner's breathing pattern..."

(d) "I / my partner tended to ignore my / partner?s breathing pattern."

(e) "I / my partner was able to influence my / partner's breathing pattern.".

Figure 4: Adapted items from the Networked Minds Social Presence (NMSP) questionnaire.

4.4.1 Differences between visual and haptic modality. While there was no consensus, overall participants tend to prefer the visual modality.Important factors were **interpretability** and **salience** of the actuation. Visual actuators seemed more *"intuitive"* [P4-1]:*" I couldn't understand the inhale or exhale properly with only the vibration, so I used to look at the visual one"* [P11-2]. However, the vibration was deemed more subtle supporting an ambient presence of the signal, that doesn't need to be attended to.This relationship between factors and actuators was not ubiquitous, as some participants felt the light was less salient then vibration as they could just see it *"from the corner of* [their] *eyes"* [P10-1]: *"once the vibrations were on I was mindful about his breathing...Once the vibration was off, I didn't pay attention, because the LED lights were not in your face."* [P12-1]. Salience also related to the factor of **availability of information** to both partners. P12-2 explained their preferences for vibrational actuator: *"I don't think I would like portraying my visuals. I would be tempted to look at my own visual."*. This created a trade-off between the interpretability of the actuated signal offered by the visual modality, and the ambient presence of the vibrational one: *"Vibration is softer, as in it will blend it. As in the way friendship happens you just get into it, you don't decide it. But with seeing, the visual experience is different. As in you understand that the wavelength is matching."* [P3-1].

4.4.2 Meaning-making. Participants had diverse ideas of how to interpret their partner's breathing signal. One common theme was a sign of **other's emotional state**, such as tension or calmness: *I was more aware of when he was a little more tense. When he took a deep inhale.* [P12-1] When speculating about the future use participants thought it could let them better understand and adapt to other's mood: *"it'll be easier to understand the vibe of the room as well. If people are excited or if they are in a sad mood. I could sense the mood before I start interacting with them, and then I can act accordingly".* [P9-1]. Other participants considered the signal as a **reflection of the quality of connection**: *"You can get to know the bond between the other person through breathing. Like is she paying attention to me, does she try to synchronize with me."* [P10-2], or the representation of **live and humanness**: *"I think it's a signal of our existence..."*[P5-1]. Another prominent interpretation was potential **comparison to norm**. Participants often speculated that seeing breathing data would tell how far away someone might be from the "correct" breathing: *it would be nice to know if you are breathing the right way. I think it's pretty cool to be sharing breathing patterns.* [P12-1]. This potential normative interpretation made some participants feel more hesitant about sharing their data: *"Let's say I climb stairs and start breathing heavily. If a person is close to me they'll question why I'm breathing so hard. Even if physically it makes sense, I'm still embarrassed."* [P11-1]).

4.4.3 Effects of social breath. Participants could use other's breathing for **emotion regulation**: *"I was influenced by his breath when I was getting anxious. He is so calm all the time... I tried to make myself calm by following his breathing."* [P8-2]. Another benefit of sharing breathing is its effect on **perceived intersubjectivity**. [P10-1] proclaimed: *"Oh yeah! Haha. It's intense, especially in the last task when you have the same breathing <...>I don't know how to describe it, but it's like you're on the same level, frequency I guess.* However, the most prominent theme was the **vulnerability of being exposed**, which could make participants *"nervous"* [P3-2] . P12-2 talked about sharing breathing: *"It's just unnecessary stress. Sometimes I'm stressed but not everyone needs to know about it."*. This also relates to the **performativity** theme, as participants felt like they would have to be on their best breathing behaviour if they knew that their breathing was *"showcased"* [P15-1]. This lead to participants deliberately adjusting their breathing to communicate it better: *"Normally I don't do heavy breathing, but looking at the visual actuator I did take some heavy breaths. Understanding I could see my partner's breathing and that he could see my own, I wanted to emphasize my breathing more prominently."* [P10-2]. Besides this collaborative motivation P15-2 speculated that a more deliberate breathing may arise from a competitive motivation: *"even if everybody breathes, there will be upstaging each other to maybe see who is more mindful or something"*.

4.4.4 Value of mediation. While others' breathing is always available for our perception, the technological mediation offered an additional value, for instance by making overt attention more **socially acceptable**: *"I can't look at her chest, she's a girl, it's awkward"* [P10-2]. P2-1 discussed how the haptic actuation comforted them by feeling their friend's breathing, while it wasn't possible without the mediation: *"It would have been weird if he was actually breathing on my body, but because it was just actuation it felt good. Especially with COVID. Knowing there is somebody who is breathing and who is* *connected—it's nice."*. They also elaborated that the light actuation made it easier to pay attention to their partner's breathing while still focusing on the task. Participants also speculated that longer term effects may be enabled through systems' initial **attenuating role**: *"After doing this experiment with the actuator, I feel like I would observe other people breathing, even without any actuators. But with the help of the actuators, it helps take the first step"* [P4-2].

5 DISCUSSION AND CONCLUSION

5.1 Limitations

Our study had several limitations: missing measurements of sensing to actuation delay; preset actuation not accounting for individual sensitivities (e.g., vibration-induced skin desensitization [1]); display salience may have been too high to be fully ambient or peripheral (cf., [4]), which could have distracted participants from their task (cf., NMSP distraction ratings in Fig. 4(c)). Despite these limitations, BreathWithMe still served its generative purpose as a design prop.

5.2 Towards multi-modal mutual breath awareness in dyadic, collaborative interactions

In this work, we asked (**RQ**) what effects visual and vibrotactile breathing displays can have on social breath experiences during colocated, collaborative tasks. To answer this, we designed and developed BreatheWithMe, a design probe which contributed insights and considerations for sharing and receiving social breathing signals across visual and haptic modalities: First, our BreatheWithMe prototype was overall an insightful window into how users perceive social breath in visual and vibrotactile form during collaborative tasks, including data exposure and social acceptability concerns. Such insight into oneself and others' has the capacity to go beyond our physiological capacities of emotion regulation and signaling of our internal emotional experiences [28], by making our physiological data a digital artifact that can be both public and private, depending on the modality used (cf., Sec 4.4.3). Second, while we found no significant effects of breathing modality visualization on breathing synchrony (as Pearson rolling correlation), deliberate breath synchronization while listening to music stimulated synchrony and a lower mean respiration rate, which lends validity to our prototype. Third, the visual modality was overall preferred over vibrotactile feedback (cf., Sec 4.4.1), despite that the absence of significant differences between modalities across the tested NMSP dimensions. However, vibrotactile feedback did not only create a more subtle ambient signal for some participants (cf., Sec 4.4.1), but also was more private, where the signal can only be available to the receiver, creating asymmetrical feedback for each partner. Lastly, we found that participants were willing to see others' breathing signals, but more reluctant to share their own. This echoes findings from Hassib et al. [17] and Lee et al. [27]. To this end, our work provided unique insights into the role that individual breath visualization modalities play within social breath-responsive systems.

5.3 Use cases and next steps for social breath-responsive systems

Throughout our interviews, several use cases for social breath-responsive systems arose. These included: augmenting video calls (e.g., Zoom) to better understand the state of the other person; supporting practices to ensure correct forms of breathing, which is reminiscent of ExoPranayama that facilitated group cohesiveness during yoga practice [39]; augmenting group interactions to help one get a sense of the room and attune to them; facilitating collaboration across tasks (cf., 'In the same boat' rowing together through breath-responsive social play [47]); and supporting new forms of telepresence and emotional communication (cf., BreathingFrame [25]). The foregoing provide promising areas for designing and deploying social breath-responsive systems across use cases, social contexts, and tasks.

Further, our work offers directions for future research: Our BreatheWithMe prototype brings to question users' sense of bodily agency [7] when continuously sharing breathing data with one another, where ambiguity (cf., Sec 4.4.2, 4.4.1), mis-inference, and manipulation can readily occur without a sensible control mechanism for *when* it is appropriate for such signals to be represented. For example, we saw that participants sometimes deliberately manipulated their breathing (Sec. 4.4.3) to improve their self-image. One consideration is how we can leverage the ambiguity of such physiological displays [20] to scale adoption of systems for public settings, to avoid misinterpretation or undesirable social displays, which can impact their social acceptability [26]. Second, such displays raise the question of where the locus of attention lies (cf., [3]) – are these displays guiding attention primarily to oneself, the other, or both? Our prototype made overt attention to other's breathing more socially acceptable (Sec. 4.4.4), since these otherwise private signals are now mediated through visual (public) or vibrotactile (private) displays. This brings to question how context-dependent *modality transitions* (e.g., from visual to vibrotactile) could support a traversal from public to private displays and vice versa? Lastly, we only considered two modalities, however it remains open how this extends to other modalities (cf., affective thermal displays [10]), and to digitally mediated environments (e.g., AR or VR displays). For the latter, steps have already been taken on how to visualize breathing in social VR [27], and how sensing and visualizing of virtual breath can increase the sensation of effort [40], yet it remains to be seen how such social breath visualization and awareness can facilitate new modes of virtual social interactions.

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