Design and Evaluation of a Touch-Centered Calming Interaction with a Social Robot

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Abstract—With advances in sensor and actuator design, intelligent computing techniques and personal care robotics, today's robots hold promise as fully interactive, therapeutic human companions. To achieve this ambitious goal, key interaction components must be identified and then systematically designed and evaluated. Based on successes of human-animal therapy, we propose affective touch as one such component. Delivering this adjunct in a controllable robot form allows us to examine its efficacy for therapeutic applications such as anxiety management. With an approach grounded in social cognitive theories for human-animal relations, we deployed a social robot, the Haptic Creature, in an interaction designed to be calming: participants held the robot on their laps and stroked it as it was breathing. As a result, their heart and respiration rates significantly decreased relative to stroking a non-breathing robot. They also reported themselves as calmer and happier.

Index Terms—Haptic human-robot interaction, social robot therapy, affective haptics, anxiety therapy, interaction design, psycho-physiological analysis, design for emotional experience

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1 INTRODUCTION

In the 1960s, in what was possibly the first scientific proposal to use animals as therapeutic adjuncts for mentally disordered populations, child psychiatrist Levinson reported improvements in his young patients' psychological state when his dog joined their therapy sessions [2]. Since then, health benefits of interacting with animals have been investigated in a variety of settings with children, adults, and the elderly. Of particular interest is animals' impact as instruments of change in mal-adapted behaviors and in promoting relaxation [3]. Love, affection, touch and nurturance of animals also encourage development of social skills, themselves important for mediating many emotional and behavioral problems [4].

Despite numerous reports of mental health benefits of interacting with animals, the use of animal-assisted activity (AAA) and therapy (AAT) today is limited—by hygiene and allergens, the high cost of training animals to meet therapeutic criteria, and the frequent infeasibility of caring for an animal given patients' mental, physical, social, and economic situation.

Retaining therapeutic benefits of interacting with animals while addressing its restrictions has already inspired considerable research in robot therapy. Paro [5], Probo [6], and Huggable [7] are examples of recently developed animal-like robots with socially therapeutic potentials. Exploratory experiments with these platforms suggest a possibility of mental health improvements similar to those produced by animals, such as decreased depression and its symptoms, enhanced coping skills, and increased social interactions [8].

Advancing Social Robot Therapy. At this stage, more rigorous investigation is required to confirm the advantages of animal-like social robot therapy and realize its possibilities. It is crucial to first identify human-robot interaction (HRI) components that effectively stimulate human emotions, then utilize these pathways to deliver therapeutic interventions. In this paper, we present our approach for identification of such HRI components and investigate affective touch as a promising one. We also report our experimental findings regarding the efficacy of purely haptic interactions to provoke a desired emotional response—a prerequisite for successful replacement of robots in therapy settings.

Therapeutic Potential of Touch. The calming nature of certain forms of physical contact gives touch a therapeutic potential for psychological disorders in which emotional tension plays a role, such as autism, attention deficit hyperactivity, depression, and anxiety [9]. Touch is a natural and feasible medium for communication of affect in such contexts and can generate measurable behavioral and physiological health improvements, such as enhanced self-esteem, increased attentiveness, and regulated stress hormones [9], [10], [11]. Moreover, touching is central to many emotive human-animal interactions: physical contact with animals (patting, stroking) produces relaxation [12], [13], and the impact of tactile animal interaction surpasses that of verbal

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Fig. 1. The Haptic Creature (photo: Martin Dee) and its underlying structure. Key elements shown are a fiberglass shell ~33 cm in length and covered with an array of touch sensors, stiffenable ears, and a moving rib cage that simulates breathing. Overall weight is ~2.5 kg [1]. Simulated breathing was used in the study reported here.

or visual [14]. We thus posit that animal-like robots can leverage its therapeutic potential.

Requirements for Experimental Platform. To explore this premise, we required a robot platform for which the *design* of the haptic behavior, the touch-sensing to control the behavior, and the kind of complementary user activity that should be encouraged have been experimentally validated or are informed by models of the influence of touch on a user's affective state. Touch has been previously considered in the design of animal-like robots such as Paro and Huggable, including for therapeutic goals. These robots are equipped with advanced actuation and sensing technologies; they move in ways intended to be physically as well as visually engaging, and use touch sensing as one of various means of triggering robot behaviors. However, the role and significance of touch in their affective communications are unknown, particularly for therapeutic contexts, and the models needed for this research do not to our knowledge exist.

A Tool to Study Affective Touch in HRI. The Haptic Creature [15] is an expressive animatronic lap-pet the size of a large cat (Fig. 1), which senses a user's touch over its entire body and expresses itself by stiffening its ears, purring, and simulating breathing [16]. Designed after human-animal interaction models and identified as animal-like by both children and adults without prompt, it uses touch as the primary medium through which its emotion interaction is directed, in both sensing and display. The robot has been used to investigate *how* emotions are communicated through the haptic channel, as a foundation for the design of affective robot behaviors [1], [17], [18]. Being haptically 'understood', in that we know how its behaviors are perceived and how users naturally display emotion gesturally to it, this platform uniquely meets the requirements of our research.

Research Questions and Contributions. To develop animal-like companion robots as effective tools for therapeutic interventions such as anxiety management, we must assess and optimize the HRI's fundamental ability to produce emotional and physiological effects similar to that of a real animal. Here, in a first step we investigate the ability of haptic human-robot interaction to produce emotional impact. In a controlled laboratory study, we evaluated the self-reported and physiological impact of brief segments of a calming interaction (user actions and robot behavior) that was first isolated and refined in pilot studies.

We were guided by questions of *Design:* what form of haptic interaction will best facilitate change towards a less-anxious emotional state? *Efficacy:* how does this interaction impact objective and subjective measures of emotion? *Practical interpretation:* does the change (if present) imply calming/relaxation? And *Mechanism:* what internal causal events best explain the changes?

We did find change. Our investigation contributes:

1) Definition of a purely haptic human-robot interaction that produces relaxation.
2) Empirical evidence for the ability of purely haptic HRI to relax participants, and of their patterns of subjective and objective emotional experience.
3) Insights into the underlying mechanisms that bring about change in emotional state.

These results set us up for the next step of therapeutic design: integrating these results into more complex interactions, carried out in more realistic contexts (e.g., with more extreme user emotions or challenging activities).

In the following we review related literature (Section 2), ground our approach to interaction design in theories of human-animal interaction (HAI), and detail the design of a calming interaction (Section 3). In Sections 4 and 5 we describe the interaction's evaluation, and in Section 6 discuss implications for the design of therapeutic robots.

2 RELATED WORK

To situate this research, we survey literature on the mental health benefits of animals and the role of touch in therapy, highlight the paucity of research on affective, haptic HRI, and introduce the Haptic Creature as a viable platform that allows focused studies on this topic.

2.1 Health and Animal-Assisted Activities

The interaction we employ is modeled on human-animal touching in a therapeutic context, and aims explicitly to elicit a similar emotional response as a prerequisite to reproducing the therapeutic benefits observed there. We thus begin with a summary of what is currently known (or not) about how these benefits do or can arise, to illustrate the possibilities of robot therapy grounded in an animal model, and the critical need to establish evidence of controllable emotional impact by the robot.

2.1.1 *Theories of AAA Relevant to HRI*

Animal-assisted interventions to achieve mental health benefits are driven by two primary views: (1) animals bring desirable changes to people's cognitions and behaviors through *natural* instinctual mechanisms (e.g. humans' innate attraction to life and living beings); or, (2) they can be deployed as a *tool* in processes 'arranged' to produce the desired change [3]. We limit our review to the tool-based view, which at present is more pertinent to therapeutic robot tools; we do not yet know if the degree to which humans can regard robots as living things is sufficient to trigger a nature-based response [19]. We focus on animal roles most relevant to anxiety.

Animals as therapeutic tools. Animals afford certain therapeutic roles in interventions that are based on social cognitive theories and role play, whereby individuals learn to modify their cognition of social and emotional stimuli. Animals, as "living and interactive tools", facilitate the learning process by providing a disturbed population with opportunities to practice and adjust their responses to the world [3].

Animals' role in therapeutic interventions. Animals help mentally disordered individuals improve their feelings of self-efficacy, performance achievement, and personal agency, in part through emotional responsiveness. Via modeling and association (as related to conditioning), animals further make it possible for these individuals to recognize causality and ultimately transfer modified behaviors interpersonally. For example, [20] describes a child with attention deficit hyper-activity disorder:

> *Here is a 10-year-old child diagnosed with ADHD, sitting and giggling and smiling as Sasha [a gerbil] crawls over his legs. So as to not frighten her, [Aaron] sits calmly—something that is hard for him to do. He eventually begins to stroke her and tells her how beautiful she is . . . Around Sasha he slows down, and she has a calming effect on him. . . . he moves slowly and talks gently. She reciprocates by snuggling and allowing his tender touch. . . . I often bring Sasha to Aaron so that he can learn to gauge his own activity level and perhaps be in more control. It is amazing to watch him transform. She immediately helps him regroup, and once he gets to hold her, his activity level is more in harmony with the others. [20]*

Interventions are designed to improve a person's self-belief of ability to behave in a desired way; the achievement additionally helps the person to find her or himself helpful and beneficial [3], which manifests as further-improved emotion regulation and behavior control (cited in [21] from [22]). This cycle, which we suggest could also be promoted with a robot partner, is observed in a case study of animals being used as teaching metaphors, with two emotionally disturbed children who practiced social skills by training a therapy dog. The AAA reduced negative comments and distractability, decreased feelings of helplessness, increased feelings of control over self and environment, and improved eye-contact and peer relationships [23].

These theories (first, of animals as tools; then, the mechanism by which they can break a disordered cycle, and conversely enable and reinforce a positive cycle in its place) can inform the development of robot therapy to produce similar effects. By imitating the key underlying mechanisms, we can theoretically obtain the benefits of AAA with animal-like robots.

2.1.2 Limitations of Animal Therapy

Animals must be trained for a planned intervention, a time-consuming and costly process. Few house pets meet the standards of a therapy animal; and some unpredictability remains at any training level, eliminating some applications [24]. These limits of access and applicability, compounded by real or perceived fears of bites, allergies, and transmission of disease, constrain the use of animals for therapeutic purposes.

2.2 Therapeutic Benefits of Touch

Touch is highly influential in communicating and stimulating emotions [11], is unique in its mechanisms [9], and contributes significantly to humans' health and well-being [10]. Physical contact is crucial for mental and social development in early childhood [25] and is a critical need into adulthood, particularly for individuals suffering from severe physical and/or mental complications such as anxiety and dementia [26], [27]. Touch has been observed to result in heightened alertness and thus improved cognitive performance, to enhance abused, post-traumatic and other psychiatric childrens' and adolescents' sleep patterns and social behaviors, and to decrease depression [9].

While mechanistic pathways are not fully understood, physiological evidence from controlled studies with animals explicitly links touching to human physiological changes due to animal interaction. Short-term reductions in blood pressure and heart rate result from stroking or petting an animal [14]; e.g., both [28] and [12] found this result after mild stress levels were induced in participants. The same changes were not observed when patting toys with similar tactile characteristics.

This suggests that not just any touch carries the affective significance of touching a living animal, and leaves us with the question of *which* difference between a live animal and a static toy is crucial; is it aliveness, or some more mechanical element, such as movement or warmth, or even quality of tactility? Encouragingly, Demello's work also points to a metric (physiology) that can be used to discriminate among the possibilities [28].

2.3 Touch in Animal-Like Robot Therapy

For the last decade, researchers have been building animal-like robots with the potential to produce health benefits similar to that of animals without suffering from animal therapy constraints, for a variety of age groups. These include Probo [6], Paro [29], and Huggable [7].

Among these robots, Paro and Huggable more saliently incorporate touch into their design. Paro, the baby seal, is specifically developed for therapeutic purposes. Covered with antibacterial, dirt-resistant fur, sensors detect touch, light and speech [5]. Huggable, a teddy bear, can see, hear and speak; register movements and contact on its skin; and move its neck, arms, and ears [7].

In the following, we report the health benefits observed with these actively haptic robots, discuss what needs further investigation, and introduce the Haptic Creature as a unique tool to understand and optimize the haptic component of HRI to imitate animal effects.

2.3.1 Health Benefits of Haptic Animal-Like Robots

At this early stage, there has not been a comparative controlled examination of whether actively haptic, animal-like robots are more effective than others; and if so, how.

Moreover, any such comparison is bound to the variant of robot therapy being practiced. For example, the robot's form may afford particular social communications and styles that best support specific therapeutic goals. For this reason, we focus on animal-like robots that tend to be held, and do not cover the reports on touch-enabled humanoids such as KASPAR [30].

Reports on health benefits of animal-like robots with bidirectional touch capability are based on Paro and focus on short-term outcomes and engagement without addressing mechanisms. These studies report positive effects on mood, social behaviors and physiological indicators of stress after interactions with Paro in the elderly, particularly those suffering from dementia [31], [32], [33], [34], [35].

These observations are encouraging but open-ended. Other limitations aside[1], the absence of a control leaves unanswered whether similar results would occur with a passive toy, and if the reported increases in social communication are experimental confounds that could also explain the health benefits observed.

Crucially, these reports do not reveal the role and significance of varied interactive elements, including touch. Their implications for the (re)design of a robot's form and behavior to improve therapeutic function are unclear. We do not know how effectively the robot communicates different emotions, or if it deploys interaction elements to their full potential. To proceed we require a haptic component that is "designed," in the sense of theory-driven optimization of responsive behavior, and empirically validated impact on user response.

2.3.2 Apparatus Used Here: The Haptic Creature

Created to study affective touch, the Haptic Creature [15] mimics non-verbal communication present in animal interactions [1]. Resembling a small mammal of ambiguous species, it communicates emotions by varying breath depth, rate and smoothness, purring strength and frequency content, and ear stiffness [17]. Under its fur is an array of sensors for recognizing a person's touch.

Framed within a two-dimensional model of affect [38], three studies have (a) shown that the Haptic Creature can successfully and consistently display a range of emotions [17]; (b) identified a vocabulary of touch gestures that people use to indicate different emotions to the robot [18]; and (c) justified that interacting with the robot can successfully influence people's emotional state [1]. This fundamental knowledge about the bilateral communication of emotion through touch with this platform and its emotional influence is a strong foundation to study the use of affective touch in therapeutic robots, and meets the requirements of the present study.

3 APPROACH AND METHOD FOR DESIGN OF THERAPEUTIC HRI

We now introduce our approach to identifying HRI components (including haptic) in the context of animal-like robots, specifically framed for anxiety therapy. We then describe how we designed the haptic interaction with the Haptic Creature.

3.1 Robot Therapy Inspired by AAA

While the idea of a therapeutic animal-like robot is not new, the mechanism by which these devices might provide health benefits (in particular, via the haptic channel) remains opaque. In existing reports, robots frequently imitate animals more phenomenically/functionally/behaviorally than mechanistically. They leverage some animal features; they have similar visual, audio, or tactile appearance and behave/function similarly by imitating animals (e.g. small neck/tail movements). But what exactly raises the resemblance, how effective are the various features, and how are these features related to animals and the way animals influence people? The use of robots in varied therapy settings is a popular topic, whereas reports on incorporating/modifying an aspect of robot's form or behavior for its influence on people are rare. We feel this is a gap and have chosen to explore it.

Our approach differs by 1) specifically articulating the premise that if a social robot can afford the same *interaction mechanisms* that theory has identified as helpful with real animals, it may produce comparable therapeutic benefits; then 2) invoking social cognitive theory for animals to model and inspire solutions. These include both possible delivery scenarios for a successful robot therapy (*how*), and at a low level, *what* about HAI might beneficially be incorporated into a therapeutic HRI. Finally, we 3) use this theory to lay out a systematic approach to tackle an otherwise intractable challenge (that of optimizing a multi-parametered physical system, with outcome metrics that can be noisy and costly to obtain) within human-therapy robot interaction design.

In the future, we envision scenarios where as interactive tools, robots promote positive changes in behavior: they can stimulate the same *emotional responses* as an animal might, to facilitate a self-perception in which emotionally disturbed individuals find themselves increasingly independent and able to control a situation. Through further modeling and association, they can then generalize their experience to other circumstances and gradually modify a mal-adapted attitude.

To this end, here we study touch as a principal interactive modality in stimulating a positive emotional response because of its importance in provoking emotions and in human-animal relations; and to build on our existing understanding of haptic affective touch.

3.2 Design of Interaction with a Haptic Robot

The first step to the larger goal of mechanistically reproducing animal-like interactions is to elicit a desired emotional response through interacting with the robot. We thus focus our attention on one candidate interaction that theory suggests is capable of producing the desired impact (as developed below), and which is amenable to experimental control including outcome measurement. That is, we study an elemental and yet complex and poorly understood interaction in a lab context with full control. With this

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[1] Small study sample sizes, incompletely described exploratory experimental design, and difficulty in replicating reported outcomes [36], [37].

TABLE 1
The Valence-Arousal (V-A) Map [38] of a Gesture Defined as 'Ideal' for Our Interaction (Section 3.2.1)

Ideal Gesture

Arousal	1.00	1.00	3.00
	2.00	3.50	4.00
	2.00	4.00	5.00
	Valence		

*Cell values are the likelihood (*1: Very Unlikely to 5: Very Likely*) that participants would use that gesture for an emotion in the corresponding V-A map region. Valence increases horizontally while arousal increases vertically; shading darkens with likelihood.*

understanding, we can in future extend its evaluation to increasingly realistic deployments.

We consider both sides of the interaction. For example, it is possible that when the human *cooperates* (consciously or not) with the robot's calming efforts, by making calming movements herself, the calming effects may be enhanced. Ekman observed a bidirectional relation between the emotional state and the way it is *facially* expressed [39], i.e., while emotions have specific behavioral indications, those behaviors can also trigger their associated emotions. We posit that motor actions made by the human in the course of interacting may similarly 'backdrive' the human's emotional state, above and beyond the effect of feeling the robot's response to his/her interaction. This notion frames the interaction design used here, by directing principled choices within a design space far too large to assess in a first exploratory study; its full verification is a task for future work.

To design this two-sided interaction, we build on the specifics of the emotions displayed by the robot or human as reported respectively in [17] and [18]. Taken from the two-dimensional model of affect, these are: distressed, aroused, excited, miserable, neutral, pleased, depressed, sleep, and relaxed. Additionally, we utilize knowledge derived from HAI research to justify our final design, in a process detailed below.

3.2.1 The Human's Expression of Emotion

To test our theories, we required a human movement that facilitates the calming effects of the robot's behaviors. We are not aware of research documenting how touching an animal in different ways can alter a person's emotional state (such data would be difficult to gather systematically with a living animal). Instead, we posited an Ekman-style motor-to-emotion back-drivability.

From the vocabulary of human emotional expressions through touch reported in [18], we started with the ten gestures that Yohanan's participants reported as using most frequently when feeling calm and relaxed (low arousal, high valence). We further narrowed this set with two criteria, illustrated in Table 1's 'ideal' gesture:

- High occurrence of high valence *and* low arousal expression (dark cells, lower right); combined with
- Low occurrence of low valence *or* high arousal: lighter cells, top and left perimeter.

Gestures that meet these criteria will have V-A maps that resemble the ideal map. We thereby chose *stroke*, *massage*, and *finger idly*. Among these, *stroke* was most suitable for our situation. The force imposed by *massage* interferes with the robot's breathing mechanism; and compared to *finger idly*, *stroke* has higher occurrence for very high valence and very low arousal. This choice is consistent with [40], which finds that stroking an animal reduces tension. We constrain *stroke* beyond the definition provided in [18] for a more ergonomic prolonged movement, and to involve both hands as we found to be more effective in pilots [41].

3.2.2 The Haptic Creature's Expressions

For the present purpose (to calm, or relax, the user), we assigned the *robot* to express its *relaxed* emotional state. This is based on a premise wherein the robot's mirroring the desired human emotional state reinforces the humans' transitioning to this state: mirroring is reported as one possible expectation that users might have of such a robot in this context [18]. This depends on the human being able to 'correctly' recognize the emotion that the robot is intended to portray, also verified in [17].

The renderings used in the present study are based on [17], slightly modified as indicated by pilot studies. To render *relaxed* (equivalent to the *pleasant* (high valence) plus *deactivated* (low arousal) state in [17]) via breathing alone, we used 20 breaths per minute (bpm) in a saw-wave profile. In pilots, this form appeared to be perceived as more relaxing than [17]'s 15 bpm sine-wave profile, possibly because breathing there was coordinated with other display elements.

4 METHODS: EVALUATING HAPTIC HRI'S CALMING EFFECT

We evaluated our stroking-breathing interaction to quantify its ability to relax participants, and compare results to those reported for human-animal interactions.

4.1 Participants

We limited participation to adults who self-reported themselves as 'normal', with a first learned language of English (preferably North American), and who had no prior experience with the Haptic Creature. The language restriction minimized noise due to nuances in interpreting instructions for English self-report scales and facilitated fluid reporting.

We used data for 38 female participants (aged 19-45, mean 23.8, std 6.6) recruited through fliers, mailing lists, and online ads that described a study with a "furry robot." It was difficult to recruit a gender-balanced pool due to subject interest, and a homogeneous sample permitted greater experimental power. This limits generalization to a mixed-gender group, although [17] does show promising indications of it.

Attitude toward pets measured by the Pet Attitude Scale (PAS) [42] showed high interest in animals (range 58-117, mean 97.6, std 12.3) for this sample.

4.2 Stimuli

Stimuli consisted of the human's gesture and the robot's expression. In this first exploration, we conservatively began with a single independent variable, and thus manipulated only the latter. We fixed the human-derived self-stimuli by requesting the participant to display the same touch gestures (a modified stroking gesture involving both

TABLE 2
Summary of Procedures

Step	Time	Description
introduction	~7 min	consent, goals, overview
demonstrations	~10 min	instruction on scales, sensors, robot and interaction, etc.
Practice section		
baseline	20 sec	neutralizing
	20 sec	baseline
robot inactive*	20 sec	neutralizing
	20 sec	interaction
robot active*	20 sec	neutralizing
	20 sec	interaction
demographics questionnaire	~8 min	age, gender, attitudes towards pets
Study section		
baseline 1	60 sec	neutralizing
	75 sec	baseline
robot inactive**	60 sec	neutralizing
	75 sec	interaction
robot active**	60 sec	neutralizing
	75 sec	interaction
baseline 2	60 sec	neutralizing
	75 sec	baseline
interview	~5 min	overall response, suggestions

*The pairs denoted by * and ** are counter-balanced. SAM and STAI-6 scales were collected at the end of baseline/interaction periods.*

hands—rationale in 3.2.1) to the robot throughout a session, while the robot rested on his or her lap.

Meanwhile, in a given trial the robot's expression was in one of two states: completely inanimate (turned off), or simulating an animal's breathing. For the same experimental control reasons, we did not render true interactivity, in which the robot would have altered its behavior in response to the human's touch. The robot's motion had the same parametrization of breathing frequency (20 bpm), waveform and amplitude throughout "active" trials.

4.3 Measurements

Our metrics were based on Russell's circumplex model of momentary affect, as in previous work with the Haptic Creature [17], [18]. We additionally measured anxiety to both characterize the interaction's emotional influence, and verify response consistency with a state of increased relaxation [41].

We assessed emotional experience through subjective self-reports triangulated with objective biometrics to capture aspects of both experiential and autonomic responses to the interaction. Selection criteria and collection logistics of these measures are detailed below; see the full experiment procedure in Table 2.

4.3.1 Self-Reports

Selection of measures. Subjective measures needed to be valid for intervals of three minutes, our trial length.

We used Self-Assessment Manikin (SAM) scales of valence, arousal, and dominance to evaluate general emotional response [44]. Measures of valence and arousal localized general emotional response, while the dominance scale helped distinguish emotions clustered in the circumplex regions. The psychometric properties of these measures have been evaluated in [44]. To reference a specific emotional state, participants selected one from nine cartoon icons for each of the valence, arousal, and dominance scales described to them as representing ranges of unhappy/happy, calm/excited, controlled/in-control respectively.

For anxiety, we used a short-form version of the State-Trait Anxiety Inventory to record the subjective levels of anxiety. STAI-6 (at six items, faster to administer) gives results consistent with the full-form STAI [45], and has acceptable concurrent validity for our study criteria. In the STAI-6, participants respond on a four-item scale (*not at all, somewhat, moderately, very much*) to six statements: "I feel [calm/tense/upset/relaxed/content/worried]."

Collection. Reliability in assessment of subjective experience can degrade through several factors, including time elapsed between experience and query [46], fatigue or boredom from queries that occur too frequently or too many times overall, and interference of queries with the interaction's flow [47]. We collected self-reports at the end of each ~3-minute period, a compromise best satisfying these constraints.

Therefore, SAM and STAI-6 scales were administered either after a baseline collection or after an interaction period with the Haptic Creature in an inactive or active trial. Both scales were presented to participants on a screen, and answered by mouse clicks. Choice of response hand was not constrained; at the time of self-report, the interaction was over.

4.3.2 Biometrics

Selection of measures. We collected three biological signals: respiration, heart electrical activity, and galvanic skin response (GSR). Out of these, three features were extracted as indicators of autonomic nervous system (ANS) activity during the interaction: respiration rate (RR), heart rate (HR), and GSR level (GSR-L) [46]. These features were calculated for the whole trial and thus do not represent the transient response. In the dimensional model of general emotional response, GSR linearly indexes levels of arousal, while HR additionally indexes valence with decreased rates corresponding to increased valence [46]. In the discrete model, all of these measures indicate anxiety upon increase [41]).

Collection. Biological signals were collected continuously during every trial and baseline throughout the experiment (Table 2). A trial lasted about 135 seconds, of which the first 60-second period was devoted to *neutralizing* and the last 60 seconds to feature extraction. Thought Technology (TT) respiration, ECG, BVP, and GSR sensors recorded respiration, heart, and GSR signals sampled at 2048, 256, 256, and 256 Hz respectively; i.e., four data streams were generated for every participant in each trial[2]. Fig. 2 depicts the positioning of these sensors on body sites. Refer to [43] for a full specification of the sensors we used.

4.4 Experiment Design

A session had two consecutive sections (practice and study), each including two counter-balanced trials (active and

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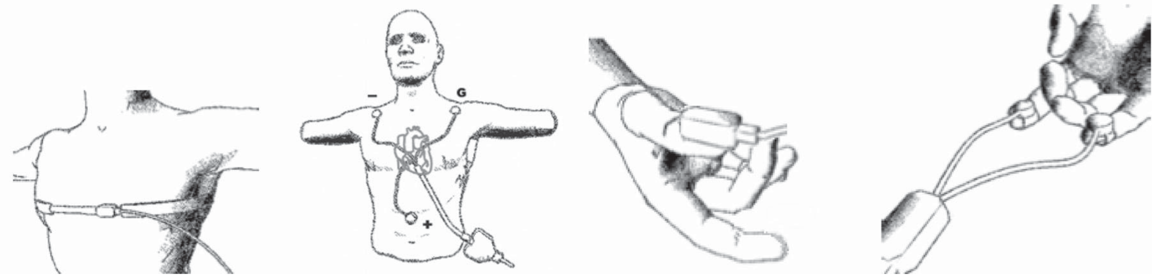
[2] Heart electrical activity and blood volume pulse signals provide similar information and here are used to provide redundancy.



(a) Respiration placement **(b)** ECG placement **(c)** BVP placement **(d)** GSR placement

Fig. 2. Placement of thought technology respiration, ECG, BVP, and GSR sensors [43]. All of these sensors were sampled at 256 Hz except for ECG sensor that was sampled at 2,048 Hz.

inactive). The practice and study sections included identical steps and measures, with the practice shorter. In active trials the robot simulated an animal's breathing; in inactive trials it was powered off to eliminate inadvertent vibrations or any other possible contributions to a perception of aliveness.

Our design was within-subjects to address large anticipated individual differences. To normalize variations related to participants' mood or idiosyncratic physiological response, we collected baseline self-reports and biometrics before the active and inactive trials, while participants sat alone (neither holding the robot nor interacting with it). We also collected a baseline after all the trials in study section to explore the overall reaction to the interaction.

4.5 Setup

Fig. 3 shows the study room. Behind the partition, the facilitator (1) administered a custom C++ program which logged and sampled sensor data at 175 ms and controlled the robot's breathing, and (2) triggered the study steps, communicated to participants on a 18.1″ LCD monitor positioned on the other side of the partition. Executed on an Intel laptop with 2.4 GHz processor running Windows 7, the C++ program hosted the communications with the TT ProComp Infiniti encoder [48] which transferred the signals collected by TT respiration, ECG, BVP, and GSR sensors installed on appropriate body sites. On the screen, participants were prompted with necessary instructions and completed self-report scales using a mouse. A video camera mounted on a tripod above the screen recorded participant's upper torso and face.

Fig. 3. Room setup. 1. Facilitator's seat: fully behind partition during trials. 2. Participant's seat. 3. Office partition. 4. Visual occlusion sheet. 5. Participant's computer screen. 6. Video camera. 7. Thought Technology encoder. 8. Haptic Creature and its cushion.

Throughout the study, the robot was either placed on its cushion to the right of the participants and out of their sight (during baseline) or on participants' laps while they were interacting with it (during inactive or active trials). Only the breathing mechanism was activated in the robot. To minimize visual and audio interactions with the robot, we occluded participants' view with a horizontal rigid sheet that extended the desk over the participant's lap, and asked them to wear a set of sound-blocking ear covers.

To minimize the effect of environmental factors which could mask the emotional response of interest [49], the setup was made as friendly as possible, with a comfortable seat and pleasant lighting.

4.6 Procedure

A session required 45-60 minutes. The procedure is outlined in Table 2. In the following, we provide details.

4.6.1 Demonstrations

The facilitator provided detailed instructions for stroking interaction: speed and approximate pressure of the human's gestures (taken from [18]), orientation of the robot on lap, and positioning of hands on it. One hand was placed behind the ribcage where the robot breathes, while the other hand performed stroking along the body of the robot (Fig. 4). Within the defined interaction, adjustments were made according to participants' preferences (e.g. whether they preferred to stroke with dominant hand or non-dominant

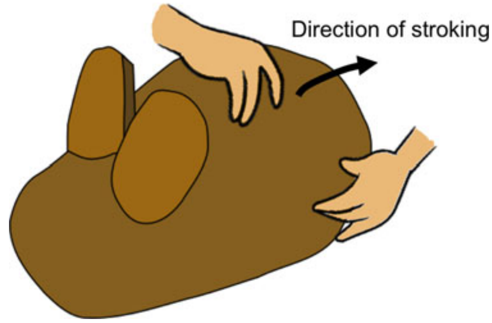


Fig. 4. Positioning of hands on robot in stroking-breathing interaction.

hand). Next, the facilitator connected the physiological sensors, and asked participants to minimize visual contact with the robot, and avoid unnecessary movements and speaking while data collection was in progress. Hand sensors were attached to the non-stroking hand, to minimize movement artifacts and improve measurement reliability.

4.6.2 Practice Section

To reduce effects associated with platform novelty (e.g., initial arousal due to uncalibrated expectations of the robot), participants were given a short version of baseline collection and an inactive and active trial. All baseline collection and inactive/active trials started with a 20 second *neutralizing* period, intended to absorb response carryover from one step to the next, where participants watched a neutralizing video (a square that moved randomly on the screen and changed colors [50]). In both inactive and active trials, the robot was on the participants' laps, powered down, and participants did not interact with it; the facilitator instructed them to rest their hands on chair and not in contact with the robot. For consistency, this was enforced during baseline as well although the robot was not present.

Next followed either a baseline, or active/inactive period. Physiological signals were collected from the onset of the neutralizing period to the end of the baseline or interaction period. At the end of baseline or interaction, participants reported their emotional experience on the provided scales (SAM and STAI-6). The length of both neutralizing and baseline/interaction periods during the practice section was set to 20 seconds to keep the study short and to mitigate response saturation.

4.6.3 Demographic Questionnaire

Participants provided age, gender, and attitude towards pets between practice and study sections. This also provided a helpful acclimatizing break.

4.6.4 Study Section

The study section was identical in format to the practice section but longer, and followed by a second baseline. In all cases, both biometric and subjective (SAM and STAI-6) data were collected. Neutralization took 60 seconds, and baseline and interaction periods 75 seconds. This allowed manifestations of emotion to develop [51] while minimizing boredom (identified in pilots as a risk for this lab-based task where participants were not encouraged to engage in simultaneous mental or physical activities).

4.6.5 Interview

Finally, the facilitator removed sensors and administered a semi-structured interview regarding experience interacting with the Haptic Creature, including their emotional state; e.g., participants were asked if they were comfortable during the interaction and how they liked the robot's breathing.

4.7 Analysis

We performed data verification and preprocessing for feature extraction on the physiological signals; and statistical evaluation on both self-reports and biometrics.

4.7.1 Data Verification

We checked video records to ensure participants had followed instructions, then visually examined RR, HR, and GSR traces during baseline/interaction periods and removed the noisy ones (criteria: out-of-range values and obvious movement artifacts). We eliminated one RR, eight ECG, and two GSR records from the pool of 38 participants who had correctly followed the instructions, leaving 37, 30, and 36 records respectively for further analysis.

4.7.2 Physiological Data Pre-Processing

We extracted physiological features from the last 60 seconds (of 75-second data collection minus the last second) of the baseline/interaction period to ensure a valid statistical analysis that requires equal length of data for feature extraction [51]. The first 15 seconds (transient response to emotional stimuli [40]) were discarded.

4.7.3 Statistical Analysis

We used the first baseline to produce "offsets" of each participant's data (indicated with Δ in results reporting), to account for mood-related distortion in self-report data, and idiosyncrasies in physiological data [52]. We then performed statistical tests on the offset data, that reflected a change with respect to baseline (i.e., offset scores were computed as $baseline - raw\ value$).

Given our within-subject design, we used a dependent sample t-test to compare offset data in inactive versus active trials. Since the sample sizes in both groups are equal for every source of data and larger than 20, the statistical test is robust to the violation of both normality and homogeneity of variance assumptions [53].

With seven metrics (four self-report metrics and three biometrics), we applied the Bonferroni correction to α of 0.05 [53], generating a test significance level of 0.007[3].

4.8 Hypothesis

We hypothesized that stroking the robot while it breathed on participants' laps would increase valence (SAM-V) and dominance (SAM-D), but decrease arousal (SAM-A), anxiety (STAI-6), and biometrics (RR, HR, GSR-L). Together these would signify increased relaxation.

5 RESULTS

Table 3 and 4 summarize the descriptive statistics of the raw/offset data and t-test analysis. In tables, $\Delta_{Inactive}$, Δ_{Active}, and Δ respectively represent $baseline - inactive$, $baseline - active$, and $\Delta_{Inactive} - \Delta_{Active}$.

SPSS 11.5.0 has generated descriptive and t statistics, while G*Power 3.2.1 has generated the effect size metrics and power.

In summary, among the seven measures analyzed for the study, four showed a statistically significant difference

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[3] Bonferroni correction ensures the probability of type I error for an experiment involving several metrics is smaller than 0.05. If the probability of type I error for each metric is P, the probability of type I error for n of them is $1-(1-P)^n$. Setting P to 0.007, we have $1-(1-P)^n < 0.05$ for $n = 7$.

TABLE 3
Means and Standard Deviations of the Collected Metrics for Specified Trials

Absolute (non-offset) values						
Groups:	Baseline 1		Inactive		Active	
Metrics:	mean	std	mean	std	mean	std
SAM-V (38)	5.53	1.18	5.55	1.31	6.63	1.05
SAM-A (38)	3.08	1.65	3.24	1.36	3.76	1.67
SAM-D (38)	5.26	1.72	5.45	1.55	6.00	1.27
STAI-6 (38)	9.82	2.49	10.37	2.67	9.18	2.52
RR (37)	15.76	2.20	18.59	1.21	18.05	1.39
HR (30)	72.31	15.72	75.06	16.40	73.82	16.71
GSR-L (36)	3.40	2.60	6.16	3.80	6.05	4.00
Offset values						
Groups:			$\Delta_{Inactive}$		Δ_{Active}	
Metrics:			mean	std	mean	std
SAM-V (38)			-0.26	0.94	-1.10	1.01
SAM-A (38)			-0.16	1.48	-0.68	1.90
SAM-D (38)			-0.18	1.01	-0.74	1.08
STAI-6 (38)			-0.55	2.07	0.63	1.53
RR (37)			-2.84	2.30	-2.30	2.46
HR (30)			-2.75	3.76	-1.50	3.13
GSR-L (36)			-2.77	2.32	-2.65	2.43

Δ *indicates values offset with respect to the baseline (baseline* $-$ *value of either inactive or active trials).*
– SAM-V, SAM-A, and SAM-D: *Self-Assessment Manikin scales of valence, arousal, and dominance.*
– STAI-6: *6-item State-Trait Anxiety Inventory.*
– RR: *Respiration Rate (breadths per minute).*
– HR: *Heart Rate (beats per minute).*
– GSR-L: *Galvanic Skin Response Level (*μ *Siemens).*
For biometrics, mean values represent the baseline/interaction period. ($\times\times$) *in each row indicates the number of samples available to compute that metric.*

TABLE 4
Statistical Analysis Comparing Offset Inactive and Active Trials with Significance Level of 0.007 (as Opposed to the Conventional 0.05; Rationale in 4.7.3)

Self-reports				
	ΔSAM-V	ΔSAM-A	ΔSAM-D	**ΔSTAI-6**
mean difference	1.08	0.53	0.55	-1.18
std	1.36	1.74	1.35	2.12
standard error	0.22	0.28	0.22	0.34
99.3 CI	[0.45, 1.71]	[-0.28, 1.33]	[-0.07, 1.18]	[-2.16, -0.20]
t	4.88	1.87	2.52	-3.45
df	37	37	37	37
p	**<0.001**	0.070	0.016	**0.001**
d	0.79	0.30	0.41	0.56
r^2	**0.39**	0.086	0.15	**0.24**
power	0.97	0.18	0.38	0.72
Biometrics				
	ΔRR	**ΔHR**	ΔGSR-L	
mean difference	-0.54	-1.24	-0.11	
std	1.09	2.31	0.81	
standard error	0.18	0.42	0.13	
99.3 CI	[-1.06, -0.02]	[-2.47, -0.02]	[-0.50, 0.27]	
t	-3.00	-2.95	-0.84	
df	36	29	35	
p	**0.005**	**0.006**	0.401	
d	0.49	0.54	0.14	
r^2	**0.20**	**0.23**	0.02	
power	0.55	0.50	0.03	

$\Delta = \Delta_{Inactive} - \Delta_{Active}$: *the difference between offset values.*
Mean difference: average of Δ *values for all the samples (in our dependent sample design, mean difference = active* $-$ *inactive, where a positive difference means the active value is larger than the inactive value).*
std: standard deviation.
CI: confidence interval for 0.007 α*-level.*
t: t statistic.
df: degrees of freedom.
p: significance level.
d: Cohen's measure of effect size (d $\approx$ *0.2: small effect, d* $\approx$ *0.5: medium effect, d* $\approx$ *0.8: large effect).*
r^2*: r-squared effect size (*$r^2 \approx$ *0.01: small effect,* $r^2 \approx$ *0.09: medium effect,* $r^2 \approx$ *0.25: large effect).*

between inactive and active trials. In the active trial when the robot was breathing:

valence (SAM-V)	↑	$t(37) = 4.88, p < 0.001, d = 0.79,$ $99.3\%CI = [0.45, 1.71]$
state anxiety (STAI-6)	↓	$t(37) = -3.45, p = 0.001, d = 0.56,$ $99.3\%CI = [-2.16, -0.20]$
respiration rate (RR)	↓	$t(36) = -3.00, p = 0.005, d = 0.49,$ $99.3\%CI = [-1.06, -0.20]$
heart rate (HR)	↓	$t(29) = -2.95, p = 0.006, d = 0.54,$ $99.3\%CI = [-2.47, -0.02].$

6 DISCUSSION

In the following three sections, we examine and interpret our results in light of our hypotheses, discuss their implications, and then consider their generalizability.

6.1 Outcomes: Impact of Our Haptic HRI

Subjective and biometric measures of valence and anxiety changed when participants stroked the robot and it was breathing. Generally consistent with our hypothesis, valence became more positive, anxiety went down and two of three physiological measures—RR, HR—decreased. Self-reported dominance and arousal (SAM-D,A) and GSR-L showed no significant effect; SAM-A's below-neutral and SAM-D's above-neutral values suggest low arousal and raised dominance across all conditions. Measures that did change fully encompass and support our hypothesis, and the remainder are neutral in interpretation, but also redundant to the others. We thus interpret the broad result as indicating increased relaxation. The change in the user's emotional state (less relaxed/neutral to more relaxed) appears to be aligned with the robot's breathing state (off or on); however, the association cannot yet be interpreted as causation since the robot's and participant's expressions may both be necessary. Determination of causality will require examination of each factor separately.

Practical significance. We found large to very large effect sizes (which are independent of sample size) for all the measures found to be significant [53].

To put the magnitude of the biometric changes we found in context: purely affective effects tend to be small relative to the much more dramatic changes seen with exercise. Our subjects were at rest and the changes are only explainable by affective influences; the stimuli were subtle and participants usually started at a neutral emotional state. Thus, we did not expect the representation of a true internal change through physiology to be dramatic, and what we found is of high interest. A crucial next step is to corroborate this with magnitudes of physiological changes deemed practically important in clinical practice.

Underlying mechanisms. We discuss our measures in the context of underlying response systems, to help understand interconnections between robot behavior, the interaction itself, and emotional response including anxiety. We infer three main points:

1) The interaction increases valence without affecting arousal.
2) Robot presence (stationary) alone does not produce self-reported emotional responses. Observed physiological responses that accompany the stationary robot state are likely generated from user movements.
3) When the robot is breathing people are calmer and happier.

6.1.1 Significance Patterns Imply Relaxation

While measures of valence, anxiety, heart rate, and respiration rate were significant, those of arousal, dominance, and GSR-L were not. Is there an explanation that addresses both the significant and insignificant results?

Dominance. A significant increase in dominance would be consistent with anxiety reduction [49]. While the dominance change was in this direction, it was only marginally insignificant with a medium effect size. A larger sample might clarify this relation.

Arousal and GSR-L. In contact with the robot's fur, participants' palm and fingers may have become sweaty, masking GSR-L variations associated with the emotional response. However, this is unlikely; the resolution of measurements was set high to capture low amplitude changes, and the sweaty palms were equally likely in inactive and active trials, particularly considering the positioning of the sensor-attached hand on the robot.

Unchanged subjective arousal and GSR-L points to an interesting aspect of the interaction given the linear association of GSR-L to arousal (4.3.2), as we will discuss next: the interaction does not affect the arousal component of the emotional response, but decreased heart rate indicates increased valence.

6.1.2 Autonomic and Experiential Responses Indicate Relaxation

At both the experiential (i.e. self-appraisal) and the autonomic (i.e., biologically regulated physiology) levels, our results are consistent and indicate relaxation. Among the two response systems organizing behaviors [54], namely appetitive and defensive, unchanged arousal and increased valence suggest that the former has been successfully activated as expected from the lowered anxiety hypothesis [55][4]. In terms of autonomous function, GSR levels are controlled by activation of the sympathetic system, and heart rate is modulated by both or either of sympathetic and parasympathetic systems [57]. Our results indicate that the interaction has activated the parasympathetic but not the sympathetic system. This is associated with the relaxation response, while activation of the sympathetic branch is associated with stress response [58].

6.1.3 Measures Are Consistent

Having shown that self-reports and biometrics are aligned and indicate relaxation, we next look for consistency among each category of measures separately (self-report and physiology).

Consistency is clear for measures of autonomic nervous system activity. Reduction in both heart rate and respiration rate indicates increased valence and improved relaxation [46].

However, less can be concluded for self-reports. In a dimensional view, anxiety can be defined as high in arousal and low (i.e., negative) in valence. In our results, the measure of arousal is unchanged, while STAI-6 (which indexes anxiety) has decreased. For lowered anxiety, we expect to see this increased valence; but also lowered arousal.

Izard's description of discrete emotion patterning for anxiety is a complex and dynamic patterning of responses [59]. It has several components and does not always happen in the same way. In one situation the most salient components are those with negative valence; in another, those with high arousal.

Izard's observation indicates our earlier expectation may be unrealistically simplified: anxiety is not always characterized by decreased valence *and* increased arousal. Hence, our dimensional self-report data does not preclude an interpretation of anxiety. Nor does it prove it on its own; but when triangulated with the data from the STAI-6, an interpretation of anxiety reduction becomes more likely.

6.1.4 Robot's Breathing Influences Anxiety

We now examine the non-offset (absolute) values of the measures (Table 3) for additional insight into the characteristics of the emotional reactions to the interaction.

Self-reports. During baseline and inactive conditions, we found neutral valence, relatively low arousal, neutral dominance, and relatively low anxiety; in active conditions, high valence, low arousal, high dominance, and relatively low anxiety[5].

These values suggest that participants were feeling neutral during baseline; i.e., our baseline sample is close to the real baseline where people are not experiencing a specific emotion. Also, the measures in inactive trials are very close to baseline for all subjective measures implying that, when it behaves as a stuffed toy, stroking the Haptic Creature has no effect.

Biometrics. Baseline samples of all the measures fall within normal adult ranges, suggesting that our baseline sample is close to the true baseline. During inactive and active trials, biometric values increase beyond normal ranges to accommodate the act of stroking.

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[4] Definition of appetitive response systems (extracted from [56, p. 44]: "... complex behaviors can be reduced to combinations of two distinct classes of action tendencies- approach and avoidance... The theories hold that appetitive motivation and the approach behaviors that follow from it are managed by what various theorists termed the behavioral activation system ... This is a regulatory system that organizes the approach of diverse incentives."

[5] For SAM scales, the reference is the mid-point of the scales (i.e., value 5), while for the STAI-6 the reference is the minimum score of 6.

6.2 Implications: Lessons for HRI Design

Stroking interaction with the Haptic Creature when the robot is breathing, symmetrically and constantly on the human's lap, produces an emotional change toward reduced anxiety, presumably through a mechanism of relaxation. In this section we discuss how these findings support the possibility of therapeutic HRI (particularly for anxiety problems) and guide its development.

6.2.1 Classical Conditioning Explains Transition

The robot simulated an animal's breathing to express its relaxed emotional state. Participants mirrored the robot by transitioning to the same state. What yields such a direct association? Can we leverage the cause for further therapeutic behavior design?

Our biometric measures give no evidence that mirroring is happening at the physiological level for the arrangements of our study (i.e., the specifics of robot breathing rate, human's initial emotional state, and her/his stroking gesture). People are not 'entraining' their own physiological functioning to the robot's breathing; the humans' average respiration rate has decreased from $\sim$18.6 to $\sim$18 bpm, diverging from the robot's breathing rate of 20 bpm and significantly different from it. Therefore, it is more probable that cognitive processes are responsible for the observed association.

One explanation is classical conditioning: here, the co-occurrence of specific animal behaviors (e.g., relaxed animal breathing) and pleasant experiences elicits the associated emotional response once the same behaviors are observed.

Our findings suggest that the robot has triggered an emotional reaction already extant in the human recipient. Further research is required to explore the root of this reaction—e.g., whether it is a conditioned association learned from prior animal contact experience, versus some other source. Should it be confirmed, robots can leverage this conditioning mechanism to provide mental health benefits that animals produce.

6.2.2 Approach Behaviors Are Facilitated

The indication that the proposed interaction has activated the appetitive response system has an important implication for robot therapy in the treatment of anxiety. The activation of a response system that counteracts avoidance and withdrawal behaviors can potentially improve anxiety, as these factors are key to the disorder's development and maintenance. Further design and experimentation are needed to utilize this potential.

6.2.3 Lessons for Robot Behavior Design

Our results suggest that humans are able to mirror the robot's emotional state naturally, with no instruction; although the mirroring is not necessarily seen in physiological mimicking (e.g., breathing did not entrain). This is an interesting complement to the finding of [18] that in certain situations, humans expect the robot to mirror their own emotional state. Further work is required to establish the interdependence of these two inclinations. One possibility is that humans expect mutual cooperation in their interactions with a robot by reciprocating the feelings. If proved, the cooperation can be assumed for robot behavior design.

Another interesting observation concerns the relation between robot's rendering parameters and the emotional response it provokes. As reported in [17], the robot's breathing rate is designed to convey arousal (faster breathing: higher arousal), while breathing symmetry renders valence (asymmetric breathing: negative valence). In our study, the breathing was slow and symmetric. Correspondingly, humans experienced increased relaxation with a salient valence content. This characterization of haptically perceived interaction in the absence of other factors such as vision and audition enables an alternative approach to further interaction design: a targeted emotional transition can be obtained by combining the appropriate rendering parameters. For example, combining slow and asymmetric breathing can yield low arousal and negative valence response.

6.3 Limitations on Generalizability

These results were obtained from a single-gender adult population with a positive attitude towards pets, for whom the conditioning case works favorably. We do not know whether similar effects would be found in populations who do not have a positive attitude toward pets and the results do not necessarily extend to male population or other age groups.

Although the study provided strong evidence for the potential of this interaction to cause such a positive emotional transition, the initial emotional state can also be a factor that impacts the transition. Here, it was only shown that the transition can occur when the interaction began from a generally neutral (baseline) state. Further study must establish whether this will occur from, e.g., an intensely anxious state.

Despite some experimental control through counterbalancing, platform novelty could be at least partially responsible for the observed effect. Response habituation must be investigated in a longer study.

7 CONCLUSIONS AND FUTURE WORK

We model interactive robots upon animal characteristics in hopes of producing similar health benefits. The ability to elicit an emotional response comparable to that of animals is necessary for the robot to potentially activate conditioning mechanisms underlying HAI's positive impact. Our study empirically supports this idea and reveals the key role of purely haptic stimulation in the absence of other modalities: the robot's breathing alone made participants significantly calmer and happier when they were stroking it on their laps. Aggregating these results with the reports in literature suggests the potential for anxiety therapy.

While Yohanan's results also demonstrated influence on the human's affective state through haptic interaction with an active robot [1], our work is the first evidence for therapeutic potentials of these purely haptic interactions that we are aware of. As such, it enables exciting opportunities for the design and development of therapeutic companion robots. Moreover, our envisioned therapeutic scenario and its supporting mechanism informs the approach to robot behavior design.

This research has identified a number of issues that require further focused examination to solidify and extend the findings reported here. These tasks include:

- Determining causality (stroking, responding to the robot's movement, or the interactivity therein), and ascertaining mechanism for the human's response and its implication for behavioral anxiety therapy.
- Evaluating the impact of full interactivity in a closed loop (here, the robot did not respond to users' touch).
- Corroborating the clinical relevance of the change magnitudes we found.
- Extending evaluation to more realistic, less controlled contexts, including individually adapted cases.
- Comparing these results to those from other populations, and to non-neutral emotional starting points.
- Investigating response habituation over time.
- Exploring dependency of results on form factor, tactility and other display elements.

The resultant deeper understanding of both underlying mechanism and the potential scope and relevance of the results will enable design of more effective interactions, and extensions to a multitude of therapeutic applications for children and adults.

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