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Human Psychophysiology Is Influenced by Physical Touch With a "Breathing" Robot

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People often physically cling to others when afraid and doing so can downregulate negative emotional experiences (e.g., Coan et al., 2006). However, in some situations, physical touch may fail to downregulate emotional experiences—such as when an individual being touched is physiologically aroused themselves. To test this hypothesis, we built plush robots with motorized plastic ribcages that were manipulated to contract and expand to simulate human breathing patterns. Participants held these robots while we measured their heart rate before, during, and after watching a fear-eliciting stimulus. Consistent with our hypothesis, participants who interacted with robots that exhibited accelerated-breathing patterns experienced a pronounced increase in their own heart rate, compared to participants who held stable-breathing and non-breathing robots. These results indicate that holding or clinging to others engaged in accelerated breathing may be ineffective or detrimental for downregulating one's own physiological arousal.

Keywords: human–robot interaction, emotion contagion, fear, breathing

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People often touch or even cling to others when they are afraid. A frightened child might grasp a parent when startled, and adults will grab partners or friends during scary movies (Hertenstein et al., 2009, 2006). There is good reason for these behaviors; the mere presence of others can help downregulate negative emotion, and interpersonal emotion regulation benefits are heightened by physical touch with humans (Coan et al., 2006; Debrot et al., 2013; Rimé, 2007; Zaki & Williams, 2013) and service animals (Sokal et al., 2021; Wołyńczyk-Gmaj et al., 2021). However, in some contexts, touch might amplify rather than diminish arousal. Prior work suggests that tactile contact can convey another person's physiological state, including heightened arousal (Hertenstein et al., 2009, 2006), which could intensify the receiver's own physiological response.

Emotion contagion occurs when a person "catches" or comes to feel the same emotion as expressed by someone else (van Kleef & Côté, 2022; Hatfield et al., 1994). A large body of research has demonstrated that emotion contagion can occur by visually observing others' facial and postural emotion expressions; observers come to feel or express the same emotion themselves (De Gelder et al., 2004; Parkinson, 2020; van Kleef & Côte, 2022). In real-life situations of fear, however, contagion may be less likely to occur through observation of others' visible expressions, because fearful individuals tend to focus their attention toward the fear-eliciting stimulus rather than other interactants (e.g., Lipp & Derakshan, 2005; Öhman & Mineka, 2001), potentially limiting the likelihood of contagion through facial of postural cues.

Nonetheless, even without visual attention directed toward a fear-expresser or the ability to observe facial expressions, emotion may be transmitted via touch. When individuals experience fear and other high-arousal emotions, they display rapid and deep breathing (e.g., hyperventilation), an observable pattern that is different from that which occurs during low-arousal emotions such as sadness or calmness, which are instead characterized by slower and stable breathing (Boiten et al., 1994; Philippot et al., 2002). This physiological indicator is not specific to humans; many animals—including cats and dogs, which are commonly used for emotional support—exhibit changes in their breathing when frightened (e.g., Horwitz & Rodan, 2018; Palestrini et al., 2010). Given that breathing requires expansion and contraction of the chest, alongside other discernable body movements, individuals who physically contact a highly aroused individual might perceive these accelerated respiratory patterns through touch. Supporting this expectation, medical professionals are encouraged to both look *and feel* for evidence of chest movements (expansion and contraction) to

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All data are available online in the Open Science Framework repository at https://osf.io/mxfn2/?view_only=ae871379f67a451ea3734b3d3c3a3c6d (see Witkower, 2023). This work was supported by Social Sciences and Humanities Research Council of Canada awarded to Jessica L. Tracy.

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establish breathing during clinical assessments (e.g., Kaneko & Horie, 2012; Ragnarsdóttir & Kristinsdóttir, 2006). Breath patterns may therefore constitute an effective and widely generalizable mechanism for communicating emotion through touch (including across species). As a result, merely physically contacting others might lead to the perception of their emotional respiration patterns, resulting in the contagion of these emotional responses.

Few studies have tested whether one individual's distinctive breathing patterns elicit changes in another's physiological arousal through touch alone. The most closely related work (Waters et al., 2017) demonstrates that mothers induced to experience stress can transfer their affective state to their infants via touch. However, this research did not test whether accelerated breathing served as the mechanism transmitting emotion nor did it pinpoint which tactile factor might drive the effect (e.g., skin conductance, grip strength, body temperature, softness). Whether faster breathing can elicit physiological arousal in another individual through touch thus remains an open question.

Other studies have demonstrated that robots mimicking mammalian breathing patterns influence observers' perceptions of the robots' emotion and likeability (e.g., Bucci et al., 2017; Klausen et al., 2022; Terzioğlu et al., 2020). However, these studies have not assessed participants' own physiological experiences in response to interacting with an artificially breathing robot, so it remains unclear whether touching a robot exhibiting artificial breathing affects these responses. Several studies have found that individuals interacting with a robot exhibiting movements designed to mimic calm mammalian breathing patterns, compared to a nonmoving robot or no robot, report feelings of calmness and stress reduction (e.g., Asadi et al., 2022; Matheus et al., 2022; Moyle et al., 2017; Sefidgar et al., 2015; Shibata & Wada, 2011). However, these studies did not manipulate accelerated-breathing patterns, nor test whether different breathing patterns displayed by robots have different effects on human physiology. Furthermore, past research on this topic has been limited by small sample sizes affording low statistical power and reduced generalizability (Ns ≤ 38) and has relied heavily on within-subject manipulations that increase participants' awareness of manipulated changes, thus increasing demand characteristics.

Overall, prior research suggests that observed or felt breathing patterns effectively communicate diagnostic information about emotion experiences, and humans seek to touch or hold others as a means of downregulating their own emotions. It remains unclear, however, whether touching or holding others who display a variety of breathing patterns differentially influences individuals' own emotional or physiological experience. More specifically, previous studies have not addressed the question of whether one's own physiological arousal is affected by touching another individual who displays rapid breathing.

The Current Research

We tested whether (a) humans can detect and recognize "fear" by touching a robot displaying chest movements simulating hyperventilation and (b) touching a robot displaying these movements increases humans' own physiological arousal. To address these questions, we built a plush robot with a motorized plastic ribcage, allowing us to manipulate its precise "breathing" patterns to be either accelerated or stable. We recruited participants to hold this robot while watching a series of videos; participants' heart rate was measured throughout the procedure, including before, during, and after presentation of a fear-elicitation video stimulus. We hypothesized that participants holding a robot that displayed an accelerated-breathing pattern, seemingly in response to a fear-eliciting stimulus, would (a) detect and interpret the robot's movements as conveying fear and (b) demonstrate an increase in their own heart rate, compared to participants holding a robot displaying stable breathing or no-breathing movement. This research is the first to manipulate artificial respiratory patterns of an organism interacting physically with human participants and to test for human emotion and autonomic nervous system contagion via touch.

Method

Participants

One hundred seven undergraduate students from the University of British Columbia were recruited to participate, but we excluded four individuals whose heart rate data could not be matched to their self-report data due to a technical error. Our final sample thus consisted of 103 undergraduates (73% women, 26% men, 1% other; 49% East Asian, 20% White, 8% Middle Eastern, 6% Hispanic/Latino, 2% African American, 15% other; $M_{\text{age}} = 20.59$ years, $SD_{\text{age}} = 2.93$ years). A post hoc power analysis indicated that this sample size provided greater than 99% power to detect the observed change in HR within the accelerated-breathing condition (based on the reported multilevel model).[1]

Procedure

All participants watched an identical series of video clips while their heart rate was monitored and they held a fur-covered robot. Participants were instructed to hold the robot in their arms, hugging it against their chest (i.e., as they might a close relationship partner, parent, child, or pet), generating maximal physical contact. Participants kept their right hand under and left hand on top of the robot, with a PulseSensor heartbeat detector on the middle finger of their right hand. They wore a pair of Koss UR23IK headphones to deliver sound accompanying the video clips and minimize disruption from incidental mechanical noise from the robot. Participants were instructed to avoid engaging in any excess movement to prevent interference with the heartbeat reading from the finger sensor. Participants were also instructed to watch the computer screen throughout the duration of the experiment (see Figure 1 for the experimental setup).

The robot was roughly the size of a small house cat. It had a soft, plush, and furry covering (see Figure 1). We designed it to be shaped and sized like a small pet instead of a human for several reasons. First, intimate and convincing physical contact between humans, like clinging or hugging behavior, occurs following a high threshold of complex interpersonal, cultural, and social norms (Fromme et al., 1989; Suvilehto et al., 2015); in contrast, humans approach and touch domesticated animals with a much lower threshold (Hunt et al., 1992). Second, it is considerably more feasible to simulate the

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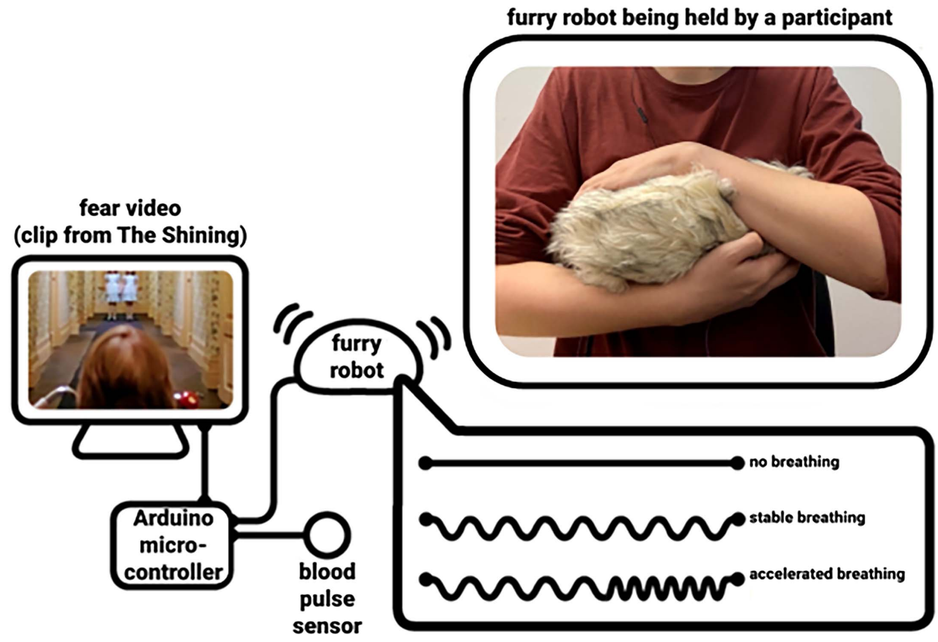
[1] It is noteworthy that this analysis does not estimate power for our primary hypothesis test. We were unable to find an intuitive method for conducting a power analysis for an interaction with a three-level factor in a mixed multilevel model analysis, and instead report power for the most important comparison: the increase in HR in response to the robot's accelerated breathing compared to other breathing conditions.

Figure 1
Diagram of the Experimental Setup



Note. This diagram shows a participant holding the fur-covered robot used in the present research (top right) as it displayed one of three breathing patterns (bottom right, manipulated between participants), while watching a video validated to elicit fear (left). The Arduino is a programable circuit board used to connect a computer to the robot and the blood pulse sensor. See the online article for the color version of this figure.

appearance of a furry animallike robot than a human, and this simulation is crucial, because robots that approach humanlike appearance but do not achieve it can elicit unsettling discomfort—an effect called the "uncanny valley" (Fong et al., 2003; Seyama & Nagayama, 2007). Finally, furry zoomorphic robots displaying breathing motions have previously been validated as reliably communicating emotional content (e.g., Bucci et al., 2016, 2017; Sefidgar et al., 2015).

To acclimate participants to the robot, they were asked to sit in a chair while holding and examining the robot. When each participant was ready to begin the experimental procedure, they were set up with headphones and the heartbeat sensor worn on their finger. Participants next watched 114 s of videos that were intended to acclimate them to the experimental context without eliciting strong emotions. The first 30 s consisted of a black screen accompanied by no sound, followed by an 84-second video of a snail crossing a wooden plank, which was accompanied by ambient sounds of nature in the background. The snail video was found on YouTube, where it was labeled "The most boring video in the world. The snail."

After the acclimation period, participants watched another 30-second black screen, followed by an 84-second fear-elicitation video clip taken from the movie *The Shining*; this clip has been used in prior work and rigorously validated to elicit the distinct emotional experience of fear (Gross & Levenson, 1995). Following the fear-elicitation video, participants viewed a final 60-second black screen. The 20 s of black screen directly preceding and following the fear clip constituted our preelicitation and postelicitation measurements of heart rate (respectively). However, we also planned to construct locally estimated scatterplot smoothing (LOESS) lines with 95% confidence intervals to measure and visualize changes in HR continuously throughout the procedure, given the high likelihood of uncovering nonlinear changes in participants' HR. Finally, all participants completed an online questionnaire before being debriefed.

While watching all the video clips, participants were randomly assigned to hold the robot as it displayed one of three breathing patterns, manipulated between participants: no-breathing, stable breathing, and accelerated breathing. In the no-breathing condition, the robot showed no movement throughout the entire session (i.e., from the beginning of the first black screen of the acclimation period through the last second of the final black screen after the fear-elicitation clip). In the stable-breathing condition, the robot displayed a stable expansive and contractive movement throughout the session designed to mimic a chest cavity when breathing at a rate roughly equivalent to human resting respiration (i.e., ∼14 breaths per minute).

In the accelerated-breathing condition, the robot engaged in a breathing pattern with modulated acceleration. This began with chest movements identical to those in the stable-breathing condition (∼14 breaths per minute), which occurred for 144 s: throughout the 114 s acclimation period and 30 s of black screen preceding the fear-elicitation video. Over the course of the fear-elicitation video, these movements changed to accelerate the expansion/contraction rate up to 30 cycles per minute (30 breaths per minute). This acceleration was designed to simulate fast breathing and hyperventilation. When the fear-elicitation clip ended, the robot's movements were decelerated, and after 60 s its apparent breathing rate returned to the preelicitation stable pace, which was maintained until the conclusion of the session. Figure 2 shows a visualization of the breathing patterns conveyed by the robot in each condition, along with the order of videoclips shown to participants.

The no-breathing condition was intended to function as an inactive control (e.g., baseline) condition, reminiscent of being in contact with something akin to a stuffed animal. The stable-breathing condition functioned as an active control—ensuring that any effects of the accelerated-breathing condition were not attributable to the general presence of movement suggesting life. By including multiple robot "breathing" conditions and a nonbreathing condition, this design allowed us to test whether the specific movement pattern displayed by the robot in the accelerated-breathing condition—and not the robot itself, or the appearance of breathing alone—upregulated participants' physiological arousal.

Following the human–robot interaction, all participants completed an online survey consisting of self-report measures asking them retrospectively evaluate the robot's behavior and their own emotions throughout the experiment. This survey was completed up to 5 min after the conclusion of the human–robot interaction. Prior to conducting the study, we did not know how long any emotional effects of the videos and robot interaction would linger, and although we endeavored to capture condition-based differences in state-level emotions after the conclusion of the task and included these measures as exploratory dependent variables, we also suspected that any subjectively experienced emotion might have dissipated after 5 min.

Transparency and Openness

Although this research was not preregistered, all hypotheses were made a priori and prior to data collection. All data are available online at https://osf.io/mxfn2/?view_only=ae871379f67a451ea3734b3d3c3a3c6d. In our analyses, we utilized several R packages to process and analyze the data, including readr for data import, tidyverse, dplyr, and tidyr for data wrangling, and ggplot2 and ggpubr for data visualization. We conducted our mixed-effects modeling using lme4 (Bates et al., 2015), assessing statistical significance with lmerTest (Kuznetsova et al., 2017). To calculate and report effect sizes, we employed the effect size package (Ben-Shachar et al., 2020). All analyses were conducted in R Version 2023.06.2 (R Core Team, 2023). Data were collected in 2017 and 2018. The standardized regression coefficients constitute our measure of effect size.

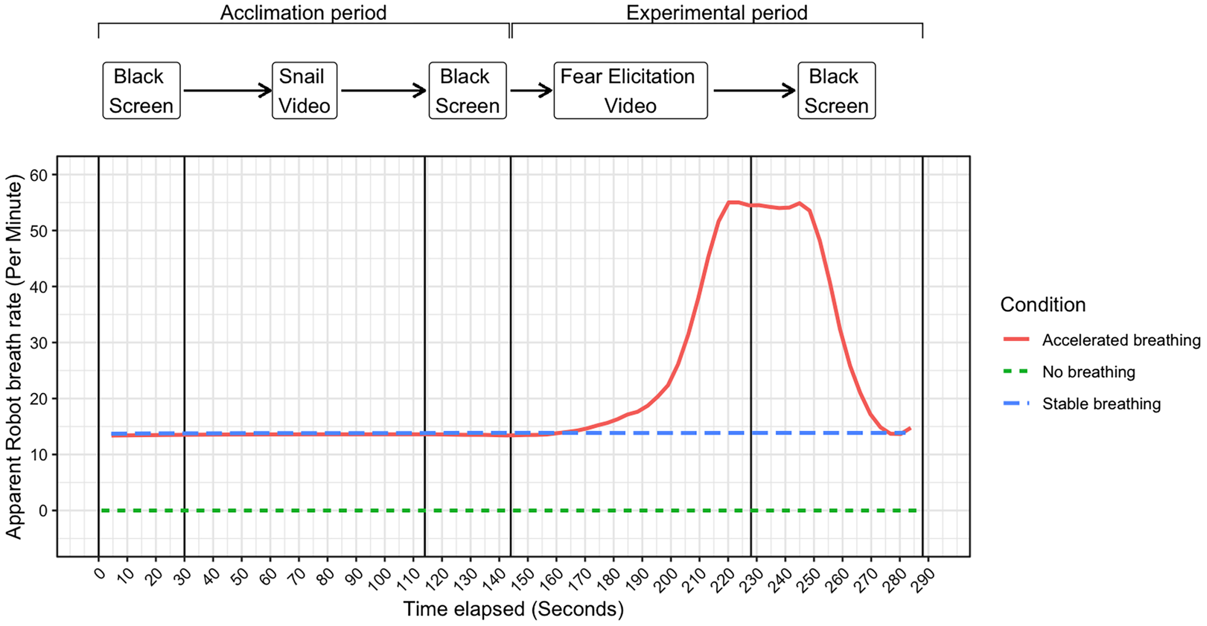
Materials

Robot Construction

To develop the robot prototype, we followed social robot design for single degree-of-freedom motion (Bucci et al., 2016) and, using a similar template structure, created the wishbone template to form the robot's skeletal structure. We laser cut the wishbone shape in varying sizes so that, even under a thick fur cover, the back of the robot had a ridged, spinelike feel. The main form was comprised of two parallel panels; each was comprised of a long and narrow piece with a large round bulb at one end, much like a tomahawk steak. When the two panels were lined up in parallel, the bulb portion formed the head (where a central motor was housed), and the long-curved narrow pieces formed a track with notches in which to secure 16 wishbone-shaped pieces. The curvature of the wishbone sides formed "ribs" and, by attaching strips of flexible plastic (23-gauge polyethylene) to the bottom of each set of ribs, we created a curved

Figure 2

Visualization of the Order of Videos Presented During the Procedure and Corresponding Robot Breathing Rate Throughout the Procedure



Note. The apparent breath rate in the accelerated-breathing condition plateaued between 220 s and 245 s, due to mechanical limitations of the robot prohibiting it from moving at a faster pace. See the online article for the color version of this figure.

and lightly pressure-resistant soft robot "belly," particularly evocative once the entire body was covered in a soft furry fabric. Fishing line was used to thread through each of the plastic strips of the belly and connect it to the central motor secured in the head.

To build and manipulate breathing behaviors, we used an Arduino Uno microcontroller to manage the motor. At the motor arm's maximum position, the fishing line pulls on the belly strips to simulate an exhale contraction; at the motor's minimum position, the fishing line is relaxed and the compliant belly relaxes similarly to express an inhale belly extrusion.

Participant Heart Rate

We assessed participants' heart rate (HR) throughout the procedure using a plug-and-play optical pulse sensor for Arduino. We chose to focus on changes in HR as our main dependent variable based on meta-analytic evidence that HR increases to a significantly greater degree during fear experiences compared to neutral (control), sadness, surprise, anger, and disgust experiences (i.e., all emotions compared to fear experiences in a meta-analysis by Cacioppo et al., 1997). We used Kubios HRV Premium to visually inspect and clean the data, using built-in features that conducted noise detection, beat correction, and nonstationary elimination automatically. We also used Kubios HRV Premium to convert the raw optical voltage data into R–R intervals (the distance between peaks in a sinusoidal waveform). Heart rate in beats per minute was obtained via an arithmetic conversion.

Self-Report Measures

Fear-Elicitation Manipulation Check. Participants were asked to retrospectively recall how "angry," "sad," "happy," "afraid," "surprised," and "bored" they felt while viewing the control video and then while viewing the fear-elicitation video. For each of the two video clips, participants provided a rating ranging from 1 (*not at all*) to 5 (*completely*) for all six emotion prompts, for a total of 12 ratings per participant. To check whether the fear manipulation was effective, we compared participants' ratings of "afraid" in response to the fear-elicitation video versus the control video. As an exploratory analysis, we also compared participants' reported feelings of boredom during the control video versus the fear-elicitation video.

Robot Expression. Participants were asked to retrospectively rate the extent to which they perceived the robot to feel "angry," "sad," "happy," "afraid," "surprised," "bored," and neutral ("The robot did not feel anything"). Participants provided responses characterizing the robot's feelings using a 5-point rating scale ranging from 1 (*not at all*) to 5 (*completely*). To check whether the robot manipulation was effective, we tested whether participants judged the robot to be more "afraid" in the accelerated-breathing condition compared to the stable-breathing and no-breathing conditions. For results of all manipulation check items across the three breathing conditions, see the Supplemental Material.

Self-Reported State Emotion. After concluding the experimental session, participants rated their own current feelings on the state-level Positive and Negative Affect Schedule (Watson et al., 1988; 20-items), the Current Mood Questionnaire (a measure of positive and negative valence and arousal; Feldman Barrett & Russell, 1998; 12 items), and fear (Harmon-Jones et al., 2016; three items). For all measures, participants responded using a 5-point rating scale, with higher numbers indicating more intense emotional experience.

Results

Manipulation Checks

Fear-Elicitation Video

To determine whether the fear-elicitation video effectively elicited fear, we compared participants' retrospective self-reported feelings of fear in response to the fear-elicitation video and control video using a multilevel model predicting self-reported fear from video type (control vs. fear-elicitation), along with random intercepts for participants to account for repeated measures (interclass correlation = 0.08). Supporting the validity of our manipulation, participants self-reported greater fear during the fear-elicitation video ($M = 3.86$, $SE = 0.13$) when compared to the control video ($M = 1.17$, $SE = 0.13$), $d = 1.41$, $t(102.85) = 14.92$, $p < .001$.

Next, we constructed a similar exploratory multilevel model predicting retrospective self-reported boredom from video type (control vs. fear-elicitation), along with random intercepts for participants to account for repeated measures (interclass correlation = 0.12). Further supporting the validity of the manipulation, participants reported greater boredom in response to the control video ($M = 4.80$, $SE = 0.20$) compared to the fear-elicitation video ($M = 1.74$, $SE = 0.15$), $d = -1.40$, $t(103.00) = 15.09$, $p < .001$.

Robot Breathing

To determine the efficacy of our between-subjects robot-breathing manipulation, we tested whether participants in the accelerated-breathing condition perceived the robot to be more afraid compared to participants in the stable-breathing and no-breathing conditions. Supporting the validity of our manipulation, participants judged the robot to be more afraid in the accelerated-breathing condition ($M = 5.57$, $SE = 0.30$) compared to the no-breathing ($M = 2.91$, $SE = 0.31$), $d = -1.20$, $t(101) = -6.11$, $p < .001$, and stable-breathing ($M = 2.94$, $SE = 0.32$) conditions, $d = -1.19$, $t(101) = -6.00$, $p < .001$. There was no difference between the no-breathing and stable-breathing conditions, $d = 0.01$, $t(101) = 0.06$, $p = .95$.

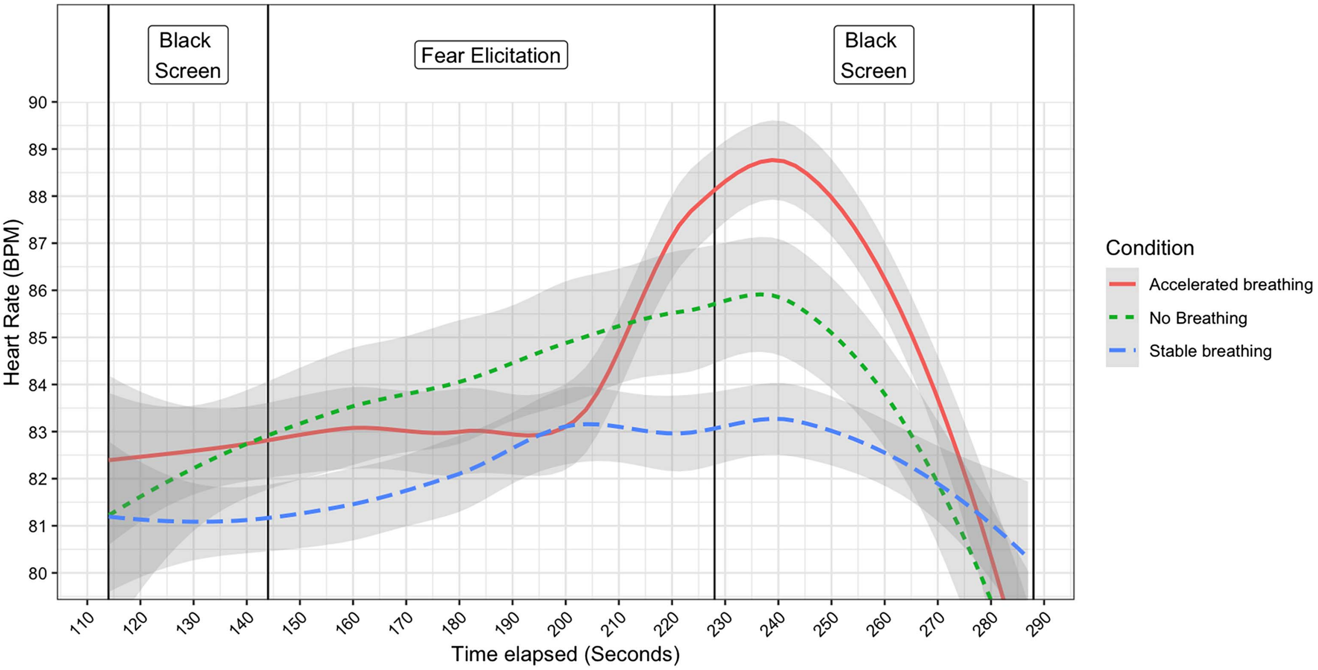
Main Analyses: Does a Robot's Breathing Pattern Affect Participants' Physiological Responses to a Fear-Inducing Stimulus?

To test whether the robot's breathing pattern affected participants' physiological responses to the fear-eliciting stimulus, we examined participants' HR during the 20 s directly preceding the fear-elicitation video ("preelicitation"; seconds 124–144 in Figures 2 and 3), and 20-seconds immediately after the video ("postelicitation"; seconds 228–248 in Figures 2 and 3). This timeframe was determined in order to capture participants' heart rate during the black screen period before emotion elicitation began and during the black screen period when the robot's accelerated breathing was at peak (see Figure 2).

We constructed a multilevel model predicting HR from robot-breathing condition (accelerated, stable, or no-breathing, dummy coded with accelerated-breathing as the reference group), time segment (preelicitation vs. postelicitation), and condition by time-segment interactions, along with random intercepts for participants

Figure 3

LOESS Lines Outlining Changes in Heart Rate Over Time for Participants in Each of the Three Robot Conditions



Note. Ribbons indicate 95% CIs around local estimates. Span of .65 used to construct LOESS lines. LOESS = locally estimated scatterplot smoothing; CI = confidence interval; BPM = breaths per minute. See the online article for the color version of this figure.

(interclass correlation = 0.39). Participants in the accelerated-breathing condition demonstrated a significant change in HR postelicitation (M = 88.6, SE = 2.30) when compared to preelicitation (M = 82.0, SE = 2.31), $\beta = .31$, 95% CI [.24, .37], $t(5494.41) = 9.02$, $p < .001$. Participants in the no-breathing condition demonstrated only a very small increase in HR postelicitation (M = 82.7, SE = 2.37) compared to preelicitation (M = 80.7, SE = 2.38), $\beta = .09$, 95% CI [.02, .16], $t(5492.94) = 2.52$, $p = .01$; a change significantly smaller than the change in HR observed in the accelerated-breathing condition, $\beta = -.22$, 95% CI [−.31, −.12], $t(5493.63) = -4.32$, $p < .001$. Finally, participants in the stable-breathing condition showed no significant change in HR postelicitation (M = 81.8, SE = 2.41) when compared to preelicitation (M = 80.3, SE = 2.41), $\beta = .07$, 95% CI [.00, .14], $t(5492.53) = 1.89$, $p = .06$; this change was still significantly smaller than the change observed in the accelerated-breathing condition, $\beta = -.24$, 95% CI [−.34, −.14], $t(5493.40) = -4.75$, $p < .001$, and not significantly different than the change observed in the no-breathing condition, $\beta = -.02$, 95% CI [−.12, .08], $t(5493.74) = 0.44$, $p = .66$.

Together, these results suggest that participants in the accelerated-breathing condition experienced an increase in HR between pre- and postelicitation, whereas participants in the no-breathing condition experienced a significantly weaker but still statistically detectable increase in HR, and participants in the stable-breathing condition did not experience a significant increase in HR. Figure 3 shows a visualization of HR over time using LOESS with a span of .65, along with 95% CIs around LOESS lines (also see Figure 4). Consistent with the multilevel model results presented above, results from the LOESS lines indicate that participants' HR throughout the experiment was significantly faster in the accelerated-breathing condition when compared to no-breathing and stable-breathing conditions, at approximately the same timepoints that the robot's breathing pattern was at its maximum rate (220–250 s into the experiment; see Figures 2 and 3).

To test the robustness of these results, several follow-up models were constructed; these demonstrated similar patterns. Specifically, we constructed models including participant gender as a covariate and removing participants who recognized the movie scene used in the fear-elicitation stimulus ($N_{\text{final}} = 79$). We also constructed models with HR centered around participants' personal baseline (with baseline defined by the average HR during the first 10 s of the black screen preceding the fear-elicitation stimulus); in one model, baseline was included, and in one it was as a covariate. In all four models, participants in the accelerated-breathing condition experienced an increase in their HR between pre- and postelicitation (βs > .31, ps < .001), whereas those in the no-breathing condition experienced only a small change in HR (βs < .10, ps < .011), which in all cases was significantly smaller than the change observed in the accelerated-breathing condition (βs < −.22, p < .001). Finally, in all four models, participants in the stable-breathing condition demonstrated no significant change in HR between pre- and postelicitation (βs < .08, ps > .056). For full reporting of all models, see Supplemental Material.[2]

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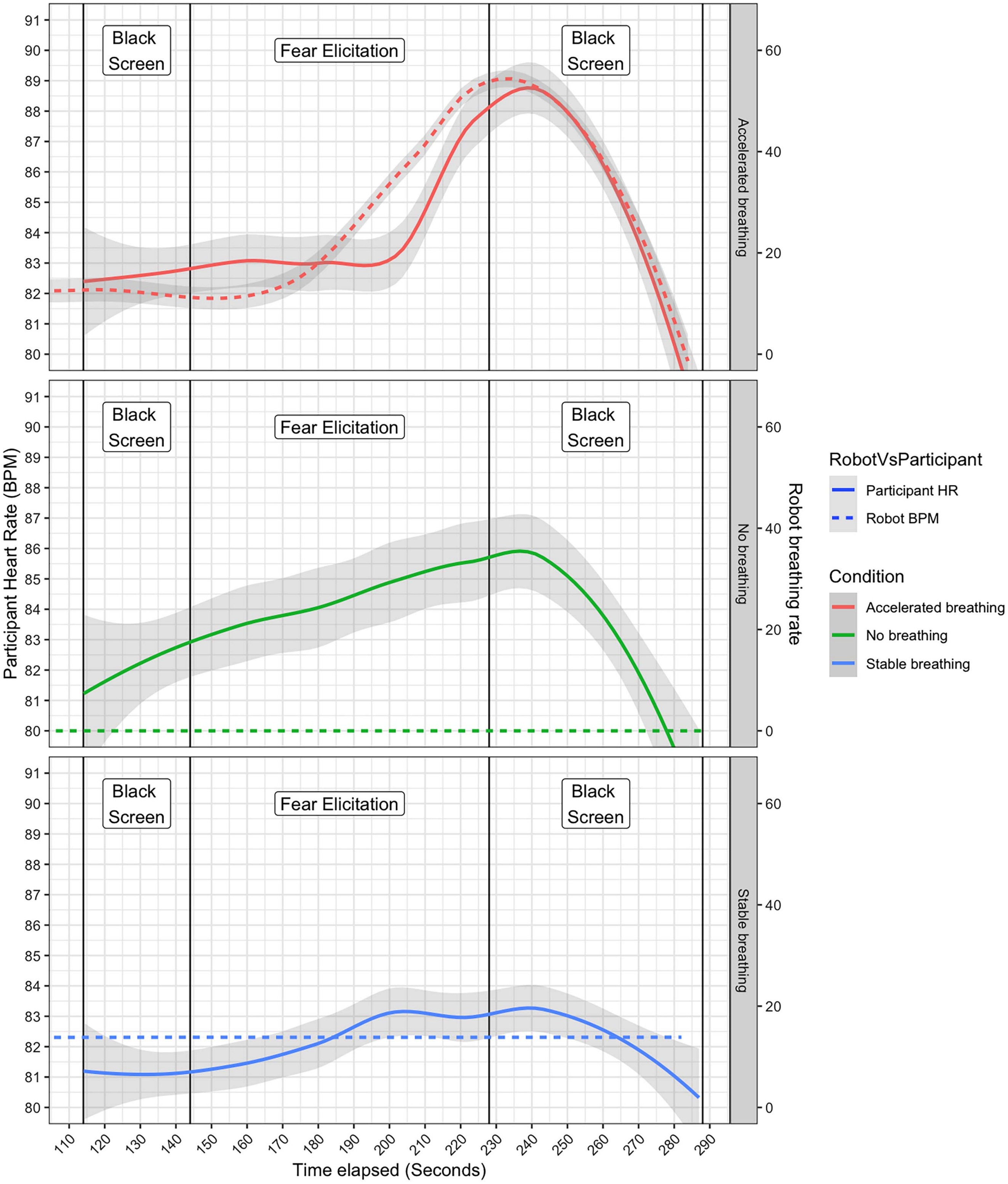
[2] Given that the robot's breathing rate did not change in the stable-breathing and no-breathing conditions, we cannot test for synchronization (i.e., with no variance in breathing rate, we cannot test for covariance with participants' HR, or differences in these relationships across conditions). For a visualization of participants' HR alongside the robot's breathing pattern, see Figure 4.

Figure 4

Locally Estimated Scatterplot Smoothing Lines Outlining Changes in HR Over Time (Solid Line), and Manipulated Breathing Pace of the Robot (Dashed Line) Over Time, in the Accelerated Breathing (Top), No Breathing (Middle), and Stable Breathing (Bottom) Conditions



Note. Ribbons indicate 95% CIs around local estimates. These data are a combination of data presented in Figures 2 and 3. The *y*-axis on the left corresponds to the participant's HR, whereas the *y*-axis on the right corresponds to the robot's breathing rate. CI = confidence interval; BPM = breaths per minute; HR = heart rate. See the online article for the color version of this figure.

We next tested the effect of robot-breathing condition on state-level self-reported emotion, which was assessed at the end of the study. No differences emerged between the three breathing conditions for self-reported fear, $F(2, 101) = 1.25$, $p = .29$; negative affect, $F(2, 101) = 1.45$, $p = .24$; pleasantness, $F(2, 101) = 2.49$, $p = .09$; unpleasantness, $F(2, 101) = 0.90$, $p = .41$; high activation, $F(2, 101) = 0.46$, $p = .63$; or low activation, $F(2, 101) = 0.66$, $p = .52$. However, there was an effect of condition on self-reported positive affect, $F(2, 101) = 3.78$, $p = .026$, indicating that participants interacting with the accelerated-breathing robot reported significantly lower levels of positive affect ($M = 1.83$, $SE = 0.11$) than participants interacting with the no-breathing robot ($M = 2.21$, $SE = 0.11$), $\beta = .45$, $t(101) = 2.21$, $p = .03$. No difference emerged between accelerated-breathing and stable-breathing ($M = 2.18$, $SE = 0.11$) conditions, $\beta = .16$, $t(101) = 0.78$, $p = .44$, or between the no-breathing and stable-breathing conditions, $\beta = .29$, $t(101) = 1.38$, $p = .17$.

These last results suggest that, for the most part, any subjectively experienced differences in fear, activation, valence, and negative affect between robot-breathing conditions were no longer detectable by the time of our self-reported emotion assessment, approximately 5 min after the conclusion of the robot interaction. However, participants who interacted with the accelerated-breathing robot seemed to have experienced a minor lingering decreased positive affect. Notably, these results are consistent with those from the HR analyses; by the final moments of the robot interaction (i.e., while viewing the last black screen), all participants had returned to their baseline HR (see Figure 3).

General Discussion

The present research is the first to test whether a robot with a chest cavity that expands and contracts in an accelerated manner, mimicking accelerated breathing, influences the physiological arousal of a human who holds the robot during a fear-eliciting event. Findings demonstrated that, while watching a video clip that reliably elicited fear, individuals who held robots displaying accelerated breathing perceived the robot as behaving more fearfully and experienced a pronounced increase in their HR. In contrast, participants who held a nonbreathing robot experienced a smaller but still statistically detectable increase in HR, and participants who held a robot exhibiting stable breathing experienced the slightest increase in HR, such that no significant change occurred. These results indicate that holding or clinging to others engaged in accelerated breathing increases physiological arousal in response to a fear-eliciting stimulus.

These findings have important implications for research on emotion elicitation and contagion. The present work is the first to pinpoint felt changes in another's breathing patterns as a potential mechanism driving physiological arousal. Our findings offer clear experimental evidence that exposure to faster breathing is a mechanism for eliciting and transferring arousal through touch. This research also has important implications for the zoomorphic robotics literature. Although previous research has shown that humans can *perceive* emotions expressed by zoomorphic robots (e.g., perceiving breathing patterns as indicative of fear, sadness, or happiness, or valence and arousal), the present study is the first to find that these patterns also elicit distinctive physiological responses in participants.

Finally, these results have important implications for human–robot interactions. For example, wearable technologies, virtual reality, interactive movies, and video games might be more evocative and efficacious for eliciting emotion when interactants are engaged with dynamic moving machines. Much in the way that controller vibrations can influence the emotional experiences of individuals playing video games, dynamic expansion and contraction of machines simulating breathing patterns—such as that used here—might have a similar effect on users' emotion and physiological experiences. Haptically interactive robots, or wearables like a vest exhibiting squeezing pulsations, might therefore be valuable tools for upregulating physiological arousal in contexts where this experience is intended or desired.

Limitations and Future Directions

It is noteworthy that no differences were observed in self-reported emotion following the procedure. While the absence of greater self-reported fear in the accelerated-breathing condition may seem inconsistent with the observed differences in physiology, this is not necessarily the case; self-reports were made well after the fear-elicitation stimulus had completed and at the same time as participants' heart rates returned to baseline (see Figure 4). Although it is possible that the Positive and Negative Affect Schedule was not sensitive enough to detect subtle changes in fear responses, the lack of differences in a secondary self-report measure of fear (Harmon-Jones et al., 2016) suggests that the timing of the measurement may be a key contributor to the null findings. Future research may therefore benefit from measuring subjectively experienced emotions continuously throughout a session like this. Another possibility, however, is that the robot influenced participants' physiology without altering their conscious emotional experience. This interpretation should be tested in future work by aligning self-report timing more precisely with physiological changes.

We also acknowledge the limitation of using heart rate (HR) as the sole psychophysiological measure of arousal, particularly given the central role of breathing in our theoretical framework. As Berntson et al. (1993) highlighted, HR alone may not fully capture the complexity of arousal responses. In addition, although we assume that participants' increase in heart rate was due to their more rapid breathing in response to touching a rapidly breathing robot, future studies that measure respiratory rate along with HR might be able to more directly pinpoint the physiological pathways through which the observed effects occur. These additional data would also provide a more comprehensive view of autonomic activity. By combining these measures, future studies can more precisely identify the mechanisms underlying responses to breathing patterns associated with high arousal, further strengthening the conclusions of this work. Nonetheless, our use of HR allowed us to uncover novel data points on physiological responses to accelerated breathing felt through touch, laying a strong foundation for future multimodal research.

Another promising future research direction is to further compare changes in HR over time for individuals engaging with robots exhibiting stable versus still (no-breathing) breathing patterns. In the present study, no significant differences emerged between these conditions when data were analyzed using a multilevel linear model and including only the first 20 s preceding and following the fear-elicitation stimulus. However, this null finding is partly a result of our analysis technique; as depicted in Figure 3, which used local estimation (i.e., LOESS lines), HR changes in the stable- versus no-breathing conditions are consistently and significantly different. The failure to capture this difference using multilevel model is almost certainly due to our multilevel model taking into account HR data shortly before and after the fear-elicitation video, but not during the video, whereas the loess line analysis (see Figure 3) includes all HR data throughout the procedure. We could not construct a linear model on HR data obtained throughout the entire procedure because these data were severely nonlinear, as expected. The results shown in Figure 3, in contrast (based on an analysis that included additional data and did not require linearity), are consistent with the suggestion that interacting with a stable-breathing robot while watching a fear stimulus can lower individuals' heart rate, replicating past research (Asadi et al., 2022; Matheus et al., 2022; Sefidgar et al., 2015).

Finally, future research should examine the effects of divergent breathing patterns on emotion experience in the absence of an external fear-elicitation stimulus. We examined upregulation of emotion during externally evoked fear experiences—an ecologically valid context in which individuals may find themselves touching others who are displaying accelerating breathing patterns, given that people often cling to others when frightened. However, future work should test whether similar effects emerge when touch occurs devoid of any external emotion context.

Constraints on Generality

The generalizability of the present findings should be interpreted in light of several constraints. First, participants were undergraduate students at a large North American university, with a mean age of 20 years, and the majority identified as women and nearly half as East Asian. Future research is needed to establish whether similar patterns of physiological contagion emerge among older adults, younger children, and individuals from different gender and cultural or socioeconomic contexts. Second, all participants were healthy, nonclinical volunteers who engaged in the task within a controlled laboratory setting. As a result, future research is needed to establish whether these findings generalize to populations with heightened sensitivity to fear or arousal (e.g., individuals with anxiety disorders), dyads engaged in everyday interpersonal touch, and to high-stakes fear contexts.

Conclusion

In conclusion, interacting with a robot exhibiting accelerated-breathing patterns can heighten an individual's physiological arousal. These findings identify respiratory cues felt through touch as a plausible mechanism for the transmission of arousal, with implications for both human–robot interaction and interpersonal emotion regulation.

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