Affecting Affect Effectively

Investigating a haptic-affect platform for guiding physiological responses

by

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Abstract

This thesis describes the development of a platform for touch-guided anxiety management via engagement with a robot pet. An existing physiological sensor suite and "Haptic Creature" robot pet are modified to influence user physiological responses through real-time interaction guided by physiological data. Participant reaction to and perception of the platform is then investigated in several experiments, with the results from these experiments used to refine the platform design. Finally, an experiment is conducted with elementary school children to investigate the ability of the platform to serve as a comforting presence during a stressful task.

It is found that participants were not able to recognize the Creature mimicking their breathing and heart rates. However, once informed of their physiological link to the Creature they were able to use the motion of this device to gain a better awareness of their own physiological state. In addition, the presence of the Creature and its activities are correlated with changes in heart rate, breathing rate, skin conductance, and heart rate variability. These changes are suggestive of a reduction in anxiety. Overall, participant response to the platform was positive, with many participants reporting that they felt the Creature to be comforting and calming. Children in particular were receptive to the Creature, and eager to use it in their stressful environment of school testing. It is found that care must be taken, however, to ensure the platform is presented in an age-appropriate manner, as sudden changes in Creature state can be alarming to the user.

The combination of physiological assessment of user affect with a small, physically comforting robot results in a unique system with the potential to serve as a companion or training aide for children or adults with anxiety disorder, especially in clinical and educational settings.

Preface

Experiments 1, 2, and the pilot experiment in this thesis were performed under UBC BREB certificate no. H01-80470. Experiment 3 was performed under UBC CREB certificate no. H09-02860.

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Glossary

affect (n) emotion or desire, esp. as influencing behavior or action

affect (v) produce an effect on, influence

alpha (α) The probability of falsely rejecting a true hypothesis.

BVP blood volume pulse

Creature The Haptic Creature

ECG Electrocardiogram

effect (n) a result, consequence, impression

effect (v) bring about

EKG Electrocardiogram

EMG electromyogram

ELF Extremely Low Frequency

HALO Haptic-Affect Loop

Haptic Creature A zoomorphic robotic companion for exploring haptic (touch-based) interaction.

HF High Frequency

HR heart rate

HRV heart rate variability

ibi interbeat interval

ICICS Institute for Computing, Information and Cognitive Systems

LF Low Frequency

p-value The probability of obtaining a statistical result as extreme as the result obtained, assuming the null hypothesis is true.

pnn_{50} The sum of the number of successive interbeat intervals that differ by more than 50 ms, divided by the total number of interbeat intervals counted.

QRS complex The series of deflection seen on an EKG during a heart beat.

RMSSSD The root mean squared standard deviation of heart rate

TAMER Touch-guided Anxiety Management via Engagement with a Robot Pet

TAMER Platform The platform designed and constructed in this thesis

SCR skin conductance response, also known as galvanic skin response (GSR)

ST skin temperature

USB Universal Serial Bus

VLF Very Low Frequency

zoomorphic having or representing animal forms or gods of animal form

Chapter 1

Introduction

As robots become better able to infer and assess human affective state, there will be a range of opportunities for robots to assist us with specific physical tasks and with more general social needs, such as playing, entertaining, and skill training. Robots will be able to adapt their behavior based upon that of their operator [1]; in doing so they may also be able to influence his or her emotional state. A gentle touch or hug from a robot that determines you are sad could cheer you up, or decreased interruptions from a robot assistant that detects your happiness with its progress could improve task performance. With physiological sensing, there is even the potential that a robot could become aware of your feelings before you are [2]. A robot detecting an increase in your heart and breathing rate could intervene before you were consciously aware that you were becoming afraid or angry, allowing for reaction times faster than a human alone could achieve.

The platform constructed and experimentally verified in this thesis is designed to begin investigation into this link between robot behavior and user emotion. A small personal robot [3] is utilized as part of an interactive feedback loop incorporating integrated biofeedback from a user wearing physiological sensors. By investigating how the behaviors of a small personal robot can change a user's physiological state, the platform will be capable of reacting to and even guiding user physiological signals in order to produce an effect in the user.

1.1 Motivation

In this work, the proposed end-use application for this platform is as a companion robot for children with anxiety or emotion related disorders, following the interaction model in Figure 1.1. Using biosensors to assess user emotional state, the platform would intervene when appropriate to encourage anxiety-therapy training and coping behaviors [4, 5]. Immune to fatigue, it would provide an untiring, uncompromising tool for a therapist, parent, or teacher, by reinforcing existing therapy techniques [6] and helping to enable their application in the non-clinical world. The haptic interaction channel allows for the interruptions by the platform to be confidential, nonintrusive, and discreet [7] — a small stuffed animal would not seem out of place in a supportive classroom environment or home, nor unusual for a child to possess, and the sense of touch can provoke comforting reactions. This interaction is a variant on the haptic-affect loop principle proposed by MacLean, Croft, and McGrenere, in which a combination of haptic stimuli and physiological sensing are used to manipulate user affective state.

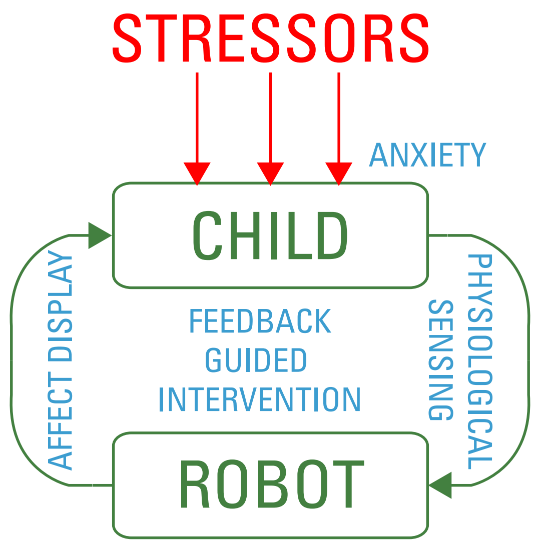


Figure 1.1: Proposed Creature–user interaction model.

The overall system block diagram is shown in Figure 1.1, which along with Figure 1.2 represents the concept described by MacLean, Garland, Croft, Van der Loos and O'Brien in earlier proposals. It describes the platform as envisioned in its eventual use. Input from the user is gathered both by touch sensing on the companion robot and from physiological sensors worn by the user. An anxiety assessment is derived from this data: touch sensors are interpreted by a gesture recognition engine that identifies how the user is holding or stroking the creature (e.g., light petting, hard squeezing. . .), and physiological data by an inference engine. This estimate of anxiety is then used to drive the robot's response model. A response rendering engine enforces transitions between commanded response states and coördinates the companion robot's mechanisms so as to depict a coherent presentation of its biomimetic mechanisms. Offline interaction is provided by the therapist to download both user physiological data and interaction information to assess therapy performance and to upload new therapy protocols as the user progresses. The overall platform is called TAMER, for Touch-guided Anxiety Management via Engagement with a Robot pet.

Before the TAMER platform can be used for therapy purposes, it is necessary to determine what effect the presence of the platform has on user physiology, and if this effect can be measured or influenced. Only after such an effect has been determined can an investigation into the guidance of user affect begin. This thesis, therefore, describes the construction and testing of a platform that can support the entire model as shown in Figures 1.1 and 1.2,

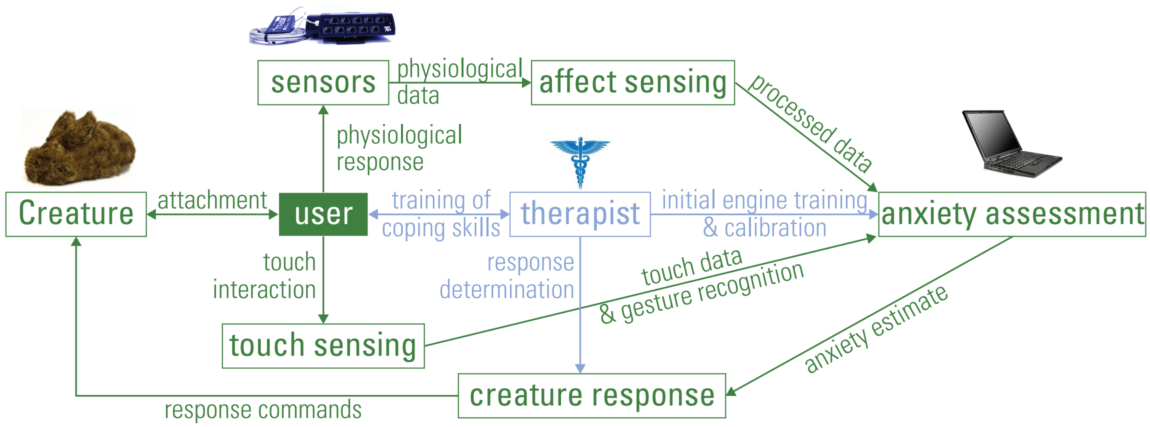


Figure 1.2: User-centered diagram of TAMER model.

beginning with previously existing robot and physiological sensing platforms, and takes a significant step forward in verifying the platform through experimental observation of the platform's effect on participant physiological signals. Specifically, an existing robot, the Haptic Creature [8], and physiological sensing platform [9] were modified and improved to function as part of the TAMER platform. The loop, excepting the therapist and touch sensing boxes from Figure 1.2, and with physiological measures related to anxiety simply measured in lieu of a full anxiety assessment engine, is then tested and verified. The platform construction is guided by feedback from pilot studies, design interactions, and the verification experiments.

1.2 Research Objectives

The overall research objectives are as follows:

1. Determine user physiological reactions to both the presence of and motion of a companion robot, particularly when the companion robot is imitating the user's physiological state.

2. Determine whether physiological reactions can be provoked in a user through manipulation of the companion robot's heart rate and breathing mechanisms.

To achieve these objectives, the following contributions were required:

1. Construction of a platform consisting of a small companion robot and physiological sensors that is capable of measuring physiological data from a user and providing haptic feedback that could evoke a physiological response. This platform is based on existing robot and physiological sensing platforms.

2. Verification and improvement of the functionality of this platform through iterated design and participant feedback.

1.3 Thesis Outline

Following a literature review, this thesis presents the design process of the TAMER platform followed by the experimental design, protocol, and outcome of testing, and finally the conclusions and recommendations toward realizing the vision of a therapeutic robot tool for anxiety therapy.

Chapter 2 An outline of recent literature in the subject areas relevant to the TAMER platform. Research related to robotic companions, robotic therapy, biofeedback and anxiety therapy, haptics and affect, physiological assessment of emotional state, and physiological interaction with robots is discussed.

Chapter 3 A description of the design and construction of the TAMER platform and details of its components: the companion robot, the "Haptic Creature," and integration of the physiological sensing system.

Chapter 4 The experiments performed with the TAMER platform and their results. Four main experiments were performed. The first was a pilot experiment to determine the feasibility of the platform. The second and third investigated the initial user reactions to the Haptic Creature and attempted to determine whether users could recognize it mirroring their physiological state, as well as the reactions to the Creature when the user was performing a task. The final experiment began to investigate reactions to the Creature during a task with child participants.

Chapter 5 The conclusions from the construction and experimental testing of the TAMER platform and recommendations for improvements and future work.

Chapter 2

Literature Review

As the TAMER platform incorporates research from a number of different areas, this literature review will serve as a broad overview of the motivations for the TAMER platform and a summary of the existing work and technology that have been incorporated in it, including basic science and engineering research in psychology and haptics. First, robotic companions and the uses of robots in therapy are discussed, followed by some of the technology and techniques used in their applications. Techniques specific to biofeedback and anxiety are discussed, as well as the general link between haptics and affect. Finally, work in physiological assessment of emotional state is presented, as well as the use of this assessment or other physiological data in interaction with robots.

2.1 Robotic Companions

Around the turn of the twenty-first century personal robots were introduced to the North American consumer market. From Japan came the Sony AIBO [10], a robotic pet dog capable of learning and responding to verbal commands. Tyco Inc. in the United States designed the Furby [11], a small furry electronic creature with the ability to move its eyes, ears, and even itself in response to human interaction. Through prolonged conversation and interaction with their owners, Furbies would appear almost as children in developing a growing command of the language around them, gradually mumbling less and less in their own gibberish language and more in their owner's. Now, for the first time, advances in computer and artificial learning technology hold the potential for robots to refine their interactions with us in a way resembling the development of a friendship or companionship.

The AIBO, as a commercial robotic pet, was the focus of a large amount of research investigating whether owners would react to this device like a loyal fireside-accompanying plastic pet or more as they would a television. Friedman et al. investigated how several hundred AIBO owners described their devices on an online web forum. Although 75 percent of the owners attributed "technological essences" to the creature; still 60 percent described it as having some sort of "Mental States," in particular believing it to have the ability to have intentions and feelings [12]. Owners spoke of their AIBO "wanting" to do things, and of feeling "sad" or "happy" based upon both actions the owners had taken and the reactions of AIBO. Of particularly importance to the concept of companionship was that

60 percent of owners attributed “social rapport” to their robotic canine, with 28 percent of posts describing an emotional connection that they had to their AIBO, and 26 percent expressing a sense of companionship with their plastic pup. It is surprising that humans were able to feel many of the same feelings they would have towards a living animal to a robot, especially one with such limited expressive and interactive ability. Although the AIBO, like the Furby, could respond to commands, there was little verbal communication other than barking, and no software algorithms attempting to emulate a greater emotional connection.

Melson et al. took on the human-robot and human-animal comparison more directly, and investigated children’s responses to both an AIBO and an Australian shepherd [13]. They found that while children were able to recognize that the AIBO was a robot and not an actual dog, they still treated it in dog-like ways, and “affirmed that it had mental states… sociality… and moral standing.” About half of the students even thought AIBO was more like a dog than a computer. Later research revealed similar results in adults, that “even while the person recognizes that AIBO is a technology, the person still affirms AIBO as a companion, and as a friend” [14]. It appears that although humans may recognize AIBO and other robotic pets as technological devices and not living creatures, they still are able to form the bonds of companionship with their robot, and with these can come health and social benefits. Banks et al. showed that elder adults in a nursing home were again able to recognize that AIBO was a robot and not a real dog. Interaction with AIBO produced the same reduction in loneliness that interacting with an actual animal dog provided [15]. The nursing home residents showed a high level of attachment to both the living dog and the robotic impersonator, but yet the effect of level of attachment was not sufficient to explain the decrease in loneliness for either interaction, suggesting some additional attachment. Tamura et al., in research with adults with dementia who might not be able to distinguish the robot from an actual pet, found that residents would often look at, communicate, and care for AIBO, and that this resulted in increased communication from the patients and improved well-being [16]. This finding supports the goal of the TAMER platform to capitalize upon these social links. It aims not to blindly reproduce some benefits of human-animal interaction, but rather to deliver targeted emotional and behavioral therapy through this medium.

The intriguing research prospects of these commercial devices led to the development of several robotic platforms strictly for research use. Instead of modifying commercial platforms designed for entertainment, these were engineered specifically to investigate the behavioral effects that robot animals could have on humans. The most prominent of these was Paro, a robotic baby harp seal developed by Shibata et al. [17]. This robot has the ability to move its eyelids, flippers, and neck, and displays sophisticated animal behaviors, such as responding to noises and sleeping. Paro also is equipped with reinforcement learning, responding to positive interactions such as gentle petting as well as negative interactions such as slapping. It can recognize and grow accustomed to its owner. During long-term interaction at a Japanese nursing home, Paro was shown not only to increase the amount of social interaction engaged in by residents with their peers, but also to reduce their stress levels and improve health, as measured by stress hormone levels [18]. Additional studies by Kidd et al. had American nursing home residents interact with Paro in a group, rather than in one-on-one settings, and saw improvements in community building among the members [19]. Robotic therapy is particularly appealing to nursing homes and hospitals where real animals may be banned for both health and hygienic reasons. The widespread use and exhibition of Paro have also allowed for cross-cultural comparisons of user impressions of robotic animals. In a recent study, Shibata et al. found that westerners were more likely to attribute to Paro a "comfortable feeling like interacting with real animals," while users from Japan and Korea tended to attribute to Paro a "favorable impression to encourage interaction." They attribute this difference to cultural differences in relationships with animals [20]. The success of this robot in therapy has been so great that Paro is now being manufactured for commercial use, targeted to the elderly and those with dementia [21]. A concern noted in these experiments was confounding impressions of specific species. Not only may a user have different expectations from a robotic dog than a robotic seal, but two users from different backgrounds may have different expectations of proper "dog" behavior. To help avoid this, the robot companion in the TAMER platform is a zoomorphic creature, with animal-like characteristics but not resembling a specific animal. Unlike Paro, it communicates solely through the haptic channel, investigating user reactions to a robot designed to be a non-specific species.

Another robot specifically designed for therapy is the Huggable, a robotic stuffed teddy bear. This robot was designed by Stiehl et al. specifically to investigate touch interactions. It features the ability to move its neck, eyebrows, ears, and shoulders (in order to hug, hence the name) with fully compliant voice coil actuators. Its unique feature is a creature-wide sensitive skin to distinguish between various touching behaviors [22]. Much like Paro, the Huggable also contains a behavior system designed to increase companion behaviors. It has the ability to look into a person's face and recognize its owner [23]. More recent work proposes the use of the Huggable in pediatric care, either as a proxy to allow distant friends and family to interact with a child, or with the hope that a child will use the robotic bear as an "emotional mirror" of themselves, allowing for doctors and nurses to receive valuable feedback that the child may be unwilling or unable to provide [24].

These robots both serve as an inspiration for and feed the design iteration of the robot companion for the TAMER platform, the Haptic Creature. It was designed by Yohanan et al. to investigate the emotional aspects of our touch interaction with animals [3]. The Haptic Creature has the ability to purr, breath, heat up, and adjust its ears, and uses these behaviors in an attempt to determine what common behaviors typical to human-animal interaction we find pleasurable. Work is currently underway to determine the emotional states users attribute to various Creature behaviors [8], and how to utilize these to affect the emotional state of the user.

In addition to robots designed for full-body touch interaction, there are several robots designed to investigate the potentials of human-robot companionship through primarily visual or audio means. In keeping with the theme of hugs, the Huggable Robot Probo was designed "as a tele-interface for entertainment, communication, and medical assistance" [25]. The robot has the appearance of something like a robotic green anteater, with a long nose, and is capable of actuating most of its face, neck, and trunk to display various emotional states. Research is currently ongoing to map its facial expressions to emotional states [26]. The iCat is a small yellow robot consisting primarily of a large face that is capable of displaying a wide range of emotions and coherently changing between emotional states [27]. The iCat is intended to investigate what emotional states, as displayed through facial expressions, are to be expected from such a robot in long-term engagement, and which would best be able to maintain engagement in the creature, thereby building a relationship. Work is currently ongoing in measuring participant engagement with the creature [28]. The Kismet robot by Breazeal is another expressive robotic face; this is designed to investigate the use of facial expressions in interacting vocally with users [29].

Unlike an animal, a robot has the potential to communicate with humans in their own language, and there are many potential uses for a robot that essentially acts as the embodiment of a voice to develop a relationship with users. Heerink et al. investigated the use of the iCat to elderly nursing home residents with conversation skills [30]. They found that while the residents were generally excited and interested to interact with the robot, the conversation activity might have been too oriented towards assisting and not sufficiently enjoyable. They hypothesized that viewing the iCat as an assistant rather than a companion would lead to less than expected utilization of the robot. Kanda et al. experienced similar results when using robots to help teach English in Japanese elementary schools [31]. After the initial excitement from introduction of the robot faded, interaction with the robot fell off markedly. However, those who continued to interact with the robot showed signs of improved English skills. While a robot designed for entertainment may not be successfully adapted to a role in therapy, a therapeutic robot must maintain a degree of entertainment and companionship in order to attract repeated, long-term engagement and use.

The TAMER platform aims to build upon these examples of robotic companions to create an engaging device with therapeutic benefits. People are capable of developing a pet-like attachment towards their robots, and the technology exists to construct small personal robots with various interaction devices. In this system we endeavor to leverage this emotional connection to manipulate user affect and feelings.

2.2 Robotic Therapy with Children

Much research into robotic companions and robotic therapy has involved the use of children, the target audience of the TAMER platform. Children, like the elderly, often have a variety of special needs that require care, and they are generally receptive to robots under the guise of a new toy. Several robots and applications of robots to therapy are described here that, like the TAMER platform, target children and attempt to influence child behavior.

Through play, robots may have the ability to elicit emotions more reliably and repeatedly than a human caregiver. Kozima et al. developed Keepon, a small, bright yellow robot that resembles a snowman, with the ability to orient its eyes on a target and bob or rock around to display emotion [32]. Primarily designed for toddlers or babies, they found that children were able to develop a steady emotional reaction to the creature. They hypothesized that by appearing so different from a human but "perceiving and acting" as we do, Keepon "motivates children to explore and communicate with it," a necessity for human-robot interaction. Their intended use for this robot is to promote interaction and engagement in children with autism spectrum disorder. Plaisant et al. developed a robot that, rather than communicate to the child, attempts to enable the child to better communicate with others [33]. The child controls the robot via arm-bands and a headset, and the robot attempts to promote "therapeutic play," either by having the child display emotions appropriate to a story in the robot to gain awareness of the emotions, or by having the robot perform rewarding tasks when certain motion goals as part of physical therapy are met. They note the advantage of a robot controlled by a child in education and therapy: giving a child the ability to have control over part of his or her environment prevents frustration and encourages success. Kronreif et al. developed the PlayROB, a robot that assists several disabled children in assembling LEGO™ structures by handling the bricks. They found that children were able to quickly adapt to use the system, and build LEGO™ structures that they may not have otherwise had the physical ability to assemble [34].

Many applications from the use of robotics in rehabilitation have also been found applicable to children. Out of many: Cook et al. used a robotic arm to assist children with motor development disabilities in gaining motor control [35], and Krebs et al. successfully used a robot exoskeleton to assist children with cerebral palsy in developing proper walking motion as well as muscle strength [36].

Robotic therapy is particularly well-suited to provide benefits to children who are developmentally disabled, particularly those with autism spectrum disorder. These children are often unable to express their emotions and can have difficulties communicating — this often leads to rapid frustration in a social environment. A robot can adapt its behavior to a child's emotional state through the use of physiological sensing to access a communications channel unavailable to humans, and can use machine learning techniques to correlate the child's activity and signals with emotional states.

Dautenhahn et al. developed Robota, a humanoid robotic doll capable of moving its legs, arms, and head [37]. This was part of the Aurora project, the goal of which was to study the role of robots in autism therapy. Robota was used in an attempt to develop interaction skills in children with autism. The robot was programmed both to dance to music and to react to the pressing of controls on a control pad by moving its limbs. They found that the robot was able to become a source of interaction for the children, a device about which they could communicate with their teacher. More importantly, after they had become comfortable interacting with the robot, they were then interested in communicating with the creator of the robot, who was a stranger to them [38].

Salter et al. developed a small spherical robot called Roball for interacting with autistic young children [39]. The robot is designed to resemble a ball to facilitate ease of play, and current research is ongoing in how best to adapt the balls behavior to children's actions in order to maximize engagement and attention.

Liu et al. mount a basketball hoop on a typical industrial pick and place robot to develop an engaging video game for children with autism [40]. They developed a basketball-shooting game with three levels of difficulty by varying the motions of the robot arm. They then attempted to maximize user engagement and liking through the use of physiological sensors to detect emotional state. They found that they were effectively able to increase child liking of their game session through the use of physiological feedback.

Robins et al. does caution, however, that in particular robots designed for the target audience of children with autism must be careful that they do not simply encourage interaction with the robot, but instead use the robot as a tool to eventually encourage interaction with other humans [41].

Leveraging this finding of receptivity to robotic therapy and interaction by young children, the primary user group of the TAMER platform will be children. Guidance into the interaction loop from therapists and child educators will help ensure that while time with the Creature and platform is playful and fun, it also provides important therapeutic benefits.

2.3 Biofeedback and Anxiety Therapy

Physiological training exercises such as yoga and other meditation have long been used for calming purposes. These approaches, however, require careful and repeated training under the supervision of an instructor to be effective. For a novice practitioner, often the concentration needed to achieve anxiety reduction cannot be established in the very anxiety-inducing situations for which they would wish them to be effective. Feedback-guided training would seem an effective learning technique, however it is only relatively recently that we have been able to measure and quantify muscle relaxation. With this technology has emerged a new field of biofeedback-guided therapy: patients are trained to reduce or stimulate certain physiological indices to help them reduce their stress or anxiety levels. Raskin et al. used biofeedback to teach adult patients to relax their *frontalis* muscle, used to lift the eyebrows, and found that several patients had their anxiety markedly or moderately improved through this technique, in one of the first pilot studies on anxiety patients. They state that "in many ways biofeedback techniques represent a modern electronic version of these older approaches" [42]. Townsend et al. found that electromyogram (EMG) relaxation training was superior to group psychotherapy in decreasing mood disturbances, as well as both trait and state anxiety [43]. In an investigation into the physiological symptoms of anxiety, Lehrer et al. found that biofeedback training to increase heart rate variability is also effective in reducing anxiety [44], and that "various forms of breathing retraining have been found to be effective treatments and/or treatment adjuncts for anxiety disorders" [45]. They also note the benefit of biofeedback guided training over simple verbal guidance.

With the advent of portable physiological sensing devices, recent studies have examined the use of real-time biofeedback. In this technique patients are alerted when they are exceeding certain physiological thresholds associated with anxiety, in order that they might begin calming procedures. Murphy et al. used a heart rate variability feedback device for patients with generalized anxiety disorder; they found that, in combination with cognitive behavioral therapy, such biofeedback could be just as effective as EMG relaxation training in reducing anxiety [46]. Reiner reported similar results: he equipped patients with a portable heart rate variability monitor, and they were instructed to monitor their heart rate variability throughout the day. Patient reported outcomes included reductions in anxiety and anger and improved sleep; participants found the feedback device to be more helpful than meditation and yoga [6]. Reiner also found that patients who were most compliant with the monitoring and training reported the greatest benefits. These results suggest the prospect that a biofeedback enabled robot, such as the Haptic Creature, could take on the role of either tutor, by training users to reduce their anxiety using its breathing mechanism, or alerter, by making users aware of their current state of heightened anxiety.

2.4 Haptics and Affect

Herteinstein states that "touch is capable of communicating valenced and discrete emotions as well as specific information" [7]. Touch can be used both to communicate and to elicit emotions. The simple act of touching has been shown to be capable of influencing user actions and opinion. Although an often under-considered element of human-robot interaction, recent attention has been focused on how to reproduce communicative touch in robots.

Various studies have confirmed that touch, even unnoticed, can have a profound impact over our behavior. Fisher et al. found that the brief touch from a librarian handing back a library card produced an increase in positive opinion of the librarian and library [47]. This effect held even when the participant was consciously unaware of the touch. Willis et al. asked passers-by on a campus and in a mall to sign a petition or complete a survey, respectively — they found that combining the request with a casual touch almost doubled participant compliance [48]. It is not only the touch by a human that can induce these effects: Vormbrock et al. found that touching a dog is correlated with changes in blood pressure [49], and Shiloh et al. found that touching rabbits and turtles reduced state-anxiety [50]. Touching the toy versions of the animals, however, did not have a similar effect on anxiety.

Several more recent studies, however, have confirmed that artificial, active touch can provoke positive reactions. Haans et al. investigated whether an armband with vibrotactile actuators could produce the same increase in altruism and compliance associated with human touch; they found that both man and machine had similar success rates [51]. Touching can even make a robot seem more humanlike: Cramer et al. found that proactive robots seemed less machine-like when they touched users [52], but also that a user's opinion of touch was influenced by robot behavior: touching reactive robots made them seem less dependable.

Tactile pleasure should be of concern in designing interaction devices. Salminen et al. investigated the responses to stimulation by a fingerprint friction stimulator: stimuli rated as unpleasant, arousing, dominating, and less approachable produced faster reaction times than those considered more pleasant [53]. Swindells et al. observed physiological reactions to operation of a haptic knob along with emotional reports, concluding that "analyzing both affective and performance measures together is crucial for good design" [54].

Both the effect of haptics on affect and the effect of affect on haptic use have been investigated through several haptic devices that attempt to communicate or influence user emotions. The intimate nature of touch in relationships has inspired several researches to see if mechanical devices can substitute for interpersonal touch. Smith et al. concluded that users were able to communicate emotion through knobs during various tasks [55]. Chang et al. developed the *Lumitouch*, a pair of linked picture frames designed to provide a sense of presence across distance. A frame would light up when a user was in front of the partner frame: by touching the frame a user could cause colors to light up on the other frame; the colors varied depending upon the location, intensity, and duration of touch [56]. Couples found this generally appealing: several developed their own "haptic language" for remote communication. Mueller et al. invented the "Hug over a Distance," in which couples could wirelessly activate an inflatable vest in their partner, simulating a hug [57]. This was generally well received, although thought impractical for every-day use [58]. The

TapTap was a similar device, essentially a haptic scarf designed to record and display touch interactions [59]. This device was proposed to enable a single user to provide therapeutic touch asynchronously to several people without the necessity of their presence.

As touch is an important link to emotion, the TAMER platform aims to use this intimate channel to affect user's emotional state. The haptic channel seems uniquely suited for this sort of task. Through it, the Haptic Creature will be able to unobtrusively display information and even communicate discreetly.

2.5 Physiological Assessment of Emotional State

While biofeedback therapy may have used physiological measurement in order to adjust and moderate emotional responses in patients, these physiological metrics could also be used to assess emotional state. Humans are sophisticated enough that single-sensor metrics are not particularly generalizable to all emotional states, but with the advent of improved computer pattern recognition and machine learning techniques, it became possible to develop the online recognition of emotional state through physiological measurements. When even humans may have trouble reading the verbal and visual clues of their fellow humans, the use of non-conscious channels for emotional communication with robots appears ideal. Humans are not typically accustomed to openly and consciously assessing and sharing their feelings, and whereas body language, posture, and gaze may be difficult for a robot to assess directly, requiring sophisticated cameras and visual processing techniques, much work has been done in using small, simple physiological sensors for the assessment of emotional state.

Picard et al. were among the first to apply the machine learning techniques that had been originally used for vocal and facial emotional analysis to physiological data [2]. They used psychological techniques to instill in participants 8 different emotions, and they achieved a success rate of 81 percent in recognizing these from blood volume pulse, skin conductance, and respiration rate sensors. They state that at the time "there were doubts in the literature that physiological information shows any differentiation other than arousal level," making this the first proof of concept of machine emotional recognition through physiological signals. Kim et al. attempted similar emotion recognition in children, using a support vector machine to classify emotional state based upon blood volume pulse, skin conductance, and skin temperature sensors. They were able to achieve a success rate of 78 percent in recognizing sadness, anger, and stress in users [60]. Wagner et al. attempted a more robust emotion classification system, using feature reduction to improve valence and arousal recognition in users strapped to electrocardiogram, skin conductance, respiration rate, and electromyography sensors and subject to emotion-inducing music. They were able to achieve 92 percent accuracy in identifying emotional state [61].

Kulić et al. attempted not to estimate discrete emotional state, but rather to develop online recognition of a user's valence and affect levels. They utilized a fuzzy-logic based inference engine to assess user arousal base upon electrocardiogram, skin conductance, and electromyography sensors, and use this as the basis for human-robot interaction [62]. They later refined their results using a Hidden Markov Model [63] to achieve an average recognition rate of 72 percent [9].

Liu et al. applied support vector machines to identify emotional state in children with autism [64], using this as the input for the robot basketball game mentioned previously. Theirs is unique in that they trained their system not by progressing the user through various emotional states, but by using both therapists and parents to assess emotional state of the children, who would not themselves be able to communicate this effectively. They were able to achieve a success rate of approximately 83 percent recognition, and improve the child's liking of the game.

Rani et al., in a recent summary of applying several machine learning techniques to a large data set, achieved an overall emotional classification success rate of 86 percent using support vector machines [65].

A major limitation with all these physiological assessment engines developed is that they are often not generalizable to every-day practical use, having been calibrated in specific, often sterile environments for specific uses. Bethel et al. caution that "research should focus on developing a diverse set of complimentary [*sic*] measures that capture the full range of human-robot interactions" [66].

Although the TAMER hardware and software support the ability to provide online assessment of physiological state through computer learning methods, the training of an assessment engine specifically for anxiety is beyond the scope of this thesis.

2.6 Physiological Interaction with Robots

Despite the limitations of these physiological assessment engines, they have already been used to some success in human-robot interactions. Takahashi et al. used skin conductance sensors in an eating assistance robot for people with disabilities [67]. By measuring skin conductance response they were able to distinguish between erratic behavior that was under user control and that which was robot generated, and use this input to fine-tune their control algorithms.

Itoh et al. utilized physiological sensing to reduce user stress when interacting with a large personal robot during interaction tasks [68]. If user stress raised above a certain value the robot would stop the activity and shake hands with the user. They found that subject stress was significantly reduced by the robot's motion. Rani et al. demonstrated affect-based control of a robot: upon sensing an increase in anxiety from its user the robot would interrupt its own task and return to assist the user [69]. Hanajima et al. programmed a robot to reduce its speed of approach towards a user based upon skin conductance response and found that this improved subjective response to the robot [70].

Kulić et al. used their previously defined mentioned algorithms to assess user emotional response to slow, medium, and fast robot trajectories with various behaviors of approach towards the user [62]. They then analyzed this information to estimate user arousal during interaction with the robot, reducing the velocity of the robot when sensed arousal is high, as this could be a dangerous condition [71]. Such a reaction has promising applications in situations where humans must work in close proximity to a robot: a robot reacting to a user's physiological indicators of danger could potentially stop much more quickly than if the user had to find and hit an emergency stop button. Thus, while a generalized emotion system is still some distance away, physiology-based input to a robot system has been shown a successful input to a robot control system to reduce stress related to human-robot interaction.

The eventual goal of the TAMER platform is to have a robot that reacts to valence changes in the assessed level of a user's emotional state of anxiety. Although at present, platform behavior and effectiveness are not based on aggregated sensor data, but rather simpler, single-sensor readings, that capability exists and can be implemented once the appropriate inference engines have been researched.

2.7 Summary

While recent works have begun to apply physiological monitoring to human-robot interaction, the TAMER platform uniquely attempts to integrate this broad background of technologies in order to guide physiological responses. Chapter 3 will describe how an existing companion robot and physiological sensing suite were combined to produce this platform. Incorporating biofeedback training techniques into a robotic companion has the potential to provide users with an untiring, consistent trainer for developing important coping techniques to deal with stress and anxiety. Results from Chapter 4 will show that users are able to successfully use the TAMER platform to mimic the breathing of the Haptic Creature. Experimental results will show that activation of the TAMER platform has a statistically significant relationship to a user's physiological measures, even when the user is performing a separate task. Physiological sensing allows for a robot companion to be not simply an alerting mechanism, informing the user of his or her undesired physical and emotional reactions to conditions, but also a teacher, targeting these conditions for reinforcement of the previously learned coping skills. The platform can potentially act as a proxy for a therapist who cannot always be present with the user, and at the same time gather physiological data for further analysis and feedback. For this children are an ideal target population, as they require constant and consistent reinforcement, but must receive such therapy without belittling and disparagement from their peers. Orienting cognitive based therapy through the haptic sense allows for non-intrusive and inconspicuous communication even in a social environment, while also using a channel that has been shown to have great effect on behavior and affect. Results from Section 4.3 will show that school-aged children are amenable to working with the Creature, and find interacting with it comforting and pleasurable. In addition, when the TAMER platform is used during computerized cognitive activities in school, it will be found to have a statistically significant relationship to physiological changes in the children, who typically enjoy having the companionship of the Haptic Creature during this stressful activity.

Chapter 3

Methods and System Design

The TAMER platform expands upon two existing technologies: a "Haptic Creature" and a physiological sensing suite. Thus, a unified platform is aimed at guiding user affect through haptic interaction, particularly for anxiety reduction purposes. The design of this system proceeded in two main parts: the construction of a new Haptic Creature, with design modifications made to support this particular use, and modification of the sensor suite both to interface with the Creature and to record physiological data related to anxiety that could be used to drive the Creature. This chapter outlines the overall platform approach and methods in Section 3.1, the hardware modifications developed in Section 3.2, the TAMER command and control framework in Section 3.3, and the modifications made due to feedback from user testing in Section 3.4. Finally, in Section 3.5, the modified physiological sensing suite for use in the platform is presented.

3.1 General Approach and Methods

The TAMER platform pairs a robotic creature designed for haptic interactions with physiological sensors in order to guide physiological responses related to affect. Three main components are needed in order to effectively manipulate affect: a sensing suite to measure physiological signals, a response engine using this information, and an interaction device. These components function in a haptic-affect loop, of which the block diagram in Figure 3.1 is an instance. The sensing suite serves to provide online feedback for the platform. Physiological data from all available sensors are analyzed in real-time by the response engine. When used to assess user affect it is trained using questionnaires or surveys from previous interactions. In the initial studies for this thesis the primary goal is not to manipulate affect directly, but rather to take the more preliminary of step of attempting manipulation of user physiological indicators, such as breathing rate or heart rate. In this case the response engine is not trained to recognize specific emotional states, but rather commands actions directly from sensor output, and adapts based upon user response to these actions. The interaction device for this platform is the "Haptic Creature" described in Section 3.1.1; in this platform it serves as a robotic companion. It is desired that through the coupling between user affect and robot actions a genuine affection and sense of connection with the robot will be engendered in the user.

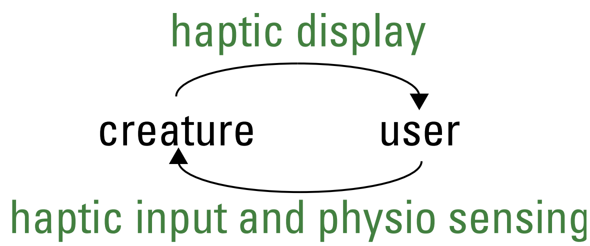


Figure 3.1: Simplified schematic of the Haptic Creature interaction loop; an example of a haptic-affect loop.

Figure 3.2 describes the overall TAMER platform. Physiological sensors attached to the user collect and transmit physiological data to the physiological sensor software. The sensor software, based on these data and desired Creature behavior, sends motion commands to the Creature, over radio, USB, Bluetooth, or an actual wire. Having received these commands, the Creature's microcontroller activates the breathing, pulse, or heating mechanisms to perform the desired motions. In typical use these commands are breathing servo position data or a pulse command. At the same time, sensor data are sent by the microcontroller through radio, USB, Bluetooth or an actual wire to the Creature display software, which displays the sensor information. These components are described in the following sections.

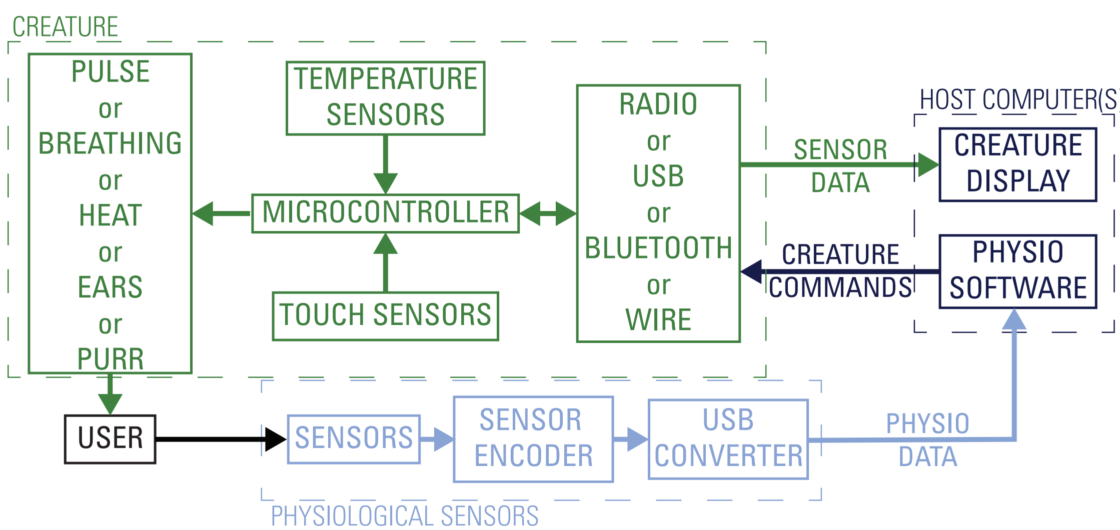


Figure 3.2: TAMER command and control scheme.

3.1.1 Creature Introduction

The concept of the Haptic Creature was initially created by Yohanan and MacLean [72], who constructed a manually-actuated prototype version of the Haptic Creature followed by a robotic version. The Haptic Creature used in this thesis is a second robotic version. It is similar to the original, but was intended not for fundamental research into the haptic expression of emotion, but for the TAMER platform, and thus minor modifications were made for this application, under the supervision of Yohanan et al. and the author. Development of an entirely unique companion robot for the TAMER platform would have been outside the scope of this thesis. The robot used in this thesis incorporates a pulse mechanism and heating pads as additional display mechanisms, which the original did not have, as well as electronics systems designed for integration into the TAMER control loop. Some of the design improvements made on this thesis's robot have been brought back to the original. For the Creature in this thesis, physical construction of the shell, creature heating pad, pulse, breathing mechanism, ears, and fur was in collaboration with Yohanan et al., with several undergraduate student design groups. However, all electronics and communication protocols presented in this thesis are unique to this thesis and wholly the work of the author. A summary of this is shown in Figure 3.3. A description of the Haptic Creature development process follows.

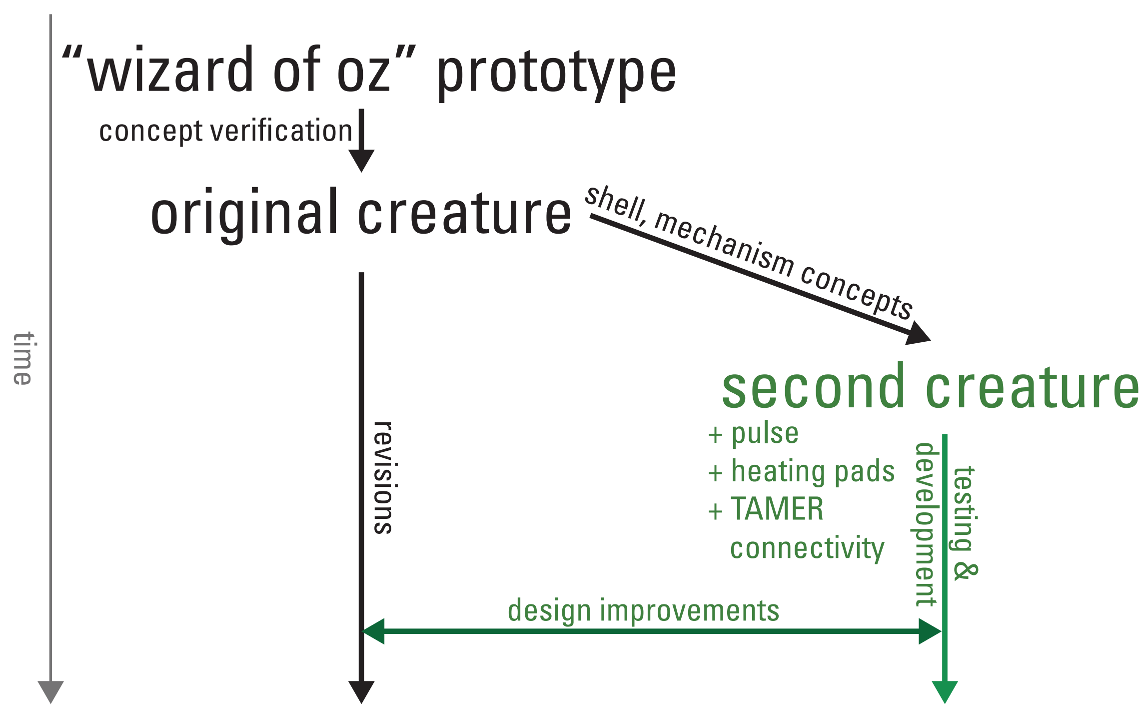


Figure 3.3: Diagram showing development of Haptic Creatures. The second Creature (green) is used as part of this thesis.

3.1.2 Creature Development

The robotic companion for this platform is the "Haptic Creature" (see Figures 3.4 and 3.5), developed by Yohanan and MacLean [72] to investigate affective touch in human-robot interaction (see Section 2.1). While much research has focused on the effect of robot appearance in interactions with humans, the Creature is innovative in that it is among the first to explore in depth our touch-based interactions with robots, and how the tactile qualities of a robot influence our perceptions of it. Such investigation is necessary: robots are no longer constructs of cold metal and motors in factories, where human contact would be dangerous, but have become smaller, more personal devices that interact with their users in more intimate ways. This research both draws from, and can serve as an aid to, the domains of human-animal and human-human touch interaction. In those fields it is typically difficult to eliminate the many confounding variables that are present in touch studies: touching from or being touched by other humans is almost always emotionally loaded, and perceptions of animal touch can be positively or negatively altered by previous experiences with them.

The Creature allows for the individual components of human-animal interaction to be

Figure 3.4: The Haptic Creature.

Figure 3.5: The Haptic Creature, upside-down, with fur removed, showing silicone skin.

studied separately. Actions such as breathing, warmth, and purring can be emulated in isolation as well as combined in both natural and abnormal ways — this is much easier and more practical than, for example, training a cat to purr repeatedly, but not to move or breathe! By manipulating these individual components, a more complete model of how each contributes to our perception of the emotional "state" of the Creature can be developed. The relations between these actions and perceived emotional states should help to develop a more fundamental understanding of the affective nature of our touch interactions.

As originally conceived by Yohanan et al. [72], the Creature had several main mechanisms to interact with users: purring, breathing, ear display, and warmth. These were drawn from the actions typical of small domestic mammals, but designed to be zoomorphic: resembling a generic animal more than any one species to avoid confounding effects. Care was also taken to ensure that the Creature's display mechanisms were purely haptic, with minimal aural or visual components, to again reduce confounding effects and narrow investigative scope. The first version constructed by Yohanan et al. was a "Wizard of Oz" prototype (this version was utilized for use in the pilot experiment of the Haptic Affect Platform, described in Section 4.1) with all mechanisms present but with the breathing and ear display manually actuated by a human operator. Initial studies by Yohanan et al. [72] investigated how these mechanisms could be combined into coherent emotional states. They found that participants were successful in identifying and distinguishing between the device asleep, content, happy, upset, and playing dead [72].

Following that testing a robotic version of the Creature was then constructed by Yohanan et al.. Several form factor and mechanism iterations followed leading to the version depicted in Figure 3.4, the first robotic model of the Haptic Creature, and that used in subsequent experiments by Yohanan et al. [3]. This version consists of a hard fiberglass shell with force sensitive resistors encompassing the structure to detect touch (separate research has been ongoing to classify these sensor inputs as common gestures, such as petting or striking [73]). The shell is covered with soft synthetic fur on all sides except the bottom, where a softer, felt-like fabric, like the abdomen of a dog or cat, is present. A servo mechanism moves the upper rear part of the abdomen to simulate a breathing motion; the mechanism is attached through springs to improve its compliance. Inside the Creature, a motor with an uneven weight attached to its shaft spins to emulate the vibrations characteristic of purring, with also a slight purring sound. The ears are constructed from the rubber bulb of a blood pressure cuff. A servo adjusts a valve connected to the outlet of the bulb to increase or decrease the rate of airflow from the cuff when squeezed, adjusting the perceived ear stiffness when squeezed.

From this “base” design of the Creature, and following the preliminary studies reported in Section 4.1, an additional creature was constructed for use in the TAMER platform by the author in collaboration with Yohanan et al. [8] and undergraduate student teams. It includes the shell and mechanisms described above, and incorporates additional mechanisms and modifications necessary for use in the TAMER platform. Unless mentioned otherwise, all references to the Creature henceforth refer to this newer, second version, the robot integrated into the TAMER platform and used during the experiments in this thesis. While the original Creature and those elements mentioned above were developed by Yohanan et al., the modifications made to the additional Creature, in particular the electronics and the applications thereof, are unique contributions of this thesis.

3.2 Hardware Additions and Modifications

The use of the Haptic Creature in this platform results from an important characteristic of the device revealed in initial prototypes: its calming potential. In casual interaction the warmth and gentle breathing sensation from the Creature were often perceived as comforting. However, in order to fully investigate this behavior there were a number of challenges and concerns to be addressed in modifying the platform from its original intended purpose of investigating affective touch. The Creature required additional robustness for longer-term operation in a less laboratory-like environment. Additional mechanical actuators were needed that, while staying within the solely haptic mode of interaction, could better represent physiological states. As part of this thesis, electronics for motor power and control, sensor input, and communication were constructed, and a communications protocol to incorporate the Creature into the TAMER interaction loop, shown in Figure 3.1, was developed. Feedback from user testing was incorporated into the design process to both test and refine these hardware changes. In this section the design considerations and challenges inherent in the TAMER are described, followed by the details of the modifications made to the Creature's display mechanisms, and electronics. The following sections describe the TAMER platform's communications and control systems, and finally the refinements to these modifications based on feedback from user interactions.

3.2.1 Design Considerations and Challenges

The two primary considerations in designing the Creature element of the TAMER platform were robustness and engagement. Robustness was a paramount design goal: the eventual usage environment for the TAMER platform includes home and school environments, where the Creature will be subject to the not-gentle handling of children. In these environments, it is expected that the Creature will be dropped, struck, and generally played with. It is necessary that the Creature be rugged enough to withstand this treatment, as well as to degrade gracefully in the event of failure, in a way that should not cause harm to the user. Compliance was necessary in Creature mechanisms — a child hugging the Creature could obstruct the motion of the breathing or pulse mechanisms, potentially causing too high a load on the servo or motor driving the mechanism. The Creature also had to be capable of surviving longer-term experiments of several hours or an entire school-day. In addition, the nature of this ultimate user group demanded consideration of the Creature's engagement ability. While acting through channels of limited expressiveness, the Creature had to be initially intriguing to the user, inducing a desire for contact and interaction, and had to maintain this desire during long-term encounters, while not being so engaging as to distract the user from his or her ordinary tasks.

To help foster this engagement a command and control framework that can be readily adapted to changing environments was necessary for the TAMER platform. The platform must be able to react quickly to short-term changes in physiological state, as well as subtly to longer-term user responses. It must also be capable of rapidly communicating interaction data, such as touch patterns, which are applicable to its present operation. The platform must be able to generate and store performance and interaction data for later analysis. As it is anticipated that experimental time with the ultimate user group may be limited, it was imperative that the experimenter be able to modify engagement parameters and Creature behavior quickly; therefore, the Creature hardware and software also had to be adjustable and reprogrammable. All of these parameters had to be fulfilled within the small size of the present shell, and, for time and budget purposes, without a whole-scale revamping of the previously existing Creature mechanisms. All modifications had to support a robust and reliable device capable of withstanding repeating long-endurance experimental trials. The modifications made to achieve these goals are described in the following sections.

3.2.2 Additional Display Mechanisms

In consideration of the primarily haptic nature of the device, the Creature's expressive channels were limited to those which produced effects discernible by touch. In order to increase the Creature's expressiveness, two additional display mechanisms were added to the Creature under the supervision of the author: a pulse mechanism to replicate the presence of a heartbeat, and heating pads to generate warmth.

Pulse

A pulse mechanism, designed and constructed by an Undergraduate Mechatronics Capstone Design Project Course team under the supervision of Yohanan et al. [8] and the author, was added to the Creature (see Figure 3.6). This expressive channel was well-suited to the TAMER platform for several reasons. As heart rate and heart beats are directly measured by the physiological sensor suite, this mechanism permits representation of a user's heart beat in the Creature. Heart rate and heart rate variability are also linked to human affective state, in particular anxiety, therefore display or manipulation of this activity could potentially affect the user's physiological state. Having a pulse also increases the "life-like" nature of the Creature in a way that maintains its zoomorphic behavior. Incorporating heart-rate into the Creature's affect presentation allows the Creature to present its own emotional states with greater fidelity and higher accuracy; these more expressive emotional states could potentially allow for increased growth of user companionship with the Creature.

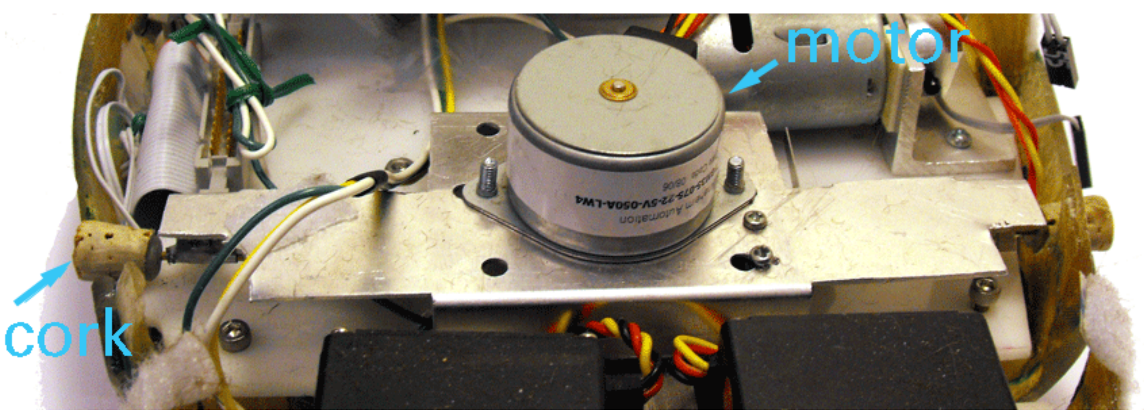


Figure 3.6: Haptic Creature pulse mechanism.

The pulse mechanism consists of a bipolar stepper motor attached to a pulley. Two rods, one on each side, with a cork on the end, are attached to the pulley via a revolute joint. The rods pass through a support bracket near the sides of the Creature. As the stepper motor rotates the pulley, these brackets force the rods to move linearly outwards and inwards. A limit switch mounted near the pulley prevents over-rotation. The net effect of a rapid clockwise then counterclockwise motion (or vice-versa) of the stepper motor is to create a brief tap or "pulse" on the point impacted by the corks. The pulse mechanism is mounted transversely near the front of the Creature, approximately where its "neck" would be if it had one, and with fur on the Creature this mechanism produces a pulse locatable in the immediate area of the mechanism. It does not, however, produce a discernible tactile effect in any other area of the Creature. A maximum heart rate of approximately 160 beats per minute was achieved in bench testing.

Heating Pads

Many users responded positively to the warmth produced by a heating pad in the "Wizard of Oz" prototype Haptic Creature [72]. Therefore, three heating pads were added to the bottom of the Creature to reproduce this warmth. The heating pads are large, flat resistors that dissipate heat when voltage is supplied. They are not noticeably felt through the fur. When operated on 500 mA of current, heat from the pads is able to be felt through the Creature's fur in approximately one minute. Feedback from DS18B20 1-wire digital thermometers mounted around the Creature's shell can be used to monitor temperature levels, and deactivate the heating pads when the desired temperature is achieved.

3.2.3 Creature Electronics Board

The Creature's main electronic board was designed by the author to support the basic functionality necessary for the TAMER platform, while allowing for easy maintainability and upgradability. The board was designed to attach to the Arduino Mega, an "open-source electronics prototyping platform based on flexible, easy-to-use hardware and software" [74]. The mating of a custom board with an off the shelf component served to provide increased functionality, improved reliability, and easier maintainability of the control system. The use of the Arduino helped to reduce potential assembly and design errors in the microcontroller and its supporting hardware, which were among the most complex parts of the electronics. It also allowed for the system to be programmed in a free, open-source developer environment and programming language based on the common C programming language: this allows for future programmers without knowledge of assembly language to maintain the codebase. The Arduino is also able to be reprogrammed without the need to remove the chip or use special programmers. Full schematics of the electronics board, as well as sample code and a parts list, can be found in Appendices C.1, C.2, and D. The Creature's electronics board and its components are shown in Figures 3.7 and 3.8.

Power Supply

The power supply for the Creature comprises several components for delivering power at the voltages and currents necessary for its mechanisms. Power for the Arduino and control board components is supplied by 5 V and 3.3 V linear voltage regulators. Filter capacitors are placed as close as possible to all integrated circuit chips to reduce line noise. Power for the motors, servos, and heaters is supplied by three Dimension Engineering 25 W step down adjustable switching regulators [75]. Adjustable voltage regulators were required to allow for motors or servos to be replaced, as well as for overall current regulation of the heaters. Switching regulators were required both for their efficiency gains: they waste less power than traditional linear regulators, reducing overall current draw, and their reduced heat production: heat buildup is of concern in the small enclosed space of the Creature. Typical operation of the heaters at 10 V, the servos at 7.2 V, and the motors at 5 V allows for maximum current draws of 2.5 A, 3.47 A, and 5 A respectively, although in typical usage this total current draw is not reached.

Power input to the Creature was provided by a 12 V wall power supply capable of supplying 5 A. The linear voltage regulators are low drop-out, allowing for microcontroller power and therefore radio communications to be maintained when input power is as low as 5.7 V. This is of particular importance when the provisions for internal powering of the Creature with a battery are utilized. Connectors are present to allow the Creature to be controlled by a 12 V NiMH battery, similar to that used in remote control cars, eliminating the need for a "tail" wire to the Creature. A Maxim MAX712CPE-ND battery charging chip and supporting circuitry allow for the battery to be charged from a wall outlet without disassembling the shell. Battery voltage can be monitored via the onboard microprocessor.

Motor Controls

The control board is capable of controlling one bipolar stepper motor and two bidirectional or four unidirectional DC motors. Motor control is provided by two Texas Instruments L293DNE dual H-bridges, each capable of supplying 1.2 A of continuous current, and utilizing integrated clamping diodes to prevent back emf. DC motor speed control is provided by PWM output at 64 kHz, 32 kHz, 8 kHz, 1 kHz, or 500 Hz. Heater control is provided by four p-channel MOSFETs capable of providing 9A of current each; typical control is on-off with hysteresis.

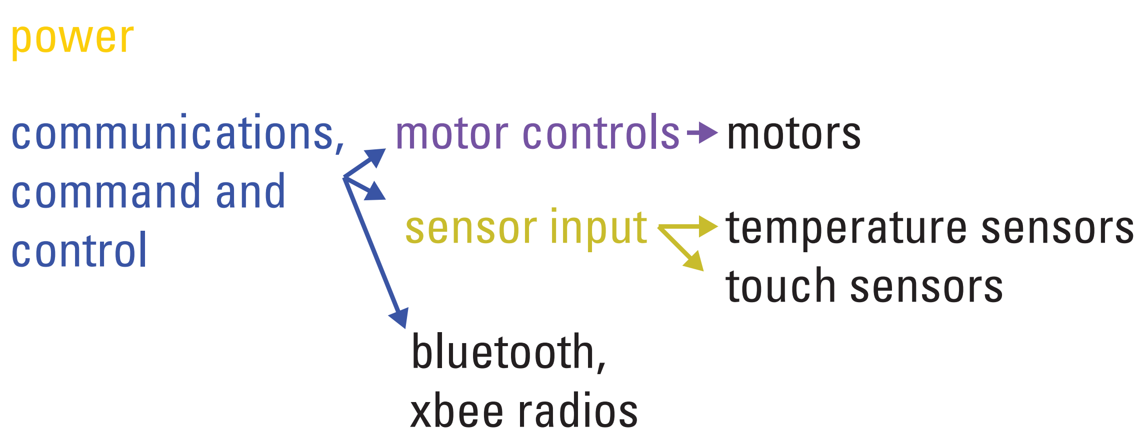


Figure 3.7: Overview of main functions of Creature electronics board.

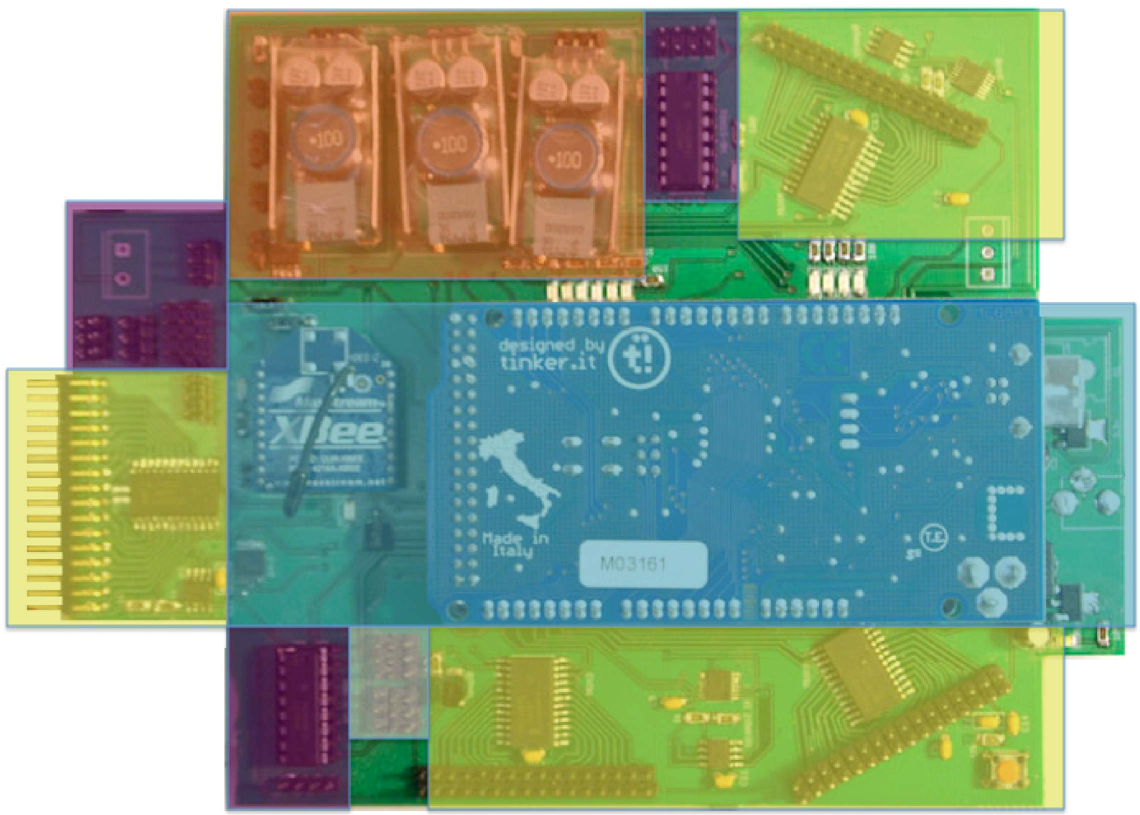


Figure 3.8: Creature Board with power (orange), motor controls (purple), sensor input (yellow), communications and command and control (blue), and temperature sensing (white) areas highlighted.

Sensor Inputs

The control board supports acquisition of touch sensor data from the sixty-four force sensitive resistors (FSRs) arrayed around the Creature. There are four individual sensing circuits: each comprises sixteen FSRs attached connected to a single sixteen to one signal multiplexer. The output of that multiplexer is connected to a circuit as shown in Figure 3.9. Two of the multiplexers share an operational amplifier and digital potentiometer to reduce hardware requirements. Sensor output runs from 0 V to 2.5 V. For greater fidelity and to aid in sensor calibration a digital potentiometer, the 100 kΩ Maxim MAX5479EUD+-ND, is used as the resistor in the sensor circuit; in general, larger resistor values cause the FSRs to saturate less quickly but lose fidelity. Sensor operation was not addressed in this thesis, but resistor values were chosen so as to gain two to three amplitude levels of touch sensing per resistor. The sensor outputs are connected to the analog input pins of the microcontroller, and the digital pins for controlling the multiplexers and digital potentiometers to the digital input and output pins of the microcontroller. Control of the digital potentiometer is via the 3-wire SPI protocol. A triple-axis accelerometer with analog output, capable of sensing up to ± 3 g, is also present on the control board.

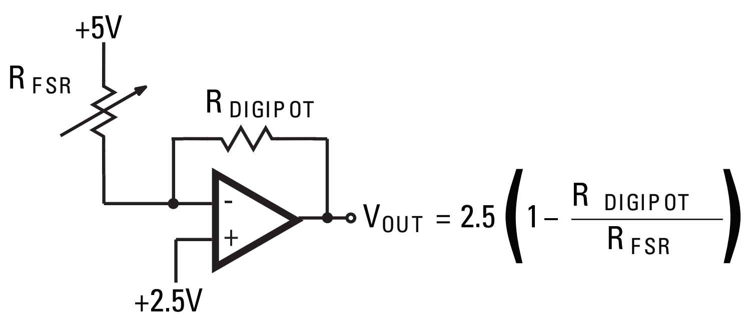


Figure 3.9: Creature force sensitive resistor circuit.

Microcontroller

The control board uses the Arduino Mega as its main controller. The Arduino Mega is a standalone microcontroller board containing an Atmel ATmega 1280 AVR microcontroller running the Arduino bootloader. The microcontroller operates at 16 MHz, with 128 kB of Flash memory. It has 54 digital output pins, 14 of which can provide pulse width modulation (PWM) output, and 16 analog input pins, as well as 4 UART serial communications channels. The use of the Arduino board allowed for the microcontroller and its supporting devices to be connected with smaller solder-traces than possible in a non-mass-manufactured board, allowing for a smaller overall footprint. The Mega also supports the SPI (Serial Peripheral Interface Bus) and I^2C (Inter Integrated Circuit) communications protocols.

Communications Equipment

There are several digital input and output methods provided by the control board. Primary input to the Creature is via the universal serial bus (USB) port on the Arduino Mega board; this is also the channel through which the microcontroller code and firmware are loaded and updated. Access to this port is somewhat difficult without disassembling the Creature's shell; therefore, a "tail" consisting of a short USB cable and power cord surrounded by fur is typically attached to the Creature. A Digi XBee® 802.15.4 RF module allows for wireless radio communication between the radio base station (see Section 3.3.1) and the Creature. The range of the XBee has been experimentally measured at greater than twenty meters, line of sight, which is more than sufficient for typical operations. A Bluegiga Bluetooth communications module (WRL-08771) allows for Bluetooth communication between the Creature and a Bluetooth-enabled computer. Both radio communication devices emulate serial ports on the Creature and the host computer; typically communications speed is 57600bps, bidirectional. Headers on the control board allow for a wired tail to be attached for additional serial communication with the microcontroller or other devices.

3.3 Communications: Command and Control

The control board was designed to support communication through several different methods and media, in order to support communication and monitoring in diverse environments. The Creature as part of the TAMER platform must be capable of both receiving data from and providing data to the physiological sensing suite, and it must be able to do this reliably and effectively. It must also be able to report Creature hardware status, in particular internal temperatures and battery voltages. In typical operation the Creature is controlled by a host computer, communicating wirelessly via the XBee radios. In locations with high electromagnetic interference or for testing purposes a wired serial connection from the radio base station may be used. The radio base station, creature status interface, and several typical usage cases of the Creature communications systems are described in this subsection. A diagram of the command and control scheme is shown in Figure 3.10. The computer hardware used during the experiments is described in Appendix B.5.

3.3.1 Design and Construction of Radio System

Wireless communication with the Creature necessarily requires two radios: one inside the Creature and another to send commands to it. A radio base station was designed and constructed to contain this second radio, and allow for a secure and safe connection with the host computer. The radio base station (see Figure 3.11) consists of a Digi XBee® 802.15.4 radio, as well as supporting components. The radio base station supports input

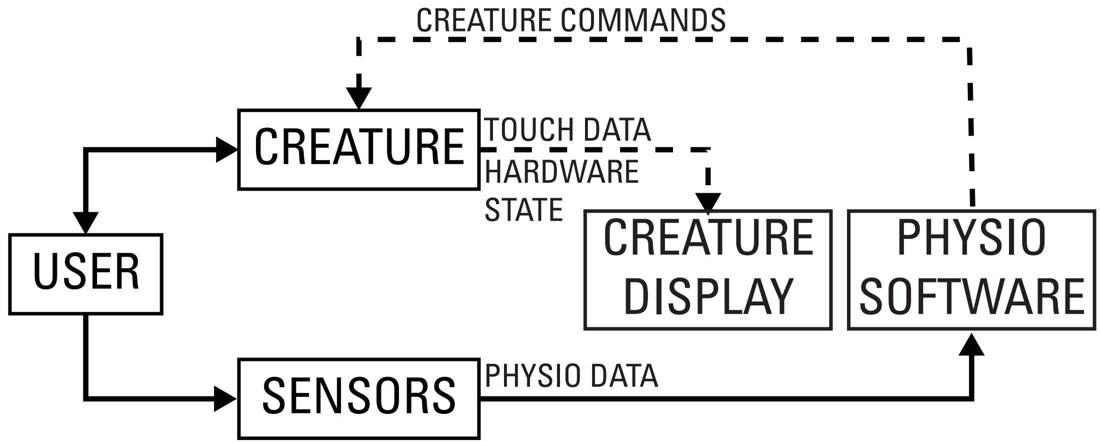


Figure 3.10: Simplified Diagram of TAMER command and control scheme. Arrows represent communications links between system components, dashed arrows identify the connections that are typically wireless.

from several sources: USB communication with a host computer, as well as two-wire serial input from any other serial device. In addition, several digital and analog input and output pins on the front cover of the unit allow for switches or potentiometers to be used to control the Creature. For future applications, an Atmel ATmega 328 chip can be attached to the radio base station board to allow for operation of the base station without a host computer. This chip is typically programmed with the Arduino bootloader to allow for use of the Arduino programming environment, and can make use of the several LEDs and a 4-digit 7-segment display on the unit's control board for user feedback. Schematics and parts lists for the radio base station can be found in Appendix C.1.

3.3.2 Creature User Interface

Use of the Creature in experiments revealed a need for additional monitoring and feedback of the Haptic Creature. A computer graphical user interface (GUI) in the Processing environment was developed to receive feedback from the Creature, and is shown in Figure 3.12. This GUI can utilize whichever communication methods are not currently being used to send commands to the Creature; during typical operation this is the Bluetooth transceiver. It provides the status of the breathing servo and pulse motor, as well as the internal temperature of the Creature. Data received are logged to a text file, for use in after-experiment performance analysis.

Figure 3.11: The radio base station for the Creature.

3.3.3 Creature Modes

The Creature is capable of operating either as part of the TAMER loop, controlled by other programs, radio controlled via the radio base station, or autonomously via onboard firmware. These methods are described in the following sessions.

Physiological Sensor Suite Input (e.g., mirroring)

In typical operation the Creature mechanisms are directly controlled by the physiological sensor suite. The physiological sensors are connected to a computer running the physiological sensing software, which is connected to a radio for command transmission for the Creature. Creature mechanisms are controlled by the physiological software according to programmed algorithms — in the simple but common usage case of the Creature mirroring the user's heart rate and pulse, the physiological software commands the position of the breathing servo to match that of the respiration sensor on the user, and triggers a pulse in the Creature when it detects one in the user. Input from the software does not have to be

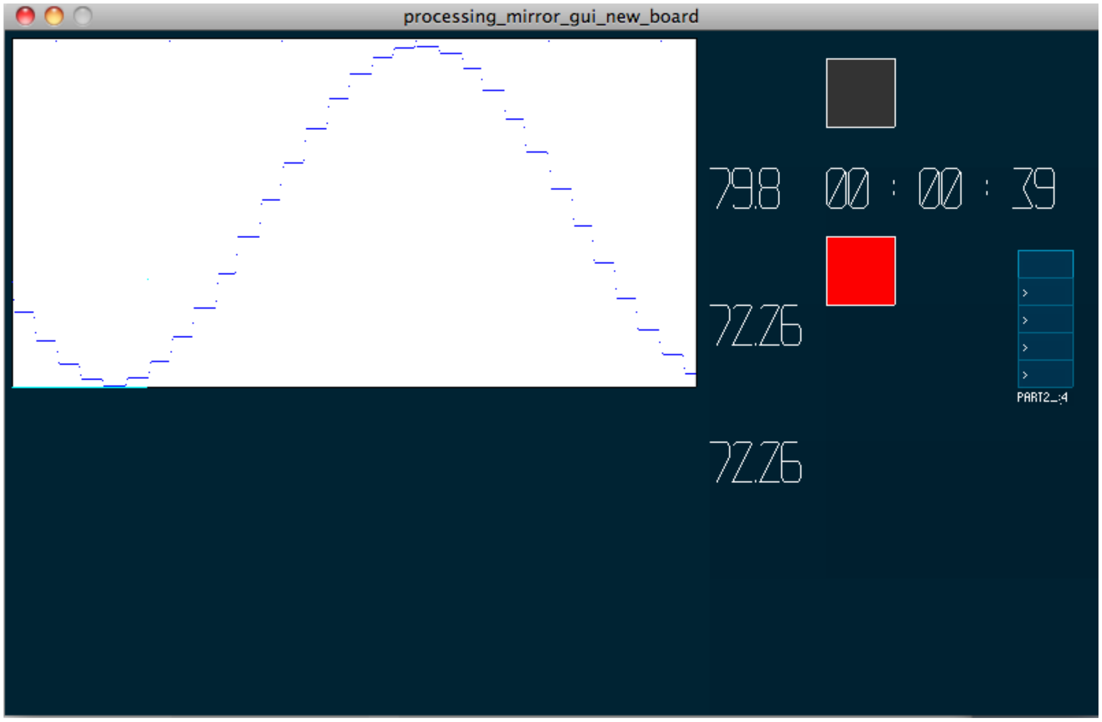


Figure 3.12: GUI for the Haptic Creature, providing motor, servo, and temperature status. A display of commanded respiration rate is shown in the upper left hand corner. To the right of that graph temperature readings from internal temperature sensors are display. On the far right is a timer system for experiments.

direct motor or servo commands; the software can also control the Creature hardware at a more general level, such as commanding a transition between pre-programmed emotional "states" on the Creature.

Direct Software Input

The Creature can also be controlled by any other software program that has access to the serial port, such as those written in the Processing language [76].

Radio Stand-Alone

The radio base station as mentioned previously can act as a standalone device by installing the ATMEGA328 microcontroller into the unit, and programming it using the Arduino enviroment. The digital and analog input pins on the radio base station can be connected to, for example, potentiometers or switches to drive the Creature. This is useful when operating the Creature for demonstrations or testing, where a host computer is not available.

Autonomous Operation

The Creature can also be programmed to act autonomously, running a preset program without external input. As this does not incorporate the functionality gained by incorporation in the TAMER loop, it is typically used only for testing or demonstration.

3.4 Feedback from Testing

After construction of the Creature for the TAMER platform, testing and informal pilot studies revealed several design concerns and suggestions for improvement that were implemented into the device. The three primary areas of redesign were related to unwanted vibrations in the Creature, temperature and cooling related issues, and user comfort.

3.4.1 Vibration and Noise

During operation of the Creature as part of this thesis a slight vibration and noise were present from the breathing and pulse mechanisms. The noise from the breathing servo was predominantly from the servo attempting to maintain a constant position against gravity pushing down the abdomen shell. The shell would fall a small amount and then be raised by the servo, creating sound from the action of the servo and vibration from the motion of the shell. The refresh rate of the servo was increased to give the shell less time in which to fall before the servo would react: this had the result of eliminating the vibration, and changed the sound emitted from a choppy one to a lower-volume purr. These changes both increased the rate at which breathing servo commands are sent from the physio software and increased the smoothness of the breathing mechanism when mirroring a user's respiration. The noise from the pulse mechanism was reduced by placing vibration dampers at the mechanism mounting points. This somewhat muffled the sound, but there is still a fairly audible click when the pulse mechanism is operated.

3.4.2 Temperature / Cooling

A similar version of the Haptic Creature experienced a servo failure due to overheating. To prevent this, the Creature was equipped with a temperature monitoring system by the author. Up to eight DS18B20 1-wire digital thermometers can be located throughout the Creature; in typical operation one is placed on the breathing mechanism servo, and another near the voltage regulators on the control board, the two primary heat generating components inside the shell. Temperature readings are taken every five seconds during Creature operation and passed to the control computer, if present. The Creature is shut down when internal temperature rises above 48.8 °C, above which damage to the internal components may occur. Figure 3.13 shows the Creature internal temperature during an experiment. Temperature is monitored in two places: on the breathing servo, and the anterior of the Creature, located the farthest away from the breathing servo and expected to be the coolest part of the Creature. Breathing servo temperature increased by eight degrees during fifty minutes of use. Although overheating concerns are therefore not a problem during typical operation, some wires were rerouted and neatened to increase available space around the primary heat generating mechanisms in the Creature, namely the servos and the voltage regulators on the control board.

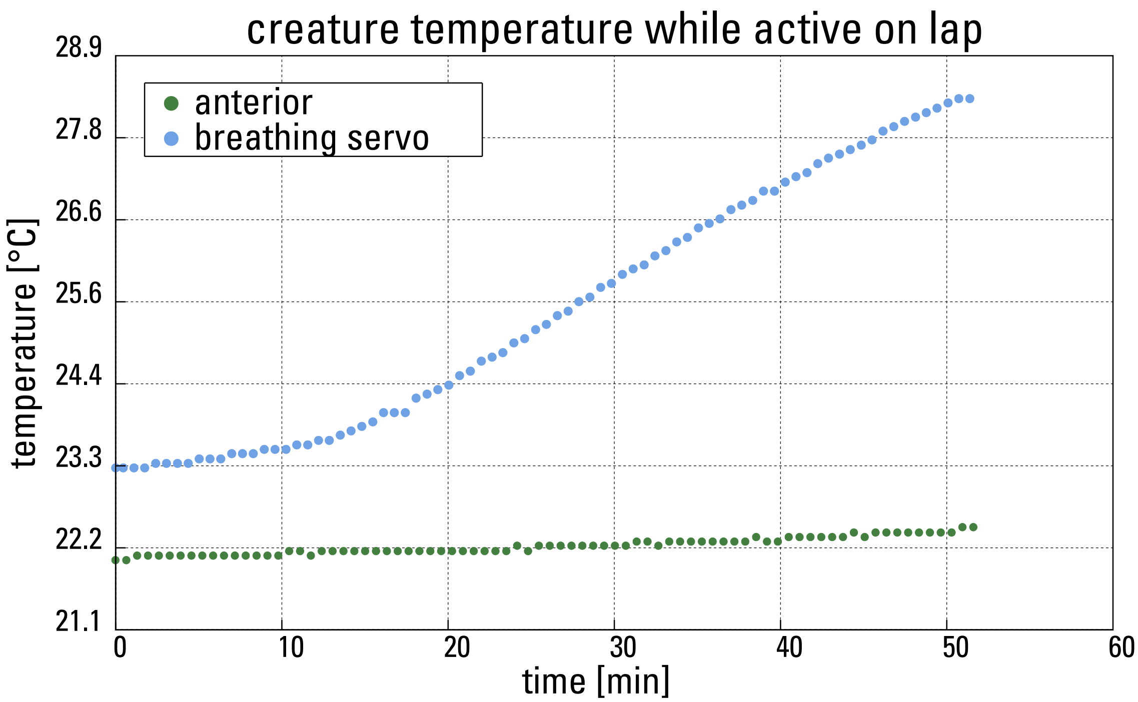


Figure 3.13: Graph of Haptic Creature internal temperature during normal use.

3.4.3 Comfort

While the fur was generally found to be soft and comfortable, the fiberglass shell could still be easily felt underneath. This was particularly evident when the Creature was resting on the lap: the Creature bottom seemed particularly hard and bony. To alleviate this a silicone skin was developed for the Creature by the author in collaboration with Yohanan et al. [8] and constructed by the author. It attaches to the fiberglass shell underneath the fur (see Figure 3.5). This skin consists of an approximately 0.25 inch thick piece of silicone in the shape of the Creature's shell. Part of the skin stretches over the ends of the shell to secure it in place.

The pad improved the comfort of the device markedly, and had the added benefit of increasing the zoomorphic characteristics of the Creature. The feel of the silicone under the fur also attempted to replicate the feeling of a dog or a cat, where there is a harder level of skeleton under the fur coat. The silicone, combined with the fur, also helps spread out the force from any touching of a skinned surface, resulting in registration of a touch by more force sensing resistors on the shell.

3.5 Online Physiological Assessment

The second major component of the TAMER platform is the physiological sensor suite, allowing for user feedback via physical channels. Figure 3.14 summarizes the physiological signals collected in this platform and the physiological metrics derived from these. Six sensors, EKG (Electrocardiogram), EMG (Electromyogram), BVP (Blood Volume Pulse), Skin Conductance, Respiration, and Skin Temperature, are currently used within this platform, both to derive the physical state of the user and to drive the actuators of the Haptic Creature. The capability exists for additional sensors to be integrated into this platform as they become available. Section 3.5.1 describes the key physiological signals used for this platform, Section 3.5.2 describes the sensors and encoder used, and Section 3.5.3 describes the reactions to and limitations of these sensors.

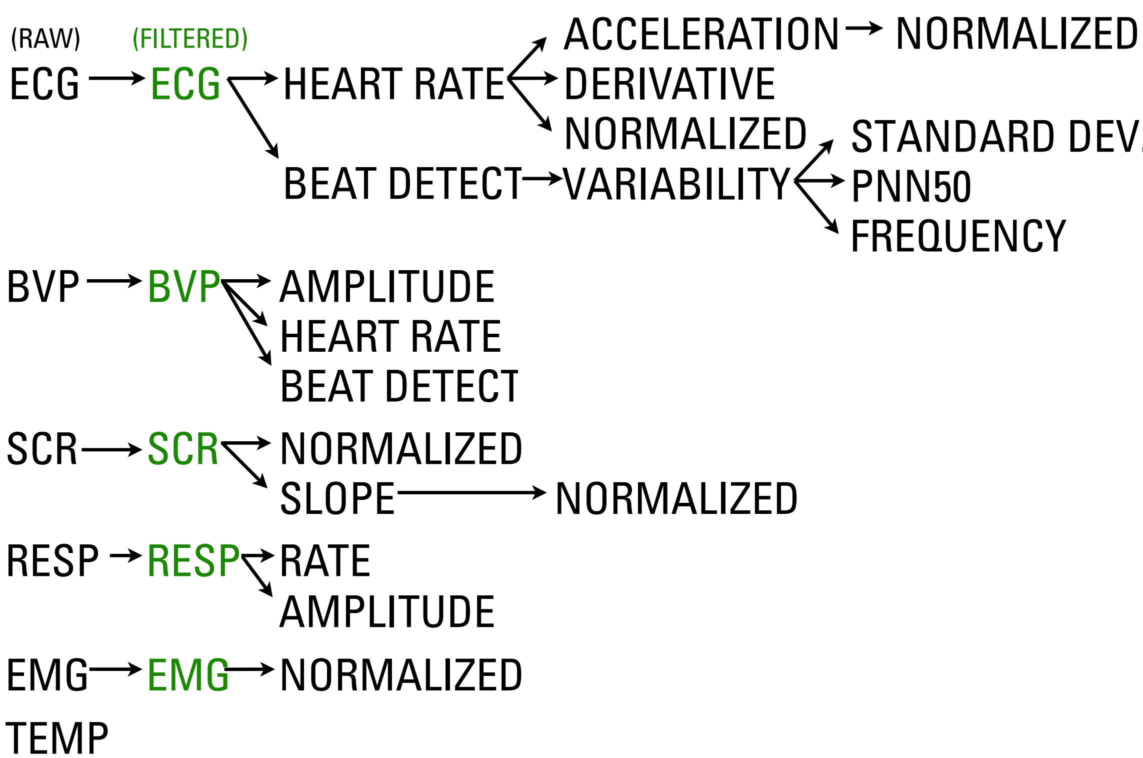


Figure 3.14: Overview of measured physiological signals and the physiological metrics derived from them.

3.5.1 Physiological Signals

The bio-sensor suite generates a large number of physiological metrics of which several are particularly important due to their relation to participant anxiety. Literature specifically regarding the links between the physiological sensors used within this thesis and anxiety is discussed here in order that the use of these specific sensors may be justified.

Anxiety can be thought of as the "fight or flight" response of the autonomic nervous system: the body prepares to respond to a threat by optimizing performance of critical systems.

Heart rate, body temperature, and blood flow to muscles are increased; while activities such as those of the digestive system or blood flow to the extremities are reduced until after the danger. When properly triggered due to an external stimulus this is considered "fear," but without such a trigger it is considered "anxiety." When this stress response is activated improperly in a person, such as in social situations, the effects can be crippling as well as unhealthy; and in cases of long-term anxiety disorders, this response may be chronic and debilitating. Physiological sensors can be used to detect the physiological changes characteristic of anxiety, and are particularly useful in situations where a person is unable to consciously detect the stress response beginning. Current research investigates both the short-term responses to stimuli as can be easily gathered in a laboratory environment and the longer-term physiological differences between those suffering from chronic anxiety and control subjects. Both are difficult due to inherent between-subject variations in common physiological metrics; the latter also due to the within-subject fluctuations over the longer time periods. Indeed, in persons with chronic anxiety disorder it may be impossible to gather a non-anxious baseline for physiological comparison; Craske states that: "the autonomic system may reestablish a balance over long periods of stress, such that dysfunction is no longer apparent except during acute panic attacks" [77]. Although it may be difficult to assess anxiety quantitatively, it is the eventual goal of the TAMER project to incorporate into the TAMER platform advanced machine learning algorithms for analyzing data from the physiological sensors. By training the system based on anxiety assessments from medical professionals it should be able to identify various levels of anxiety in a user, and might even be able to eventually distinguish levels of anxiety in sufferers of chronic anxiety, which would otherwise be difficult. For the experiments in this thesis it is assumed that participants did not suffer from a chronic anxiety disorder in which their physiological responses would be reduced, and therefore comparisons are made to a physiological baseline gathered during the experiment. Disturbing images, intensive tasks, and timed and scored cognitive training exercises are used in an attempt to induce physiological changes in the participants that would be similar to anxiety, as they have been both self-reported to induce anxiety and used in other studies that purport to induce anxiety in their subjects.

Eventual comparison of the physiological data from these experiments to physiological data from patients undergoing anxiety as determined by a medical professional would confirm whether or not anxiety was actually induced. Here, changes in both long-term and short-term heart rate, skin conductance, heart rate variability, respiration rate, skin temperature, and corrugator muscle activity are discussed. These are the primary sensors and metrics used in the physiological sensing suite of the TAMER platform.

Heart Rate and Skin Conductance

Heart rate and skin conductance response are perhaps the two physiological metrics most highly and often correlated to anxiety. Both are primarily associated with short-term, induced anxiety: indeed the increase in skin conductance is often called the "startle response" due to its quick onset and rapid disappearance. Bankart et al. induced anxiety by informing subjects that they were likely to receive an electric shock after a countdown period [78]. The probability that they would be shocked was varied. They found that during the countdown period both heart rate and skin conductance increased linearly. After the first shock, heart rate quickly ceased to increase and stabilized, but maintained an elevated rate compared to baseline throughout the experiment. Skin conductance continued to increase throughout the experiment. Telling subjects that their shock would be mild reduced this effect, but it was still present. Öhman et al. investigated whether this response was driven by conscious activity [79]. They showed pictures of snakes and spiders to users for 30 milliseconds, too short a duration to consciously perceive the image, and found that skin conductance response was similar to those groups that had been shown the pictures for long enough to consciously perceive them. They also found that those who had previously expressed fear of spiders and snakes had more elevated skin conductance responses than those who had not, and that they felt more negative, more aroused, and less dominant after their exposure to the images. These, among other studies in the literature, suggest that elevated skin conductance and heart rate are correlated with experimentally induced anxiety, and that the level of such elevation is increased by an increased perception of anxiety. Assessment of non-experimental anxiety confirms these results. Caprara et al. measured the skin conductance levels of patients about to undergo a dental procedure [80]. They found that increased skin conductance was an objective and reliable test for identifying anxiety in patients.

Hoehn-Saric et al., in several studies, investigated the effects of a clinical anxiety diagnosis on skin conductance and heart rate response to stressful tasks. They found that when given a stress-inducing task, subjects tended to show reduced skin conductance and heart rate variability (heart rate variability as standard deviation), and that this reduction in variability was greater in those who had been diagnosed with chronic anxiety [81]. They further examined this lack of variability to conclude that chronic anxiety patients typically react with less physiological flexibility to every-day stress, but have an increased reaction to anxiety-provoking stimuli [82] than control subjects.

Heart Rate Variability

Various changes in heart rate variability have been correlated with an increase in either general or specific anxiety responses, and a reduction in heart rate variability is now commonly associated with anxiety. Dishman et al. measured heart rate variability in gym patrons for five minutes while resting [83]. They found a correlation between a reduced normalized high frequency component of heart rate variability and the patron having perceived emotional stress during the previous week. They did not find a correlation between self-reported susceptibility towards anxiety and heart rate variability.

Generalized anxiety disorder is also associated with resting variations in heart rate variability. Blom et al. investigated heart rate variability in subjects with generalized anxiety disorder or major depressive disorder, and found them to have lower high frequency and low frequency components of heart rate variability, as well as a reduced standard deviation of heart rate interbeat intervals compared to controls [84]. Thayer et al. also investigated this subject pool [85]. They found that subjects with generalized anxiety disorder had shorter interbeat intervals and lower high frequency component of heart rate variability even while resting, and that when instructed to worry they had even shorter interbeat intervals, lower high frequency component of heart rate variability, and a reduction in successive interbeat intervals that differed by more than 50 milliseconds. Friedman et al. subjected subjects susceptible to severe panic attacks, severely afraid of blood, and controls to stressful tasks in a lab [86]. They found that the control subjects had longer heart rate inter beat intervals, higher variance in heart rate inter beat intervals, greater high frequency component of heart rate variability, and lower low frequency to high frequency ratios than those susceptible to panic attacks.

Respiration

While hyperventilation is the most obvious respiration-related indicator of anxiety, several studies have investigated whether more subtle variations in respiration rate could be an indicator of increased anxiety. Several results were not promising: Suess et al. induced anxiety by threat of electric shock, and while they saw an increase in heart rate during the task, this was not correlated with a change in respiratory activity [87]. However, more recent work does suggest a link between respiratory variability and anxiety. Martinez et al. found that patients diagnosed with panic disorder had greater respiratory variability in both rate and amplitude than controls, even after receiving medication for the disorder [88]. Niccolai et al. in a recent meta-analysis of the literature, confirm that increased respiratory variability is well-correlated with panic disorder [89].

Skin Temperature

Skin temperature has often been used to help identify emotions, and has been associated with both anxiety and relaxation. In general, a decrease in skin temperature is correlated with an increase in anxiety. Rimm-Kaufman et al. found that hand skin temperature increased when participants were exposed to a video designed to generate happiness, but decreased when asked threatening personal questions [90]. Mittelmann et al. induced anxiety in subjects by questioning them during psychoanalysis: they found that a decrease in finger skin temperature was associated with anxiety [91]. Boudewyns et al. again subjected subjects to electric shock in order to induce anxiety; they found that finger skin temperature decreased during the stressful condition and increased during relaxation, and was correlated with participant self-reports of arousal [92].

Electromyogram

Surface electromyography of various muscle groups has been used to assist in the classification of various emotional states. Increased muscle tension has been associated with anxiety disorders and stress, and brief muscle responses can be associated with startle events. Smith et al. investigated *corrugator* or eyebrow muscle response to disturbing images designed to induce anxiety, and found that these images were correlated with increased EMG activity [93]. They also found that baseline images of increased anxiety before the disturbing images were associated with a larger response over neutral photos. Cacioppo et al. found that EMG *corrugator* muscle activity could be used to distinguish between positive and negative emotion inducing pictures, even when there were visible changes in facial expression [94]. Dimberg concluded that “facial EMG technique may be a sensitive tool for measuring emotional reactions” [95], and found that anger-inducing photos increased *corrugator* muscle activity as opposed to neutral photos [96].

It is important to note that while the above data show correlations in various physiological metrics to anxiety, the actual inference of anxiety from physiological data, especially in an online modality, is challenging. The human body is a complex organism, and the physiological metrics measured are affected by the activities of numerous bodily systems, all of which can have different short and long-term reactions to stimuli. Responses are often not consistent across the population, and are in some cases not even present at all. Laboratory induction of anxiety in a controlled environment can help in identifying these effects, but in a real-world environment they are often obscured by the noise from every-day interactions. While the various low-frequency signals are useful in the classification of anxiety disorders, and have been used to judge the effects of various robotic interventions, their utility for short-term human-robot interaction is limited.

In recognition of these limitations, the initial use of the TAMER platform has been either in controlled laboratory settings or in scenarios in the outside world with limited reaction to external stimuli — participants were at a computer in a classroom, but not interacting with their classmates. Additional sensor platform training in recognition of anxiety will be necessary before the platform can used in every day activity.

3.5.2 Physiological Sensors Used

In this section the primary sensors used for collecting physiological information are described. The hardware and software platform for physiological sensing is a later version of that used by Kulić et al. in their human-robot interaction research in the CARIS lab. The initial usage of the sensor platform by Kulić et al. was to detect anxiety in human-robot interaction: see Section 2.5. Additions made by this author include the porting of the software to a more recent operating system, as well as the capability for the software to communicate with the most recent Thought Technology hardware and the Haptic Creature. Only where changes have been made in the processing of physiological signals are they described in this section, otherwise see reference [97] for signal processing and filtering details. An image of a user wearing the physiological sensors typically used with the TAMER platform is shown in Figure 3.15.

Encoder

The data acquisition device used for this platform is the Thought Technology [98] *FlexComp™ Infiniti* (pictured in Figure 3.16). This encoder is designed for clinical physiological measurement and biofeedback training. This encoder has ten channels capable of recording at 2048 samples per second, although data are sampled at 256 Hz within the platform. Data are transferred from the encoder via a fiber optic cable to a converter located near the host computer, and then converted to USB to connect to the host computer. The encoder is powered by four AA batteries.

EKG (Electrocardiogram)

EKG (Electrocardiogram) or heart electrical activity is measured by the *EKG Sensor T9306M* (see Figure 3.17), a 3-lead electrocardiography sensor. The sensor is connected either to a 3-terminal electrode as in Figure 3.18(c) and attached to the center of the chest, or to an extender cable as shown in Figure 3.17. In the latter case, three electrodes are attached to the participant's chest: a negative electrode on the right shoulder, a positive electrode to the left of the navel, and a ground electrode on the upper left portion of the chest. This was the method that was typically used during experiments. Although the

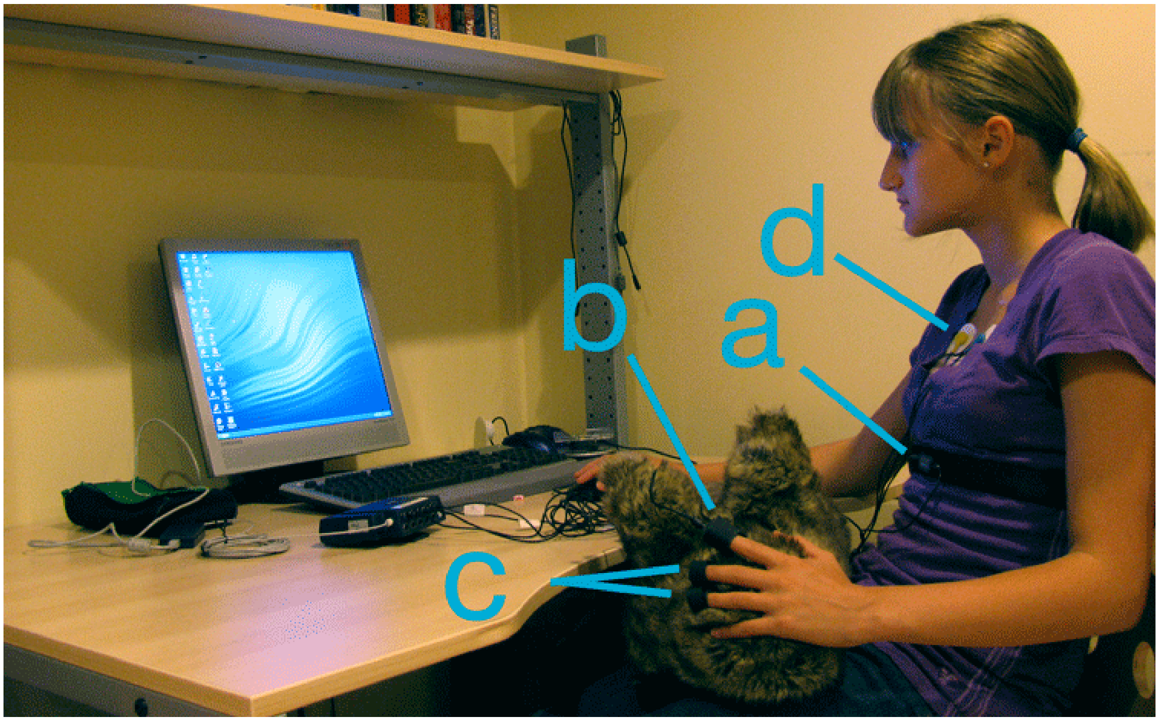


Figure 3.15: User holding the Haptic Creature and wearing physiological sensors: respiration rate (a), blood volume pulse (b), skin conductance (c), and EKG (d). The EMG sensor is not shown, it would have been placed on the forehead.

extender cable required the use of additional cabling, the use of three smaller electrodes attached to the periphery of the chest instead of one large electrode in the center of the chest reduced the amount of body hair contacted by the electrode glue, resulting in greatly improved participant comfort (particularly male) when removing the sensors. It also provided better signal quality, as there was less susceptibility to noise from fidgeting of the body core, and the single electrodes proved less susceptible to losing their connection due to perspiration. Similar electrodes are used for the EMG sensor, and in all cases the electrodes used are single-use and disposable. Participants were typically asked to attach the sensors themselves.

A QRS detection algorithm [99] is then applied to the signal data to detect the occurrence of a heart beat. From this data heart rate, heart acceleration, and heart rate variability are calculated, as are normalized versions of the same.

EMG (Electromyogram)

Electromyogram or muscle activity is measured by the *EMG MyoScan-Pro™ Sensor T9401M-60* (see Figure 3.18): a pre-amplified surface electromyography sensor. This sensor is typically connected to the forehead to measure the activity of the *corrugator supercilii* muscle;

Figure 3.16: Thought Technology *FlexComp™Infiniti* Encoder.

Figure 3.17: Thought Technology *EKG™ Sensor T9306M*, attached to triode electrodes for placement on chest.

for this location care must be taken to ensure the sensor cable does not interfere with the user's vision. It can also be attached to other muscles to measure their electrical activity. This signal is filtered and then normalized as in Kulić et al. [97].

(a) Back of Sensor (b) Front of Sensor (c) Side of Sensor

Figure 3.18: Thought Technology *EMG MyoScan-Pro™ Sensor T9401M-60*. (c) shows sensor with electrode attached.

Skin Conductance

Skin Conductance Response (SCR) (or Galvanic Skin Response (GSR)) is measured by the *Skin Conductance Sensor SA9309M*, as shown in Figure 3.19. The sensor measures the electrical resistance of the skin, and is the same type of sensor used in lie detector tests. Skin conductance is affected by the amount of moisture present in the skin, as released by glands when sweating or in response to stress or fear. During experiments the Skin Conductance Sensor is worn on the index and middle finger of the participant's non-dominant hand. The sensor electrodes must be cleaned with alcohol after each use, and are replaced after fifty uses.

This signal is then filtered, and the derivative taken to produce a skin conductance derivative measurement. Both are normalized as in Kulić et al. [97].

Figure 3.19: Thought Technology *Skin Conductance Sensor SA9309M*.

BVP (Blood Volume Pulse)

Sensor The Blood Volume Pulse Sensor SA9308M (as shown in Figure 3.20) is a photoplethysmography sensor. It measures the reflectivity of the skin to infrared light, a property dependent upon the amount of blood present in the underlying tissues. A heartbeat causes a sudden increase in the amount of blood present; therefore, this sensor is able to measure the occurrence of a pulse. This sensor is typically attached to distal end of the thumb of the participant's non-dominant hand, and secured in place by a velcro strap. It is used when the more-invasive EKG Sensor is not desired or appropriate; however, care must be taken to ensure the sensor is attached tightly enough to the finger to record a signal, but not so tight as to impede circulation and cause discomfort to the participant. The sensor does not measure in absolute units, but rather percentage change in blood volume.

Processing An example sensor signal is shown in Figure 3.21. The raw blood volume pulse signal is passed through a 7th-order low pass Butterworth filter with a 3 Hz cutoff, as a user's heart rate should not exceed about 120 beats per minute during experiments. The filtered signal is then passed through a peak-detection algorithm, which looks for a change in first derivative to determine the occurrence of a heartbeat. From this time series, heart rate and heart rate variability can be extracted.

Figure 3.20: Thought Technology *Blood Volume Pulse (BVP) Sensor SA9308M*, front and rear.

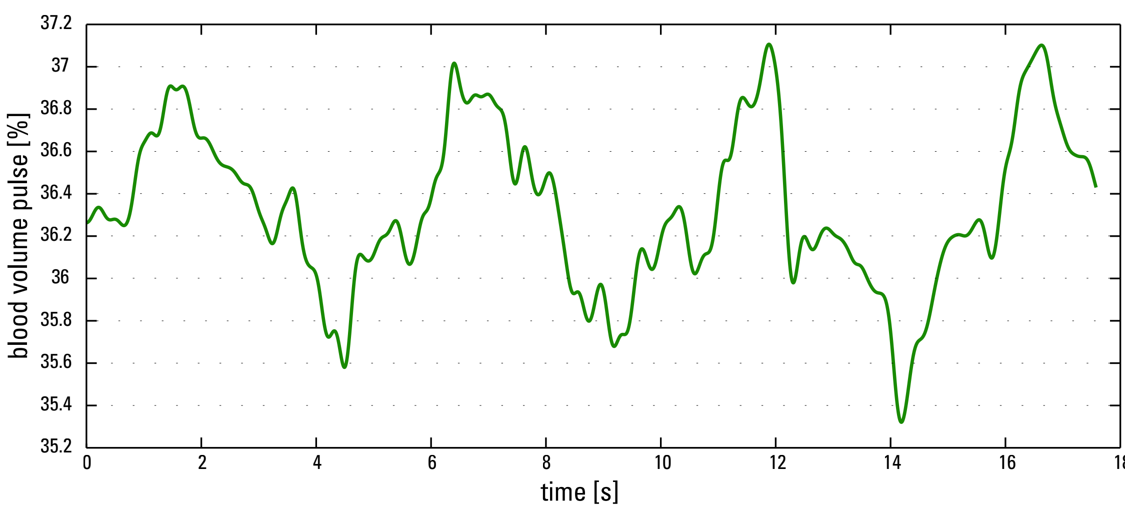


Figure 3.21: A sample unfiltered blood volume pulse signal, showing four heartbeats.

Heart Rate Variability Heart rate variability is a general term describing several metrics derived from heart rate that describe activity of the autonomic nervous system. It is computed from a series of interbeat intervals (IBIs), or time between heart beats, and can therefore be calculated from either the electrocardiogram or blood volume pulse sensor. Use of the Electrocardiogram (EKG) sensor theoretically gives better performance as the EKG directly measures the electrical activity of the heart. The blood volume pulse sensor measures a more distant effect of the heart beat, the increase in blood in a distal digit. In practice this difference is minimal, and often one sensor will offer higher reliability than the other due to the physical characteristics of the particular user: the EKG sensor can be difficult to attach on a subject with a large amount of chest hair, and the blood volume pulse (BVP) sensor can shift and become detached if the subject's thumb moves too often. Several variability metrics are calculated, as defined in the following paragraphs.

Root Mean Squared Standard Deviation The root mean squared standard deviation of heart rate is calculated as follows, where n is the number of observations:

$$SD_{RMS} = \sqrt{\frac{\sum_{i=1}^{n}(ibi_{n+1} - ibi_n)^2}{n}} \tag{3.1}$$

A running 10-second average of root mean squared standard deviation is generated by the physio software; this value can be computed for longer time periods as well.

PNN$_{50}$ PNN_{50} is calculated as the sum of the number of successive interbeat intervals that differ by more than 50 ms, divided by the total number of interbeat intervals counted.

$$PNN_{50} = \frac{\#\text{ of }(ibi_{n+1} - ibi_n) > 50}{n} \tag{3.2}$$

Frequency Analysis Frequency variation in the interbeat interval series is calculated for extremely low, very low, low, and high frequency bands using commonly accepted ranges [100], as shown in Table 3.1. The integral of the power spectral density function of the signal is used to calculate the power of each frequency band. For samples less than five minutes in length extremely low frequency and very low frequency data are typically unreliable [101]. Also calculated is the LF / HF ratio as follows:

$$\text{LF / HF ratio} = \frac{\text{low frequency power}}{\text{high frequency power}} \tag{3.3}$$

Table 3.1: Heart rate variability frequencies.

band	lower limit [Hz]	upper limit [Hz]
extremely low frequency (ELF)	0	0.0033
very low frequency (VLF)	0.0033	0.04
low frequency (LF)	0.04	0.15
high frequency (HF)	0.15	0.4

Respiration Sensor

Respiration rate, amplitude, and waveform are measured by the Respiration Sensor SA9311M, as shown in Figure 3.22 This sensor consists of a strain gauge connected to a large velcro strap. This strap is worn around the upper abdomen over the participant's clothing, and tightened so that the strain gauge is on the front of the abdomen. The strain gauge expands and contracts with the user's breathing. The sensor does not measure expansion in absolute units, but rather percentage expansion.

Figure 3.22: Thought Technology *Respiration Sensor SA9311M.*

Processing An example respiration rate signal is shown in Figure 3.23. The processed signal is shown in Figure 3.24. The raw respiration signal is passed through a 5th-order low pass Butterworth filter with a 1 Hz cutoff. The filtered signal is then passed through a peak-detection algorithm, which looks for a change in the first derivative to determine the peak of a breath (peaks are identified by blue triangles in the figure, troughs by the purple triangles), similar to how peaks in the blood volume pulse signal are detected. The peak-to-peak distance between breaths is then used to calculate the participant's breathing rate (L1 or L2). The normalized current respiration amplitude is calculated as follows:

$$\frac{\text{Respiration Amplitude}_{\text{current}} - \text{Respiration Amplitude}_{\text{min}}}{\text{Respiration Amplitude}_{\text{max}} - \text{Respiration Amplitude}_{\text{min}}} \tag{3.4}$$

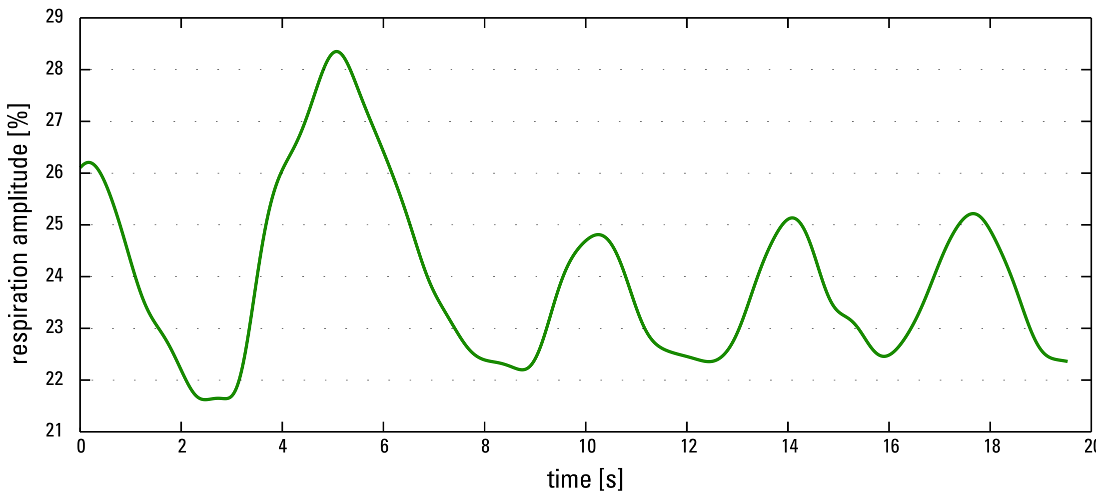


Figure 3.23: A sample filtered respiration signal.

Normalization from smallest to largest expansion is necessary for calculations, as the percentage compression and expansion for a single breath for each user can vary widely. Typically this is about five to six percent of the full sensor range for a deep breath. On some subjects, particularly very small ones, the upper abdomen may not give a large enough range of motion, and the sensor may have to be placed lower on the abdomen, around the belly. Such a placement is undesirable, as belly motion can be affected heavily by speech. Although the algorithm has generally proved robust to short phrases or questions, longer periods of speech can result in erroneous data. Respiration rate and breath length are terms typically used to describe user breathing; they are the inverses of each other.

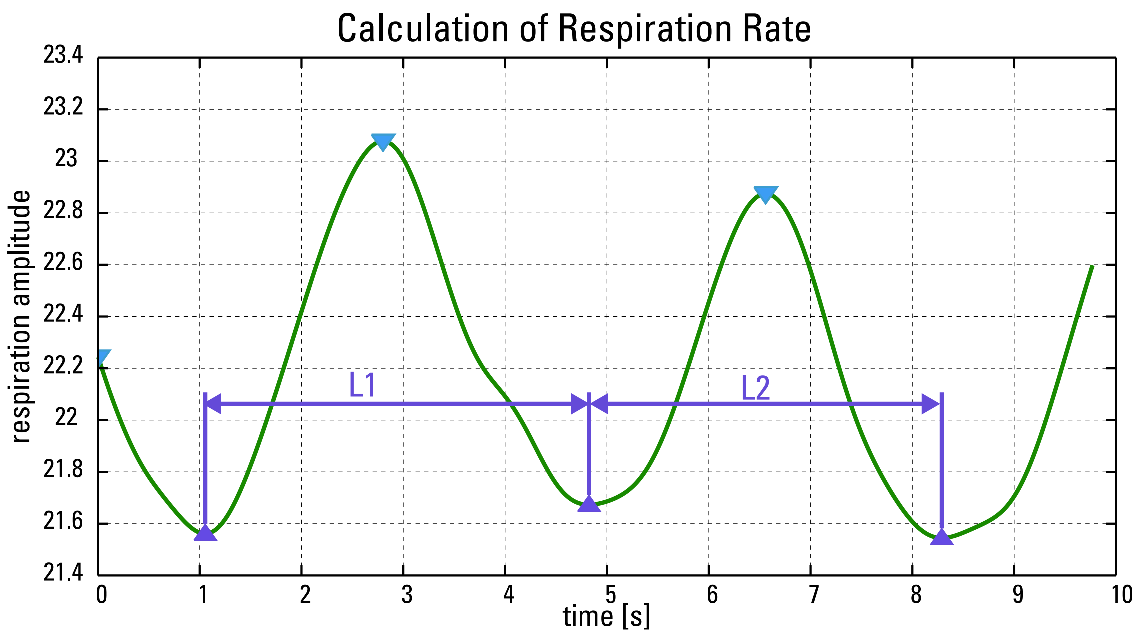


Figure 3.24: Calculation of respiration rate.

Skin Temperature

The Temperature Sensor SA9310M (as shown in Figure 3.25) measures the skin temperature of a peripheral digit. This sensor was worn on the ring finger of the participant's non-dominant hand, and attached by a piece of medical tape. No filter is used as the signal is relatively noise-free and slow moving; a sample signal is shown in Figure 3.26. Data are recorded in degrees Celsius. As with all sensors placed on the fingers, care must be taken to ensure that the sensor does not become detached during use, and that the sensor does not slip down to the underside of the finger, which may be in contact with a warmer surface.

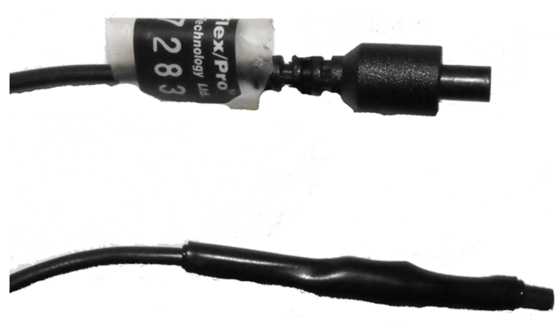


Figure 3.25: Thought Technology *Temperature Sensor SA9310M*, showing sensor and connector to encoder

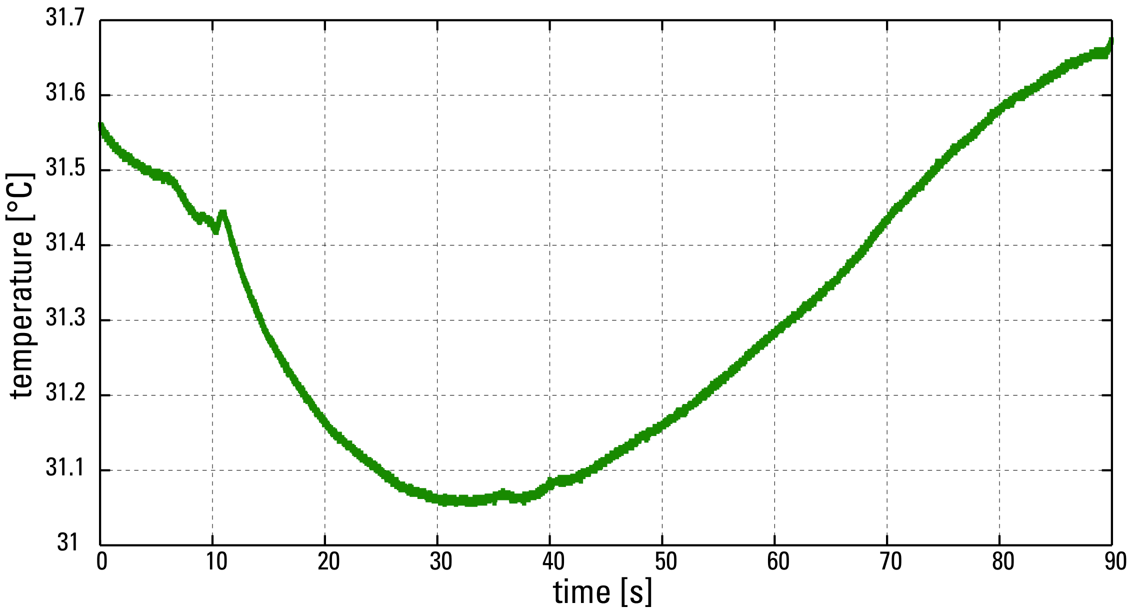


Figure 3.26: A sample skin temperature signal.

3.5.3 Sensor Application Notes

Actual use of the sensors in both brainstorming, pilot studies, and experiments as part of this thesis provided valuable feedback on the use of the sensors in experimental environments. In particular, maintaining proper sensor functioning is a challenge inherent to physiological experiments — most physiological experiments have at least a few people whose data are unusable. The sensors attached to the fingers were particularly prone to coming loose during experiments, as subjects typically made contact with the Creature with their hand attached to the sensor. The most sensitive to motion is the blood volume pulse sensor, which requires a tight fit on the thumb to record a proper signal. Motion in the body core could also affect sensor readings: fidgeting could result in noise in the EKG signal, and talking resulted in disruption of the respiration rate signal. In general, however, the large number of wires required to physiologically monitor a subject is a greater hindrance to non-experimental use of the sensors than these motion concerns.

Chapter 4

Experiments

A series of four experimental trials was performed to evaluate the functionality of the TAMER platform and to investigate its efficacy in guiding physiological responses. The first, a pilot experiment, was a preliminary examination into the feasibility of using the Haptic Creature as an anxiety-reducing device: participants were asked to view disturbing images with a proof-of-concept version of the Haptic Creature. Overall results were encouraging enough to support construction of the TAMER platform. Experiment 1 and Experiment 2 investigated the ability of the Haptic Creature to influence physiological responses. In Experiment 1, the initial physiological and subjective responses to the Creature were observed, and participants were exposed to the Creature mimicking their breathing and pulse. In Experiment 2 participants were asked to use the Creature as a training tool, breathing with it, and then had the Creature in their lap as they performed a task. In the final experiment, Experiment 3, the Creature was tested in a target environment, namely an elementary school that supports children with learning challenges, many of them anxiety related. Children were introduced to the Creature and then given the Creature to have during a stressful activity. In this chapter the experiments and experimental results are described.

4.1 Pilot Experiment: Response to Disturbing Images

4.1.1 Introduction and Motivation

Initial reactions to the first Haptic Creature prototype revealed the potential for the device to provoke a comforting and calming response in its users [72]. The Creature's similarity to both a stuffed animal and an actual animal suggested the potential for the Creature to produce similar comforting effects. Here, a pilot study was undertaken to investigate this general hypothesis. Information obtained from this experiment was also desired to assist in the design of the second Haptic Creature prototype.

4.1.2 Experimental Design Considerations

The first step in developing such an experiment was to determine both how to best induce anxiety in adult participants, and whether the physiological sensing would be able to recognize such anxiety. Inducing anxiety in experimental participants is difficult both practically and ethically: participants can have widely differing responses to the same stimuli, anxiety-inducing scenarios are limited, and threats of harming or actual physical harm to the participant are not permitted under ethics regulations. It is also necessary to have a non-anxious baseline from the participants to help determine the physiological indicators of anxiety. Therefore, although long-term anxiety or general stressful situations such as the middle of exam week could be ideal scenarios in which relaxation therapy would be effective, the determination of this more chronic and persistent anxiety would be beyond the timescale of the preliminary experiments and the clinical capabilities of the researchers, thus necessitating an investigation of short-term anxiety induction and response. In addition, in order to produce a measurable effect during the limited time-span of an experiment, the anxiety stimulus must be able to quickly induce anxiety in the participant. Typical psychological methods of inducing anxiety in experiments are such procedures as rapid-fire yelling of math questions to be answered, or playing a stressful puzzle or video game. These were deemed impractical for two reasons. First, they were viewed as too distracting from the Haptic Creature prototype, and second, they required the use of the participant's hands — participants would need to keep their hands, which would also be encumbered with the physiological sensors, on the Creature during any experiment, as the hands are the primary channel through which the Creature communicates. It is important, eventually, to have their hands available for other activities while using the Creature. Potentially hand-reliant tasks could raise the questions of how much physical interaction with the Creature would be required for it to be effective, and how inhibiting the hand sensors would be. These are discussed below in Sections 4.3.4, 4.3.6, 4.4.5, and 5.3.2. Therefore, additional anxiety inducing methods were investigated.

In a pilot study, six participants were asked to watch a two-minute video clip of a movie picked for its believed ability to induce anxiety [102] while physiological data, skin conductance, EKG, and EMG, were collected. Analysis showed an increase in skin conductance and heart rate during the movie. This response, however, was inconsistent across trials, highly transient, and dependent upon an individual's engagement with the video. In most cases, this response peaked for only part of the scene, remaining at a lower state for the majority of the film. While clearly real, these responses were neither sustained nor controllable enough for use during an experiment. A more stable visual source of anxiety was therefore sought. The International Affective Picture System [103] is a set of images designed to provoke either positive or negative reactions in subjects, and correlated with physiological effects in both skin conductance and corrugator muscle activity [104], both of which are directly measured by the physiological sensor suite. Images such as mutilations, snakes, insects, and dead bodies, corresponding to high anxiety induction, were selected. By using a variety of images, it was expected that participants would be more likely to experience at least one anxiety inducing stimulus.

Since this pilot experiment was done prior to the construction of the Haptic Creature version described in Section 3.1.1, the "Wizard of Oz" prototype constructed by Yohanan et al. [72] and shown in Figure 4.1 was used during the experiment. This prototype is a manually actuated predecessor of the present Haptic Creature. It consists of a warming element, a purring mechanism, inflatable ear-like appendages, and a pneumatically activated breathing mechanism. In operation during the experiment the breathing and purring mechanisms are activated at a constant, moderate rate by a facilitator.

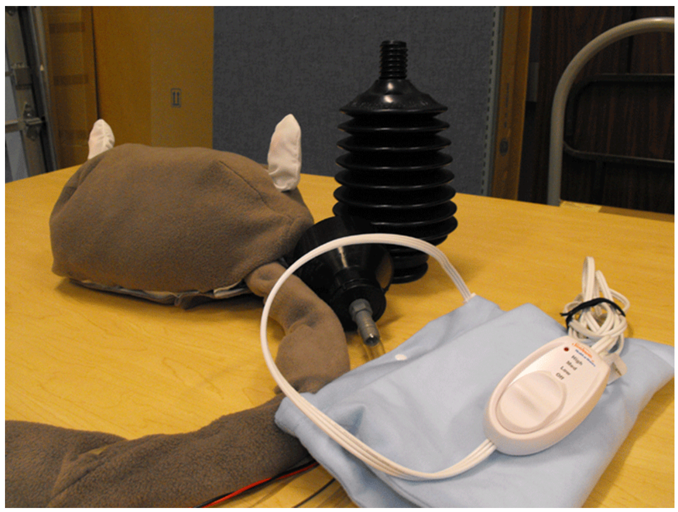


Figure 4.1: "Wizard of Oz" Haptic Creature Prototype used in pilot experiment, showing bellows used to simulate breathing and heating pad.

4.1.3 Research Questions

There were two main research questions for this preliminary experiment.

- Would the prototype Haptic Creature be effective in reducing the level of anxiety experienced by a participant during the viewing of disturbing images, as measured by physiological sensors and surveyed self-assessments?
- What changes would be measurable or captured by the physiological sensors during the experiment, and could they be correlated with anxiety?

Physiological data were investigated both for an EMG reaction to the disturbing images, due to their visual nature, and for changes in average heart rate and skin conductance, which are two commonly accepted methods of measuring anxiety [105, 106]. A description of the calculations performed for this and the following experiments is included in Appendix A.2.

4.1.4 Experiment Procedure

This experiment took place in an ICICS experiment room that had been cleared of equipment. Participants sat in an office chair facing an HDTV television screen affixed to the wall. The encoder for the physiological sensors was placed on a small table beside the participant. Wiring from both the biosensors and the “Wizard of Oz” prototype Haptic Creature ran from the participant to a fake wall placed to the participant’s right. The wall served to hide the prototype’s actuators, computer equipment, and the experiment facilitators. During the experiment participants were viewed through cameras present in the room; unusual interactions with the prototype were noted. There were three main parts to this experiment: a preliminary questionnaire, two separate slideshow viewings, and a post-experiment questionnaire. The overall experiment procedure is outlined in Figure 4.2.

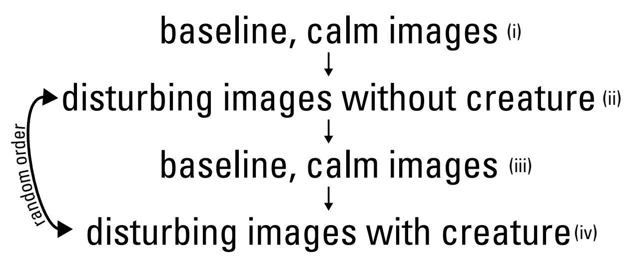


Figure 4.2: Diagram of Pilot Experiment procedure.

Preliminary Questionnaire

After signing consent forms, participants were given a written survey asking for general demographic information as well as the participant’s experience and comfort with touch-based interaction. A copy of the questionnaire is included in Appendix B.1.1.

Sensor Attachment and Baseline

The participants were then fitted with three physiological sensors: skin conductance (SCR) on their non-dominant hand, three-lead electrocardiogram (EKG) on their chest, and surface electromyogram (EMG) on the *corrugator* muscle of their forehead. Sensor functionality was tested and confirmed before the facilitators retreated behind the wall. The participants then viewed a slideshow of calming nature scenes for two minutes whilst baseline data were gathered.

Disturbing Images Slideshows

The participants were given the “Wizard of Oz” prototype for either the first or second slideshow — the order was determined randomly. Once given the prototype, the participant was asked to sit with it for two minutes to gain familiarity with the device. While in the participant's lap, the prototype was manually actuated by an experiment facilitator to generate a breathing and purring sensation. Participants were instructed to focus their eyes on the screen and not on the Haptic Creature during slideshow viewing. When the prototype was taken from the participant, it was removed to behind the fake wall.

Each slideshow consisted of twelve disturbing images, and each was shown for ten seconds for a total of 120 seconds of disturbing images. The order of images shown was randomly determined for each participant from the total set of 24 images. After the first slideshow, the prototype was then given or taken away, and the participant was again shown two minutes of calming nature scenes while another baseline was gathered — giving the participant time to recover from the influence of the previous slideshow. The second slideshow then followed.

Concluding Questionnaire

After the second slideshow was completed, the physiological sensors were removed from the participant, and they were asked to rate their responses to both the images and the haptic device via survey. A copy of the questionnaire is included in Appendix B.1.2. Before beginning the"Overall Response" section of the questionnaire, participants were informed of the two operating modes of the Creature during the experiment.

4.1.5 Results

Ten participants, seven male and three female, between the ages of 20 and 30 took part in the experiment. All were undergraduate and graduate computer science and engineering students, and were compensated for their time (approximately 30 minutes). Due to an equipment malfunction one participant's physiological data were not useable, but his questionnaire data were included.

Self Reported Results Participants were surveyed as to their states of anxiety, agitation, and surprise during the disturbing image slideshows, both with and without the "Wizard of Oz" Haptic Creature prototype, on a 5-point Likert Scale, with adjectives used previously for reporting affective state during human-robot interaction experiments [107]. Descriptions of quantitative survey results refer to general trends, not statistical analyses. Results are shown in Table 4.1. Participants had lower self-reported mean anxiety, agitation, and surprise with the prototype than without.

Participants were also surveyed as to their levels of comfort with the prototype during the experiment; these results are shown in Figure 4.3. Nine out of ten participants found the Creature comforting.

Table 4.1: Pilot Experiment: Self-reported Likert-scale responses to anxiety, agitation, and surprise (1 = strongly felt, 5 = weakly felt).

	Prototype Present		No Prototype	
State	Mean	Std. Dev.	Mean	Std. Dev.
Anxious	2.3	1.2	1.7	0.6
Agitated	2.0	1.1	1.7	0.7
Surprised	2.8	1.2	1.7	0.7

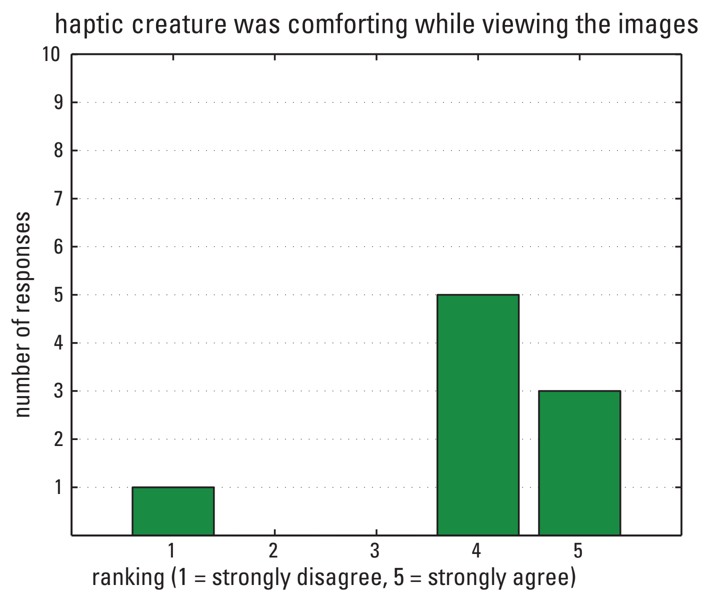


Figure 4.3: Preliminary experiment participant responses to statement "Haptic Creature was comforting while viewing the images."

Participants were also surveyed as to whether they felt that the motions of the prototype were distracting while viewing the images; these results are shown in Figure 4.4. Participants generally expressed agreement with this statement; only 2 mildly disagreed.

Participants were also surveyed as to whether they felt that the Creature would help them reduce their anxiety in other situations; these results are shown in Figure 4.5. As a group, participants did not express any conclusive general opinion.

There were no particular patterns identified from within-individual data, likely due to the small sample size. Participants were not given detailed interviews about their survey responses; they were, however, asked to provide comments on the Creature and the experiment.

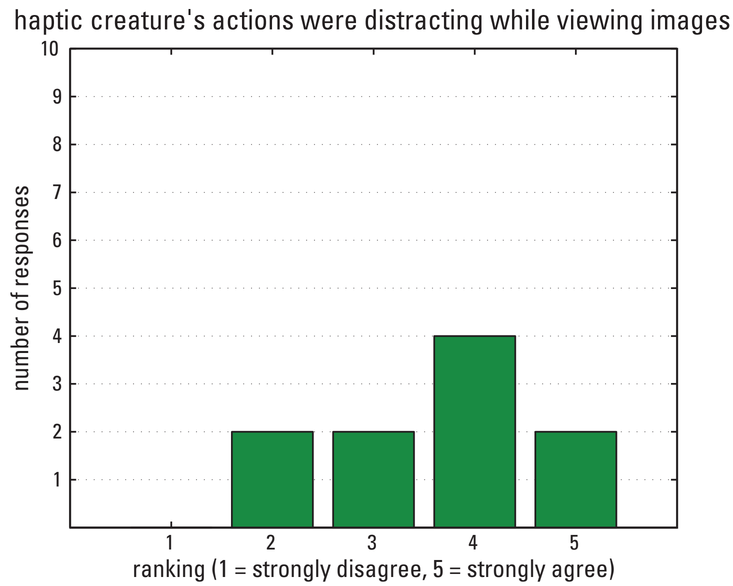


Figure 4.4: Preliminary experiment participant responses to statement "Haptic Creature's actions were distracting while viewing the images."

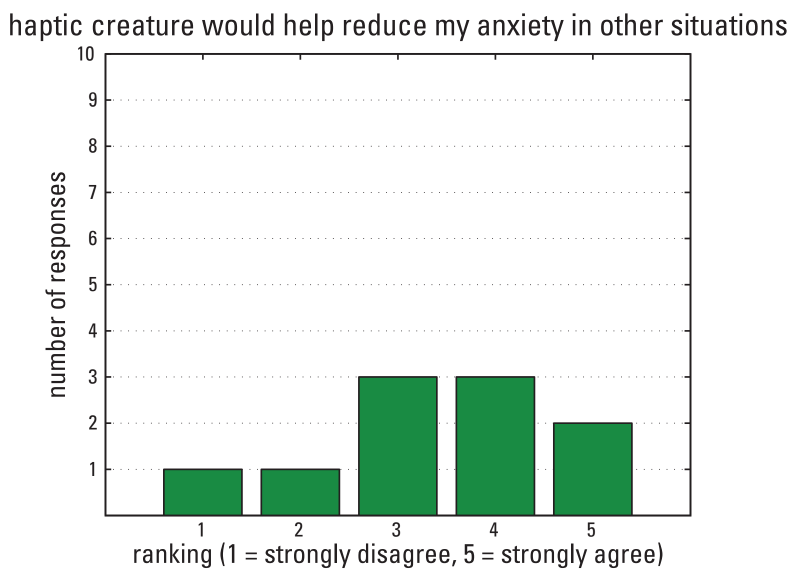


Figure 4.5: Preliminary experiment participant responses to statement "Haptic Creature would help reduce my anxiety in other situations."

Physiological Results Counting and visual inspection revealed that all subjects had a skin conductance response to at least six disturbing images in each slideshow, as marked by an increase in skin conductance when the image was presented. Therefore, statistical comparisons were made using the five images with the highest initial skin conductance responses for each subject. An example of skin conductance response for a subject during the calming images is in Figure 4.7, and for the same subject during the disturbing images, showing the initial response to images, is shown in Figure 4.8. Note the large transients that occur at the onset of several new images; these indicate an orienting response. Regardless of whether they were holding the prototype, all subjects responded to at least six images with a jump in skin conductance of more than 20%. None had a significant response to all twelve images, and there was no order related trend in these responses. The mean normalized skin conductance response with the Creature was significantly greater ($M = -0.261, SD = 0.143, p < 0.05$) than the mean normalized skin conductance response without the Creature. A graph of mean skin conductance response is shown in Figure 4.6.

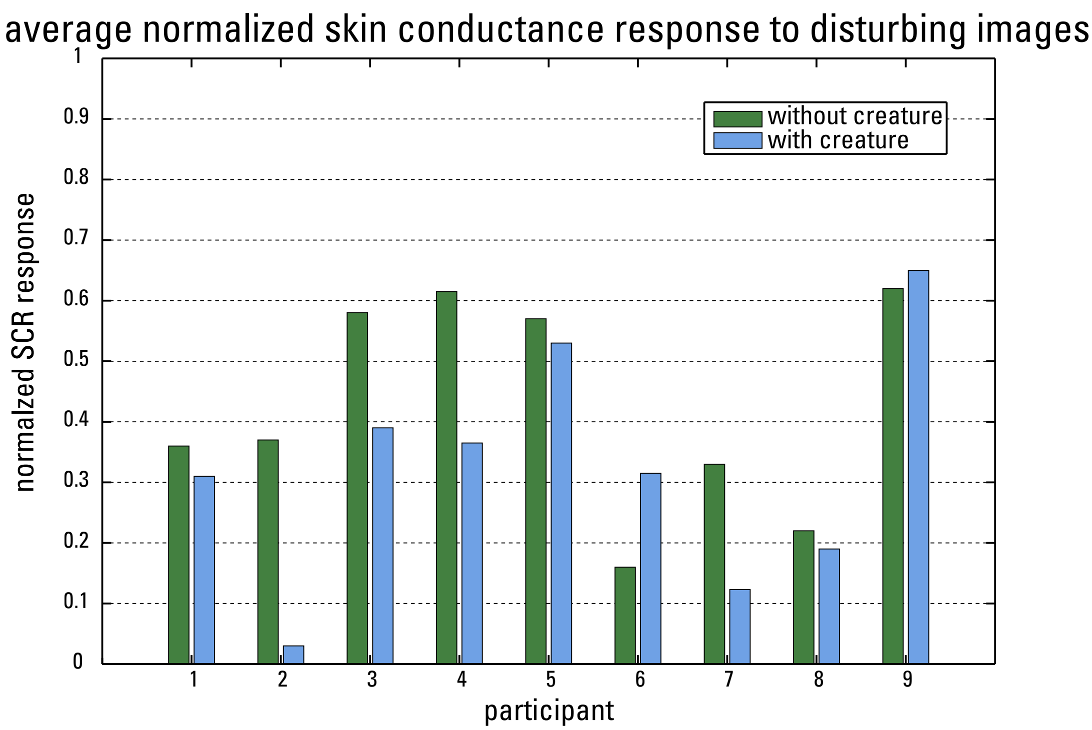


Figure 4.6: Average normalized skin conductance response for disturbing image slideshow with and without Haptic Creature prototype for each participant.

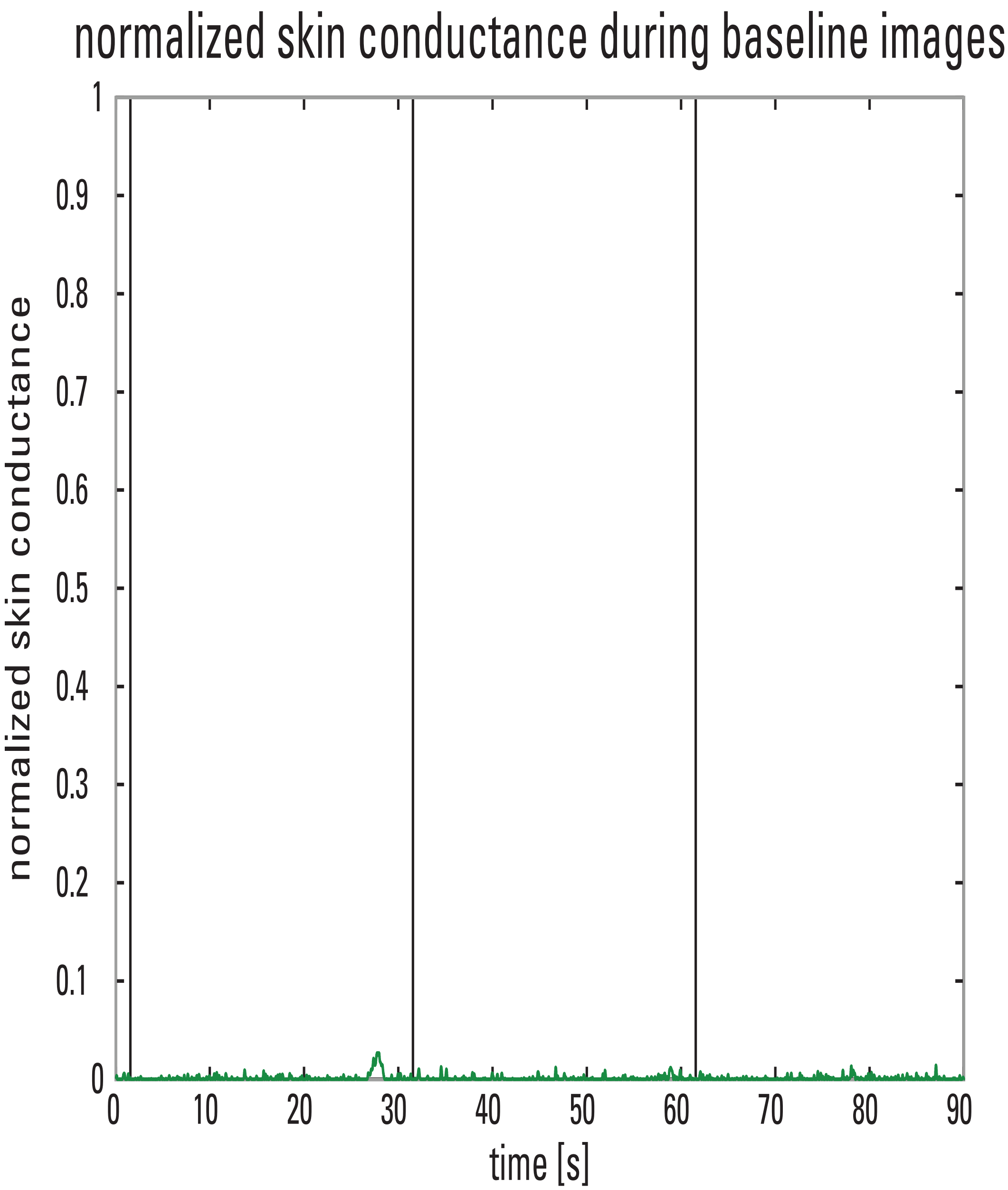


Figure 4.7: Typical normalized skin conductance response for a participant during calming image set, the baseline. The vertical line represents the start of a new image. Baseline is typically less than five percent of maximum response.

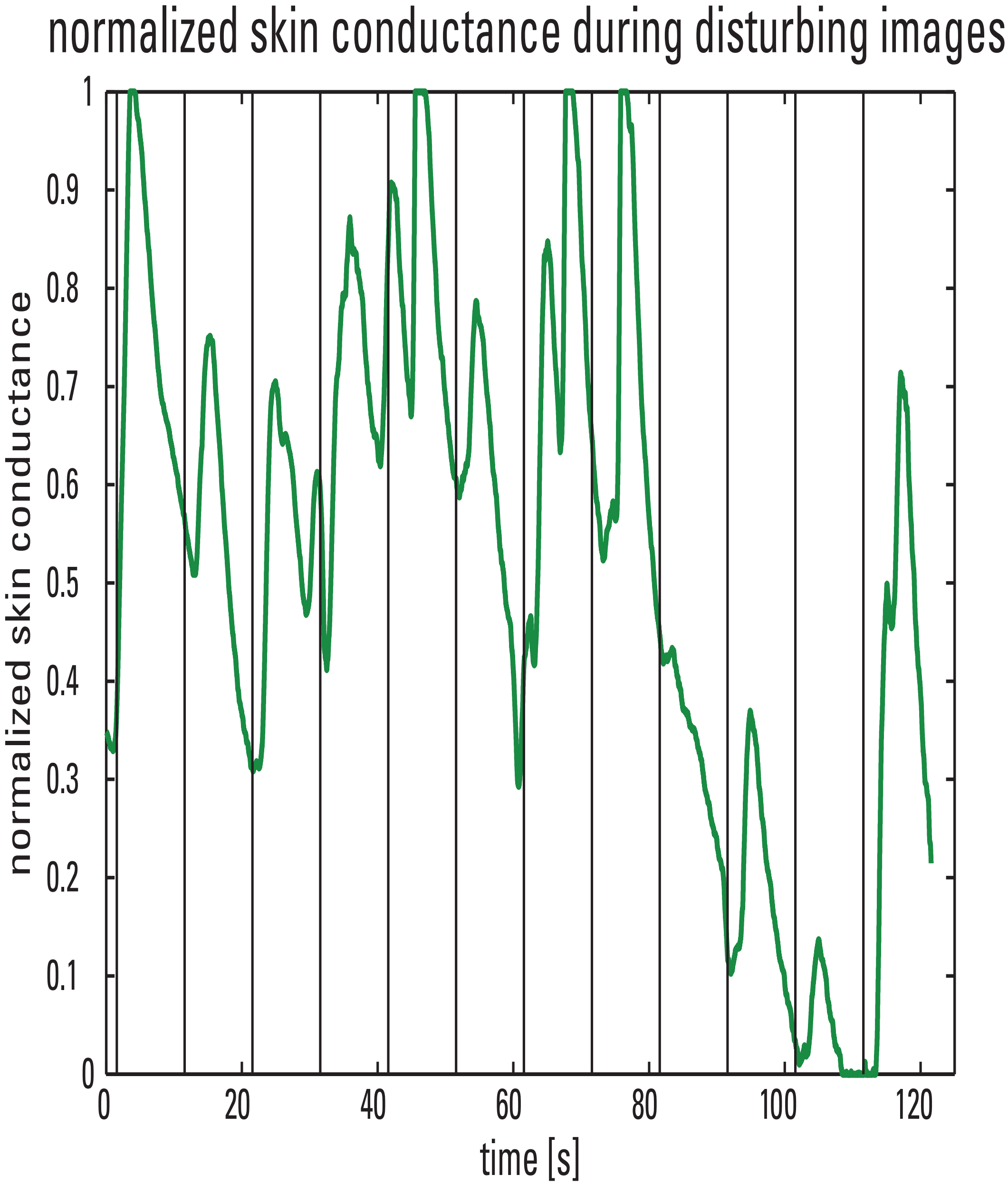


Figure 4.8: Typical normalized skin conductance response for a participant during disturbing image slideshow. The vertical line represents the start of a new image.

As summarized in Table 4.2, the disturbing images induced significant changes in mean heart rate, mean normalized EMG, mean normalized heart rate acceleration, mean normalized derivative of skin conductance, heart rate standard deviation, and arousal as compared to the calming images. Arousal (as per Kulić et al. [108]), normalized skin conductance, and the normalized derivative of skin conductance were significantly less during the disturbing images with the Creature than without the Creature.

Table 4.2: Summary of significant results from Pilot Experiment.

physiological metric	comparison	mean	SD	p
mean heart rate [bpm]	calming images to disturbing images without creature	1.86	3.59	< 0.001
mean normalized EMG	calming images to disturbing images without creature	0.032	0.081	0.05
mean normalized heart rate acceleration	calming images to disturbing images without creature	-0.00630	0.00290	0.002
mean normalized skin conductance derivative	calming images to disturbing images without creature	0.0204	0.037	0.007
heart rate standard deviation [bpm]	calming images to disturbing images without creature	-3.32	5.19	0.046
arousal	calming images to disturbing images without creature	0.0522	0.0802	0.016
mean normalized skin conductance	images without creature to images with creature	-0.261	0.143	0.007
mean normalized skin conductance derivative	images without creature to images with creature	-0.0154	0.0130	0.047
arousal	images without creature to images with creature	-0.0602	0.0769	0.001

4.1.6 Discussion

Responses from the surveys revealed many useful comments and several general trends. Participants reported either feelings or strong feelings of anxiety, agitation, and surprise, and all responded to at least six of the disturbing images in each set with the peak in skin conductance typically associated with a startle response [109]. There was no order-related trend of which images produced this response, suggesting that the participants did not become acclimatized to the disturbing images during the session. No participant had a physiological response to all of the images. Mean heart rate, EMG, heart rate acceleration, and heart rate standard deviation were also affected by the disturbing images. The EMG reaction to the disturbing images was likely due to their visual component, and the heart rate changes are consistent with a more anxious or aroused state. After the experiment, many subjects also reported to the facilitators that they found some of the images disturbing. It is likely that the disturbing images were successful in inducing anxiety in the participants.

In general, participants reported lower anxiety, agitation, and surprise with the Haptic Creature prototype than without. In addition, skin conductance response and inferred arousal (as per Kulić et al. [9]) during the disturbing images were significantly less with the Creature than without. With such a small sample size, physiological results were encouraging, indicating that this approach was worthy of further research. Survey data indicated that subjects generally found the Haptic Creature prototype a comfort while viewing the distracting images: this was encouraging feedback for both the form-factor of the Creature and the idea that a small robotic creature would be of any help in reducing a subject's anxiety. In comments, many subjects specifically commented on the creature's warmth as comforting, and several mentioned finding its simulated breathing prominent. Some indicated that they found the gentle breathing of the Creature pleasant; interestingly, a few volunteered that this caused them to become more aware of their own breathing. It is therefore also likely that the Haptic Creature prototype had an effect on the participants.

Participants did, however, report that the prototype caused moderate to high levels of distraction during the image viewing. A device that purely distracts from sources of anxiety would be of limited utility, as this distraction would be of short duration and would preclude the accomplishment of other tasks. It is, however, possible that some subjects found the entire experience of the Haptic Creature unusual and hence distracting, and that their subjective reporting of distraction would be decreased after spending additional time with the Creature. Although some participants may have found the Creature distracting, most subjects did not seem to find the prototype so distracting as to be annoying. There was also net-positive but varied response to the proposition that the Haptic Creature prototype might reduce anxiety in stressful situations other than that of viewing disturbing images. There is also an experimental concern in that the Creature was never presented to the user in its inactive state, to determine whether Haptic Creature prototype presence alone was sufficient to induce these seen effects.

4.1.7 Conclusions

Not all participants reacted to every disturbing image, but all had a skin conductance (SCR) response to at least six of the disturbing images in each set with a peak in skin conductance. A change in mean EMG, heart rate, heart rate acceleration, and heart rate standard deviation was also correlated with the images. The presence of the Haptic Creature prototype was correlated with reduced levels of both mean and normalized skin conductance response values, as well as inferred arousal, during the anxiety-inducing disturbing video task. Participants generally reported the Haptic Creature as comforting during the experiment, particularly liking its warmth and gentle breathing.

4.1.8 Feedback for Iterated Design

The overall positive feedback to the prototype device encouraged future investigation, and provided valuable guidance as to Creature and TAMER platform experiment design, as well as experimental methods. Many of the lessons learned from this experiment were incorporated into the design of the Haptic Creature used for future experiments. Participants' favorable opinion of the warmth that the prototype was able to produce through its heating pad led to the installation of additional heating pads into the Creature. Due to participants' high comfort rating attributed to the plushness of the Creature, additional padding was added to the new Creature. In designing the control system of the new prototype, particular attention was paid to ensuring that the Creature would be able to interface with the physiological sensor suite directly, without requiring an additional experimenter to operate the Creature. This also reduced the complexity of using the system.

Deficiencies in the physiological sensing platform were also recognized and addressed. This preliminary experiment revealed that the existing physiological sensor software was insufficient for longer-term affect based experiments. In particular, it was difficult to correlate the sensor data logs with specific experimental conditions: the various stages of the experiment had to be identified by carefully timing the start of the experiment and noting at what time various events occurred relative to this — a potentially error-prone measurement when dealing with shorter-term physiological events. Participants remarked upon the breathing activity of the prototype, and many felt that the Creature's breathing increased their awareness of their own breathing. As breathing exercises and training are an important aspect of current anxiety training, it was necessary to add the respiration rate sensor to the physiological sensors. As a result of rewriting the sensor software to support the respiration rate sensor, the ability to use both the skin temperature and blood volume pulse sensors was gained.

This experiment also formed the basis for several methodological changes in the following experiments. Inducing anxiety ethically was always a challenging task. While the IAPS picture set seemed effective at inducing anxiety, they provoked an emotionally loaded encounter – many participants remarked upon the gruesomeness of the images, and expressed displeasure at having to view them. Longer-term studies along this vein would involve the viewing of many more images, which would not only be extremely displeasurable to participants, making recruitment difficult, but was highly unlikely to be approved (and would indeed be inappropriate) for the targeted platform age group of children. There were also limitations on the sensor suite's ability to recognize anxiety: the existing inference engine proved unable to adequately measure anxiety and, more importantly, levels of anxiety in participants. The engine had been trained primarily on visual stimuli, and may not have been able to recognize the more subtle human reactions to changes in emotional state. As work to improve the emotional state recognition engine was already ongoing in a separate process, it was decided to focus the trial experiments of the platform on what the physiological sensors were capable of doing well: measuring effects of raw physiological metrics such as breathing rate, heart rate, and skin conductance. While ongoing work was investigating self-reported emotional responses to the Haptic Creature, there had not yet been research investigation of *physiological* reactions to interaction with the Haptic Creature. If physiological reactions occurred from the Haptic Creature, there could be the potential to command these reactions through particular motions and activity state of the Creature to reduce the physiological metrics related to anxiety.

4.2 Experiment 1: Recognition of Mirroring and Initial Reactions to Creature

Following the preliminary experiment, the TAMER platform, as described in Chapter 3, was constructed. The following experiments, Experiment 1 and Experiment 2, describe small-scale studies that were intended as much for obtaining feedback and verification of the platform systems as beginning to explore the potential physiological effects of the Creature, and possible roles for the Creature in anxiety reduction. The first experiment performed had two primary motivations: to begin the investigation of human physiological response to interaction with the Haptic Creature, and to determine whether participants could recognize the Haptic Creature mirroring their breathing rate and heart rate. By linking the Creature's pulse and breathing mechanisms to those of the participant, as recorded by the physiological sensors, the Creature has the ability to "mirror" a user's breathing rate and pulse. This ability has several possible applications, some of which are particularly applicable for use within the TAMER platform, such as an alerting scenario, in which the Creature attempts to inform its user of his or her own breathing rate and heart rate by mirroring. In a stressful or anxiety inducing situation, participants may not recognize that they are becoming more stressed and anxious, or the degree to which that is the case. By seeing their own breathing and heart rate in the Creature, users could gain increased awareness of their own physiological state and take appropriate coping actions. Therefore, the primary goal of this first experiment was to determine user reaction to this mirroring: both their subjective responses and whether they could recognize it in the Creature.

A second goal of this first experiment was to determine whether the programmed actions of the Creature's mechanisms were recognized as both lifelike and appropriate to the Creature. Pilot studies and informal initial interactions suggested that users were able to distinguish between various "states" of the active Creature through the application of behavioral state terms typically associated with a living animal: e.g., the Haptic Creature, when its breathing mechanism displayed fast breathing, would be perceived as "breathing heavily;" whereas a slower breathing rate and lower intensity in the Creature would be perceived as "resting." It was not evident, however, whether a human participant's breathing rate and heart rate imposed on the Creature would be perceived in the same way. The small creatures that humans are generally familiar with, such as dogs or cats, typically have a higher heart rate and breathing rate than their owners. Consequently, the expected "normal" baseline activity of the Creature could in fact be at this level, which would be around the level of an excited human; normal human resting breathing rates and heart rates could appear lethargic in the Creature. This would impact both user recognition of mirroring as well as user determination of the Creature's emotional state. Accordingly, participant subjective responses as to their perceptions of Creature motion were collected and discussed.

Physiological manipulation of the user was approached indirectly in this experiment. Interacting with a pet has been associated with physiological reactions such as decreased heart rate [49] and breathing rate, as well as reduced levels of anxiety [110]. There was, therefore, the potential that the zoomorphic appearance and behavior of the Creature would allow it to provoke similar results. In order to have such effects, it was necessary to confirm that the Haptic Creature was, in fact, able to convey a sensation of both breathing and heart rate to the user, and that this could be recognized. At the very least, however, the Creature's similarity to a stuffed animal could also potentially give comfort. To investigate this, user physiological data were collected both for initial reaction to the Creature as well as during the entire interaction session.

4.2.1 Research Questions

These motivations led to three primary research questions and goals:

- Examine participants' qualitative opinions of overall Creature feel and their reaction to medium-term interaction with the Creature. Are participants able to identify breathing and pulse mechanisms, and do they find these mechanisms appropriate to the Creature?
- Determine if participants are able to identify the Creature mirroring their breathing and heart rate, and if so, what are their reported reactions to it?
- Examine initial physiological reaction to the Creature. Does the Creature's state, either motionless, breathing steadily, or mirroring the user, have an effect on physiological metrics of the participant?

In order for participants to recognize the Creature mirroring their physiological state, they would have to be able to distinguish the motions of their own breathing and heart rate in the Creature from those of the Creature operating at a constant breathing and heart rate. Therefore, physiological responses in skin conductance, blood volume pulse, EKG, and respiration rate were measured while the Creature was inactive, actively breathing at a constant rate, and then mirroring the participant's respiration and heart rate for ninety second periods. This length was chosen to allow the experiment to be completed within a half-hour time period to encourage participant participation: differentiation between stages was seen in pilot studies of this length. Participants were surveyed as to their impressions of the Creature's mechanisms and their reactions to the physiological mirroring.

4.2.2 Experiment Procedure

Experiments took place in an experiment room that had been emptied of all equipment except for a table placed against the wall. During the experiment participants remained seated, facing the wall, at the large table. The physiological sensor encoder was placed on the table, to the right of the participant. The wire from the sensors, the experiment facilitator, the Haptic Creature support equipment, and computers were located behind a fake wall to the right of the participant. A web camera affixed to the top of the wall was used to observe the participant during the experiment. Participants wore noise-canceling headphones during the experiment. The experiment consisted of the four phases shown in Figure 4.9, and described here.

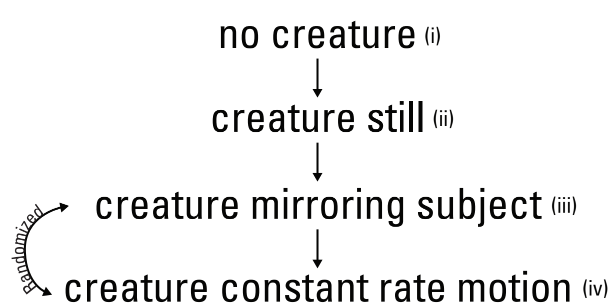


Figure 4.9: Diagram of Experiment 1 procedure.

After signing consent forms, participants were fitted with skin conductance (SCR), blood volume pulse (BVP), and skin temperature (ST) sensors on their non-dominant hand, as well as three-lead electrocardiogram (EKG) and respiration rate (RR) sensors. The sensors were then activated and tested. If necessary, adjustments were made to sensor fit to ensure that they were properly functioning.

(i) No Creature

Participants were then asked to sit calmly for ninety seconds while a baseline was gathered, which began when the facilitator had returned behind the wall. As this stage was the initial baseline gathered for the participant, it was necessarily always performed first.

(ii) Creature still (CS)

The participants were then introduced to the Haptic Creature, and given it to be placed in their lap. They were instructed to sit quietly with the Creature on their lap, and to feel free to pet and interact with the Creature. They were requested to try to maintain at least one hand on the Creature at all times during their interaction. After the facilitator had returned behind the wall, physiological data were gathered for ninety seconds. As this stage incorporated a combination of initial reaction to the Creature and reaction to the still Creature, it was always performed second.

(iii) Creature mirroring subject (CM)

The facilitator then returned to the participant and informed him or her that the mechanisms of the Creature would now be activated. After the facilitator returned behind the screen the Creature was then turned on. It began mirroring the participant's breathing and heart rate: a detected pulse from the EKG sensor triggered a pulse on the Creature, and the output of the respiration rate sensor was commanded on the Creature's breathing mechanism. This continued for ninety seconds, during which time physiological data were continued to be gathered. The order of this stage and of the "Creature constant motion," stage iv, was counterbalanced.

(iv) Creature constant motion (CCM)

The Creature's constant motion stage was then begun. In this mode, the Creature has a respiration rate and intensity of twelve breaths per minute, as well as a pulse rate of seventy beats per minute, typical of a resting human adult. The transition from the previous stage to this mode occurred without comment from the facilitator. This stage continued for ninety seconds, during which time physiological data were continued to be gathered. The order of this stage and the "Creature mirroring subject" stage were counterbalanced; in both cases transitions occurred smoothly and without comment.

(v) Experiment Ending and Questionnaire

The physiological data collection was then ended, and the Creature removed from the subject. The participant then removed the sensors, and a post-experiment questionnaire was administered; a copy is included in Appendix B.2.1.

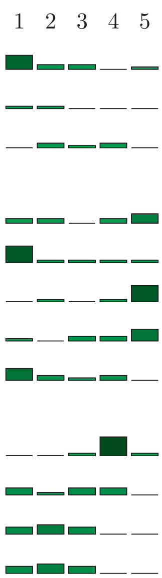
4.2.3 Results

Ten subjects, three female and seven male, took part in this experiment. None had participated in previous experiments. All were graduate or undergraduate engineering or computer science students between the ages of eighteen and thirty.

Self-Reported Results

Descriptions of quantitative survey results refer to general trends, not statistical analyses. Only two subjects were able to recognize the Creature behavior during the mirroring stage as mirroring their breathing and heart rate. The responses from the post-experiment questionnaire are shown in Table 4.3.

Table 4.3: Table of results from Experiment 1 questionnaire (1 = strongly disagree, 5 = strongly agree), n = 10.



Responses (1 2 3 4 5)	Statement
	It was easy to recognize the creature mirroring my breathing.
	I found the creature mirroring my breathing comforting (if noticed).
	I found the creature mirroring my breathing disturbing (if noticed).
	The creature's breathing made me more aware of my own breathing.
	It was easy to recognize the creature mirroring my pulse.
	I found the creature mirroring my pulse comforting.
	I found the creature mirroring my pulse disturbing.
	The creature's pulse made me more aware of my own heart rate.
	I found the creature comfortable on my lap.
	I was startled by the activation of the creature.
	I found the creature's motion disturbing.
	I found the noise of the creature distracting

Physiological Responses

Group-wise and within-subjects comparisons were performed for several physiological metrics. Pool-wise comparisons are summarized in Table 4.4, based on two-tailed dependent sample t-tests ($\alpha = 0.05$). Within-subjects comparisons were performed where more than one data point existed for each participant for each stage, namely for their series of individual breath lengths and heart rate interbeat intervals.

Table 4.4: Summary of results from Experiment 1. Significant results are in bold.

physio metric		comparison stages			units
		CS–CM	CS–CCM	CM–CCM	
breath length mean	mean	0.263	0.115	-0.148	ms
	sd	0.801	0.928	0.439	
	p	0.351	0.718	0.338	
breath length sd	mean	**-0.358**	-0.104	0.254	ms
	sd	**0.458**	0.649	0.420	
	p	**0.043**	0.643	0.102	
heart rate mean	mean	**-3.90**	+2.00	-1.54	bpm
	sd	**4.64**	4.17	2.23	
	p	**0.045**	0.212	0.075	
heart rate variability	mean	**-0.023**	-0.012	0.010	bpm/ms
	sd	**0.024**	0.025	0.023	
	p	**0.022**	0.186	0.215	
skin temperature mean	mean	**0.759**	0.741	-0.008	°C
	sd	**0.585**	**0.582**	0.003	
	p	**0.040**	**0.047**	0.956	
skin temperature sd	mean	0.017	0.052	0.034	°C
	sd	0.199	0.069	0.155	
	p	0.808	0.066	0.548	
skin conductance mean	mean	**2.18**	**1.96**	-0.515	S
	sd	**2.01**	**1.49**	0.404	
	p	**0.022**	**0.047**	0.104	
skin conductance sd	mean	-0.127	0.007	0.134	S
	sd	0.364	0.202	0.310	
	p	0.322	0.925	0.227	

Breath lengths The series of breath lengths for each subject between the Creature still, Creature constant motion, and Creature mirroring stages using a two-tailed within-subjects unequal variance t-test ($\alpha = 0.05$). Six of ten participants were found to have a significant difference ($p < 0.05$) between breath lengths with the Creature still and the Creature in constant motion, and seven between breath lengths with the Creature still and the Creature mirroring the subject. Of those seven, three also had a significant difference ($p < 0.05$) between breath lengths with the Creature in constant motion and the Creature mirroring the subject.

Breath length series were similarly compared with the breath length of 2.5 seconds, the commanded breath length for the Creature during the Creature constant motion stage. Comparisons were made with actual participant breathing rates during the Creature still, Creature constant motion, and Creature mirroring stages. Results for a significant difference

($p < 0.05$) between command breath length and participant breath length failed to conclude anything for five people during the Creature still phase, and five others during the Creature constant motion and Creature mirroring stages. The mean and standard deviation of breath lengths are graphed in Figure B.31.

4.2.4 Discussion

Qualitative Results Overall initial reactions to the Creature were investigated through survey questions and interview responses to determine participants' qualitative opinions of overall Creature feel and whether they found the Creature's actions appropriate to the Creature. These responses were typically positive, with no overtly negative opinions of the Creature's feel or behavior, nor of interaction with it. Most participants, upon their introduction to the Creature, expressed a desire to touch and feel it. Participants generally agreed with the statement "I found the Creature comfortable on my lap" (see Figure 4.10). This comfort level with the Creature was important both in that participants were able to tolerate the placement of a new device on their lap, and in that they were comfortable with such a device moving and being "active" in such a personal and private part of the body. Participants in general expressed their like of the motion of the Creature: one described that it "made the Creature seem much more real and lifelike." One participant noted that she found "feeling the pulse of the Creature was really comforting." When asked what they liked most about the Creature, a majority of respondents mentioned a positive reaction to the Creature's warmth on their lap. There were no complaints about the breathing or pulse mechanisms seeming disturbing or disconcerting; most stated that this behavior was in line with their expectations for the Creature. However, most participants did find the pulse mechanism of the Creature to be noisy and moderately distracting. There was an audible clicking sound whenever a pulse took place that was quite noticeable in the quiet of the experiment room.

Although comfortable with the Creature, participants were less successful in linking the Creature's breathing and pulse with their own. There was no consensus on whether the Creature's breathing and pulse made them more aware of their own breathing and pulse (see Figure 4.11). One participant noted that she became worried about the Creature when its breathing rate changed, an indication that perhaps this participant viewed the Creature as having some form of "life."

Responses were investigated to determine if participants were able to identify the Creature mirroring their breathing and heart rate, and if so, their reported reactions to it. Results are reported in Figure 4.12. As a group, participants were consistently unable to identify the Creature mirroring their own breathing and pulse, with only a single participant able to recognize this behavior. Most thought that there were two or three different

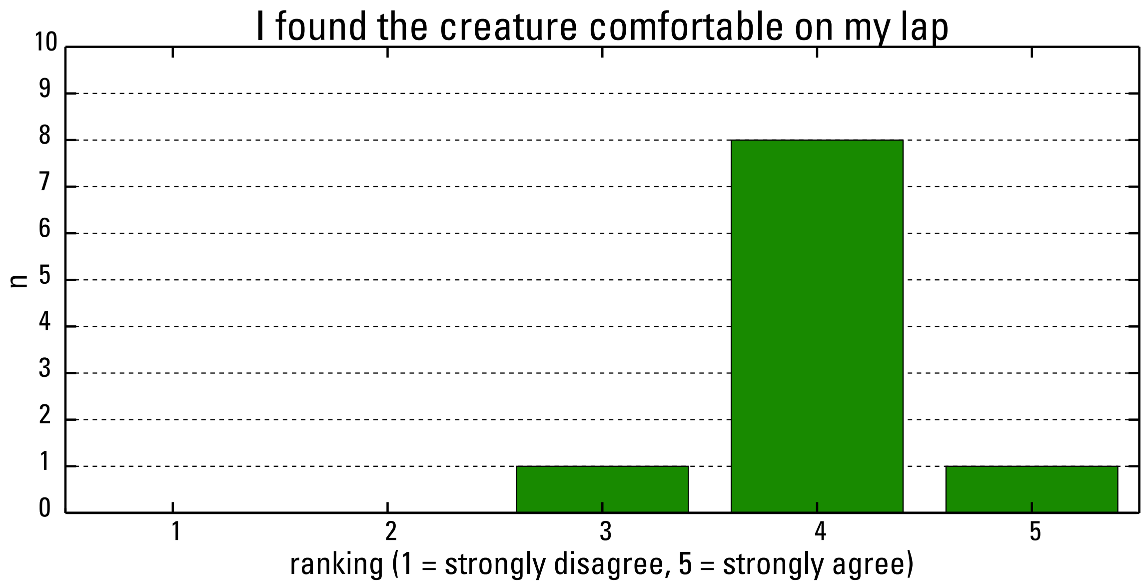


Figure 4.10: Experiment 1 participant responses to statement "I found the creature comfortable on my lap."

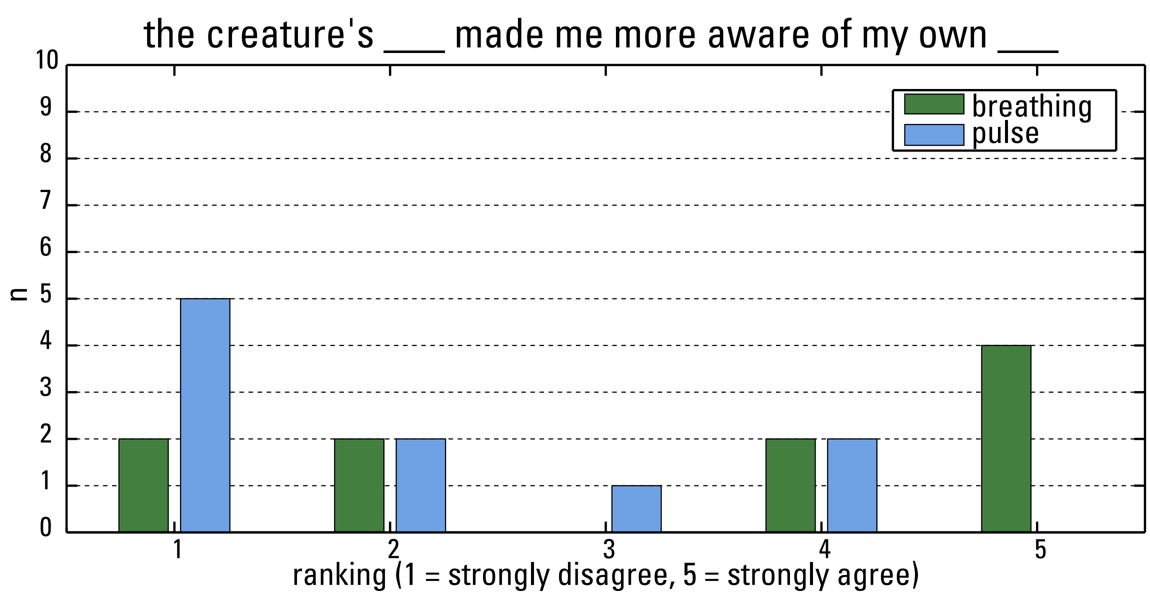


Figure 4.11: Experiment 1 participant responses to question of whether "creature's actions made them more aware of their own."

operating modes of the Creature; these modes were typically identified as "fast and slow" or "smooth and random," not as mirroring. Once informed that the second mode of the Creature was mirroring their breathing and pulse, most participants expressed surprise; one participant even stated that he "did not think I was breathing that fast or heavy." Almost all rated mirroring as very difficult to observe. One participant stated: "mirroring could be made more obvious." Without any explanation that the Creature would mirror the participant, it appears that there was no expectation that such mirroring could occur. On reflection, when a small animal is placed on our laps, while we may investigate its breathing and heart rate to assess its emotional state, most of us do not immediately compare its breathing rate and heart rate to our own.

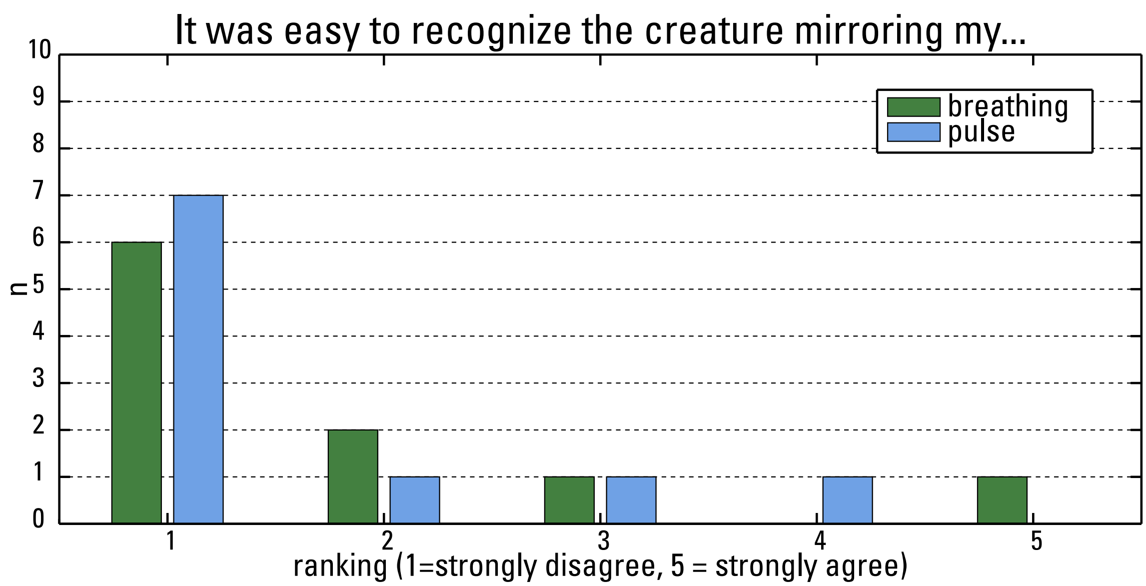


Figure 4.12: Experiment 1 participant responses to statement "It was easy to recognize creature mirroring my…".

The one participant who was able to recognize the Creature mirroring her breathing and pulse was unable to offer an explanation for this ability, but did hypothesize that because she plays a musical instrument she may be more cognizant of her own breathing than other people. She had a strongly negative reaction to mirroring, responding that "I really did not like this. I found it difficult to breath normally. It was much better to match my breathing to the Creature." As she had been exposed to the Creature constant motion stage before the Creature mirroring stage, it is likely that during the Creature constant motion stage she was attempting to match her breathing to that of the Creature. It is possible that the sudden transition from attempting to match the breathing of the Creature to now finding herself guiding the Creature could be disturbing. Indeed, the participant would ultimately find herself in a sort of positive feedback loop until the limits of the Creature's respiration mechanism were reached.

Physiological Reactions Initial physiological reactions to the Creature were investigated. Physiological reactions to the Creature were generally inconclusive. Comparisons were first made between the breath lengths of participants during each stage. Breath lengths were determined from analysis of the respiration sensor waveform: peaks and troughs were detected and from this breath length was calculated. Where there were obvious noise artifacts in the signal (most likely from movement or talking), attempts were made to interpolate the breath length by identifying the underlying wave pattern. The respiration rate sensor is particularly sensitive to the motions of the abdomen that occur during speech, as this often greatly overshadows the breathing motion. Figure 4.13 shows the breath lengths of a participant during the experiment. During the baseline the participant took longer breaths than during the Creature constant motion or Creature mirroring stages, and indeed the mean of both the Creature constant and Creature mirroring stages is close to the commanded 2.5 second breath length of the Creature during the Creature constant motion stage. Figure B.31 show the mean and standard deviation of breath lengths for all participants during the experiment.

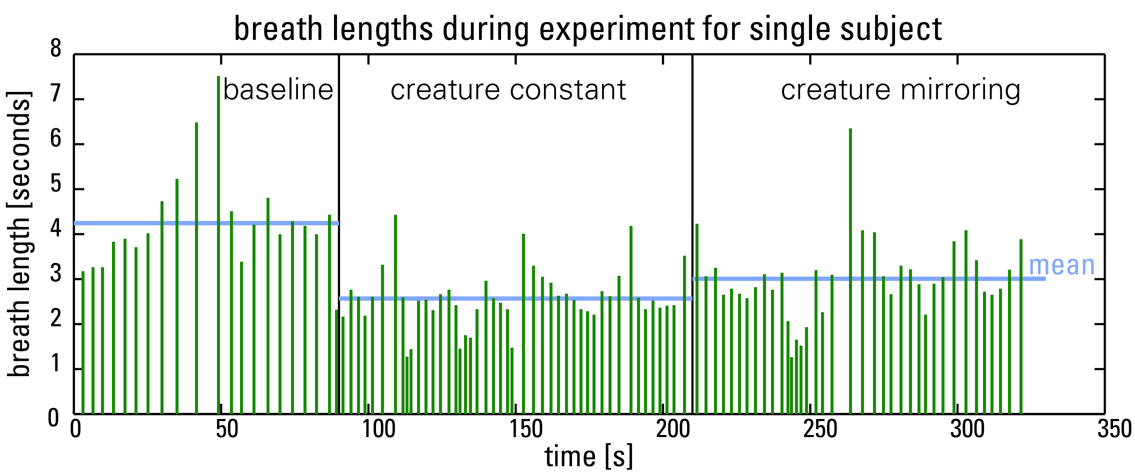


Figure 4.13: Breath lengths of a participant during Experiment 1.

The activation of the Creature was strongly correlated with a change of breathing rate for the participant in six out of ten of the participants. The same six saw both a change from the Creature still stage to Creature constant motion stage, as well as the Creature still stage to the Creature mirroring stages. An additional three saw a difference between their breath lengths during the constant motion and mirroring stages. It should be noted that the subjects who did not react to the constant motion Creature also did not react to the mirroring Creature, their mean breath lengths remained similar throughout the entire experiment, and the standard deviation of breath lengths for them generally remained low and similar for each stage.

T-tests were also conducted to determine if the participants' breath lengths were distinguishable from the Creature's constant motion breath lengths. They were distinguishable during the baseline for five out of ten participants, and then also during the Creature constant motion and Creature mirroring stages by five (different) subjects. This is an indication that the chosen commanded breath rate was similar to that of the average resting respiration rate. Two of the six subjects whose breathing rates were affected had breathing rates that were indistinguishable from the Creature's.

The important result in group trends was that overall there was a significantly lower standard deviation of breath lengths during the Creature motion stage as compared to the Creature still stage. This implies that breathing became more "regular" as a result of the active Creature, and that the steady and repeated motion of the Creature was able to induce a similar steadiness in the subject's breathing. A similar increase in steadiness was shown by the reduction of heart rate and heart rate variability.

Analysis of the series of heart rate interbeat intervals for each participant indicates that nine out of ten participants had a change in heart rate from the Creature still stage to the Creature mirroring stage, and seven from the Creature still stage to the Creature constant motion stage. We propose that this heart-rate change was induced by the Creature. Mean heart-rate was significantly less during the Creature constant motion stage than during the baseline, making it likely that this change induced by the Creature was in the negative, i.e. more relaxed, direction. Heart rate standard deviation, or heart rate variability, was also significantly reduced during the Creature constant motion stage as compared to the baseline.

The increase in mean skin conductance is likely due to sensor drift during the course of the experiment. Most participants saw a brief peak in skin conductance when the Creature was activated, indicative of the startle response, but there were no other large peaks during the experiment.

The increase in skin temperature for both the Creature constant motion and the Creature mirroring stages as compared to the Creature still stage is likely indicative of an increase in relaxation during the experiment. It is unlikely that this was caused directly by the warmth of the Creature as the skin temperature sensor was worn on the back of the ring finger of the non-dominant hand, and therefore was generally placed farther away from the Creature's main source of warm, its breathing mechanism. A trial experiment with the temperature sensor mounted on the anterior dorsal end of the Creature did not reveal any significant temperature change after five minutes of the Creature's mechanisms being activated.

A summary of the significant results from the experiment is shown in Table 4.5.

Table 4.5: Summary of significant results from Experiment 1.

physiological metric	comparison	mean	SD	p
breath length sd	Creature still to Creature constant motion	-0.358 s	0.458 s	0.043
mean heart rate	Creature still to Creature constant motion	-3.90 bpm	4.64 bpm	0.045
heart rate variability	Creature still to Creature constant motion	-0.023 s	0.024 s	0.022
mean skin temperature	Creature still to Creature constant motion	0.759 °C	0.585 °C	0.040
	Creature still to Creature mirroring	0.741 °C	0.582 °C	0.047
mean skin conductance	Creature still to Creature constant motion	2.18 S	2.01 S	0.021
	Creature still to Creature mirroring	1.96 S	1.49 S	0.047

4.2.5 Conclusions

Users did not report any overtly negative reactions to overall interaction with the Creature. Participants had a high awareness of the breathing mechanism of the Creature, but a lower awareness of its pulse mechanism. Participants found the Creature comfortable on their laps and had no disturbing reactions to or adverse opinions of the motion of the Creature during their interactions with it. Nine of the ten participants were not able to recognize the Creature mirroring their own physiological state. Exposure to the Creature produced a reduction in heart rate variability, mean heart rate, and the standard deviation of breath lengths, as well as increase in skin temperature during the Creature constant motion stage as compared to baseline; these are physiological indications of relaxation. The reduced heart rate and breath length standard deviations are closer to the Creature's, which ran at a constant rate during the constant motion stage.

4.2.6 Feedback for Iterated Design

This experiment provided valuable feedback as to the utility of the haptic anxiety reduction platform. In its first use with test participants, the functioning hardware and software components of the system were validated. Participant reports caused several hardware and procedural modifications to be made to the platform.

The first area of concern was Creature noise. Several participants noted the noise of the Creature as "distracting," and response to the questionnaire question about Creature sound indicated a similar reaction. Efforts were therefore made to reduce the sounds emitted by the Creature. The greatest source of noise, the Creature's pulse mechanism (see Figure 3.6) was removed and lubricated, with foam padding added where the pulse mechanism is attached to the Creature. The Creature's startup routine was also adjusted to prevent sudden noises emanating from the pulse mechanism if the Creature needed to be reset or lost power during operation. Additionally, the Creature's breathing servo refresh rate was increased to eliminate a vibration sound that was noticeable when the breathing mechanism was under heavy load. After these modifications, the Creature's sound output level was noticeably lower, and in observations with noise canceling headphones little to no Creature sound was able to be discerned. In extremely quiet environments such as the experiment testing rooms the use of noise canceling headphones is now recommended where practical.

Noise emitted by the Creature turned out to be a much more solvable problem than the companion problem: noise emitted by the participant, namely talking. Speech requires air to be directed over the vocal cords, and in the process the normal respiration waveform is disrupted. The respiration rate sensor proved extremely sensitive to interference from talking; this sensitivity often led to inaccurate estimates of respiration rate that required manual correction. As a result, care is now taken to ensure that the experiment facilitator is out of sight during the experiment, so that the participant is not inclined to speak. If the respiration rate estimate appears to be abnormally high or low additional time is taken on the baseline stage so that the respiration rate can be recalculated.

The inability of most participants to recognize mirroring during the experiment may have been symptomatic of a lack of formal introduction to the Creature. Interaction with the Creature is intuitive only when it is viewed as a robotic pet whose mechanisms add the mechanical sensations of life to an otherwise inanimate object. The concept of a robotic pet physiologically linked to its user did not occur to most participants, even after they themselves were equipped with physiological sensors. This is not necessarily surprising, as the physiological sensors are most often used in experiments to record reactions to various stimuli, and very rarely are used as the direct input for another system. Before future experiments, care should be taken to describe the functioning of the Creature: both the various mechanisms and the fact that it is capable of reacting to physiological sensor input from the participant. This will ensure that the participants know what to look for in terms of Haptic Creature activity changes, as well as provide a baseline for expected Creature breathing rate and pulse rate that is near to their own. The strong negative reaction that a participant had upon finding the Creature mirroring their breathing rate indicates that this capability may not be advisable in scenarios where the participant is following the Creature's breathing, as it could potentially lead to an uncomfortable positive feedback loop. A sudden change to mirroring may be useful as a high-salience indicator to alert the participant during a task.

4.3 Experiment 2: Creature Entraining and Reactions During a Task

While Experiment 1 investigated mostly the subjective response to the Creature, answering the questions of “Will people like it?” and “Will people be receptive to it?”, an attempt to manipulate the user’s affect, a key goal of the TAMER platform, had not yet been performed. During Experiment 1, there had been an observation of increased “steadiness,” that is, a decrease in standard deviation of both breathing rate and heart rate during the experiment attributed to the Creature. This had been an encouraging result: it showed that the Creature was able to at least somewhat have influenced the user’s physiological state. It was proposed to further investigate this ability of the Creature, both directly, by asking users to follow the Creature, and indirectly, by examining the Creature’s physiological effect when the user was performing a task.

The primary goal of this experiment was to investigate whether a change in Creature “physiological state” as conveyed through its respiration and pulse mechanism has an effect on a participant’s physiological state (as measured through pulse and respiration rate). Unlike in the previous Experiment, where the Creature had simply been activated or deactivated, here a more focused change in Creature activity was adopted, one that would also be of use in determining whether participants might find higher or lower activity levels in the Creature more noticeable. In this experiment, the Creature was progressed from a physiological state mirroring the participant’s respiration and pulse (their baseline) to a state with either a faster respiration rate and higher pulse, or a slower respiration rate and a lower pulse. After some time in this new state, the Creature was progressed back again to the original pulse and respiration state baseline. This is shown in Figure 4.15. Time period lengths were chosen to allow the experiment to be completed within a half-hour time period to encourage participant participation: overall experiment lengths were generally greater than in the previous Experiment due to the shorter questionnaire.

The gradual adjustment in Creature activity would prevent any disconcertion from the Creature being suddenly activated or deactivated, and would also preclude recognition of a sudden change in Creature activity. A difference of 20 percent from baseline in respiration rate and 20 beats per minute in heart rate was chosen as representing a distinguishable difference in Creature activity levels while not exceeding the capabilities of the platform. Larger deltas resulted in extremely fast and noisy Creature motions, often to a distracting level, during the elevated activity level state. The transitions between the high and low activity levels were generally shorter than the constant motion stages, as where physiological comparisons were made between the high and low activity states a large enough time was needed for participant physiological metrics to stabilize.

A secondary goal of this experiment was to determine if the Creature could influence its user when the user was not directly engaging with the Creature. This would help support the role of the TAMER platform in its ultimate end environment: one in which the Haptic Creature acts as merely accompaniment while the user performs another task. There were two stages of interaction with the user to investigate this. In the first, the participant was invited to interact with the Creature in a focused way, through petting or stroking the Creature, for several minutes. In the second, participants held the Creature on their laps while performing a secondary task, in this case reading literature. It was expected that they would find the Creature's motions and actions comforting, but not distracting from their task.

In the previous experiment it had been found that participants required a thorough introduction to the Creature. Even after being equipped with physiological sensors, participants did not recognize that the Creature could be linked to their own physiological state, and several of the Creature's mechanisms, particularly the pulse, are not obviously found without careful inspection. As part of the introduction, therefore, it was decided to ask the participant to mirror the Creature's breathing and heart rate for a brief period, a procedure henceforth called "entrainment" (cf. "mirroring"). This would help accomplish several goals. Breathing rate training as part of relaxation therapy is an important part of many anxiety reduction techniques, and the Haptic Creature's abilities to display controlled breathing rates could give it the ability to act as a trainer. If users could successfully mirror the Creature's breathing, it would help to confirm one possible usage scenario of the TAMER platform. By matching user breathing with the Creature's, this entraining would also help provide an expected activity level for the Creature of the user's own breathing rate and heart rate, giving participants a calibration on what activity levels to expect from the Creature for the rest of the session.

4.3.1 Research Questions

In this experiment the following research questions were posed:

- Can participants consciously mirror the Creature's respiration rate when instructed to do so? If so, does this mirroring affect the participant's physiological state?
- Does Creature motion affect participants' physiology either when interacting with the Creature or when performing a task with the Creature on their laps?
- Is the Creature distracting to participants when they are asked to perform a simple, non-stimulating mental task?

Overall group trends were analyzed. Skin temperature, heart rate variability, heart rate acceleration, and skin conductance were examined for any prevailing trends through pool-wise comparison between stages using two-tailed dependent sample t-tests ($\alpha = 0.05$).

4.3.2 Procedure

Experiments took place in an experiment room which had been removed of all equipment except for a table placed against the wall. During the experiment participants remained seated, facing the wall, at the large table. The physiological sensor encoder was placed on the table, to the right of the participant. The wires from the sensors, the experiment facilitator, the Haptic Creature support equipment, and computers were located behind a fake wall to the right of the participant. A web camera affixed to the top of the wall was used to observe the participant during the experiment. The experiment consisted of the four phases shown in Figure 4.14, and described here.

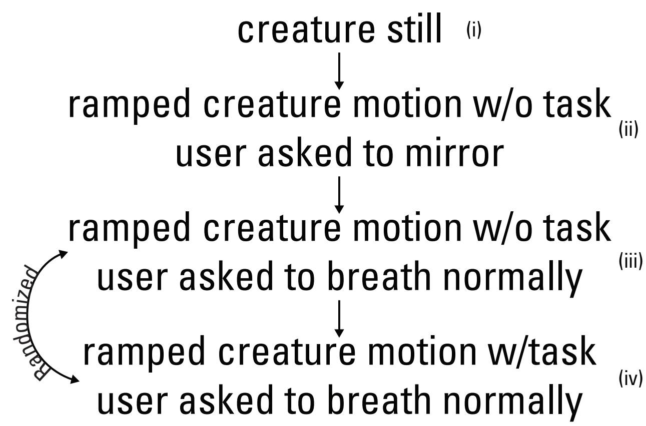


Figure 4.14: Diagram of Experiment 2 procedure.

Introduction and Baseline

After signing consent forms, participants were fitted with skin conductance (SCR), blood volume pulse (BVP), and skin temperature (ST) sensors on their non-dominant hand, as well as three-lead electrocardiogram (EKG) and respiration rate (RR) sensors. The sensors were then activated and tested. If necessary, adjustments were made to sensor fit to ensure that they were properly functioning. Participants were then asked to sit calmly for ninety seconds while a baseline was gathered.

Stage 1: Creature Still

Participants were given the Haptic Creature. It was placed on their lap, and its respiration and pulse mechanisms were described and pointed out. They were instructed to sit quietly with the Creature and to feel free to interact with it by petting, stroking, or touching. Physiological data were continued to be gathered for ninety seconds after the facilitator had moved out of sight of the participant. These ninety seconds are stage 1 in Figure 4.14

and in other references.

Stage 2: Ramped Creature Motion, User Asked to Mirror

Participants were then informed that the mechanisms of the Creature would now be activated. After the facilitator had returned behind the screen, the Creature began to mirror the physiological state of the user in both heart rate and respiration. The facilitator then returned to the participant, and invited him/her to mirror the Creature's breathing with his/her own. Once the facilitator returned behind the screen, the Creature then immediately began a progression consisting of a thirty second "ramp" to a breathing rate and heart rate 20% higher than that of Stage 1, sixty seconds at the new, higher rate, and then a sixty second ramp down to a breathing rate and heart rate 20% lower than that of stage 1, followed by sixty seconds at that rate. The Creature was then deactivated. These two hundred and ten seconds are stage 2 on Figure 4.14 and in other references.

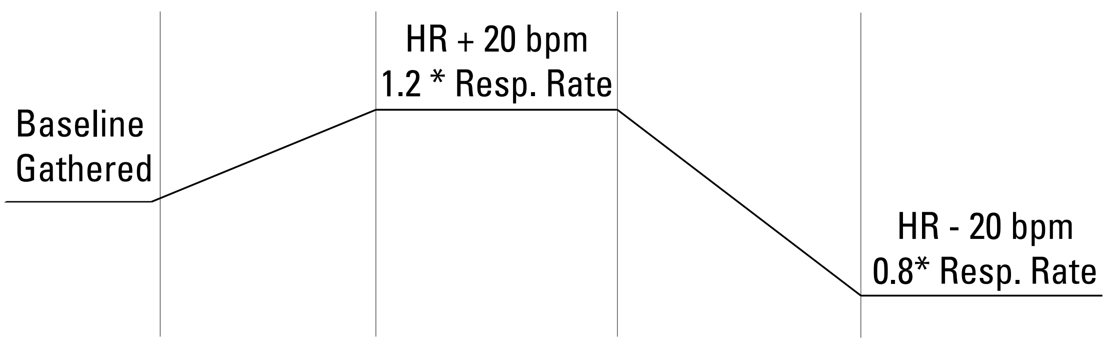


Figure 4.15: Ramped Creature motion, as used during experiments.

Stage 3: Ramped Creature Motion With User Task, User Asked to Breathe Normally

Participants were then assigned a reading task. They were asked to read selections from three Graduate Record Examinations™ [111] reading passages, count the number of words containing four syllables, and write this number at the bottom of the page. They were instructed to keep at least one hand on the Creature at all times, and to keep the reading material on the desk rather than hold it in their hands. During this stage the Creature performed a ramped motion similar to that of stage 2 but longer, consisting of a sixty second "ramp" to a breathing rate and heart rate 20% higher than that of stage 1, one hundred and twenty seconds at the new, higher rate, and then a one hundred and twenty second ramp down to a breathing rate and heart rate 20% lower than that of stage 1, followed by one hundred and twenty seconds at that rate. The Creature was then deactivated. These four hundred and twenty seconds are stage 3 on Figure 4.14 and in other references.

Stage 4: Ramped Creature Motion Without User Task, User Asked to Breathe Normally

Participants were then instructed to sit calmly with the Creature while the same ramp progression as in stage 3 is performed. These four hundred and twenty seconds are stage 4 on Figure 4.14 and in other references.

Questionnaire

The Creature was collected, the sensors removed, and a post-experiment questionnaire administered. A copy of the post-experiment questionnaire is included in Appendix B.3.1.

The order of stages 3 and 4 was determined randomly. Stage 2 was always performed first to ensure that participants were aware of the Creature's mechanisms' location and actions, as well as the intended relation between the Creature's mechanisms and their own breathing and heart rate.

Nine undergraduate or graduate computer science and engineering students between the ages of twenty and thirty, four of whom were female, took part in this experiment. None had participated in the previous experiments. Participants were compensated for their time.

4.3.3 Results

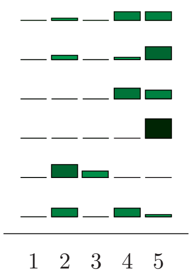
Qualitative and then physiological results are reported in this section.

Qualitative Results

A summary of the questionnaire results is shown in Table 4.6. Descriptions of quantitative survey results refer to general trends, not statistical analyses. Participants reported a high ability to easily mirror the Creature's breathing, and generally a high awareness of the Creature's breathing and pulse.

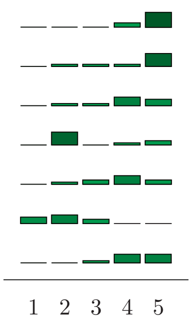
Table 4.6: Questionnaire results from Experiment 2 post-experiment survey (1 = strongly disagree, 5 = strongly agree).

When asked to mirror creature:



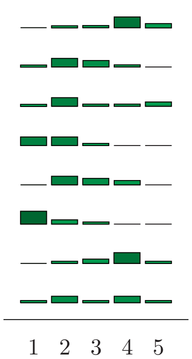
I was able to easily mirror the creature's breathing
I was aware of the creature's pulse
I was comfortable with creature on my lap
I was aware of my own breathing
I was aware of my own heartrate
I found noise of creature distracting

While sitting with active creature:



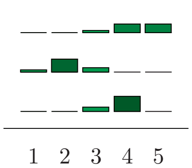
I was aware of the creature's breathing
I was aware of the creature's pulse
I noticed changes in the creature's breathing
I noticed changes in the creature's pulse
I was aware of my own breathing
I was aware of my own heart rate
I was comfortable with creature on my lap

During reading task:



I was aware of the creature's breathing
I was aware of the creature's pulse
I noticed changes in the creature's breathing
I noticed changes in the creature's pulse
I was aware of my own breathing
I was aware of my own heart rate
I was comfortable with creature on my lap
I found creature's motion distracting

Overall:



creature made me more aware of breathing
creature made me more aware of heart rate
enjoyed interacting

Physiological Results

Breath Lengths Typical physiological results from the experiment are in Figure 4.16, which shows a participant's breathing rate and heart rate during the second stage of the experiment, in which they were asked to mirror the Creature. In the leftmost frame of the graph the baseline is gathered. At the sixty second mark on the graph the Creature has ramped down to a constant value of 80% of baseline, and here the participant's mean respiration rate is almost the same as commanded respiration rate — the commanded and mean breath length lines overlap. During this time period the mean heart rate is increased slightly from baseline, but not to near the commanded value of twenty beats per minute greater than the baseline mean heart rate. In the other constant motion stage of the experiment, starting at the one hundred and eighty second mark on the graph, participant respiration rate remains almost constant at the commanded respiration rate of 120% of the baseline, here again the commanded and mean breath lengths overlap. During this period the mean heart rate is increased slightly both from the previous period and the baseline, whereas the commanded heart rate was twenty beats per minute lower than baseline.

All participants showed greatly reduced standard deviation of breath lengths when asked to mirror the Creature, and this reduction somewhat tended to stay, with standard deviations remaining lower for most participants when both sitting calmly and performing the task than during baseline. On average, standard deviations were slightly but not significantly higher when performing the task than when sitting calmly. There was a statistically significant difference in the standard deviation of breath lengths between the baseline and the training stages ($M = 1.15\,\mathrm{s}, SD = 0.535\,\mathrm{s}, p < 0.05$), the baseline and sitting calmly ($M = 0.780\,\mathrm{s}, SD = 0.686\,\mathrm{s}, p < 0.05$), and the baseline and performing a task ($M = 0.596\,\mathrm{s}, SD = 0.524\,\mathrm{s}, p < 0.05$), as well as between the training stage and sitting calmly ($M = -0.377\,\mathrm{s}, SD = 0.411\,\mathrm{s}, p < 0.05$) and the training stage and performing the task ($M = -0.560\,\mathrm{s}, SD = 0.395\,\mathrm{s}, p < 0.05$).

In general, mean breath length was significantly different in lengths during the faster and slower commanded respiration series both during the training stage ($M = -2.91\,\mathrm{s}, SD = 1.98\,\mathrm{s}, p < 0.05$), the Creature with the task ($M = 1.46\,\mathrm{s}, SD = 1.18\,\mathrm{s}, p < 0.05$), and the Creature without the task ($M = -0.0540\,\mathrm{s}, SD = 0.296\,\mathrm{s}, p < 0.05$). Means were calculated for the steady portion of Creature motion, when it was operating a constant breathing rate, not the ramp.

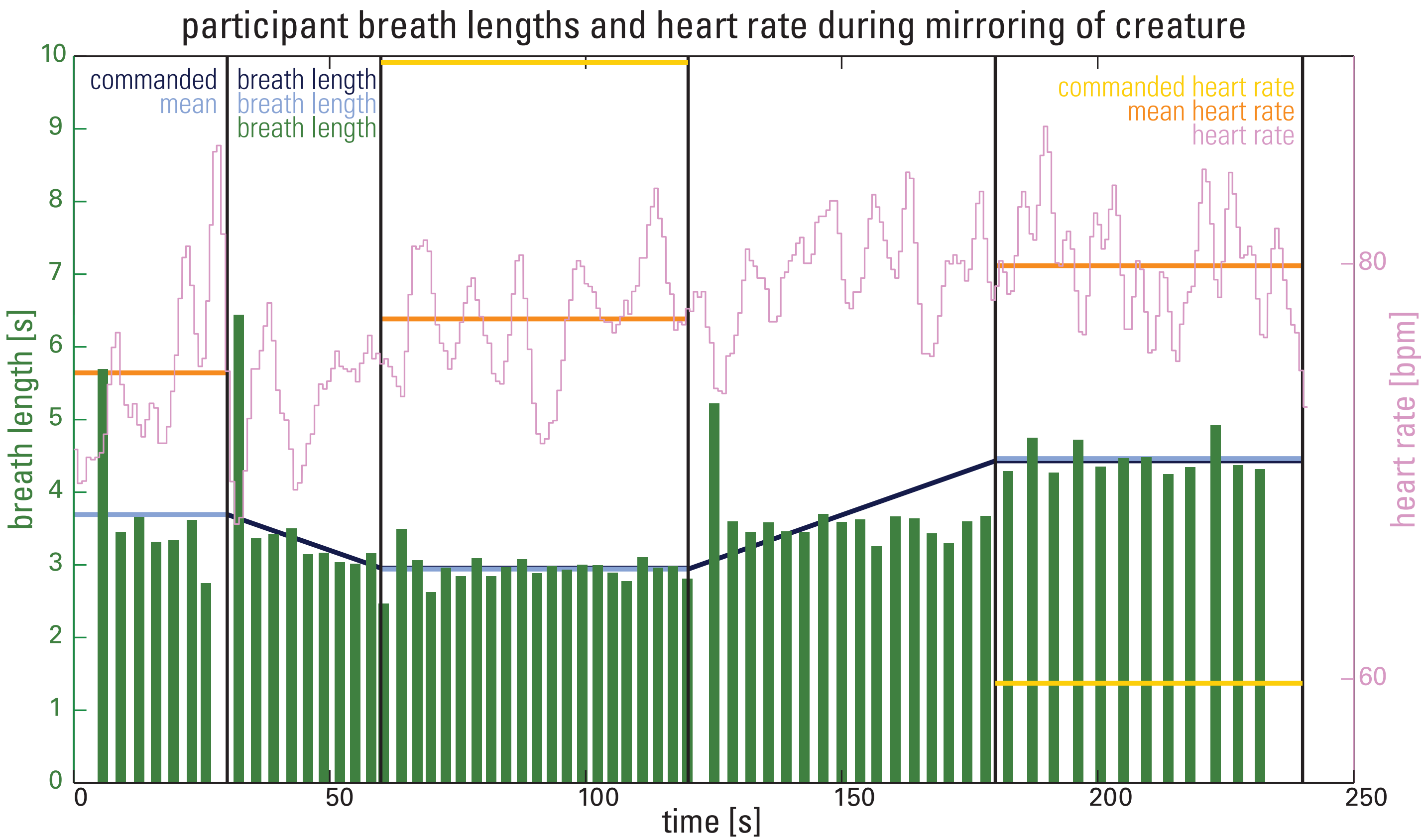


Figure 4.16: Breath lengths and heart rate for a participant during stage 2 of Experiment 2. Green vertical bars represent a single breath.

Heart Rate Heart rate was compared using three metrics: interbeat interval (ibi), heart rate variability, and mean heart rate.

Interbeat Interval During the training session eight out of nine participants saw a reduction in the standard deviation of heart rate interbeat intervals. All participants saw an effect from the Creature when sitting calmly with it versus the baseline ($p < 0.05$), and six out of nine saw an effect from the Creature motion during the task versus the baseline ($p < 0.05$).

Heart Rate Variability Heart rate variability metrics were calculated for each phase for each subject. Overall, there was no significant difference in heart rate variability between or within stages, except for the percentage of high frequency components, which did not show a significant decrease ($p > 0.05$) from Stage 1 to Stage 2, but did show a significant difference between Stages 2 and 3 ($M = -16.4, SD = 12.5, p < 0.05$), 2 and 4 ($M = -23.0, SD = 18.2, p < 0.05$) , and 3 and 4 ($M = -6.59, SD = 12.7, p < 0.05$).

Mean Heart Rate There was no significant difference ($p > 0.05$) in mean heart rate between or within the stages.

Skin Conductance There was no significant difference ($p > 0.05$) in skin conductance between or within the stages.

Skin Temperature There was no significant difference ($p > 0.05$) in mean skin temperature between or within the stages.

A summary of physiological results is shown in Table 4.7.

Table 4.7: Summary of results from Experiment 2, significant results are in bold. Stage 1: Creature Still; Stage 2: Ramped Creature Motion, User Asked to Mirror; Stage 3: Ramped Creature Motion Without User Task, User Asked to Breathe Normally; Stage 4: Ramped Creature Motion Without User Task, User Asked to Breathe Normally. Breathing rate data is located in Section 4.3.3.

metric		comparison stages						unit
		1–2	1–3	1–4	2–3	2–4	3–4	
breath length sd	mean	**1.15**	**0.780**	**0.596**	**-0.377**	-0.183	**-0.560**	s
	sd	**0.535**	**0.686**	**0.524**	**0.411**	0.205	**0.395**	
	p	**< 0.001**	**0.002**	**0.009**	**0.011**	0.183	**< 0.001**	
heart rate mean	mean	0.222	1.22	2.11	1.00	1.89	0.889	bpm
	sd	4.89	2.70	3.31	4.99	5.13	3.81	
	p	0.901	0.236	0.109	0.586	0.328	0.528	
heart rate sd	mean	-0.100	0.178	0.122	0.278	0.222	-0.056	bpm
	sd	1.43	1.32	2.44	1.54	2.73	1.72	
	p	0.848	0.714	0.891	0.623	0.824	0.930	
heart rate var rmsssd	mean	13.6	14.2	12	0.667	-1.55	-2.22	
	sd	32.0	43.1	46.3	19.1	23.7	8.89	
	p	0.265	0.378	0.484	0.924	0.857	0.500	
heart rate var pnn50	mean	-3.37	-2.99	-3.3	0.382	0.064	-0.318	
	sd	11.0	7.50	9.08	7.66	11.2	7.13	
	p	0.409	0.292	0.333	0.891	0.987	0.902	
heart rate var hf%	mean	30.5	14.1	7.50	**-16.4**	**-23.0**	**-6.59**	%
	sd	16.4	21.1	28.9	**12.5**	**18.2**	**12.7**	
	p	< 0.001	0.096	0.483	**0.006**	**0.007**	**0.008**	
heart rate var lf%	mean	-1.44	2.56	10.2	4	11.7	7.67	%
	sd	24.3	16.3	25.4	25.8	24.1	15.3	
	p	0.871	0.669	0.288	0.673	0.207	0.194	
heart rate LF/HF	mean	-1.54	-0.736	0.146	0.800	1.95	1.15	
	sd	5.42	4.01	4.21	4.47	3.97	2.49	
	p	0.446	0.618	0.787	0.627	0.202	0.228	
skin temperature mean	mean	-0.795	-0.807	-1.47	-0.012	-0.676	-0.664	°C
	sd	1.01	1.66	2.05	1.19	2.14	1.91	
	p	0.055	0.184	0.064	0.977	0.372	0.328	
skin temperature sd	mean	0.489	0.49	0.305	0.001	-0.185	-0.185	°C
	sd	1.75	1.84	1.98	0.234	0.475	0.457	
	p	0.427	0.447	0.657	0.996	0.276	0.259	
skin conductance mean	mean	0.097	0.071	0.081	-0.026	-0.016	0.010	norm
	sd	0.386	0.287	0.323	0.115	0.098	0.09	
	p	0.475	0.481	0.476	0.518	0.634	0.75	
skin conductance sd	mean	-0.030	-0.055	-0.074	-0.025	-0.044	-0.020	norm
	sd	0.118	0.096	0.096	0.077	0.084	0.058	
	p	0.467	0.125	0.051	0.365	0.150	0.338	

4.3.4 Discussion

Questionnaire Results

Analysis of participant survey results focused on three areas: their comfort with the Creature and awareness of its mechanisms, the effect of the Creature on their awareness of their own breathing rate and pulse, and their reaction to the Creature while they were performing the reading task.

Participants reported a greater awareness of the Creature's mechanisms than their own corresponding activities. Participants were in general aware of the Creature's breathing during the experiment, although they were slightly less aware during the reading task (see Figure 4.17). The design of the breathing mechanism likely allows for its activity to be monitored with minimal attention from the user. It produces a motion in the Creature's abdomen that is quite salient over a large area of the Creature, requiring only a brief touch to obtain awareness of the current breathing rate and position. It should be possible to maintain contact with the Creature with minimal attention as only a brief touch is necessary, but required, to monitor its breathing.

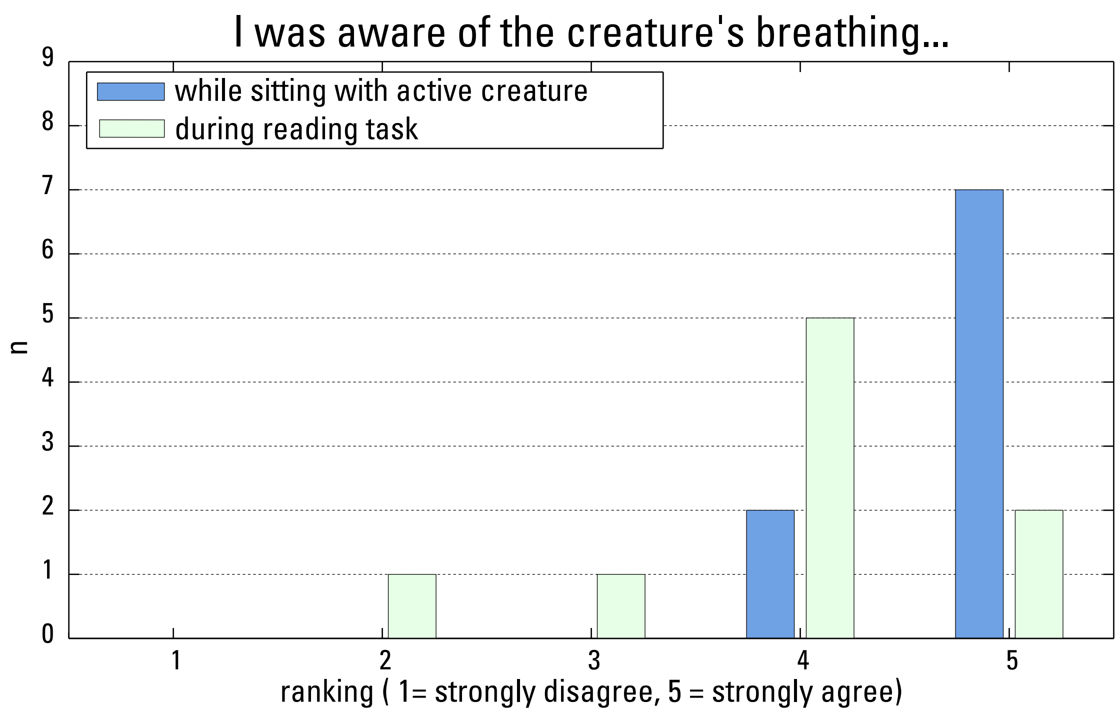


Figure 4.17: Experiment 2 participant responses to survey statement "I was aware of the creature's breathing."

In comparison, the Creature's pulse is more difficult to locate and much greater effort is required to maintain awareness of the Creature's heart rate. The effect of the pulse mechanism can only be felt in the "neck" area of the Creature, near the head, and to do so requires placement of the hand in that area. Although the neck area is a somewhat natural position to place the hand when interacting with the Creature with both hands, it is not as likely to be regularly touched when the participant is primarily interacting with the Creature with one hand, as during the reading task. This is likely the cause for participants reporting much less awareness of the pulse during the reading task, as expected. In general, however, they showed a high awareness of the Creature's pulse (see Figure 4.18).

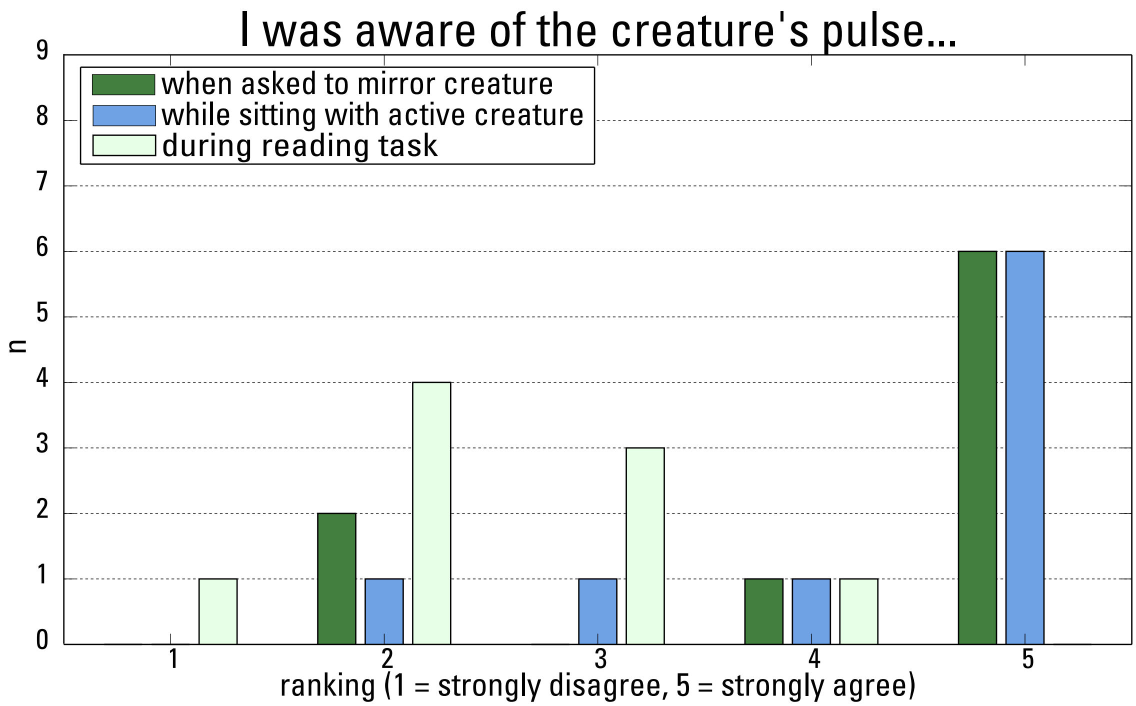


Figure 4.18: Experiment 2 participant responses to survey statement "I was aware of the creature's pulse."

Concerning the research question posed related to whether the Creature's breathing and pulse would cause the participants to be more aware of their own breathing and pulse, participants reported a very high awareness of their own breathing when asked to mirror the Creature (see Figure 4.19). The task naturally requires concentration on breathing rate and intensity. This awareness carried over into the later stages of the experiment, with all but one participant reporting an awareness of their breathing while sitting with the active Creature. Following the same trend as awareness of the Creature's breathing, participants' awareness of their own breathing was less during the reading task, with several participants reporting that they were not aware of their own breathing during the task.

It was also a research question as to whether participants would be aware of their own heart rate or that the Creature would be able to increase participants' awareness of their

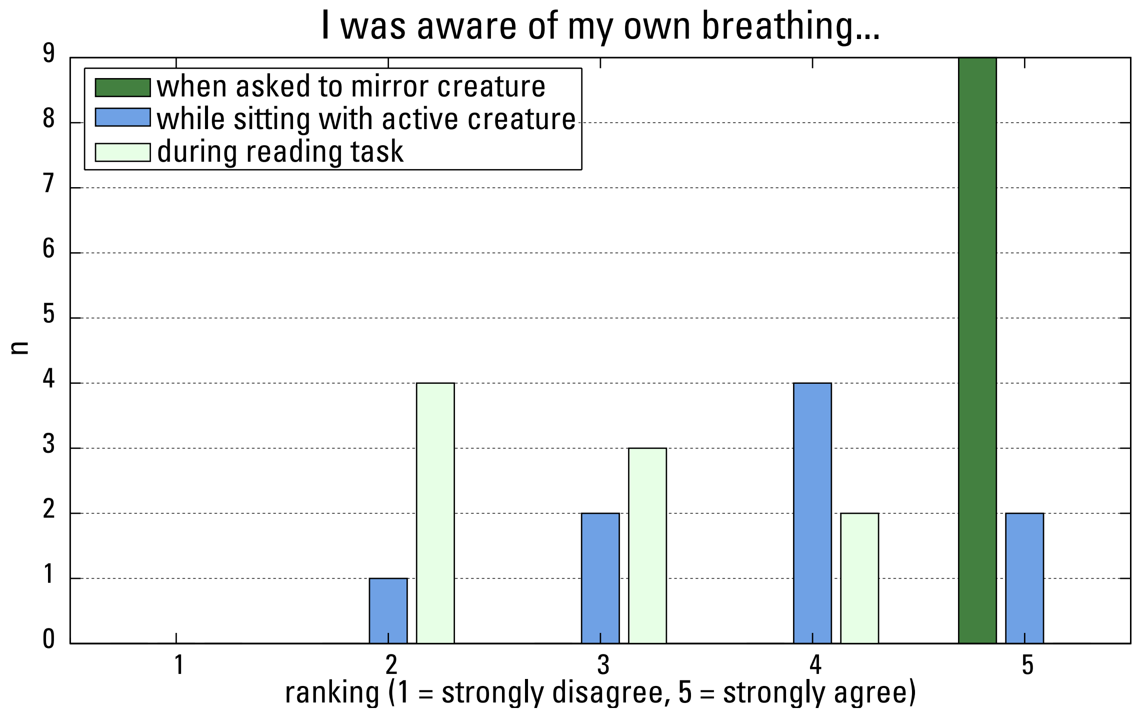


Figure 4.19: Experiment 2 participant responses to survey statement "The creature's breathing made me more aware of my own breathing."

own heart rate. In general, people do not have a high awareness of their own heart rate except in extreme conditions, where it is "pounding," or beating fast enough that they are able to notice it. This result was shown in the reported results, as all participants reported some level of disagreement with the statement "I was aware of my own heart rate" (see Figure 4.20). Participants reported slightly higher disagreement during the reading task, but overall levels of disagreement for all three stages were quite high. Without extensive training, the most common way of being aware of one's own heart rate is by taking one's pulse, and participants were generally precluded from doing this during the experiment by sensor wires and the instruction to attempt to maintain one hand on the Creature at all times. Even if the Creature had invoked an increased mental awareness that they have a pulse, participants would likely have been unable to determine their pulse.

As in the first experiment, reaction to interaction with the Creature was positive overall, with participants reporting comfort in having the Creature on their laps, and no discomfort with Creature motions and activity. It was desired that participants would not find the Creature overly distracting during their reading assignment; however, user feedback on that subject was mixed and inconclusive (see Figure 4.21). It was noted that during higher levels of engagement with the reading assignment, participants would use at least one hand and sometimes both to assist them in reading the pages; this would preclude haptic interaction

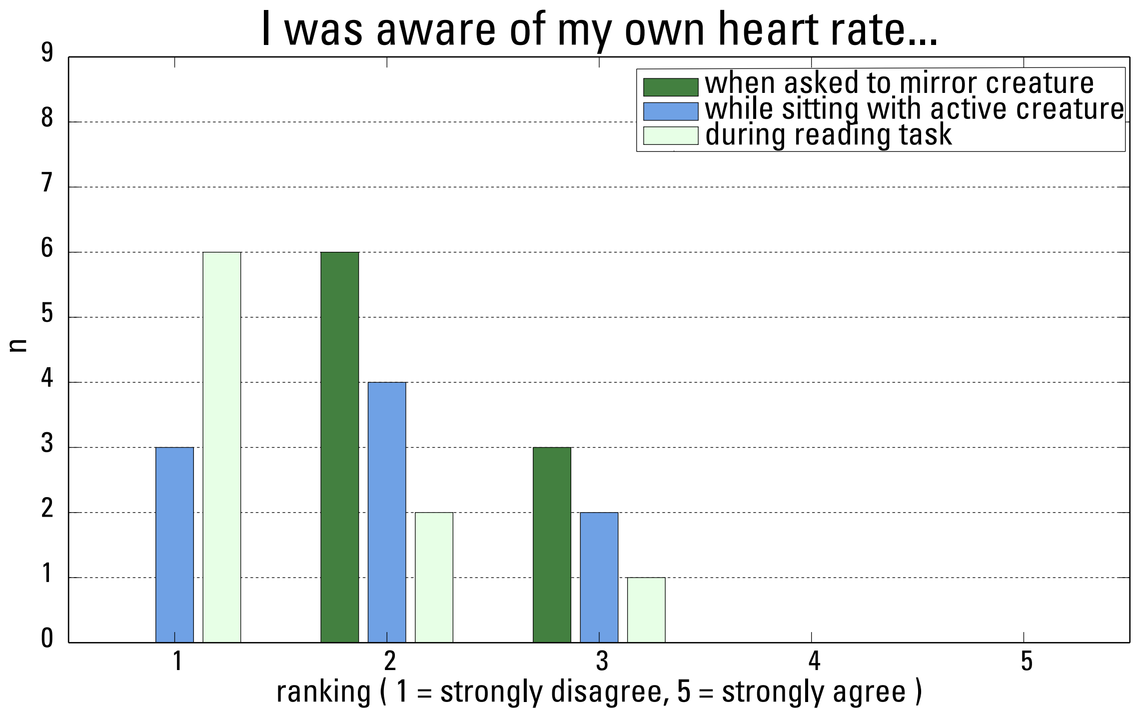


Figure 4.20: Experiment 2 participant responses to survey statement "The creature's pulse made me more aware of my own heart rate."

with the device and potentially mitigate some of the potential distracting effect of the Creature. The fact that participants are not forced to monitor the Creature, and that they can always remove their hands from it, may prevent it from becoming an intrusive distraction, but may also make it less effective.

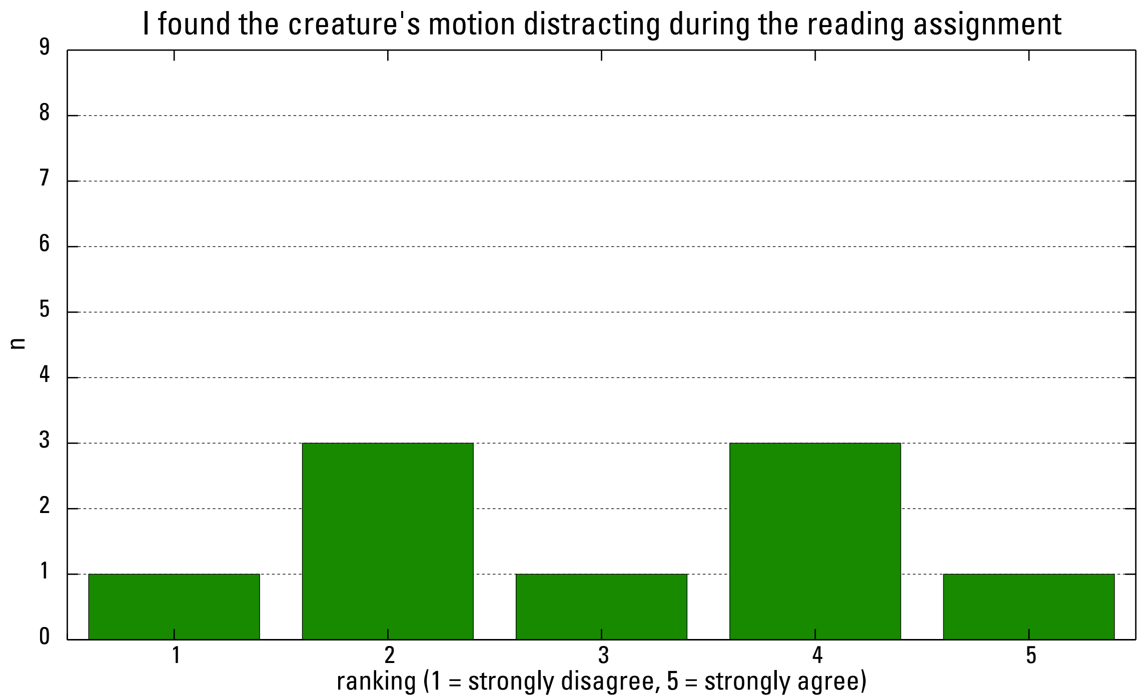


Figure 4.21: Experiment 2 participant responses to survey statement "I found the creature's motion distracting during the reading assignment."

Physiological Results

Stage 2 (ramped creature motion, user asked to mirror) is always administered prior to Stages 3 and 4 (ramped creature motion with and without task) for reasons of experiment flow and introduction to the Creature. This constitutes a randomization restriction, which might have implications on the interpretation of results incorporating Stages 3 and 4 (e.g. potential confounds with effects of adaptation, learning, habituation or fatigue and boredom). We saw this as a necessary constraint. Creature entrainment of breath rate when participants were asked to mirror the Creature was confirmed through the respiration measurement. There are likely several reasons why entrainment of heart rate was not similarly successful. In particular, participants were not instructed to mirror the Creature's heart rate, and even if they had been, most would not have had the ability to do so, as they reported little to no awareness of their own heart rate. It appears likely that entraining had no effect on mean heart rate, as there was no pattern to the trend of mean heart rate between the slow pulse and high pulse stages of the entraining. Skin temperature did, however, increase during the training, an indication of decreased participant arousal.

The physiological effects noted during the longer-term interaction with the Creature were also promising, if less pronounced. The standard deviation of breath lengths not only showed a general trend of decreasing greatly during the mirroring stage, as would be expected when commanded to breathe at a steady rhythm, but this reduction in breath rate variability remained even when the participant was not instructed to mirror: breath length variability was less both when sitting calmly and when performing the task than during the baseline. Participant breath length variability was slightly higher when performing the task than when sitting calmly for all participants, but still remained below baseline. This suggests that some aspect of the entrainment lingered even after the training stage. This reduction in breath rate variability corresponding to Creature motion was also noted in the previous experiment when the Creature was activated at a constant rate, but not when it was mirroring the participant. A likely explanation for this is that participants, understanding that the Creature was displaying a breathing rate similar to theirs, were identifying with the rhythmic stability of the Creature's breathing rate, and "keying in" on it to cause an increased stability in their own breathing rate. This could also explain the decrease in standard deviation of heart rate shown during Creature motion in Experiment 1. Such a "stability effect" could potentially serve as an anxiety coping mechanism, by providing comforting reassurance and by reinforcing anxiety-reducing physiological metrics. A marked decrease in the high frequency percentage of heart rate variability was also noted between the baseline and the mirroring stage. As the high frequency component of heart rate variability is driven primarily by respiration, it is likely that this is partially an effect of the slow breathing exercises undertaken by the participant mirroring the Creature. For many participants, this value remained low during the remainder of the experiment: eight had a lower hf % when sitting calmly with the Creature than during the baseline, and six during the reading task.

A summary of significant physiological results is shown in Table 4.8.

Table 4.8: Summary of significant results from Experiment 2. Stage 1: Creature Still; Stage 2: Ramped Creature Motion, User Asked to Mirror; Stage 3: Ramped Creature Motion Without User Task, User Asked to Breathe Normally; Stage 4: Ramped Creature Motion Without User Task, User Asked to Breathe Normally.

physiological metric	comparison	mean	SD	p
breath length sd	stage 1–2	1.15 s	0.535 s	< 0.001
	stage 1–3	0.780 s	0.686 s	0.002
	stage 1–4	0.596 s	0.524 s	0.009
	stage 2–3	−0.377 s	0.411 s	0.011
	stage 3–4	−0.560 s	0.395 s	< 0.001
mean breath length fast–slow	training mode	−2.91 s	1.98 s	0.003
	Creature with task	1.46 s	1.18 s	0.008
	Creature without task	−0.0540 s	0.296 s	0.008
heart rate hf%	stage 2–3	-16.4	12.5	0.006
	stage 2–4	-23.0	18.2	0.007
	stage 3–4	-6.59	12.7	0.008

4.3.5 Conclusions

Participants were able to consciously mirror the Creature's respiration rate when instructed to do so. This mirroring produced a reduction in the overall mean standard deviation of breath lengths for participants, as well as changes in mean heart rate for eight out of nine participants. Either this training stage or the motion of the Creature also produced physiological effects in participants during the remainder of the experiment. The standard deviation of breath lengths remained significantly less during all stages with the Creature than during the baseline, but was significantly higher during the stages with the task than when training. When the Creature was present, there was a significant difference in overall participant mean breath length between when the Creature was moving at a slow constant rate and a fast constant rate — this was likely a response to Creature motion.

The high frequency component of heart rate variability was significantly different between the training stage and both task stages, as well as between the task stages. In general participants reported feeling comfortable with the Creature on their lap, and despite finding the Creature a bit noisy, most did not find it disturbing or distracting during their task. Overall, participants typically reported a high awareness of the Creature's breathing, and a lower awareness of the Creature's pulse; this corresponded with a much greater awareness of their own breathing than their own pulse.

4.3.6 Feedback for Iterated Design

This experiment completed the readiness testing of the TAMER platform. With the refinements in Creature mechanisms and performance made after the first experiment, no major changes were necessary. However, several modifications were made to the overall platform to improve function during future experiments. These included logistical changes, additional data logging capability, and some cosmetic refinements.

While the physiological sensors continued to record adequate data, linking the data to both specific moments in the experiment and Creature activity proved difficult. The logging of data from the Creature was found to malfunction occasionally, with several participants' Creature logs missing several sections. Software protocols were adjusted to be more robust, and alerting added to notify the facilitator when Creature logging had failed.

Finally, several cosmetic improvements were made to tidy up the sensor wiring to reduce the risk of tangles. Where possible the cables were bundled and rerouted away from commonly accessed areas.

Much of the procedure from this experiment was carried over into the next experiment. Of concern was the length of time required to gain meaningful physiological data from interaction with the Creature. After two hundred and ten seconds of sitting still with the Creature on their lap, moving at a fairly constant rate, many participants became bored. They looked away from the Creature and began to search around the room for other stimuli; some even asked the facilitator if the experiment were over yet. This is representative of the maximum amount of time participants can be expected to focus solely on the Creature before it becomes tedious. More varying motions of the Creature could be of use in maintaining engagement, but would not have allowed for the physiological effects sought for in this experiment to be measured.

4.4 Experiment 3: Experiment with Children

The experience and success gained from the previous experiments provided the methodological foundation to conduct an experiment with the Creature in a more representative environment. Due to the potential for increased receptiveness, or at the very least varied physiological responses from this very different age group, it had previously been decided that this school experiment would take place regardless of the findings of Creature success in manipulating physiological metrics in the previous experiments. Therefore, the resulting success of the Creature in affecting breathing and heart rate metrics was encouraging. A subject pool of children was expected to provide a very different experience than that of young adults: children were certain to be more physically demanding upon the Creature, due to either rough play or lack of care, but it was expected that they would also prove more physiologically receptive to the Creature.

The location for this experiment was the Eaton Arrowsmith School [112], "a co-educational, non-denominational, independent day school for elementary and secondary school students with learning differences/disabilities." This school was chosen both for its location on the University of British Columbia campus and its staff's willingness to work with researchers, as well as its unique curriculum and student population. Although the school's students are not clinically diagnosed with severe emotional, behavioral, or intellectual disorders, they have experienced difficulty functioning academically in the regular school system. During their time at this school they spend several hours each day building cognitive skills through repetitive training exercises. This makes this group an ideal subject pool for the TAMER platform, as they spend the majority of their school day performing timed, intense, stress inducing activities. Many of these activities are performed individually on the computer, allowing for experimental sessions to be performed without disrupting the students' daily routine.

The procedure for this experiment draws heavily from that of the previous experiments, especially Experiment 2. There were several main research goals. The first goal was to confirm that the computer activity performed by the student was able to induce measurable physiological changes, and to determine what are these physiological changes. The computer activity chosen for this experiment was called "Clocks." This computer program is used as part of the school's curriculum. During the activity, the screen displays a clock face with tick-marks but no numbers. For each trial, a time is represented using hands of equal length, and the student must input the time displayed based upon the relation between the hands. For example, a clock with one hand pointing towards the 11 position, and another pointing between the 3 and the 4, but close to the 4, must be displaying 3:50; it could not be displaying 11:18. If the hour hand were pointing straight at the 11 position, the minute hand would have to be near the 12 mark on the dial. This exercise is fairly simple for two or three hands, but becomes increasingly difficult as more hands are added (eventually thousandths of a second, second, minute, hour, day, month, year, century, and millennium are displayed on the clock). The students must answer as quickly as possible and are given feedback after each clock and their overall score at the end. The assigned difficulty level is increased after the student masters a level, so that the students are always working at a high level of difficulty for them. Students generally have a high level of engagement with the program and are motivated to produce as high a score as possible as their performance is tracked and assessed. They typically perform this activity for up to half an hour at a time. To investigate this activity, physiological data of students performing the activity were recorded.

A second goal was to investigate whether the Creature could be effective in alleviating stress or anxiety during this task. Students were asked to perform the task with the Creature on their lap both still, moving more slowly than their baseline heart rate, and moving more quickly than their baseline heart rate. To determine this, physiological data were gathered to assess any changes from Creature presence and Creature motion, and students were asked their impressions of the Creature during the task and whether it helped or distracted them.

The final, and perhaps most important goal, was to evaluate children's receptiveness to and comfort level with the TAMER platform. Informal pilot studies had been conducted with children on a one–to–one basis as well as with non-EAS school groups, but this was the first time a large-scale study was conducted involving the Haptic Creature, physiological sensors, and children. Receptiveness to the sensors and the Creature was observed, and children were asked what they liked about the Creature and how they felt while playing with it.

4.4.1 Research Questions

This experiment investigated the following research questions:

- Do participants find the Haptic Creature calming or engaging, based upon subjective response?
- Do the students' computer activities induce physiological changes, and are any of these linked to an increased level of stress or anxiety?
- Is the Haptic Creature able to induce physiological changes in participants during the experiment, either when still or moving slowly or quickly relative to the participant's own rates?

Similar to previous experiments, the mean heart rate, heart rate standard deviation, heart rate skewness, heart rate rms standard deviation, heart rate variability: pnn50, vlf%, lf%, mf%, and hf%, skin conductance, skin conductance derivative, electromyogram, electromyogram derivative, skin temperature, skin temperature standard deviation, respiration rate, respiration rate standard deviation, respiration amplitude, and respiration amplitude standard deviation (see Section 3.5.2) were calculated and compared among and between all five experiment stages (see Figure 4.22) for all subjects using two-tailed dependent sample t-tests (all $\alpha = 0.05$). Additionally, the series of each participant's heart rate interbeat intervals (ibi) and breath lengths for each stage were compared within subjects using a two-tailed independent sample t-test ($\alpha = 0.05$).

4.4.2 Experimental Procedure

This experiment consisted of five major stages, as shown in Figure 4.22. This experiment took place in an office: the participant sat on one end of a table in front of a personal computer, the experimenter and equipment were diagonally opposite, as far away as possible, at the other end of the table. Participants were taken out of their regular classroom activities during the school day for a thirty minute experiment session, the length of a typical school period, and the timings of each stage chosen to accommodate this length. Twenty-four participants, ages seven to thirteen, took part in the experiment. Participants wore noise-canceling headsets during the experiment. Permission slips were collected from the students' parents and assent forms from the students by the school's teachers before the experiment.

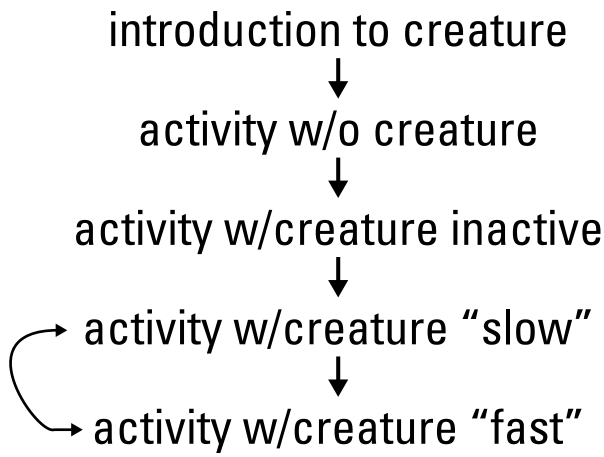


Figure 4.22: The Experiment 3 procedure diagram.

Introduction to Creature

Each participant was brought into the room, and told that they were about to participate in an experiment with the Creature. The student was then asked if they would mind wearing the physiological sensors. They were fitted with six sensors: the skin conductance, blood volume pulse, and skin temperature sensors on their non-dominant hand, as well as the heart rate (EKG), EMG on the corrugator muscle of the forehead, and respiration rate sensors. They then had the Creature placed on their lap. An introduction to the Creature was given, in which the mechanisms of the Creature were described and a demonstration of the Creature both mirroring the participant and being actuated at a constant rate were shown. Participants were given an opportunity to pet the Creature and ask questions about it. After the introduction session the Creature was removed. The entire process was scripted to take approximately five minutes, with the gathering of physiological data starting after the sensors were donned, and lasting for about three minutes. This served as the baseline for the Experiment.

Activity Without Creature

The participant was then instructed to begin their computer activity. He or she continued for about four minutes while physiological data were gathered.

Activity With Creature Inactive

The participants were then interrupted from their task and given the Creature. They were instructed that it might move, and to resume the activity. The Creature remained motionless for three minutes.

Activity With Creature Slow

After four minutes the Creature was activated with a breathing rate 20% slower and a heart rate 20 beats per minute less than that of the participant's during the activity with creature inactive stage. The Creature remained in this state for four minutes.

Activity With Creature Fast

The Creature then transitioned for ninety seconds from the "slow" rate to the "fast" one: with breathing rate 20% faster and a heart rate 20 beats per minute higher than that of the participant during the activity with creature inactive state. The Creature remained in this state for four minutes, and was then deactivated.

The order of the "fast" and the "slow" stages was counterbalanced, with the transition being modified appropriately. The activity without Creature state was always performed first, this minimized the disruption to the participant caused by handing them the Creature or taking it from them, which necessarily distracted them from their computer activity.

Experiment Conclusion

The Creature was removed from the participant, and then the sensors were removed while the participant was asked to discuss his or her experience. The experimenter initiated a conversation with all subjects during each session to elicit comments on their experience, with the goal of assessing their level of comfort and determining their subjective reactions. Notes were logged immediately following the session to avoid interrupting the flow of the sessions and yet maximize the amount of detail retained related to each session. No explicit questionnaire was used for this discussion.

4.4.3 Results

Twenty-six students, 14 female and 12 male, between the ages of 7 and 14 participated in the experiment, with an average age of 10.9. An image of a user during the experiment, attached to the physiological sensors and holding the Haptic Creature, is shown in Figure 4.23.

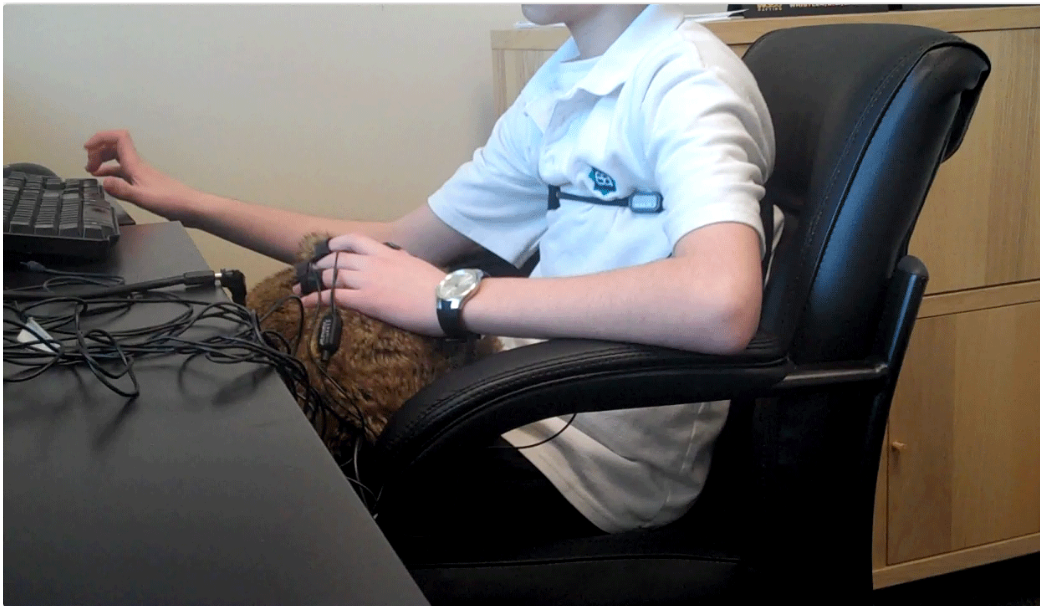


Figure 4.23: Experiment 3 participant during experiment.

Data from seven participants were not used for group-wise physiological comparisons. Of these, two were unable or unwilling to complete the specified computer activity, two had equipment failures, and for three there were external disruptions during the experiment that made their data unsuitable for comparison. For the remainder, the computer activity induced a reduction in heart rate variability $pnn50$, heart rate variability hf%, mean skin conductance, and respiration rate standard deviation (all $p < 0.05$), an increase in heart rate standard deviation and the standard deviation of skin temperature (all $p < 0.05$), as well as a change in heart rate variability vlf% ($p < 0.05$) as compared to baseline.

Creature presence during the activity induced an increase in heart rate standard deviation, heart rate variability vlf %, skin conductance derivative standard deviation, mean skin temperature, and skin temperature standard deviation (all $p < 0.05$) as compared to performing the activity without the Creature. A summary of significant results is shown in Table 4.9.

Subjective reactions to the Creature and experiment are discussed in Section 4.4.5, raw data is located in Appendix B.4.1.

Table 4.9: Summary of significant results from Experiment 3.

comparison	physiological metric	mean	sd	p	unit
baseline to activity without Creature	heart rate variability sd	422	418	< 0.001	ms
	heart rate pnn50	-0.054	0.099	0.013	
	heart rate vlf%	2.12×10^{-4}	2.31×10^{-4}	0.019	
	heart rate hf%	-0.001	0.002	0.015	
	norm. skin conductance mean	-0.121	0.170	0.002	
	skin temperature sd	0.124	0.239	0.019	°C
	respiration rate sd	-29.8	66.8	0.039	bpm
activity without Creature to activity with Creature	heart rate variability sd	-85.4	260	0.037	ms
	heart rate vlf%	-1.74×10^{-4}	2.51×10^{-4}	0.001	
	norm. skin conductance derivative sd	0.015	0.0246	0.011	
	skin temperature mean	1.23	1.67	< 0.001	°C
	skin temperature sd	0.257	0.507	0.032	°C

4.4.4 Additional Investigation with the Creature

After the first round of experiments was completed, the school at which the experiments were performed asked if the experimenters could return to perform trials with several participants who were not in school during the first round, but were still eager to participate. Due to equipment and space limitations it would have been impossible to maintain adequate controls with the first round of experiments. Therefore, their data were not pooled with others, but subjective results are reported here for completeness. An additional three students were used to pilot different interaction styles with the Creature. For these students the Creature ran for a longer amount of time, or at a different rate than the previous experiment. Four students who had previously participated in the experiment were brought back to determine second reactions to the Creature. They also participated with the Creature operating continuously for a longer amount of time, and at different speeds than as previously. Physiological data from this part of the experiment were not analyzed or reported as the experimental conditions for this group were comparatively poor (the quiet room previously used for the study was not available, and a different, noisy and high traffic room was used). However, subjective reactions to the experience of participating with the creature and the experimental setup were recorded, and those reactions are included in the discussion in the following section.

4.4.5 Discussion

Overall reactions to the TAMER platform and the experiment were quite positive. Students were excited to participate in the experiment; those who participated were sufficiently motivated enough to return a signed permission slip from their parents. They were not motivated just for the opportunity to miss class, since the school does not follow a traditional schedule. The Creature was undoubtedly the most appealing part of the experiment. Participants were uniformly enthusiastic about getting to know the Creature: all wanted to pet it, and upon entering the experiment room, most were disappointed that they had to have the physiological sensors attached before they could interact with the Creature.

Physiological Sensors

Reception to the physiological sensors was generally positive, most children were comfortable with the application and wearing of them. Two students expressed extreme apprehension of the sensors — one was calmed with the help of her personal assistant, and another by slowly putting on one sensor at a time. Although the name and purpose of each sensor was explained when they were put on, most seemed uninterested in their descriptions. Several students also expressed interest in viewing their physiological data on the computer. Once the sensors were on, the respiration sensor often required adjustments to ensure proper function. Although overall sensor performance during the experiment was good, a few common glitches were noticed during the experiment. In particular, both the EKG sensor and the BVP sensor would intermittently drop out, although almost never at the same time. Due to this redundancy useful heart rate data were collected, however this did necessitate manually selecting the cleanest signal for each time period. The EKG sensor was particularly prone to coming loose during experiments. To make the sensor less intrusive for the child and experimenter, instead of the common three-lead electrodes placed on separate areas of the chest, a single triode electric was placed in the middle of the chest. This is known to be less sensitive and less reliable, as the weight of the entire sensor is supported by one electrode, and skin adherence of that one electrode can be greatly reduced by perspiration. The blood volume pulse sensor was attached to the finger with a velcro strap that could occasionally become loose or cause the sensor to lose alignment; more often than not this occurred as the participant was petting or stroking the Creature. The skin conductance sensors were also attached by velcro to the fingers, and for two participants the skin conductance sensor electrodes became detached during the experiment.

Once the sensors were attached, participants generally did not express discomfort with them during the experiment. Although participants did not seem particularly encumbered by the hand sensors, more demanding activities would not likely have been possible. They would have been unable to write with the hand mounted sensors on, and typing would have been difficult, but possible. Participants were naturally cautious of touching objects with their sensor hand. Several would initially hold their hand in the air without touching anything, and participants often had to be told that it was all right to pet and touch the Creature with the hand bearing the sensors. Once they were told that they could touch the

Creature, however, their interaction with it did not seem to be affected by the sensors. A few participants also found the EMG sensor distracting in that the wire, although generally held up by their headphones, could fall down and obstruct vision. The sensor was also difficult to attach to smaller children, who did not have a large forehead area relative to the size of the sensor. As analysis of the EMG data did not reveal any distinguishing characteristics; it was left off for the final subjects.

A combination of the many wires and the logistics of the experiment room did make the sensors more cumbersome than they might otherwise have been. Although the wires had been bundled since the previous experiment, the large number of wires connected to the participant did make it somewhat difficult to pass the Creature to them. Due to the layout of the room, it was necessary to hand the Creature to the participant on the same side as the encoder. Had the Creature been able to be on the other side of the participant this would not have been a problem. There was also a worry that if a participant decided to hurriedly leave the experiment room they would drag a large number of sensors and wires with them, possible causing equipment damage, but fortunately this did not happen during trials. The caution most students showed with the sensors also makes this possibility unlikely, although a child in the middle of an anxiety attack might not show such caution.

Reaction to Creature

Reaction to both Creature presence and Creature motion was positive. Almost all participants were comfortable with having the Creature in their laps. One student was reticent about Creature on his lap, and desired to interact with the Creature on the desk before he would let it be placed there. Once he achieved initial comfort with the Creature, he was not uncomfortable during the remainder of the experiment. Students were surprised and pleased to find that the Creature was able to emulate their own breathing rate and heart rate. When asked, they felt that the breathing did not seem or sound mechanical. No students complained that the Creature was too heavy or noisy during the experiment. Several students said that the Creature reminded them of their own pets, particularly the warming sensation on the lap. In fact, the majority of students who participated in the experiment reported that they have or had had a dog or a cat at home.

Creature motion and Creature activity also generally elicited positive reactions. A common comment after the experiment was that “the Creature felt alive.” Many students after the experiment asked if they could have their own Creature. In particular, several students who reported not being able to have a pet at home expressed that they would like to have the Creature as a substitute. Students also said that they liked the Creature better when it was moving than when it was not. Students also preferred a gently moving Creature to a still one. By sending a null command to the respiration servo, instead of turning it off completely, a gentle humming sound and noise, similar to a continual purr, could be emitted from the Creature. Students preferred this somewhat active resting state to the Creature not moving at all.

Interaction with the Creature

Two typical interaction styles with the Creature were observed. In one the Creature seems to serve as a "comforting presence," in the other as a "brief reassurance." Most students performed their computer activity as normal, but petted the Creature during the activity. They reported the Creature as "comforting" and "pleasant" to have on their laps. Several also reported that they found the Creature to be "calming." A few students, however, would take a break from the computer activity periodically to stop and look at the Creature, petting it and occasionally breathing with it. These breaks were usually correlated with either the end of a computer activity "level" or the completion of a computer activity problem. One student suggested that the Creature helped her do better on the activity, another that the Creature was comforting to her when she got an answer wrong. Although the computer activities are timed, and thus taking a break during a level might not be beneficial for grading purposes, taking a brief break after a level to interact with the Creature, if helpful in reducing stress and anxiety, could have a beneficial effect on performance in the next level.

Just as adults were generally unable to distinguish between different Creature motion states, so were the students. Several students reported after the experiment that they had thought the Creature was mirroring their breathing and pulse the entire time. One student said it "felt like him and I [the Creature] were one." Another said that "I found it calming, it reminds me of my stuffy [stuffed animal]." Not all reactions to the Creature were positive, however. Several students reported that they felt the Creature to be distracting during the activity, and would have preferred it not move during the activity. The initial activation of the Creature also disturbed several students, who either jumped slightly, or briefly looked at the Creature when it turned on.

A level of anthropomorphization of the Creature was observed in the students' reactions to the Creature. They would become worried when the Creature stopped moving, or after a few minutes into the experiment if the Creature had not yet been activated. A few asked if the Creature was "sleeping" when it was not moving, or whether it was awake when it was moving. Older children tended to ask more if the Creature were "on" or "off," and those more self-aware of the experiment would often ask if something was wrong when the Creature stopped moving.

The physiological results shown from this were consistent with previous experiments, in that there were changes in heart rate variability associated with the Creature. This "steadying" effect, also seen in Experiments 1 and 2, was associated with Creature presence. There was no difference between the activity of the Creature "fast" and the Creature "slow" during the experiment. The computer activity reduced heart rate variability with a reduction in heart rate standard deviation and pnn_{50} that is consistent with the reduction in heart rate variability typically associated with stress, whereas Creature activity increased these metrics. Skin temperature increased as compared to the baseline during both the activity and creature presence stages, this change is most likely due to the increased level of physical and mental exertion caused by the computer activity. The "activity without creature" and "activity with creature inactive" stages were always performed first for reasons of experiment flow and introduction to the Creature. This constitutes a randomization restriction, which might have implications on the interpretation of results from this Experiment (e.g. potential confounds with effects of adaptation, learning, habituation or fatigue and boredom). We saw this as a necessary constraint.

A change to a 30% difference from participant levels in breathing rate and pulse rate for the low and high activity states resulted in a Creature respiration rate that was almost uncomfortably fast, and was reported to be distracting by the test subjects. This was also impractical, since such a large difference or a small error in measurement of respiration rate could result in commanded respiration and pulse rates that nearly exceed the capabilities of the mechanism. The longer-term time frame of investigations allowed for meaningful calculations of the mean of various physiological signals and indices that were not possible in the shorter-term experiment.

4.4.6 Conclusions

Overall, students had a positive reaction to interaction with the Haptic Affect Platform. The students reported that they found the Creature comforting during the activity, and expressed a wish to interact with it again. Stressful computer activity induced changes in heart rate variability standard deviation, pnn50, and vlf%; skin conductance mean and standard deviation of derivative; and skin temperature mean and standard deviation. The changes in heart rate variability and skin temperature are typical of response to stressful events. The Haptic Creature was able to induce several physiological changes in participants during the experiment. Creature presence induced changes in heart rate variability standard deviation and vlf%; skin conductance standard deviation of derivative; and skin temperature mean and standard deviation.

4.4.7 Feedback for Iterated Design

This experiment provided many lessons and suggestions for interactions where children are the primary subject group, as well as valuable feedback on the TAMER platform's hardware and software. There were several refinements to experimental protocol that should be incorporated into future experiments with the platform. First, the sensors should be placed on the student before they are shown the Creature or other experiment equipment, as most will be more interested in those things than putting on the sensors. Due to the small size of the experiment room in this experiment it was impossible to hide the Creature completely from view as the students were walking in, and many immediately wanted to see and pet the Creature once they started the experiment. The students did not seem to suffer particular distress from having the Creature removed from their laps during the experiment; therefore, this was unlikely to have affected their task performance.

Care must also be taken when describing the experiment to the students. Once several were told that they would be performing a computer activity they immediately started performing the computer activity, even before they had sensors attached. In two cases the computer screen had to be turned off so that they would break away from the activity to don the sensors. Unsurprisingly, children in this subject pool had demonstrably less impulse control than previous adult participants, and were not capable of waiting independently. They did, however, express a high level of enthusiasm and receptiveness towards the Creature.

Experiments in which strict adherence to experimental protocols are necessary to maintain experimental controls are challenging with younger participants, as they may not be able to accurately follow directions. For this experiment, there were no criteria for exclusion of participants. Several students who participated in the experiment were unable to complete the experiment protocol in a way that allowed for meaningful comparisons of physiological data between them and the other participants. Two had no experience with the computer “Clocks” activity that was being used, and two were unwilling to complete the clocks activity. These students were still enthusiastic to see the Creature and, as users, could potentially derive valuable benefits from the TAMER platform, but are not practical participants when limited experimental time is available.

For shy or reticent students, a gradual interaction with the platform was found to be the best way to make them comfortable with it. Students who were wary of the sensors became more comfortable with them once the first sensor was put on and shown to cause no harm, and would eventually allow the remainder of the sensors to be put on them. Similarly, several students did not wish to have the Creature on their lap at first, and instead gently petted the Creature while it sat on the desk. After some time seeing Creature motion, the students would let the Creature be placed on their lap. This progressive interaction with the Creature took much longer than the typical experiment session, but allowed for students who otherwise would not have been able to participate to interact with the Creature.

In addition to this gradual interaction, students would also benefit from a more coherent Creature “story,” detailing the expected motions and behavior of the Creature. As mentioned previously, students, particularly the younger ones, tended to anthropomorphize the Creature, and would become concerned when it stopped moving, started moving, or did not move for a long period of time. A narrative that incorporated both the Creature mechanisms and expected Creature actions would help alleviate student anxiety about experiment equipment performance, allowing them to focus more on their activity and emotional state. Separate research is ongoing to have the Creature display coherent emotional states: an explanation that the Creature is "sleeping" or "awake" would help children understand what the Creature is capable of doing and what to expect from it during the experiment. At the same time, care must be taken in describing the purpose of the Creature to potential subjects, or the parents of potential subjects. In this experiment there was a general awareness that the Creature was part of a study about anxiety and anxiety-reducing techniques, which may have colored self-reported comments from the students. While, as in a drug trial, describing the purpose of the Creature should not interfere with results, a greater emphasis on terms such as "companion" or "assistant" would reduce the concerns that user reports were influenced by the experiment vocabulary.

While platform participants were concerned about expected Creature behavior, they were also occasionally confused about their own expected behavior. For this experiment students were not instructed to do anything other than pet the Creature during the activity. Several came up with innovative uses of the Creature, including pausing to relax with the Creature between activities, but several seemed confused by the lack of guidance for Creature interaction. Specific behavior instructions, such as pausing to breathe with the Creature or petting the Creature only during certain activities could lead to additional physiological benefit.

The computer activities chosen for this experiment may not give useful information about the efficacy of the Creature in anxiety reduction. Students in general had various reactions to the computer activity. Some maintained a high level of engagement with the screen, devoting their attention to it rather than the Creature. This was evident in some students' body language, where they would make visible or audible gestures of frustration upon getting an answer wrong, or success upon completing a problem. Others were unenthused by their computer activity, and did not seem to care about their score or success rate. It is possible that this level of engagement with the computer activity affected the effect of the Creature on the participant. It is also possible that the physiological effects of the computer activity are not constant, but vary during the course of an activity session. If the computer activities are to be used for further experiments with the Creature, longer-term analysis of the physiological effects of the computer activities must be investigated. It is possible that physiological effects and scores on the activity are correlated: if true, this could be a useful measure of engagement with the task.

The platform hardware could also benefit from from several further refinements. The amount of wires necessary for the sensors necessitates a stationary subject, and therefore precludes long-term engagement with the platform. Improved sensor form-factor, perhaps in the form of wearable clothing, would allow for the use of the TAMER platform in more diverse user environments. Creature hardware could also still be improved by the development of a quieter pulse mechanism, which would allow for use in a classroom. Although the noise was not loud enough to be noticed by the experiment participant when wearing noise canceling headphones, it would be disruptive in a quiet classroom environment.

4.5 Reflections on Results

With the completion of these experiments, the TAMER platform has been iteratively revised and developed into a functional and engaging tool that is attractive and intriguing to children and many adults. It has been shown to have an effect on heart rate and breathing rate metrics. Next steps are to commence longer-term studies of interaction with the platform, to determine both the functionality of the hardware of the system over longer durations as well as working towards developing effective software strategies to accomplish the anxiety reduction goal. These experiments were mostly undirected in that goal; the breathing and heart rate of the Creature were varied in order to determine what effects are provoked in the human user, without attempting more focused interventions. The fact that physiological effects were produced was promising, but even more important was the interaction data gathered that will allow for future effective use of the TAMER platform. It was always the intention to involve therapists and psychologists in the development of the TAMER platform feedback loop, and now that the TAMER platform hardware has stabilized, it may be time to develop interaction scenarios and assessment strategies for therapeutic benefit.

Chapter 5

Conclusions and Recommendations

This thesis presents a research platform and a set of research questions and experimental observations related to the platform's use. This chapter first discusses the research outcomes and a methodological critique of the experiments, followed by the conclusions and recommendation for platform design.

5.1 Experimental Outcomes

The overall research objectives were to determine the reactions to the Haptic Creature, and to determine whether physiological reactions can be provoked or manipulated in the user through the use of the TAMER platform. The experiments revealed several behavioral and physiological outcomes from Creature presence and actions. In particular, participants tended to find the Creature's presence comforting. Although they were not generally able to recognize the Creature mirroring their breathing or pulse, once they were informed of this ability they found it intriguing and comforting. It was a concern that this would be perceived as "creepy" or intrusive, but this was an uncommon response. The mirroring also seemed to give participants, particularly the younger ones, a sense of meaning for the experiment and an understanding of the purpose of the physiological sensors. Participants were able to successfully perform the reverse, matching their breathing to that of the Creature, but this did not have any heart rate effects. Suddenly switching from this user-following mode to Creature mirroring mode without informing them did, on occasion, result in what may be described as a positive feedback loop, which one participant found quite uncomfortable in this experiment.

Participants preferred an active Creature to an inactive Creature: they preferred even a gentle purring to no motion or sound at all. There was high receptiveness to the Creature among children, who generally did not find the Creature distracting during other activities. A summary of some significant physiological effects found during the experiments is below.

During the pilot experiment:

- Disturbing images correlated with changes in mean heart rate, mean heart rate standard deviation, mean heart rate acceleration, mean EMG, mean derivative of skin conductance, mean arousal.

- Creature presence correlated with reduced mean skin conductance, mean derivative of skin conductance, mean arousal.

In Experiment 1:

- Mean heart rate and heart rate variability significantly different between creature constant motion and creature still stages.
- Mean skin conductance and skin temperature higher during creature constant motion and creature mirroring user stages than creature still stage.
- Standard deviation of breath lengths less during Creature motion stage than Creature still stage

In Experiment 2:

- Mean breath length significantly different between entraining, creature with task, and creature without task stages.
- Creature presence correlated with a difference in mean heart rate.
- Standard deviation of breath lengths significantly less during Creature entraining, creature with task, and creature without task stages than baseline.
- Hf % of heart rate variability significantly different between Creature entraining and Creature with task, Creature entraining and Creature without task, and Creature without task and Creature with task stages.

In Experiment 3:

- Computer activity correlated with reduced mean standard deviation of heart rate, heart rate pnn_{50}, and skin conductance.
- Computer activity correlated with increased mean derivative of skin conductance, skin temperature, standard deviation of skin temperature, and heart rate vlf %.
- Creature presence correlated with increase in mean heart rate standard deviation, heart rate vlf %, standard deviation of derivative of skin conductance, skin temperature, and standard deviation of skin temperature as compared to computer activity without Creature.

5.2 Methodological Critique and Recommendations

5.2.1 Platform Presentation

The experimental protocol for the TAMER platform used throughout these experiments proved ineffective in certain areas. In particular, there is a great need for explanation when presenting the Creature and the experiment. As mentioned, most participants were not able to recognize the Creature mirroring their breathing and heart rate without an explanation that this would occur. Even after they had just been equipped with physiological sensors that measure their breathing and heart rate, participants were surprised that a link between them and the Creature could be established. Many participants also did not notice the pulse mechanism in the Creature — it was only able to be felt over a small area of the Creature, and should be identified before use. It is necessary to fully describe the mechanisms of the Creature to the participant before the experiment, they are not likely to recognize the mechanisms on their own. The application of the physiological sensors and interaction with the Creature represents a fairly novel event for most participants, and although the zoomorphic nature of the Creature may imply that it contains certain expressive mechanisms, these are not always evident upon initial investigation.

It is also important that the Creature's mechanisms be activated during this introduction, and that the Creature operate at a breathing and pulse rate appropriate for the experiment, in order to set a proper expectation for the behavior of the Creature. The actual breathing and pulse rate of animals the Haptic Creature's size is different than that of a human, and the awareness of this fact in participants will also vary. The Creature's normal physiological activity level must be established as similar to that of a human.

The timing of this introduction is also important. Consent forms, questionnaires, and physiological sensors should be administered and attached before the participant is able to see the Creature. Participants, in particular children, often wanted to interact with the Creature upon seeing it for the first time, and expressed a desire to hold it and pet it. It was then necessary to temper their enthusiasm in order to attach the physiological sensors, and in the case of several students it was particularly difficult to take away their attention from the Creature in order to setup the experiment. However, there is also the possibility that participants having seen the Creature during this and prior experiments before undergoing their baseline assessment may have inadvertently reduced the effects on the experimental results of any sort of "novelty effect" caused by exposure to the Creature, as it would now also influence their physiological baselines. Most participants also found initial Creature motion new and interesting, but the actions of the Creature mechanisms were simple enough that transitions between Creature activity states during the experiments were not likely to induce a significant effect, and indeed the transitions were not often recognized by the participants. Participants, particularly children, were typically excited to interact with the Creature, and this enthusiasm lasted through their experimental sessions. A clinical introduction to the Creature should leverage this initial appeal to help develop a long-term working relationship with the TAMER platform. Although in actual operation the Creature's motion is quite subtle and non-intrusive, allowing for users to focus on other tasks, a more sophisticated model of emotions for the Creature could help improve a user's attachment to the Creature. The increased amount of time required to discover all of the Creature's eventual operating behaviors should guarantee adequate observation time for the child's psychologist to observe his or her interactions with the Creature and train his or her behaviors.

5.2.2 Platform Interaction

A Coherent Story

In experiments with children, and possibly in experiments with adults, there is also the need for a coherent "story" to explain Creature activity and motions during an experiment. Children, especially, were surprisingly aware of the behavior of the Creature during the experiment. If the Creature had not moved after a long time period, or stopped moving after being active, they would often express worry or be upset that the Creature was broken, or that something in the experiment was not working. An explanation of the Creature's behavior implying that the Creature may be asleep sometimes, awake other times, and curious or happy for part of the experiment would help to relieve participant anxiety about Creature functionality, and provide an expectation for Creature behavior. Care should be taken, however, to ensure that a story of the Creature does not impose a specific species, with possible confounding associated behavior expectations, onto the Creature. Informal surveys revealed descriptions of the Creature as variously a cat, rabbit, mouse, pig, guinea pig, or simply a "furry thing," with no one answer predominating. Avoiding identifying the Creature as a specific species, although presenting creative challenges in developing a story, helps to avoid possible negative reactions to the Creature due to a user's previous interactions with the chosen species. In particular, this greatly simplifies the introduction of the Creature to children, as a detailed investigation of a user's past interactions with animals is not necessary before presenting the Creature to them.

A behavior model for another version of the Haptic Creature has been developed that links various Creature mechanism activity levels to Creature emotional states, as interpreted by users. Integrating this model into the TAMER platform could allow for more advanced interaction during experiments. At the very least, a comparison between the Creature's typical activity rates when mirroring a human and the emotional states ascribed to the Creature running at those rates could prove informative.

Such a behavior model should also be incorporated into the next stage of TAMER platform experiments, that of longer-term engagement with the system. Creature behavior during these experiments was extremely simple, it acted as essentially a physiological metronome on the lap of the subject, occasionally changing tempo but only gradually. While short-term results with this method were promising, the eventual usage targeted for the TAMER platform is longer-term anxiety reduction. Although the physiological results from the experiments presented here were promising, these may not occur in a long-term experiment, and may require more sophisticated Creature behaviors to maintain engagement. Longer-term experiments, particularly with a broader subject pool, may also reveal personality or background characteristics that would tend to make certain users particularly more or less receptive to engagement with the Creature. No such trends were observed in these studies.

Additional experiments, such as comparing the effects of the Creature to a child's companion stuffed animal, could also provide valuable feedback as to the effectiveness of the TAMER platform compared to typical therapy methods.

Interaction Models

In order to enable longer duration experiments, as well as to improve the shorter experiments, there is a need for more focused and directed interaction with Creature. Except when asked to follow the Creature's breathing, participants were not given any instructions on how to interact with the Creature. Often participants, particular adult participants, seemed uncertain of how to behave with the Creature. Child participants were aware that the Creature was related to a study on anxiety, and therefore might help to calm them down, but were not aware of how this would actually occur. More detailed instructions to participants about the desired effects of the Creature, and what actions they could take to help achieve them, might help the participants achieve greater success in accomplishing these goals.

Observations of interaction with the Creature during the experiment suggest three potential interaction models to be experimentally investigated. The first is Creature guided interaction, where the Creature is used to lead the participant through a series of breathing exercises. Experimental data showed that participants could easily follow the Creature's breathing with their own: this could be of potential use in anxiety inducing situations. Many relaxation techniques involve deep breathing exercises, and the Creature could provide calming and engaging guidance in this task. A short break to breath slowly and deeply with the Creature either before, after, or in the middle of an anxiety-provoking task might be able to produce calming effects in the participant, and allow them to access their previously taught strategies for coping with stress more easily.

The second is Creature mirroring of users to improve awareness of their own physiological state. Participants generally reported a low awareness of their own heart rate. Using the Creature to improve the user's self awareness could help in training them to recognize increased levels of stress or an impending anxiety attack. By having knowledge of their own typical and stressed body states, users could again intervene with situation appropriate coping skills.

The third interaction model is that of intervention. Once the TAMER platform is capable of recognizing either anxious states or the precursors to anxiety, the Creature could become active only when the user is approaching an anxiety attack. Instead of running all the time mirroring the user, the Creature would activate only when necessary, alerting the user to their anxious state. Once active, the Creature could then attempt to calm down the user. A simple slow, steady breathing rhythm similar to that used in the present experiment might prove sufficient in reducing anxiety, but more sophisticated behaviors are possible. For example, the Creature itself could present an anxious state, either by mirroring the user or acting independently. The user could then be trained to reduce the Creature's level of anxiety by breathing slowly or performing other therapeutic techniques, and the Creature's activity level could gradually decrease in response to changes in physiological metrics. These behaviors should be investigated as allowing for longer-term use of the Creature and TAMER platform in anxiety reduction.

5.3 Platform Design

5.3.1 Outcomes

Overall, the individual components of the TAMER platform were integrated to produce an effective and reliable system. However, there are several improvements that could be made to improve overall functionality.

Creature

The Haptic Creature was shown to be an effective device for displaying affect through breathing and heart rate mechanisms, while being comfortable for and engaging with its users. Participants reported high levels of comfort with the Creature: they were receptive to it being placed on their laps and moving around, and found its fur to be soft and pleasing to the touch. In particular, participants responded positively to the warmth of the Creature and its life-like attributes. They desired that it gently purr even when still, as opposed to just sitting as a dead-weight on their lap. The Creature's breathing mechanism was successfully able to portray breathing, it was recognized as such by users. The Creature's pulse mechanism was particularly noisy, but it did successfully generate a pulse sensation in a narrow area of the Creature.

Sensors

Participants, both the adults and mildly-anxious children, were surprisingly receptive to wearing the physiological sensors, and generally did not find them distracting or uncomfortable during experiments. Several minor problems were associated with sensor functionality during experiments. The EKG sensor, when mounted to the chest with a single triode electrode, instead of three separate electrodes, would occasionally become detached during experiments, leading to loss of signal. The blood volume pulse sensor, and indeed all the sensors attached to the fingers, could occasionally become detached during the experiment. Participants were typically hesitant to touch anything with the hand attached to the sensors, and had to be instructed that it was acceptable to pet the Creature with that hand. Once told, they did not seem encumbered by the sensors. Had the participants attempted to move around during the experiment, however, they would have found their motion constrained by the sensors. The numerous wires required for the sensors were continually getting tangled, and there was a concern that a sudden large motion by a participant, such as a nervous child desiring to leave the room, could cause damage to the equipment. This scenario did not occur during experiments, however.

5.3.2 Recommendations

There are several changes recommended for the hardware and software of the TAMER platform. The Creature, although functional, requires several modifications that would allow for more effective-longer term experiments, and help to move the Creature from a laboratory environment to a less clinical setting, such as a school or a home. In particular, the noise of the pulse mechanism was moderately audible, and would be noticeable in the quiet of a classroom. A pulse mechanism that created a motion able to be felt over a larger area of the Creature could make the pulse mechanism more effectively able to convey the pulse sensation. Creature noise must be assessed to reduce it to a level that would not bother other students in a quiet room. The gentle vibration that participants preferred to the Creature being completely inactive did have an audio component; the use of the purring mechanism instead of the breathing mechanism linkage to create this sensation should be investigated. In addition, consideration should be made towards eliminating as many wires to the Creature as possible. Presently, with the radio system in use, the power cable is the only wire that must be attached to the Creature. Provisions exist on the electronics board for an internal battery pack to be mounted; the use of this should be investigated. The need for an external power supply not only restricts the usage of the Creature, but there is also the risk that the cable could become inadvertently disconnected during use, disabling the Creature prematurely.

The software for reading the physiological sensors and controlling the Creature was adequate for the experiment. However, to support both this platform and other experiments with the physiological sensors, the integration of additional timing and observational inputs, such as video feeds and push-button controls, should be developed. Linking the physiological data to exact moments in the experiment, or indeed to exact times in general is often difficult. A more advanced sensor suite incorporating video and physiological data, as well as a better system for marking notable occurrences during an experiment, would greatly simplify data analysis, and potentially allow for more subtle results to be uncovered. In addition, the physiological data gathered should be used at a higher level than simply mean values. Medical interpretation of the physiological data gathered by the platform, or the use of an inference engine or machine learning techniques to estimate clinical assessments of anxiety, such as the Multidimensional Anxiety Scale for Children [113], based on training data provided by psychologists, could provide more reliable estimations of the effect the platform has on anxiety levels. Better online estimation of anxiety levels could allow for a more effective platform, as the specific Creature activities could be associated with their effects on anxiety and then used appropriately in a therapy regimen. A physiological sensing system with both the form factor and capability to support longer-term observations could also allow for the identification of chronic anxiety with the physiological sensors. This along with medical observations would aid the determination of any effects of the TAMER platform on longer-term, chronic anxiety.

Sensor form factor is one of the limiting factors of this platform. The present sensors are somewhat intrusive, and require both a large amount of time to set up and many wires to be connected to the participant. Reducing the amount of wires necessary to be attached to the participant, or, ideally, eliminating wires all together, would both improve participant experience and allow the sensors to be used on mobile participants in an actual classroom environment. Combining several sensors into a single form factor, such as a piece of clothing or a glove, could also help participants who were reticent about having the sensors attached to feel more comfortable. Additionally, several of the sensors, particularly heart rate and heart rate variability, can generate useful data over observation periods of several hours or even days, that may be useful in anxiety reduction. Integration of these long-term wearable sensors into the platform could produce improved results and more useful data.

Better integration of the sensor data into the experiment procedure might also lead to interesting avenues of investigation and applications for the platform. Several children were interested in viewing their physiological data on the computer, and wanted to know more about the sensor readings. The children who participated in the computer activity were score and goal focused, due to typically having their performance assessed during these activities. Cataloging physiological measures related to anxiety and then displaying them to the user has been shown to be of benefit for adults. Feedback to users of both long-term and short-term physiological data as both a visual and a haptic (Creature) display could assist them in recognizing anxiety inducing behaviors and therefore eliminating them. Even at this young age, these children are already quite familiar with improving score-based performance.

Overall TAMER platform functionality was sufficient for the experiment, but these changes recommended should improve platform performance.

5.4 Conclusion

This thesis has described the construction of the TAMER platform and the initial testing and experimental verification of the same. The Haptic Creature constructed as part of the TAMER platform distinguishes itself from other robotic companions by recreating physiological activities through a solely haptic presentation method, and is, uniquely, capable of reacting to a user's sensed physiological state or displaying a user's state with its own mechanisms. This link establishes an advancement in biofeedback technology, as it should be easier, especially for children, to relate to a robot than to a pulse or heart rate monitor. Physiological interaction with robots is advanced: the TAMER platform demonstrates real-time reaction to a user's physiological state and real-time interaction with the potential to guide the user's physiological state in a controlled feedback loop. Further, the TAMER platform has been demonstrated in a school environment. Results from the experiments in this thesis support the potential of the TAMER platform to be used in anxiety management therapy. Users of the Haptic Creature, in particular children, reported a strong desire to interact with and work with the Creature; they also found it comforting and calming during tasks. Users were able to follow the Haptic Creature in a breathing related experiment. Physiological effects from the Creature were also found in users interacting with the creature — a first step towards fully controlled manipulation of user physiological state.

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Appendix A

Derivations

A.1 Creature Physiological Mirroring Derivations

The following variables are used throughout these derivations:

y Commanded Creature breathing servo amplitude (roughly how high the abdomen appears) [0,1]

r User average respiration rate [breaths per second]

t time [seconds]

l User average breath length [seconds]

p User averaged heart rate [bps]

i Commanded Creature interbeat interval (time between heart beats) [seconds]

A.1.1 Derivation of Ramped Breathing Motion Commands

A sinusoidal wave increasing frequency at rate k:

$$y = \cos(2\pi t(f_0 + \frac{k}{2}t)) \tag{A.1}$$

General

From t_0 to t_1:

$$k = \frac{r_2 - r_0}{t_1 - t_0} \Rightarrow y_1 \quad = \quad -\cos\left(2\pi(t - t_0)\left(\frac{(r_2 - r_0)(t - t_0)}{2(t_1 - t_0)} + r_0\right)\right) \tag{A.2}$$

$$\boxed{y_1 = -\cos\left(2\pi(t - t_0)\left(\frac{(r_2 - r_0)(t - t_0)}{2(t_1 - t_0)} + r_0\right)\right)} \tag{A.3}$$

and:

$$y_1(t = t_1) = -\cos\left(2\pi(t_1 - t_0)\left(\frac{(r_2 - r_0)(t_1 - t_0)}{2(t_1 - t_0)} + r_0\right)\right) \tag{A.4}$$

From t_1 to t_2:

$$\begin{aligned}
y_2 &= -\cos(2\pi r_2 t + \beta) && \text{(A.5)}\\
y_2(t = t_1) &= y_1(t = t_1) && \text{(A.6)}\\
-\cos(2\pi r_2 t + \beta) &= -\cos\left(2\pi(t_1 - t_0)\left(\frac{(r_2 - r_0)(t_1 - t_0)}{2(t_1 - t_0)} + r_0\right)\right) && \text{(A.7)}\\
2\pi r_2 t_1 + \beta &= 2\pi(t_1 - t_0)\left(\frac{(r_2 - r_0)(t_1 - t_0)}{2(t_1 - t_0)} + r_0\right) && \text{(A.8)}\\
\beta &= 2\pi(t_1 - t_0)\left(\frac{(r_2 - r_0)(t_1 - t_0)}{2(t_1 - t_0)} + r_0\right) - 2\pi r_2 t_1 && \text{(A.9)}
\end{aligned}$$

$$\boxed{y_2 = -\cos(2\pi r_2 t + \beta) \text{ where } \beta = 2\pi(t_1 - t_0)\left(\frac{(r_2 - r_0)(t_1 - t_0)}{2(t_1 - t_0)} + r_0\right) - 2\pi r_2 t_1} \tag{A.10}$$

and:

$$y_2(t = t_2) = -\cos(2\pi r_2 t_2 + \beta) \tag{A.11}$$

From t_2 to t_3:

$$k = \frac{r_4 - r_2}{t_3 - t_2} \Rightarrow y_3 = -\cos\left(2\pi(t - t_2)\left(\frac{(r_4 - r_2)(t - t_2)}{2(t_3 - t_2)} + r_0\right)\right) + \gamma) \tag{A.12}$$

$$\begin{aligned}
y_2(t = t_2) &= y_3(t = t_2) && \text{(A.13)}\\
-\cos(2\pi r_2 t_2 + \beta) &= -\cos\left(2\pi(t_2 - t_2)\left(\frac{(r_4 - r_2)(t_2 - t_2)}{2(t_3 - t_2)} + r_0\right)\right) + \gamma) && \text{(A.14)}\\
\gamma &= 2\pi r_2 t_2 + \beta && \text{(A.15)}\\
y_3 &= -\cos\left(2\pi(t - t_2)\left(\frac{(r_4 - r_2)(t - t_2)}{2(t_3 - t_2)} + r_0\right)\right) + \gamma) && \text{(A.16)}\\
& && \text{(A.17)}
\end{aligned}$$

$$\boxed{\begin{aligned} y_3 = -\cos\left(2\pi(t - t_2)\left(\tfrac{(r_4 - r_2)(t - t_2)}{2(t_3 - t_2)} + r_0\right)\right) + \gamma) \text{ where } \gamma &= 2\pi r_2 t_2 + \beta \\ \beta &= 2\pi(t_1 - t_0)\left(\tfrac{(r_2 - r_0)(t_1 - t_0)}{2(t_1 - t_0)} + r_0\right) - 2\pi r_2 t_1 \end{aligned}} \tag{A.18}$$

and:

$$y_3(t = t_3) = -\cos\left(2\pi(t_3 - t_2)\left(\frac{(r_4 - r_2)(t_3 - t_2)}{2(t_3 - t_2)} + r_0\right)\right) + \gamma) \tag{A.19}$$

From t_3 to t_4:

$$\begin{aligned}
y_4 &= -\cos(2\pi r_4 t + \delta) && \text{(A.20)}\\
y_4(t = t_3) &= y_3(t = t_3) && \text{(A.21)}\\
-\cos(2\pi r_4 t_3 + \delta) &= -\cos\left(2\pi(t - t_2)\left(\frac{(r_4 - r_2)(t - t_2)}{2(t_3 - t_2)} + r_0\right)\right) + \gamma) && \text{(A.22)}\\
2\pi r_2 t_3 + \delta &= 2\pi(t_3 - t_2)\left(\frac{(r_4 - r_2)(t_3 - t_2)}{2(t_3 - t_2)} + r_0\right) + \gamma && \text{(A.23)}\\
\delta &= 2\pi(t_3 - t_2)\left(\frac{(r_4 - r_2)(t_3 - t_2)}{2(t_3 - t_2)} + r_0\right) + \gamma && \text{(A.24)}
\end{aligned}$$

$$\boxed{\begin{aligned} y_4 = -\cos(2\pi r_4 t + \delta) \text{ where } \delta &= 2\pi(t_3 - t_2)\left(\tfrac{(r_4 - r_2)(t_3 - t_2)}{2(t_3 - t_2)} + r_0\right) + \gamma \\ \gamma &= 2\pi r_2 t_2 + \beta \\ \beta &= 2\pi(t_1 - t_0)\left(\tfrac{(r_2 - r_0)(t_1 - t_0)}{2(t_1 - t_0)} + r_0\right) - 2\pi r_2 t_1 \end{aligned}} \quad \text{(A.25)}$$

Examples

Where $r_2 = 1.2r_0$; $r_4 = 0.8r_0$; $t_0 = 30$; $t_1 = 90$; $t_2 = 150$; $t_3 = 210$:

$$y(t) = \begin{cases} -\cos(2\pi(t - 30)(r_0 + \frac{1}{600}r_0(t - 30))) & t < 30 \\ -\cos(\frac{12}{5}\pi r_0 t - 84\pi r_0) & 30 \leq t < 90 \\ -\cos(2\pi(t - 150)(r_0 - \frac{1}{300}r_0(t - 150))) & 90 \leq t < 150 \\ -\cos(\frac{8}{5}\pi r_0 t + 372\pi r_0) & 150 \leq t < 210 \end{cases} \quad \text{(A.26)}$$

Where $r_2 = 1.2r_0$; $r_4 = 0.8r_0$; $t_0 = 60$; $t_1 = 180$; $t_2 = 300$; $t_3 = 420$:

$$y(t) = \begin{cases} -\cos(2\pi(t - 60)(r_0 + \frac{1}{1200}r_0(t - 60))) & t < 60 \\ -\cos(\frac{12}{5}\pi r_0 t - 168\pi r_0) & 60 \leq t < 180 \\ -\cos(2\pi(t - 300)(r_0 - \frac{1}{600}r_0(t - 300))) & 180 \leq t < 300 \\ -\cos(\frac{8}{5}\pi r_0 t + 744\pi r_0) & 300 \leq t < 420 \end{cases} \quad \text{(A.27)}$$

A.1.2 Derivation of Ramped Pulse Rate

General

From t_0 to t_1:

$$i_1 = \frac{60}{p_0 + \frac{p_2}{t_1 - t_0}t}; \quad \text{(A.28)}$$

From t_1 to t_2:

$$i_2 = \frac{60}{p_2} \quad \text{(A.29)}$$

From t_2 to t_3:

$$i_3 = \frac{60}{p_2 + \frac{p_4}{t_3 - t_2} t}; \tag{A.30}$$

From t_3 to t_4:

$$i_4 = \frac{60}{p_4} \tag{A.31}$$

Examples

Where $p_2 = 1.2p_0$; $p_4 = 0.8p_0$; $t_1 = 30$; $t_2 = 90$; $t_3 = 150$; $t_4 = 210$:

$$i(t) = \begin{cases} \frac{60}{1.2p_0 + \frac{p_0}{30t}} & t < 30 \\ \frac{50}{p_0} & 30 \leq t < 90 \\ \frac{60}{0.8p_0 + \frac{1.2p_0}{60t}} & 90 \leq t < 150 \\ \frac{75}{p_0} & 150 \leq t < 210 \end{cases} \tag{A.32}$$

Where $p_2 = 1.2p_0$; $p_4 = 0.8p_0$; $t_1 = 60$; $t_2 = 180$; $t_3 = 300$; $t_4 = 420$:

$$i(t) = \begin{cases} \frac{60}{1.2p_0 + \frac{p_0}{30t}} & t < 60 \\ \frac{50}{p_0} & 60 \leq t < 180 \\ \frac{60}{0.8p_0 + \frac{1.2p_0}{120t}} & 180 \leq t < 300 \\ \frac{75}{p_0} & 300 \leq t < 420 \end{cases} \tag{A.33}$$

A.1.3 Derivation of Ramped Breathing Motion Commands [Simplified Motion]

General

From t_1 to t_2:

$$\boxed{y_A = -\cos(2\pi r_A t)} \tag{A.34}$$

and:

$$y_A(t = t_2) = -\cos(2\pi r_A t_2) \tag{A.35}$$

From t_2 to t_3:

$$k = \frac{r_c - r_a}{t_3 - t_2} \Rightarrow y_B = -\cos\left(2\pi(t - t_2)\left(\frac{(r_A - r_C)(t - t_2)}{2(t_2 - t_3)} + r_A\right) + \beta\right) \tag{A.36}$$

$$\begin{aligned} y_B(t = t_2) &= y_A(t = t_2) && \text{(A.37)} \\ -\cos(\beta) &= -\cos(2\pi r_A t_2) && \text{(A.38)} \\ \beta &= 2\pi r_A t_2 && \text{(A.39)} \\ & && \text{(A.40)} \end{aligned}$$

$$\boxed{y_B = -\cos\left(2\pi(t - t_2)\left(\frac{(r_A - r_C)(t - t_2)}{2(t_2 - t_3)} + r_A\right) + 2\pi r_A t_2\right)} \tag{A.41}$$

and:

$$y_B(t = t_3) = 4\pi(t_3 - t_2)(r_A + r_C) + 2\pi r_A t_2 \tag{A.42}$$

From t_3 to t_4:

$$y_C = -\cos(2\pi r_C t + \gamma) \tag{A.43}$$

$$\gamma = y_B(t = t_3) = 4\pi(t_3 - t_2)(r_A + r_C) + 2\pi r_A t_2 \tag{A.44}$$

$$\boxed{y_C = -\cos(2\pi r_C t + 4\pi(t_3 - t_2)(r_A + r_C) + 2\pi r_A t_2)} \tag{A.45}$$

Experiment 3

In Experiment 3, where $r_A = 1.2r_0$; $r_C = 0.8r_0$; $t_1 = 0$; $t_2 = 240$; $t_3 = 350$:

$$y(t) = \begin{cases} y_A = \cos(2.4\pi r_0 t) & t < 240 \\ y_B = \cos(2\pi(t - 240)(\frac{6}{5}r_0 - \frac{1}{550}r_0(t - 240)) + 576\pi r_0) & 240 \le t < 350 \\ y_C = \cos(1456\pi r_0 + \frac{8}{5}\pi r_0 t) & 350 \le t < 590 \end{cases} \tag{A.46}$$

In Experiment 3, where $r_A = 0.8r_0$; $r_C = 1.2r_0$; $t_1 = 0$; $t_2 = 240$; $t_3 = 350$:

$$y(t) = \begin{cases} y_A = \cos(1.6\pi r_0 t) & t < 240 \\ y_B = \cos(2\pi(t - 240)(\frac{4}{5}r_0 - \frac{1}{550}r_0(t - 240)) + 384\pi r_0) & 240 \le t < 350 \\ y_C = \cos(1264\pi r_0 + \frac{12}{5}\pi r_0 t) & 350 \le t < 590 \end{cases} \tag{A.47}$$

A.1.4 Derivation of Ramped Pulse Rate [Simplified Motion]

General

From t_1 to t_2:

$$i_A = \frac{60}{p_A}; \tag{A.48}$$

From t_2 to t_3:

$$i_B = \frac{60}{p_A + \frac{p_C}{t_3 - t_2} t}; \tag{A.49}$$

From t_3 to t_4:

$$i_C = \frac{60}{p_C}; \tag{A.50}$$

Experiment 3

In Experiment 3, where $p_A = 1.2p_0$; $p_C = 0.8p_0$; $t_1 = 0$; $t_2 = 240$; $t_3 = 350$:

$$i(t) = \begin{cases} \frac{50}{p_0} & t < 240 \\ \frac{60}{1.2p_0 - \frac{0.4p_0}{90t}} & 240 \leq t < 350 \\ \frac{75}{p_0} & 350 \leq t < 590 \end{cases} \tag{A.51}$$

In Experiment 3, where $p_A = 0.8r_0$; $p_C = 1.2r_0$; $t_1 = 0$; $t_2 = 240$; $t_3 = 350$:

$$i(t) = \begin{cases} \frac{75}{p_0} & t < 240 \\ \frac{60}{0.8p_0 + \frac{0.4p_0}{90t}} & 240 \leq t < 350 \\ \frac{50}{p_0} & 350 \leq t < 590 \end{cases} \tag{A.52}$$

A.2 Physiological Sensor Data Analysis Methods

During experiments, the following physiological measures were typically calculated.

- mean heart rate
- heart rate standard deviation
- heart rate skewness
- heart rate rms standard deviation
- heart rate variability:
  - pnn50
  - vlf%
  - lf%
  - mf%

  - hf%

- skin conductance
- skin conductance derivative
- electromyogram
- electromyogram derivative
- skin temperature
- skin temperature standard deviation
- respiration rate
- respiration rate standard deviation
- respiration amplitude,
- respiration amplitude standard deviation

For an experiment with n physiological measures m calculated, t stages p, o subjects s, for each physiological measure the physiological measure for each subject for each stage ν was calculated. For pool-, or group-wise comparisons, two-tailed dependent sample t-tests with α of 0.05 were performed between the columns of ν.

$$m_n = \begin{bmatrix} & p_1 & \cdots & p_t \\ s_1 & \nu_{1,1} & & \\ \vdots & & \ddots & \\ s_o & & & \nu_{o,t} \end{bmatrix}$$

From these comparisons it was possible to state whether the condition difference between stages had an effect on that physiological measure.

Participant's heart rate interbeat intervals (ibi) and breath lengths were a series variable, there were numerous samples for each participant for each stage for each experiment. for these two variables only, two-tailed independent sample t-tests were used within subjects to determine for each participant if the series of ibis or breath lengths were different between stages. Between subjects comparisons were not performed. From these comparisons it was possible to state whether a participant's ibi or breath lengths were different between stages.

In response to the examination committee, a Bonferroni comparison does not seem appropriate for this situation. These results are also clearly labeled as exploratory, and comparisons made here are single analyses on separate sensor channels for the users.

There are no statistical analyses that I am aware of that can be performed on the qualitative survey results to produce significant results. A graph of the survey results is therefore included where these are discussed in the text.

Appendix B

Experiment Documents

This chapter contains the experiment data not included in the main body. For each experiment a pre-experiment questionnaire, post-experiment questionnaire, sample data, sample comparisons, and participant consent form are included. As explained in each experiment's "Experiment Procedure" section, there was no pre-experiment questionnaire for Experiments 1, 2, and 3; and no post-experiment questionnaire for Experiment 3. The following is a list of what is included in this section:

- Preliminary Experiment
  - Pre-Experiment Questionnaire
  - Post-Experiment Questionnaire
  - Sample Data
  - Sample Comparisons
  - Participant Consent Form
- Experiment 1
  - Post-Experiment Questionnaire
  - Data Tables
  - Sample Data
  - Sample Comparisons
  - Participant Consent Form
- Experiment 2

  - Post-Experiment Questionnaire
  - Data Tables
  - Sample Data
  - Sample Comparisons
  - Participant Consent Form

- Experiment 3
  - Sample Data
  - Sample Comparisons
  - Participant Consent Form
  - Participant Assent Form

A table of contents is also located in the Table of Contents.

B.1 Preliminary Experiment

B.1.1 Pre-Experiment Questionnaire

Participant Questionnaire for Haptics and Anxiety Study

1. Age:

   ☐ 18-22

   ☐ 23-26

   ☐ 27-30

   ☐ 30+

2. Gender:

   ☐ Male

   ☐ Female

3. Profession or Program of Study:

---

4. Do/Did you have pets or do you regularly interact with pets. If so, what kind of pets?

---

5. In general do you enjoy the company of animals? If so, what kind of animals (if different from above)?

---

6. Do you often interact with young children or babies?

   ☐ Yes

   ☐ No

7. If yes, list a few of your most pleasurable interactions *(e.g., carrying the child, tucking them into bed...)*:

---

8. Did you have stuffed toys when you were a child?

   ☐ Yes

   ☐ No

9. Do you currently interact *(e.g., play, cuddle, sleep with, etc...)* with a stuffed toy?

   ☐ Yes

   ☐ No

10. Please rate your comfort with the following 'physical touch' situations:

Being hugged by a loved-one:

(not comfortable)	1	2	3	4	5	*(very comfortable)*

Being hugged by a new acquaintance:

(not comfortable)	1	2	3	4	5	*(very comfortable)*

Shaking hands with a colleague:

(not comfortable)	1	2	3	4	5	*(very comfortable)*

Shaking hands with a stranger:

(not comfortable)	1	2	3	4	5	*(very comfortable)*

Patting a family member's back:

(not comfortable)	1	2	3	4	5	*(very comfortable)*

Patting a friend's back:

(not comfortable)	1	2	3	4	5	*(very comfortable)*

Are there other situations that you would like to mention?

B.1.2 Post-Experiment Questionnaire

Post-Experiment Questionnaire for Haptics and Anxiety Study

1. Please answer the following questions on the given scales.

Please rate your emotional state while watching the first set of images:

(Anxious)	1	2	3	4	5	*(Relaxed)*
(Agitated)	1	2	3	4	5	*(Calm)*
(Quiescent	1	2	3	4	5	*(Surprised)*

Please rate your emotional state while watching the second set of images:

(Anxious)	1	2	3	4	5	*(Relaxed)*
(Agitated)	1	2	3	4	5	*(Calm)*
(Quiescent	1	2	3	4	5	*(Surprised)*

I found the haptic device comforting while watching the images:

(Strongly Disagree) 1 2 3 4 5 *(Strongly Agree)*

I found the actions of the haptic creature to be a distraction while watching the images:

(Strongly Disagree) 1 2 3 4 5 *(Strongly Agree)*

I feel that the haptic creature would be useful in reducing my anxiety in other situations:

(Strongly Disagree) 1 2 3 4 5 *(Strongly Agree)*

2. Please comment on your reaction to the haptic creature:

____

____

____

Definitions:

anxious: troubled or uneasy in mind.

relaxed: at ease, free from constraint or tension.

agitated: excited, disturbed in mind.

calm: quiet, still, tranquil, serene.

quiescent: being at rest; quiet; still; inactive or motionless.

surprise: to come upon or discover suddenly and unexpectedly.

B.1.3 Sample Data

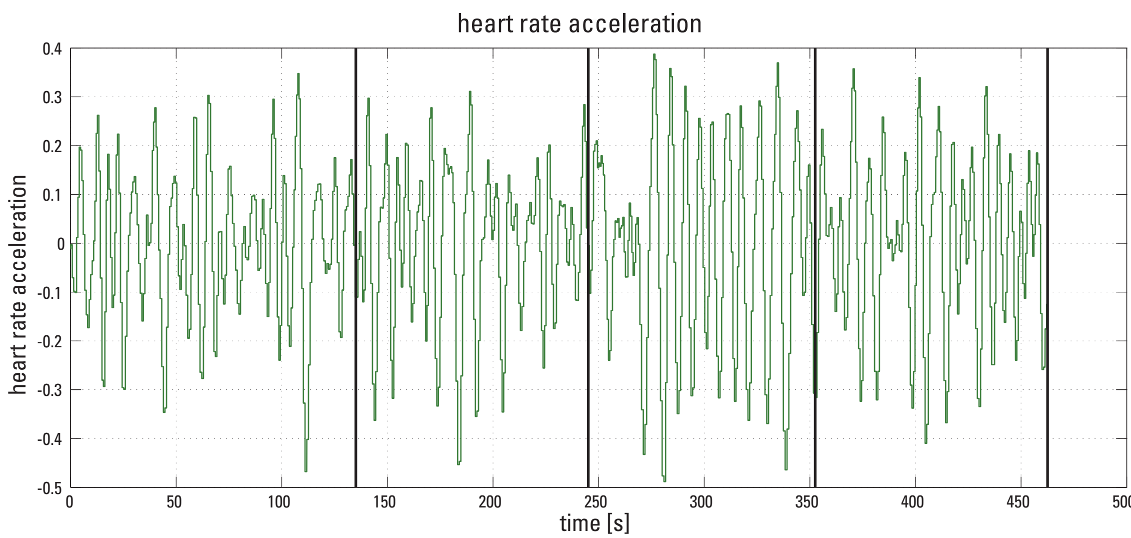

Figure B.1: Heart rate acceleration for a participant during the Pilot Experiment. Black lines delineate experiment stages.

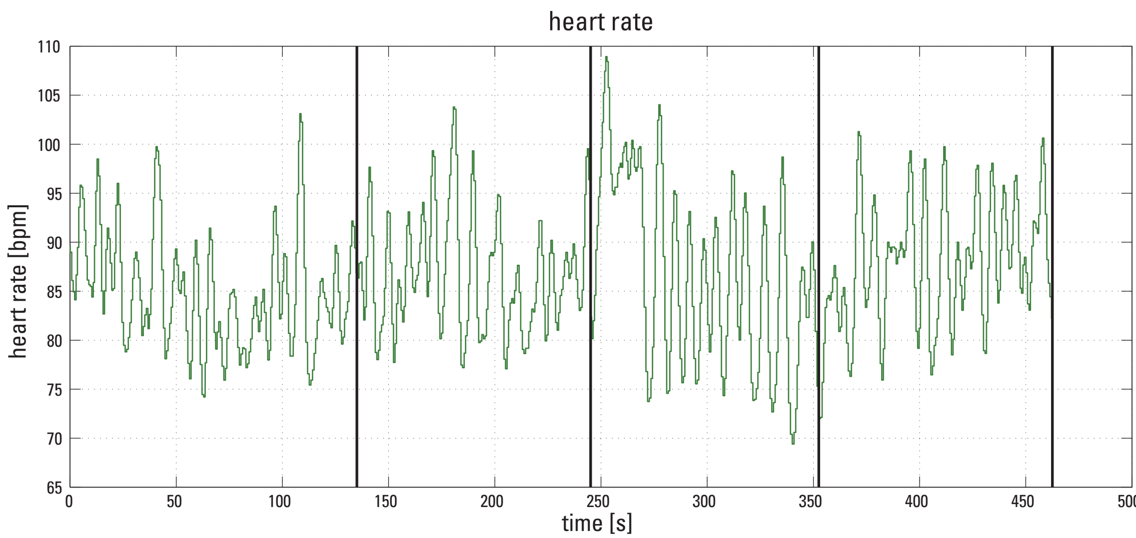

Figure B.2: Heart rate for a participant during the Pilot Experiment. Black lines delineate experiment stages.

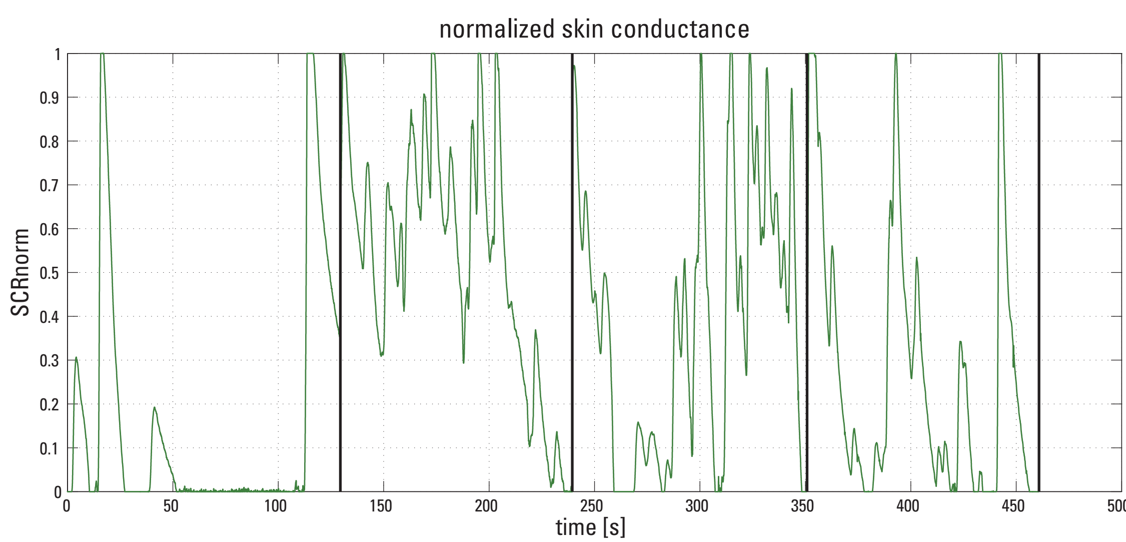

Figure B.3: Normalized skin conductance for a participant during the Pilot Experiment. Black lines delineate experiment stages.

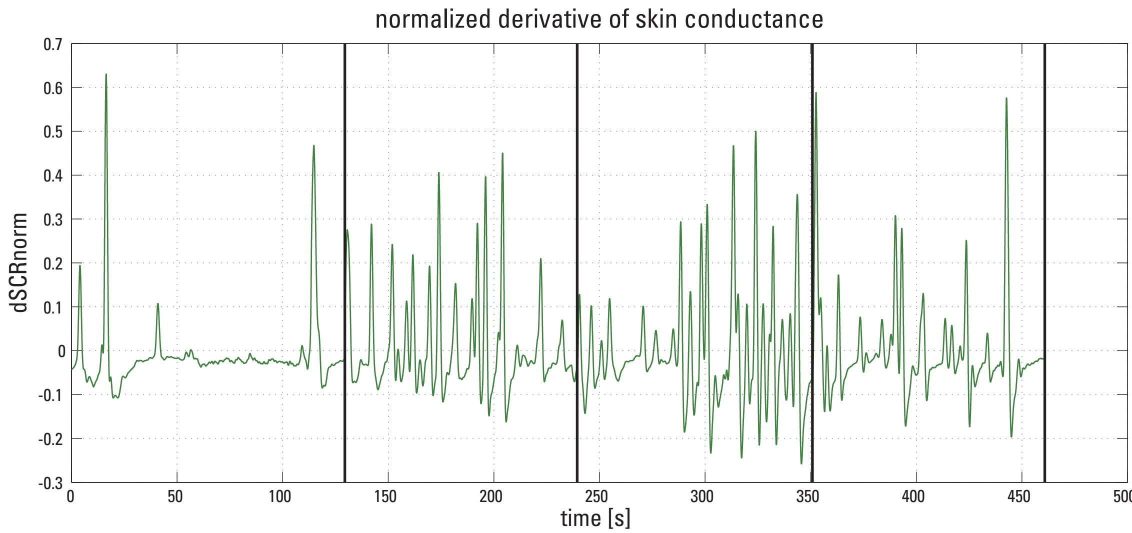

Figure B.4: Skin conductance derivative for a participant during the Pilot Experiment. Black lines delineate experiment stages.

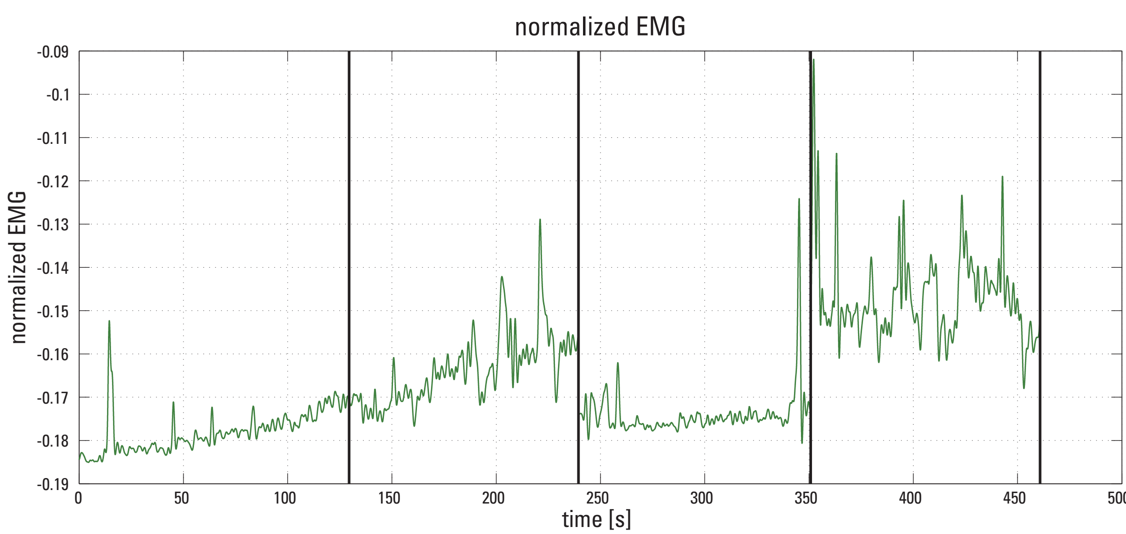

Figure B.5: Normalized EMG for a participant during the Pilot Experiment. Black lines delineate experiment stages.

B.1.4 Sample Comparisons

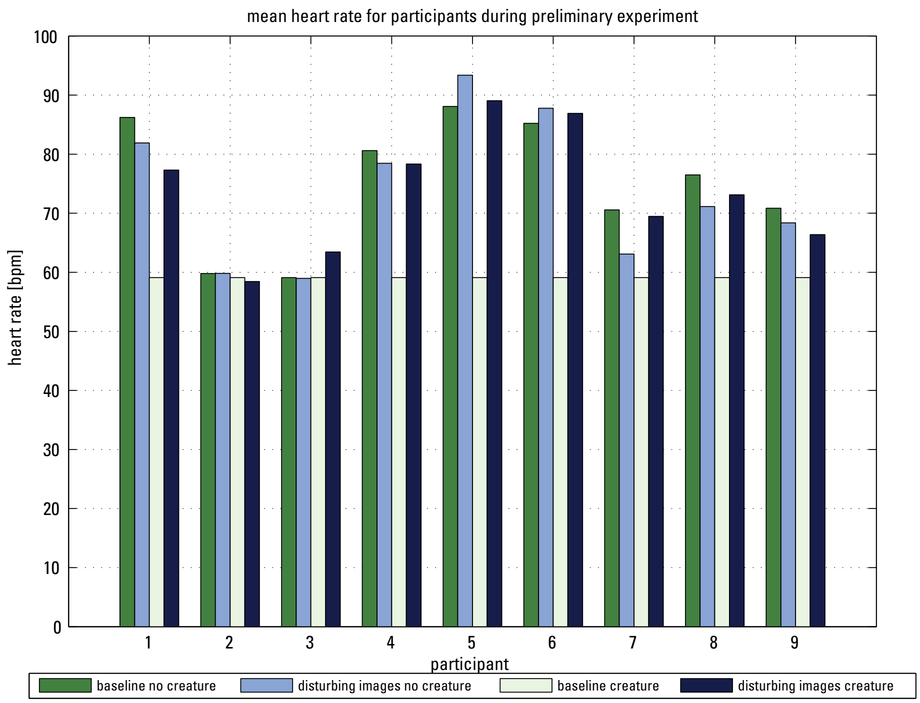

Figure B.6: Mean heart rate for participants during Pilot Experiment.

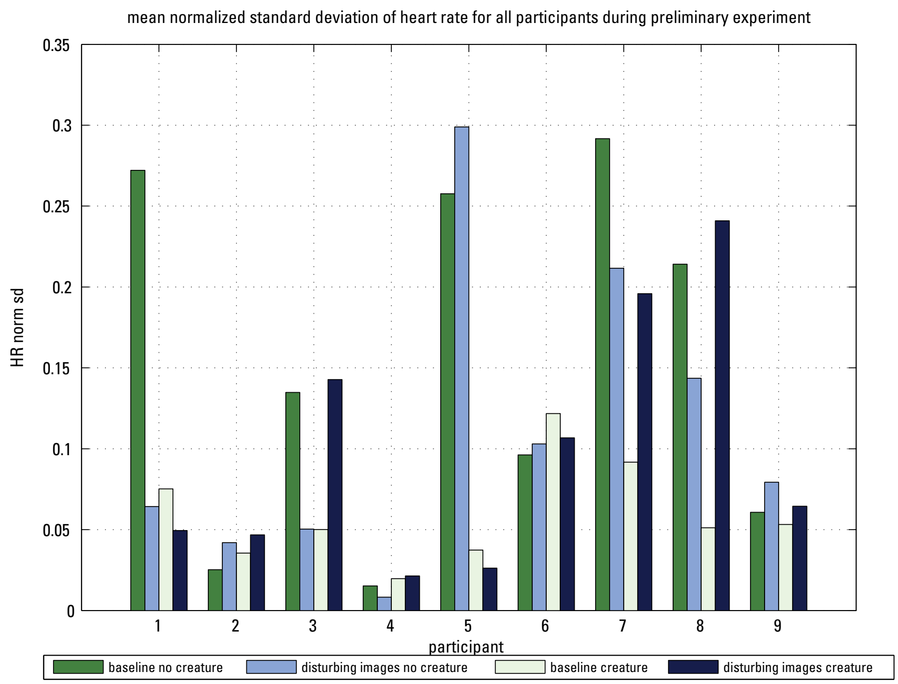

Figure B.7: Standard deviation of normalized heart rates for participants during Pilot Experiment.

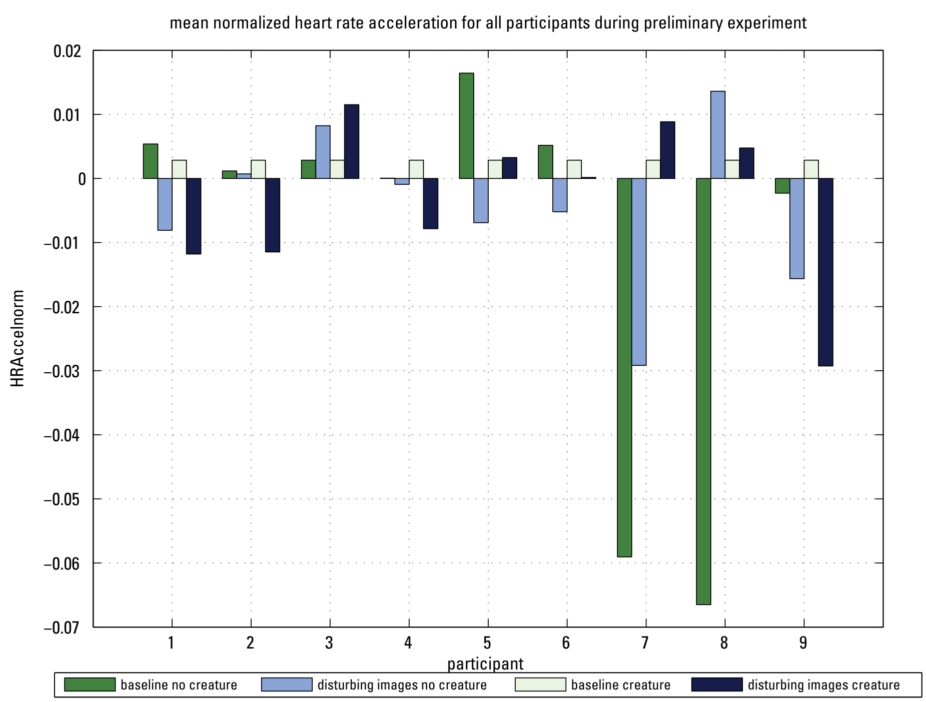

Figure B.8: Mean normalized heart rate acceleration for participants during Pilot Experiment.

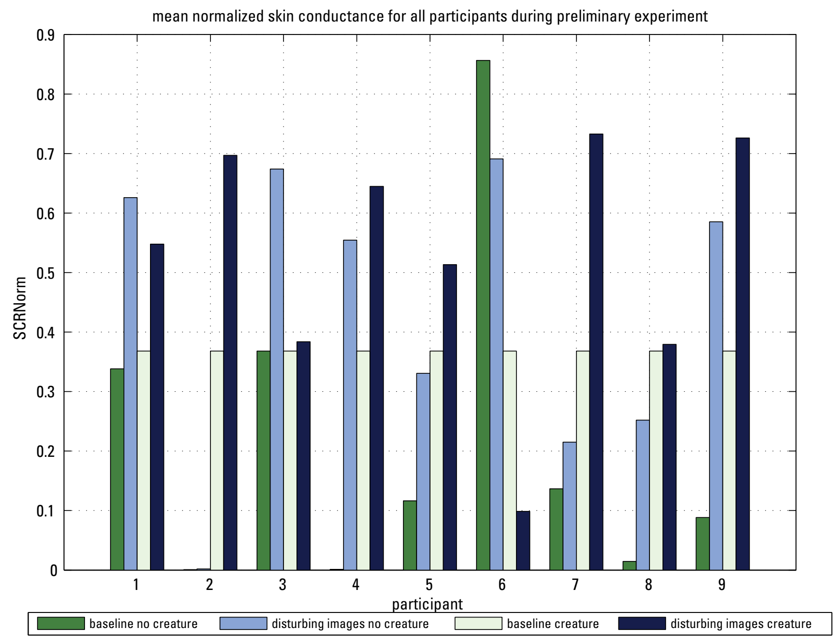

Figure B.9: Mean normalized skin conductance for participants during Pilot Experiment.

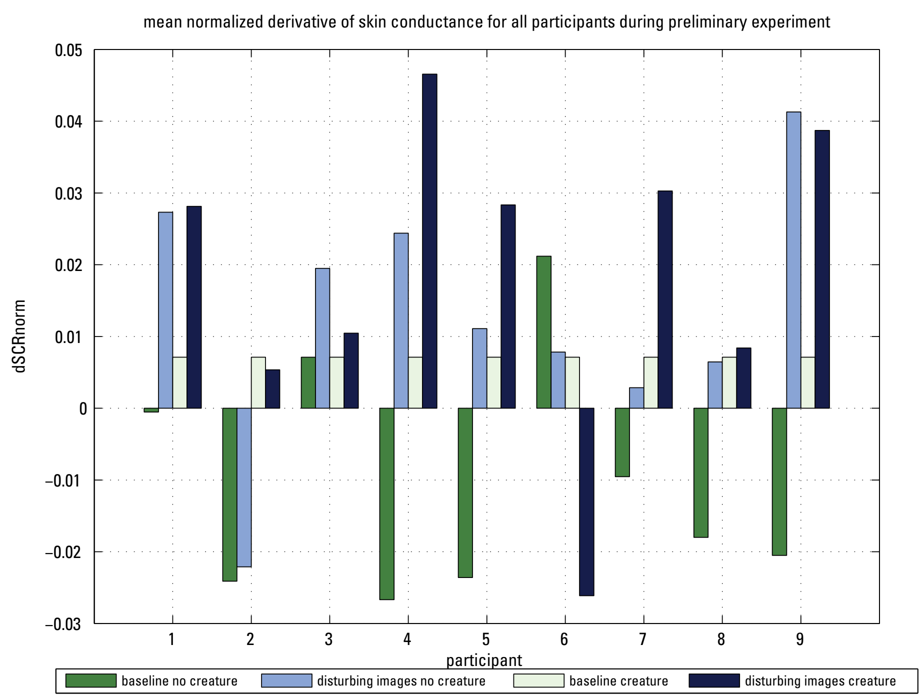

Figure B.10: Mean normalized derivative of skin conductance for participants during Pilot Experiment.

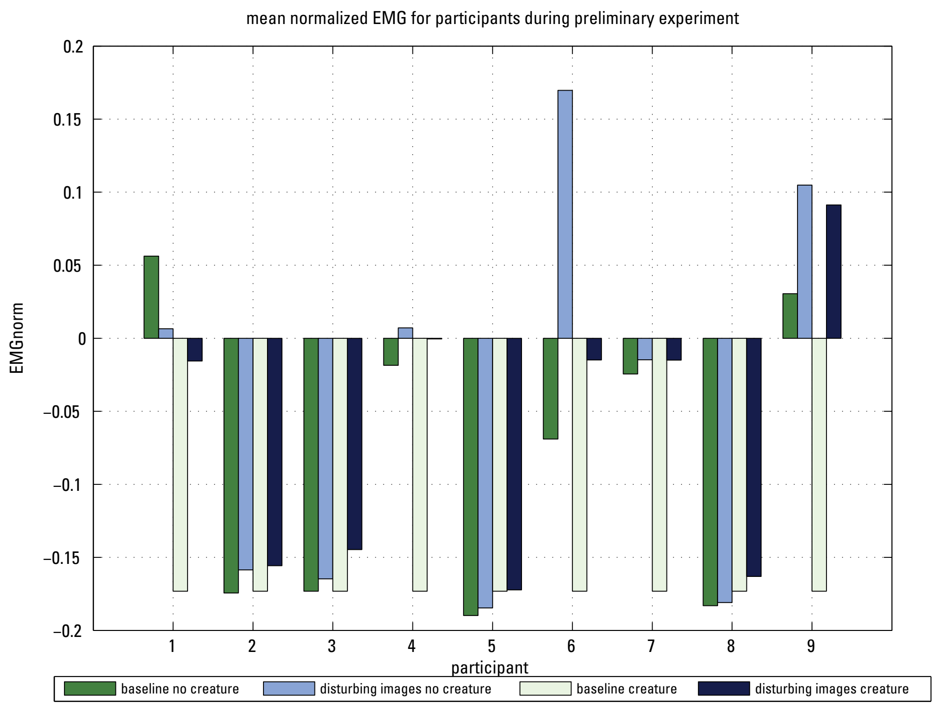

Figure B.11: Mean normalized EMG for participants during Pilot Experiment.

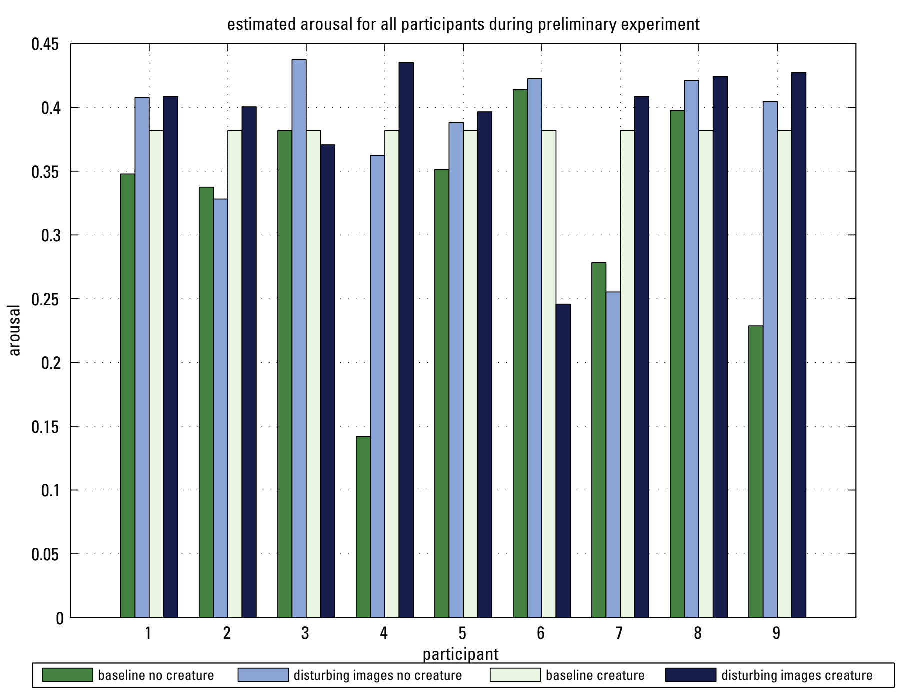

Figure B.12: Mean estimated arousal for participants during Pilot Experiment.

B.1.5 Participant Consent Form

THE UNIVERSITY OF BRITISH COLUMBIA

Department of Computer Science

2366 Main Mall
Vancouver, B.C. Canada V6T 1Z4
tel: (604) 822-3061
fax: (604) 822-4231
(PARTICIPANT'S COPY CONSENT FORM)

Project Title: Physical user interfaces: Communication of information and affect
(UBC Ethics #B01-0470)
Principal Investigator: Associate Professor K. MacLean, tel. 604-822-8169

The purpose of this study is to examine the role of haptic (touch sense) feedback on anxiety levels. You will be asked to wear external (i.e., non-invasive) sensors that collect some basic physiological information such as the heart rate, respiration rate, some muscle activity, and perspiration. Please tell the experimenter if you find the sensor positioning uncomfortable, and adjustments will be made. You will be asked to answer questions in two questionnaires as part of the experiment. The study will be viewed by the experimenters in a separate room via a webcam. It will not be recorded.

For this study, you will also be asked to view two slide-shows of pictures that you may find disturbing. The outline of the study is as follows: You will first be asked to answer a questionnaire. You will then be connected to the bio-sensors. Then you will then be shown a two-minute slide show of approximately ten pictures. Next you will be given a haptic creature that you will hold while watching another set of pictures shown in the same format as before. Finally, you will complete another questionnaire. If you are not sure about any instructions, do not hesitate to ask.

REIMBURSEMENT:	$5 per ½ hour session
TIME COMMITMENT:	½ hour session
CONFIDENTIALITY:	*Your results will be confidential: you will not be identified by name in any study reports. Test results will be stored in a secure Computer Science account accessible only to the experimenters.*

You understand that the experimenter will ANSWER ANY QUESTIONS you have about the instructions or the procedures of this study. After participating, the experimenter will answer any questions you have about this study.

Your participation in this study is entirely voluntary and you may refuse to participate or withdraw from the study at any time without jeopardy. Your signature below indicates that you have received a copy of this consent form for your own records, and consent to participate in this study.

If you have any concerns about your treatment or rights as a research subject, you may contact the Research Subject Info Line in the UBC Office of Research Services at 604-822-8598.

B.2 Experiment 1

B.2.1 Post-Experiment Questionnaire

Creature Impression

I found the creature comfortable on my lap. *(strongly disagree)* 1 2 3 4 5 *(strongly agree)*

Did this impression change at all once the creature started moving?

What changes would you recommend to make the creature more comfortable?

Creature Activity

Describe your overall impression of the creature's activity

What did you like the most about the creature's activity?

What did you like the least about the creature's activity?

Did you expect this sort of activity from the creature?

I was startled by the activation of the creature.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I found the creature's motion disturbing.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I found the noise of the creature distracting.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*

How many distinct creature operating modes were you able to observe?

Please describe all the modes you were able to observe.

Which sequence did you find more pleasurable?

Overall Response

It was easy to recognize the creature mirroring my breathing.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I found the creature mirroring my breathing comforting.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I found the creature mirroring my breathing disturbing.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
The creatures breathing made me more aware of my own breathing.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*

Was it evident that the creature was mirroring your breathing?

It was easy to recognize the creature mirroring my pulse.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I found the creature mirroring my pulse comforting.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I found the creature mirroring my pulse disturbing	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
The creatures pulse made me more aware of my own heart rate.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*

Was it evident that the creature was mirroring your pulse?

Describe your overall reaction to the creature mirroring your breathing rate and pulse.

Were you surprised at your breathing rate when you felt it in the creature?

Were you surprised at your breathing rate when you felt it in the creature?

B.2.2 Data Tables

Table B.1: Table of results from Experiment 1 questionnaire (1 = strongly disagree, 5 = strongly agree).

Responses						Statement
1	**2**	**3**	**4**	**5**	**na**	
6	2	2		1		It was easy to recognize the creature mirroring my breathing.
1	1				8	I found the creature mirroring my breathing comforting.
	2	1	2		5	I found the creature mirroring my breathing disturbing.
2	2		2	4		The creature's breathing made me more aware of my own breathing.
7	1	1	1	1		It was easy to recognize the creature mirroring my pulse.
	1		1	7		I found the creature mirroring my pulse comforting.
1		2	2	5		I found the creature mirroring my pulse disturbing.
5	2	1	2			The creature's pulse made me more aware of my own heart rate.
		1	8	1		I found the creature comfortable on my lap.
3	1	3	3			I was startled by the activation of the creature.
3	4	3				I found the creature's motion disturbing.
		4	5	1		I found the noise of the creature distracting

Table B.2: Results for two-tailed unequal variance t-test between breath lengths for each subject between all stages. 'Y' indicates a significant difference between the two stages.

	subject										
condition tested	1	2	3	4	5	6	7	8	9	10	**Σ**
still–constant motion	0.005	0.475	< 0.001	0.226	0.007	< 0.001	0.7482	0.014	< 0.001	0.145	**6**
still–mirroring	0.002	0.116	< 0.001	0.558	0.033	< 0.001	0.631	< 0.001	0.011	0.184	**7**
constant motion–mirroring	0.049	0.129	0.027	0.385	0.417	0.400	0.451	0.080	0.176	0.738	**3**
still–2.5 s breaths	0.050	0.970	0.121	0.021	0.368	0.012	< 0.001	0.528	0.018	0.117	**5**
constant motion–2.5 s breaths	< .001	0.727	0.942	0.018	0.144	0.167	< 0.001	0.020	0.261	0.005	**5**
mirroring–2.5 s breaths	0.069	0.313	0.598	0.001	0.157	0.469	0.014	0.016	0.534	0.015	**5**

Table B.3: Results for two-tailed unequal variance t-test between series of interbeat intervals for each subject between all stages. 'Y' indicates a significant difference between the two stages.

condition tested	subject 1	2	3	4	5	6	7	8	9	10	Σ
still–constant motion	0.314	$<$ 0.001	$<$ 0.001	0.385	0.078	$<$ 0.001	0.120	0.090	$<$ 0.001	0.009	**7**
still–mirroring	$<$ 0.001	$<$ 0.001	$<$ 0.001	0.565	0.005	$<$ 0.001	0.085	0.009	$<$ 0.001	$<$ 0.001	**9**
constant motion–mirroring	$<$ 0.001	0.800	$<$ 0.001	0.148	0.478	0.185	0.749	0.218	0.062	$<$ 0.001	**5**
still–70bpm	0.004	0.478	0.688	$<$ 0.001	0.712	0.916	0.228	0.003	0.014	$<$ 0.001	**5**
constant motion–70bpm	0.010	0.810	0.017	$<$ 0.001	0.583	0.684	0.716	0.015	0.806	$<$ 0.001	**5**
mirroring–70bpm	0.223	0.779	0.059	$<$ 0.001	0.390	0.630	0.779	0.065	0.492	$<$ 0.001	**4**

B.2.3 Sample Data

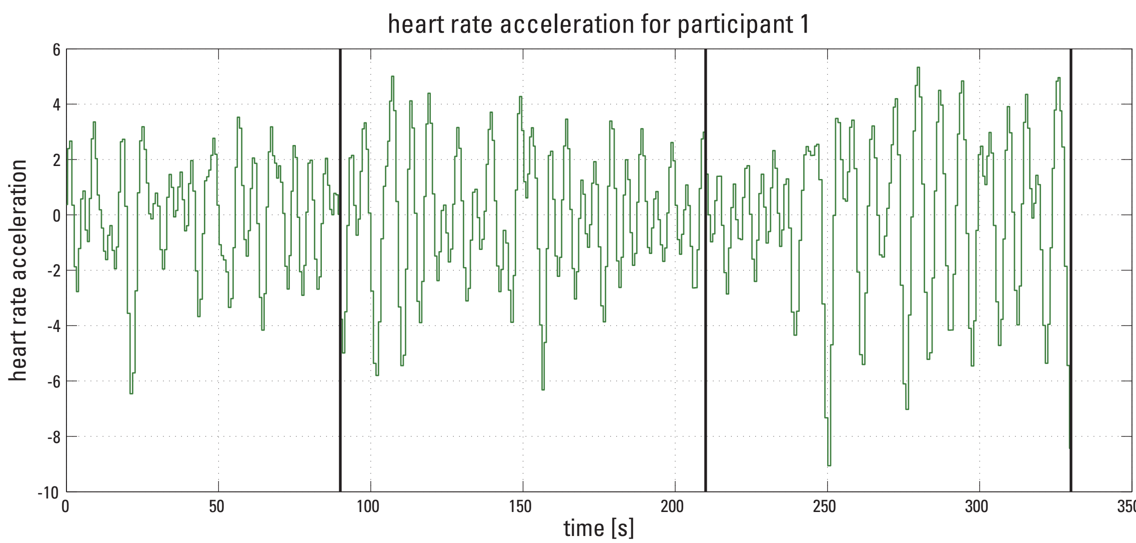

Figure B.13: Heart rate acceleration for a participant during Experiment 1. Black lines delineate experiment stages ii, iii, and iv as listed in Figure 4.9.

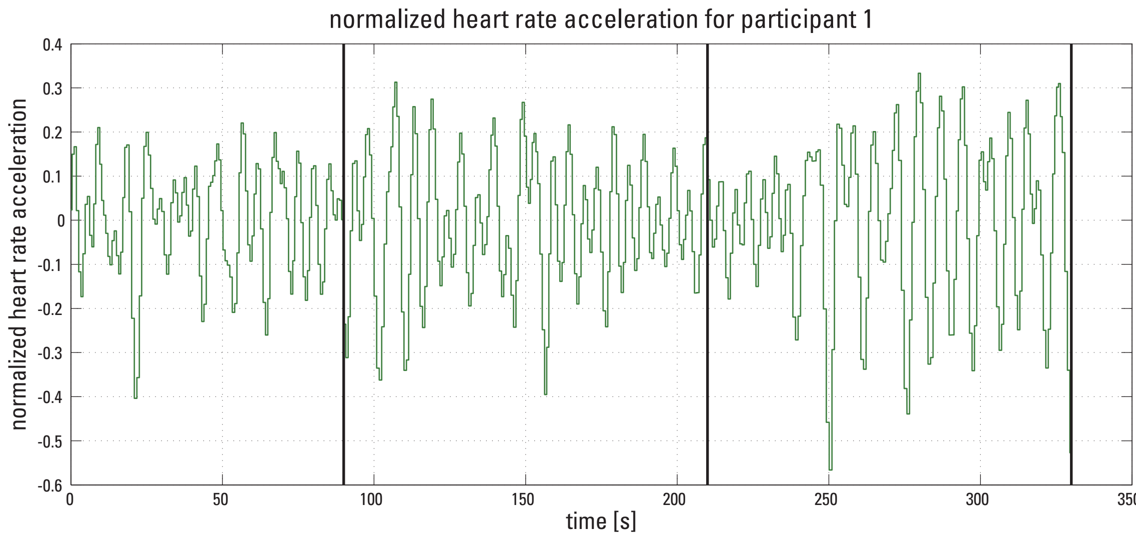

Figure B.14: Normalized heart rate acceleration for a participant during Experiment 1. Black lines delineate experiment stages ii, iii, and iv as listed in Figure 4.9.

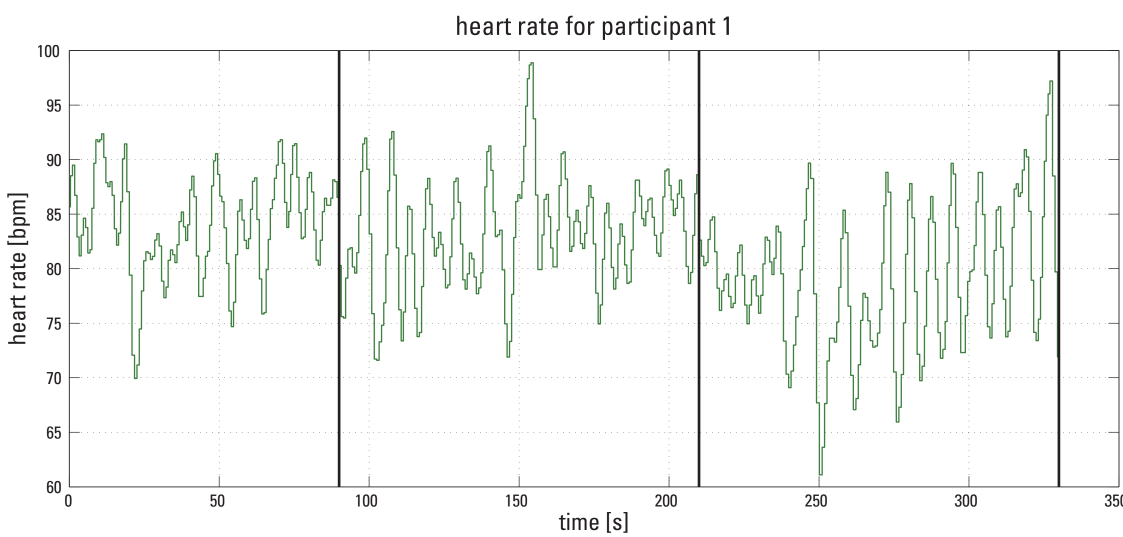

Figure B.15: Heart rate for a participant during Experiment 1. Black lines delineate experiment stages ii, iii, and iv as listed in Figure 4.9.

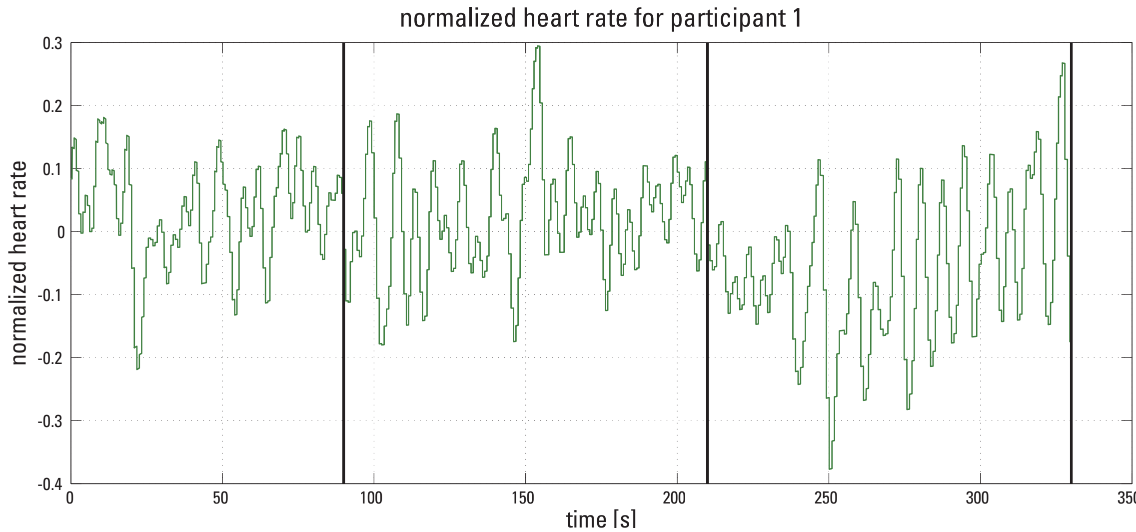

Figure B.16: Normalized heart rate for a participant during Experiment 1. Black lines delineate experiment stages ii, iii, and iv as listed in Figure 4.9.

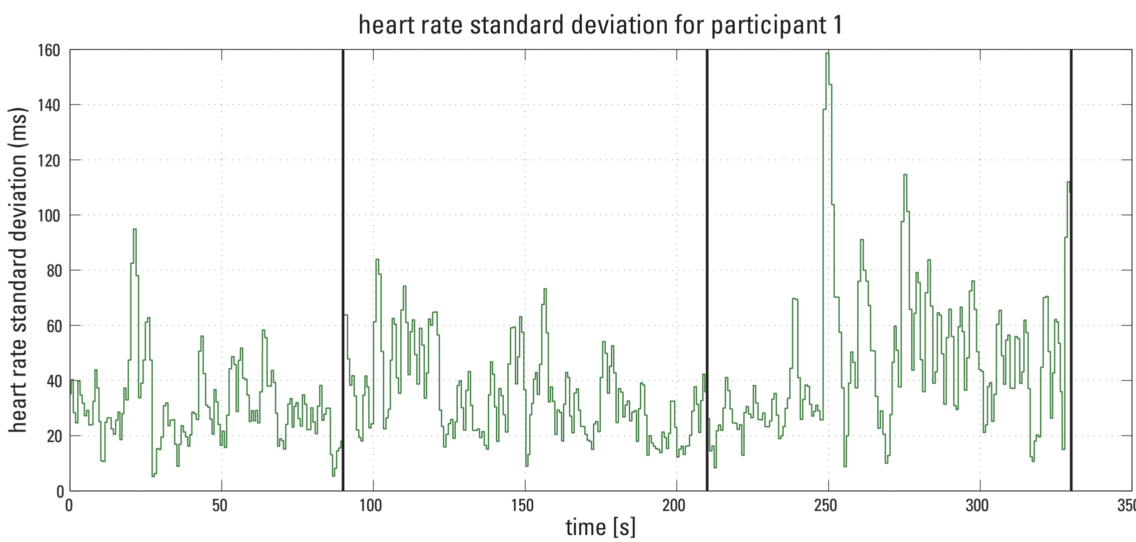

Figure B.17: Normalized heart rate standard deviation for a participant during Experiment 1. Black lines delineate experiment stages ii, iii, and iv as listed in Figure 4.9.

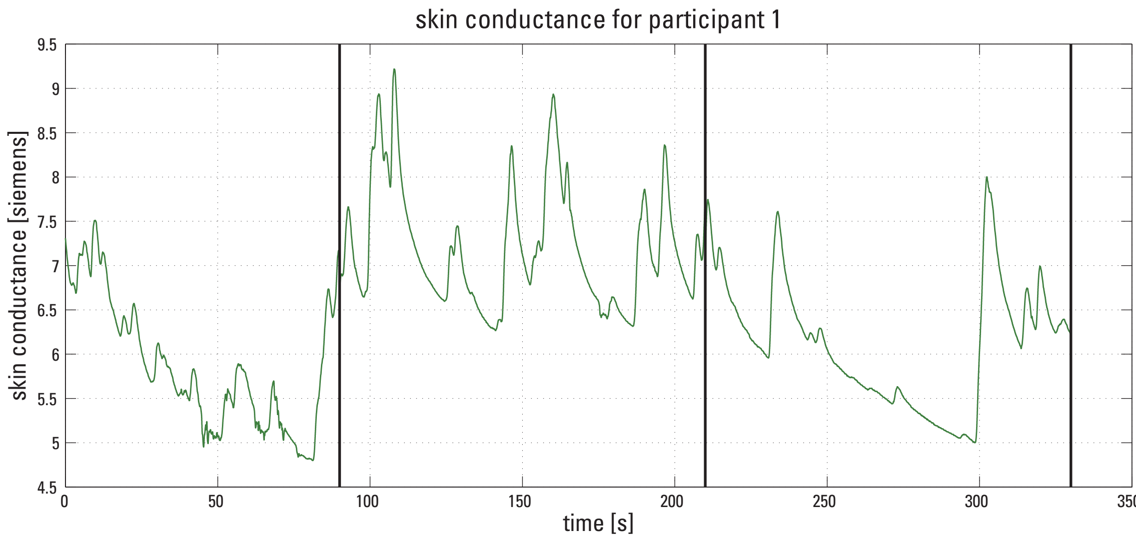

Figure B.18: Skin conductance response for a participant during Experiment 1. Black lines delineate experiment stages ii, iii, and iv as listed in Figure 4.9.

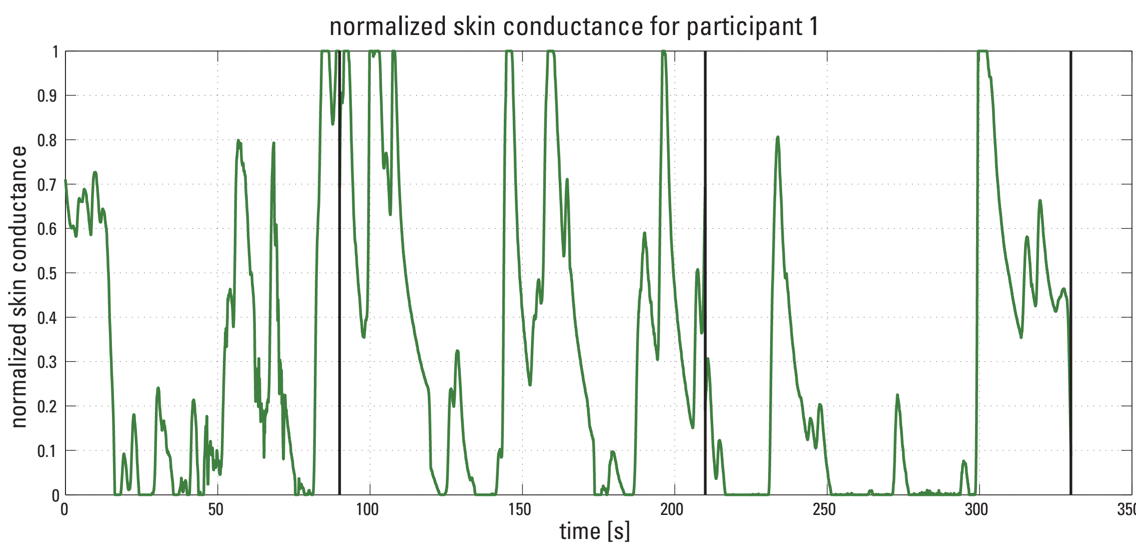

Figure B.19: Normalized skin conductance for a participant during Experiment 1. Black lines delineate experiment stages ii, iii, and iv as listed in Figure 4.9.

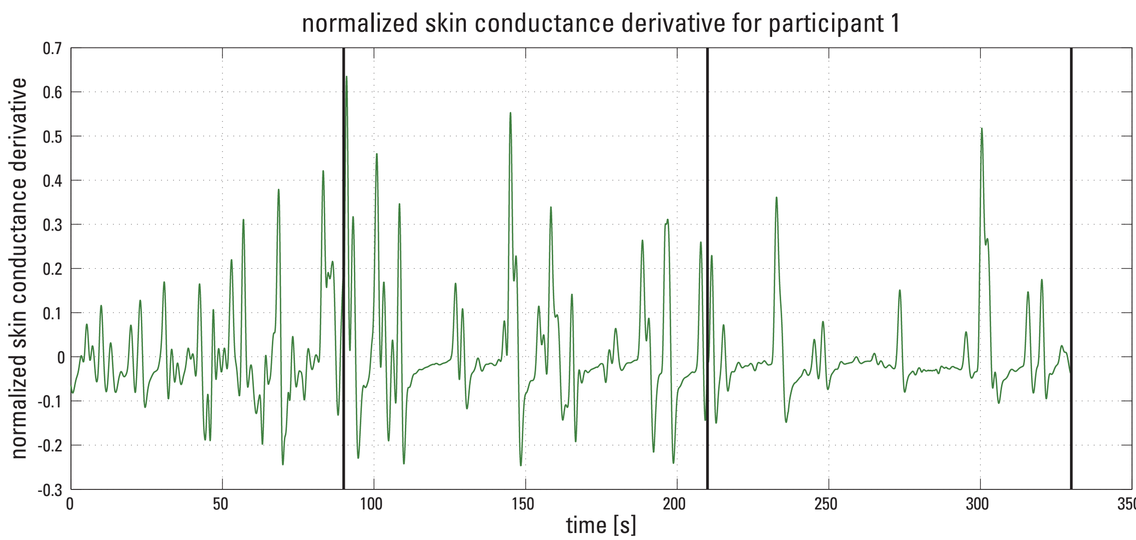

Figure B.20: Skin conductance derivative for a participant during Experiment 1. Black lines delineate experiment stages ii, iii, and iv as listed in Figure 4.9.

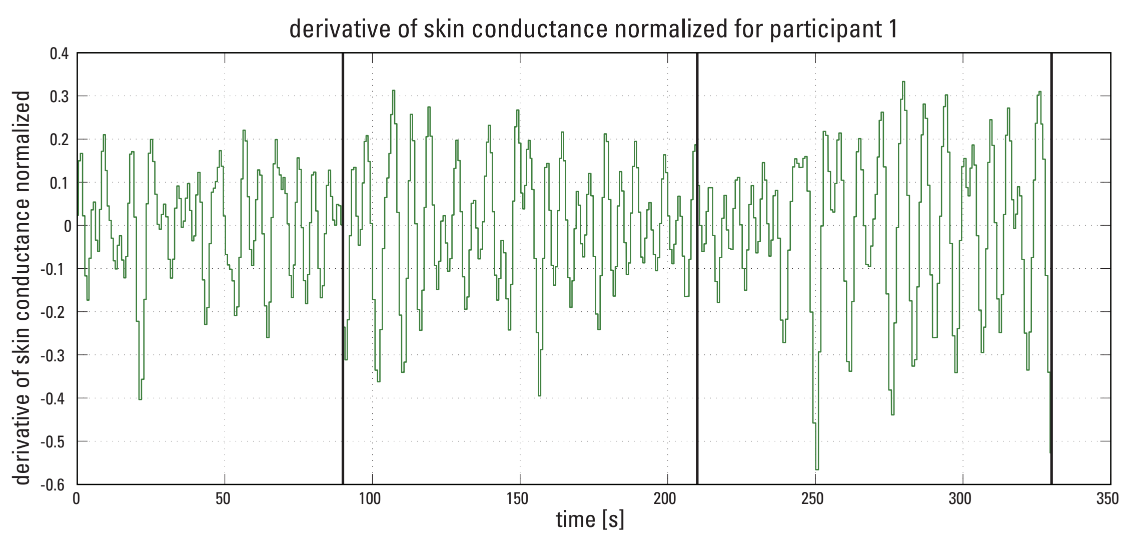

Figure B.21: Normalized skin conductance derivative for a participant during Experiment 1. Black lines delineate experiment stages ii, iii, and iv as listed in Figure 4.9.

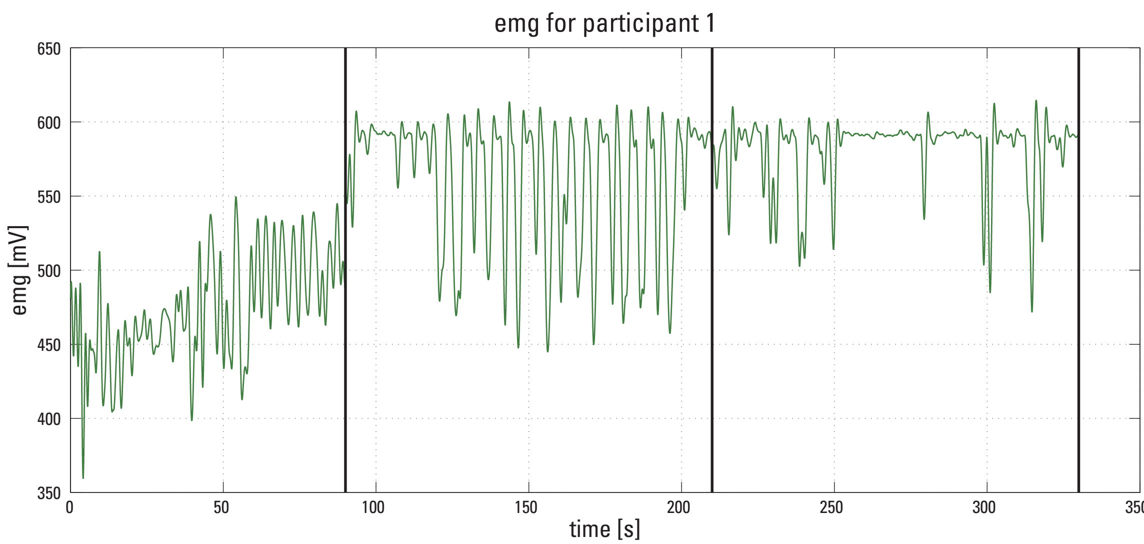

Figure B.22: EMG for a participant during Experiment 1. Black lines delineate experiment stages ii, iii, and iv as listed in Figure 4.9.

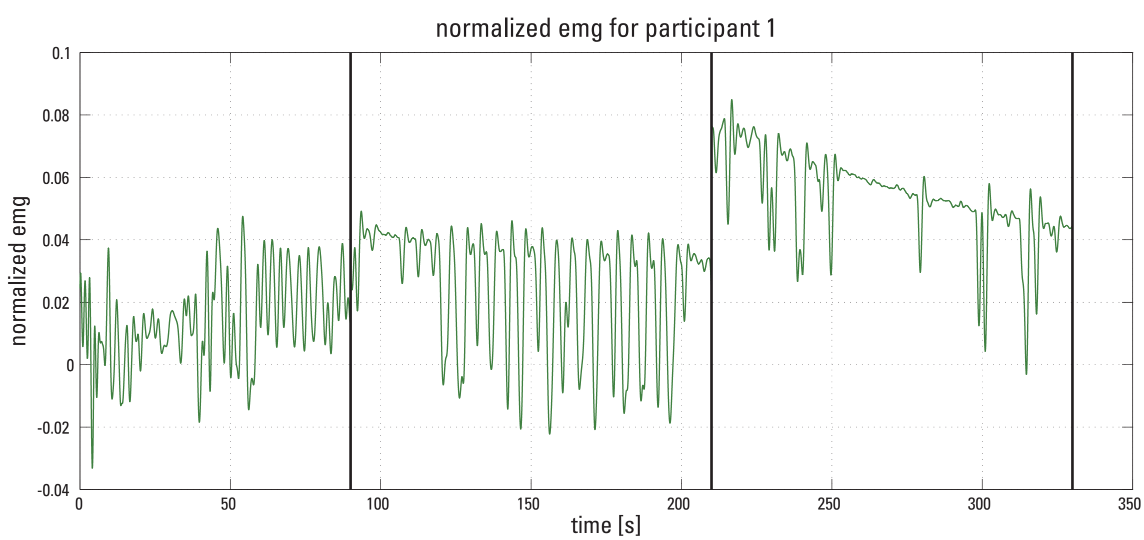

Figure B.23: Normalized EMG for a participant during Experiment 1. Black lines delineate experiment stages ii, iii, and iv as listed in Figure 4.9.

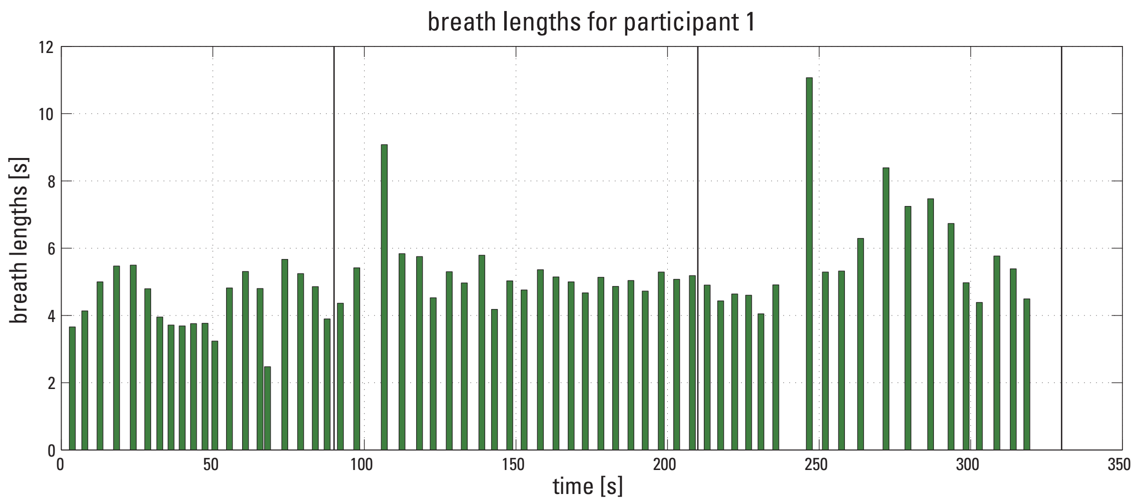

Figure B.24: Breath lengths for a participant during Experiment 1. Black lines delineate experiment stages ii, iii, and iv as listed in Figure 4.9.

B.2.4 Sample Comparisons

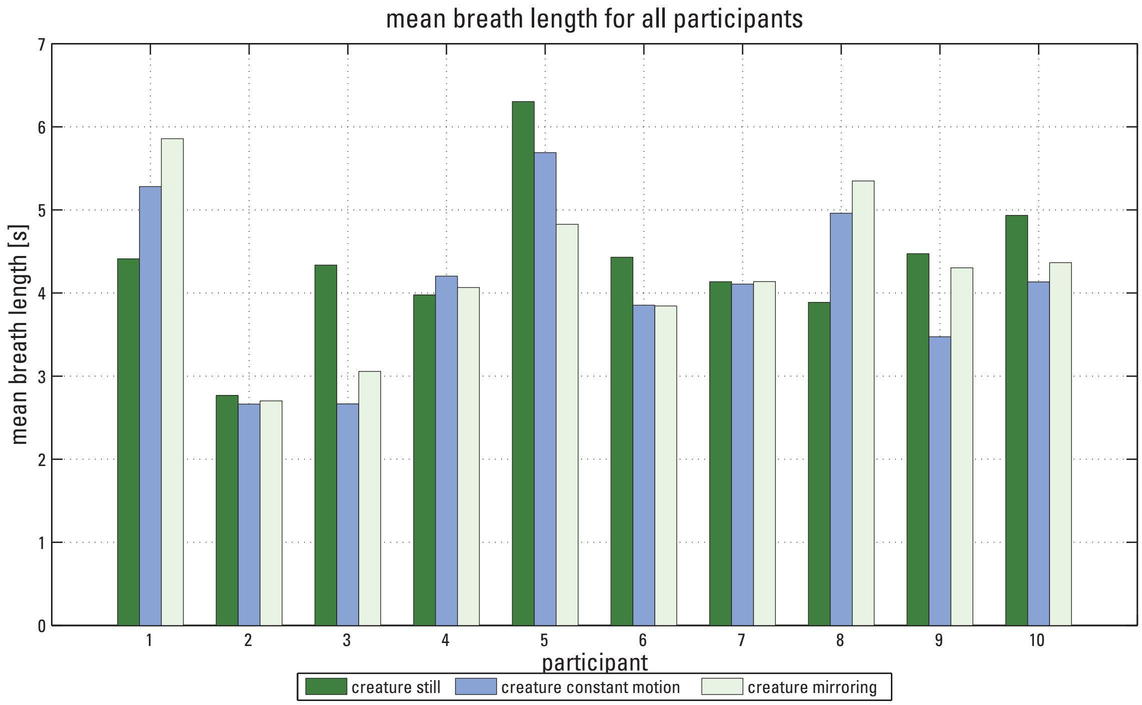

Figure B.25: Mean breath lengths for participants during Experiment 1.

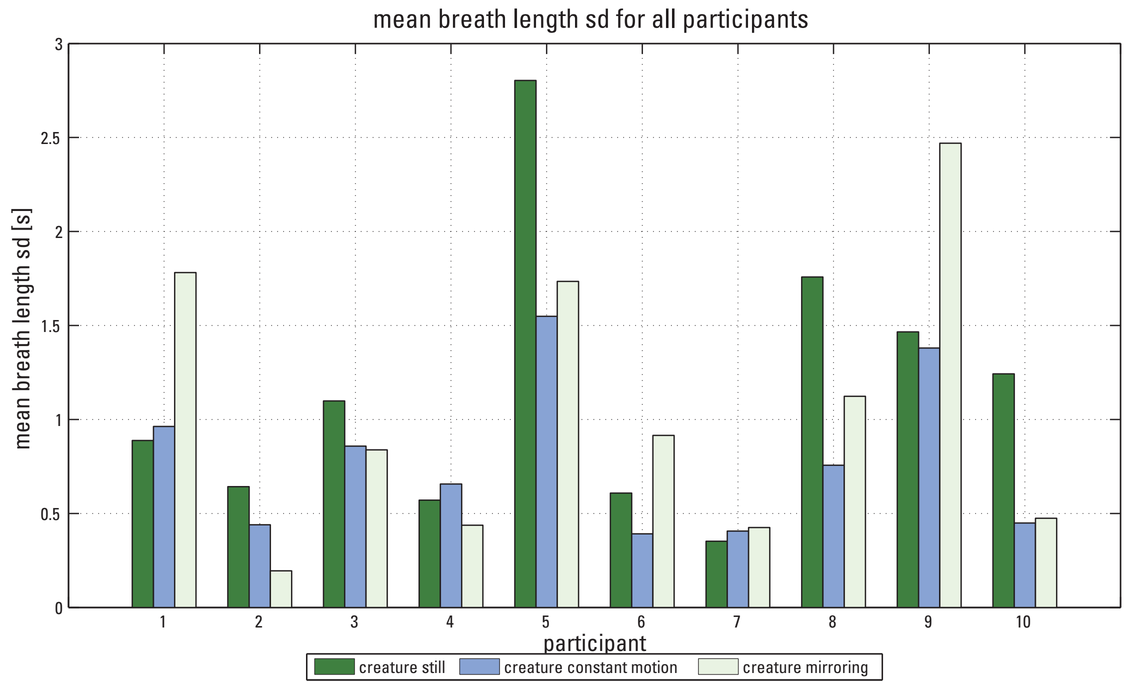

Figure B.26: Breath length standard deviation for participants during Experiment 1.

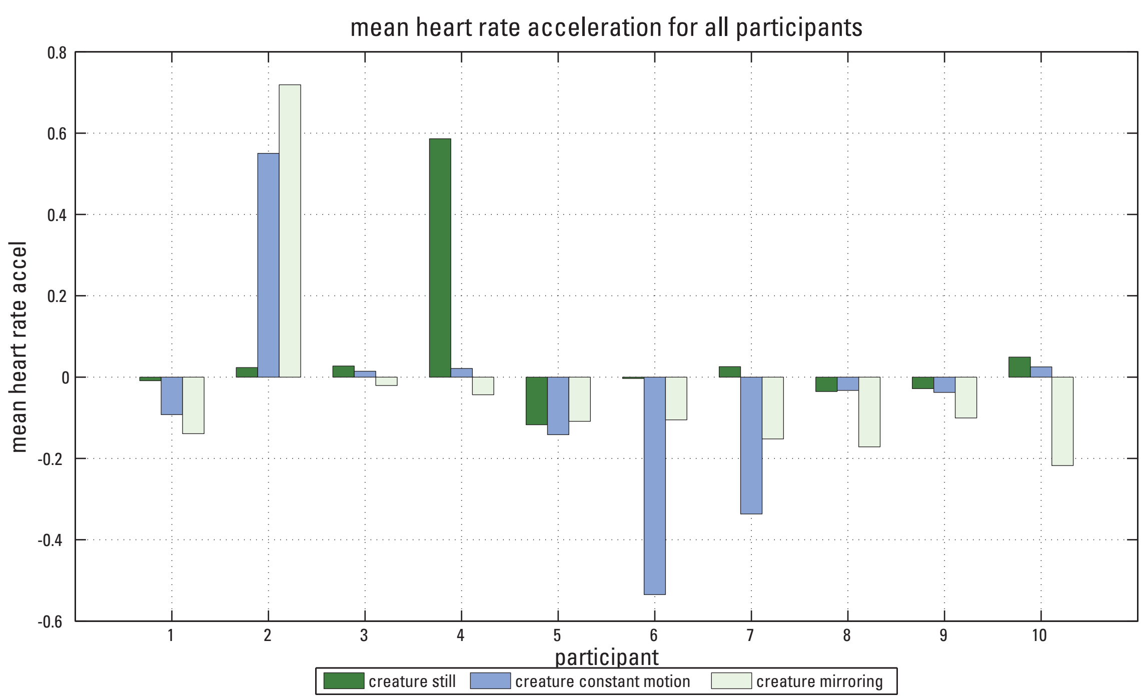

Figure B.27: Mean heart rate acceleration for participants during Experiment 1.

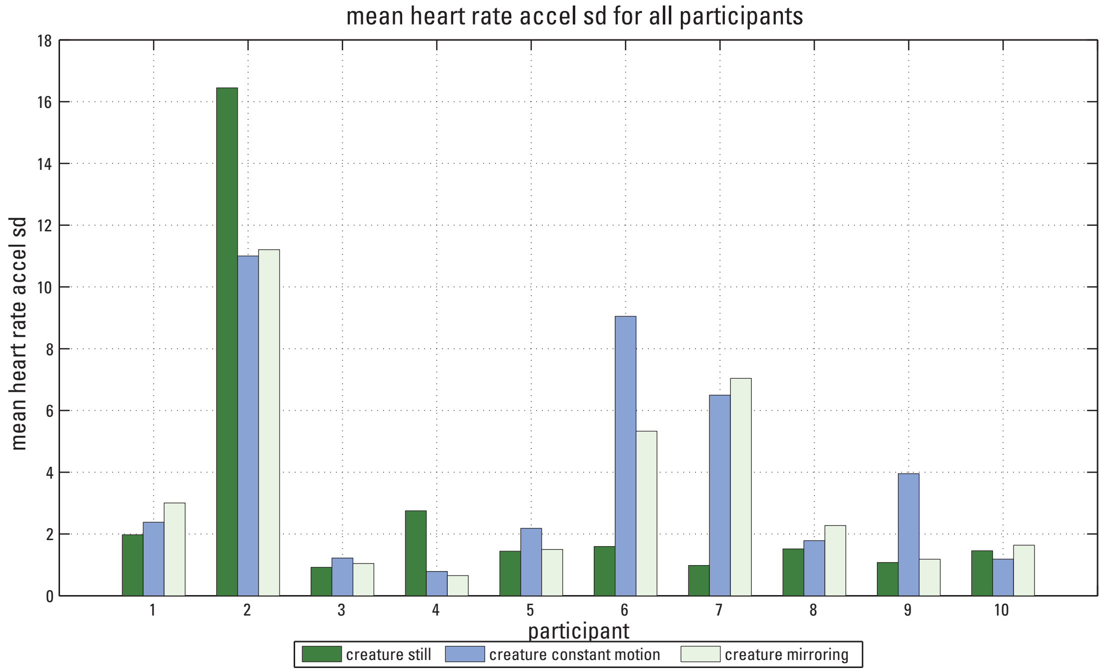

Figure B.28: Heart rate acceleration standard deviation for participants during Experiment 1.

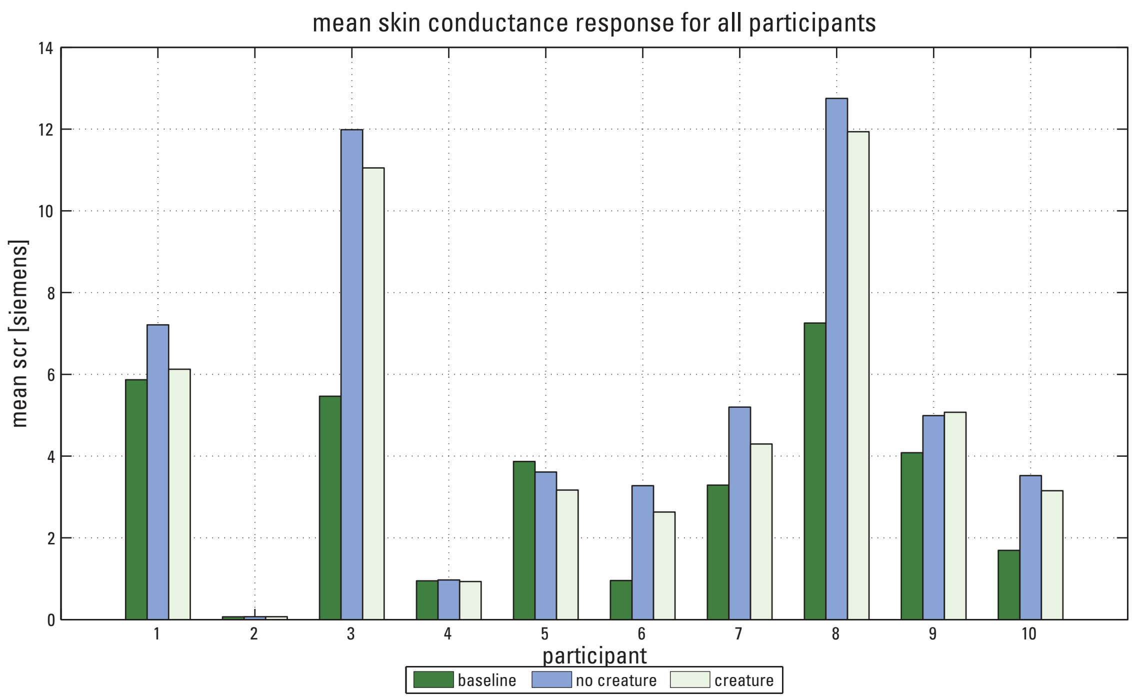

Figure B.29: Mean skin conductance for participants during Experiment 1.

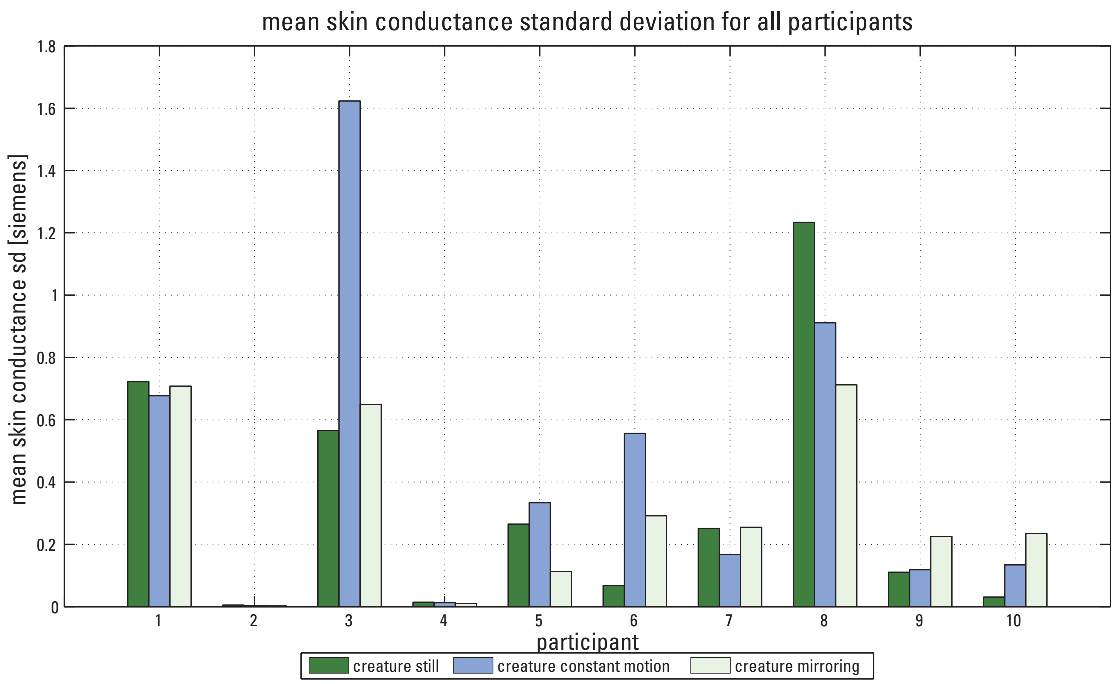

Figure B.30: Skin conductance standard deviation for participants during Experiment 1.

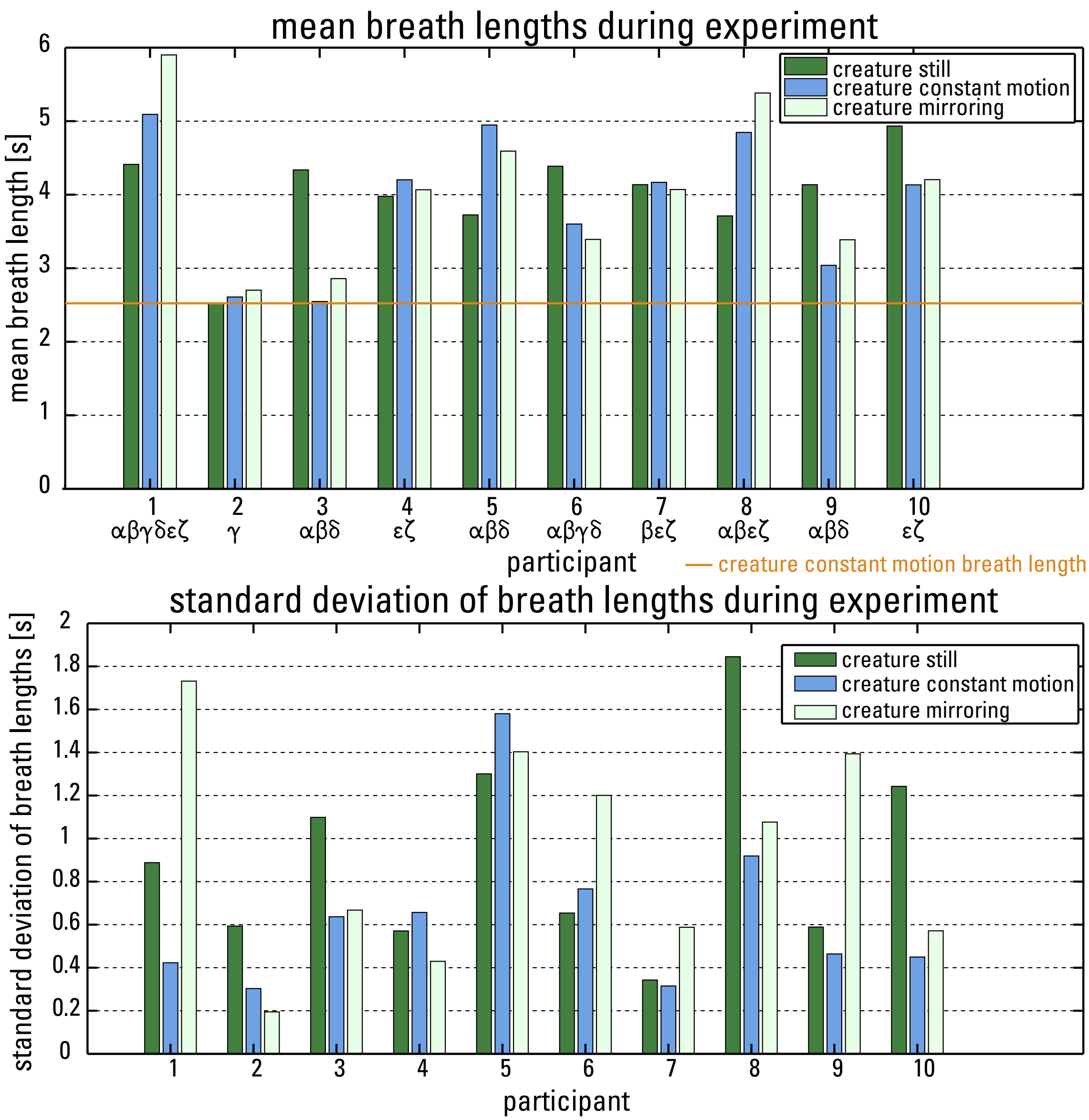

Figure B.31: Mean and standard deviation of breath lengths of participants during each stage of Experiment 1. Greek letters refer to within-subject mean differences. For each participant, α indicates significant difference between still and constant motion stages. β indicates significant difference between still and mirroring stages. γ indicates significant difference between constant motion and mirroring stages. δ indicates significant difference between still stage and constant motion and constant 2.5 s breaths. ϵ indicates significant difference between constant motion stage and constant 2.5 s breaths. ζ indicates significant difference between mirroring stage and constant 2.5 s breaths. The standard deviation of the constant motion stage is at or close to zero.

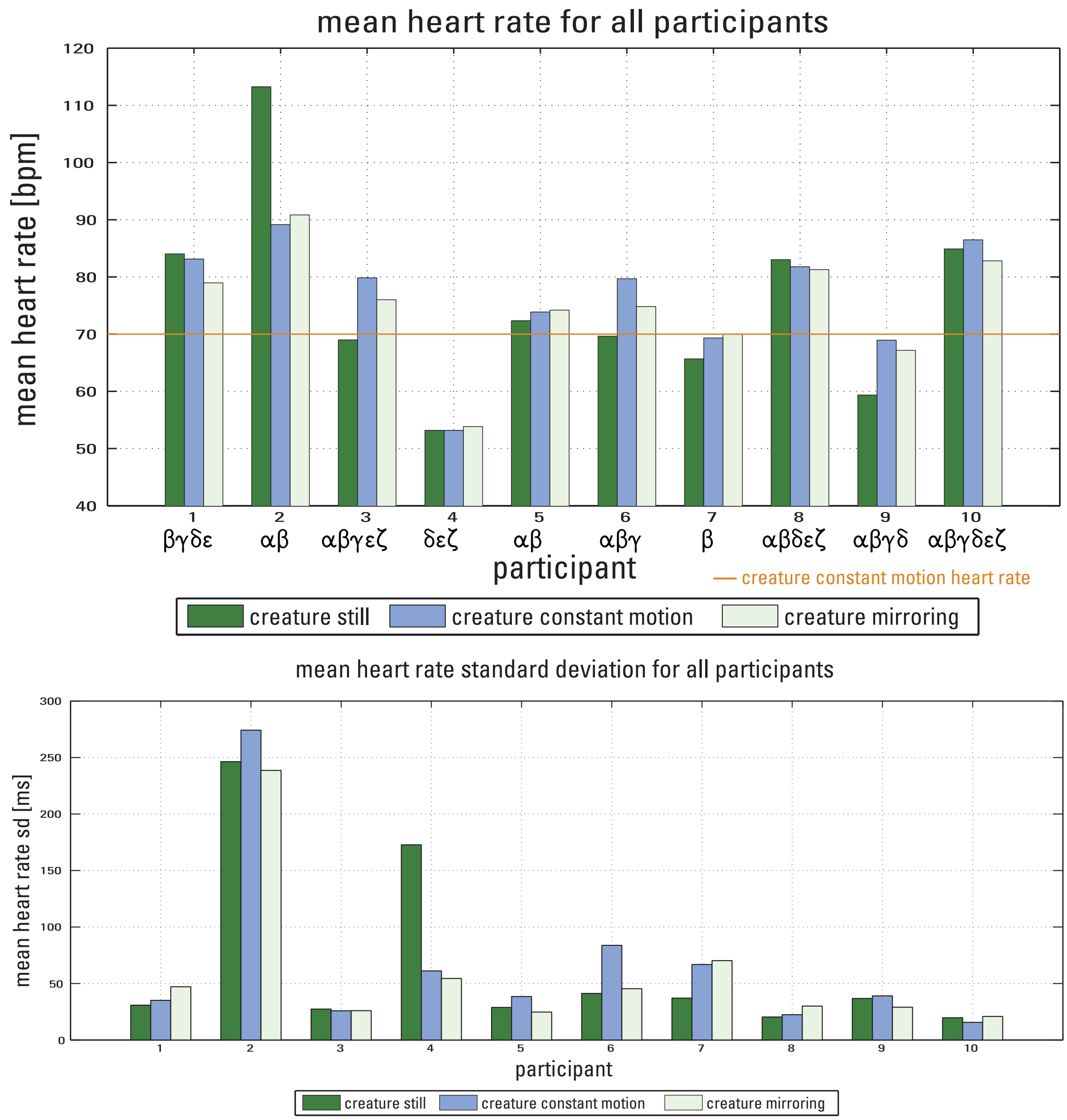

Figure B.32: Mean and standard deviation of heart rate for participants during Experiment 1. Greek letters refer to within-subject mean differences. For each participant, α indicates significant difference between still and constant motion stages. β indicates significant difference between still and mirroring stages. γ indicates significant difference between constant motion and mirroring stages. δ indicates significant difference between still stage and constant motion at 70bpm. ϵ indicates significant difference between constant motion stage and constant motion at 70bpm. ζ indicates significant difference between mirroring stage and constant motion at 70bpm. The standard deviation of the constant motion stage is at or close to zero.

B.2.5 Participant Consent Form

THE UNIVERSITY OF BRITISH COLUMBIA **Department of Computer Science**
2366 Main Mall
Vancouver, B.C. Canada V6T 1Z4
tel: (604) 822-3061
fax: (604) 822-4231
(PARTICIPANT'S COPY CONSENT FORM)

Project Title: Investigation of haptic-affect loop through the haptic creature
(UBC Ethics #B01-0470)

Principal Investigators: Dr. Karon MacLean, Department of Comptuer Science, 604-822-8169
Dr. Elizabeth Croft, Department of Mechanical Engineering, 604-822-6614
Student Investigator: Joseph P. Hall III, Department of Mechanical Engineering, *jphiii@interchange.ubc.ca*

The purpose of this study is to examine your reaction to interaction through touch with a robotic pet.

You will be asked to hold and touch a small robot that may gently move. You will be asked to wear external (i.e. non-invasive) sensors that collect some basic physiological information such as heart rate, respiration rate, some muscle activity, and perspiration. Please tell the experimenter if you find the sensors uncomfortable and adjustments will be made. You will be asked to answer questions in a questionnaire as part of the experiment. Parts of this experiment will be videotaped for later analysis.

If you are unsure about any instructions, do not hesitate to ask.

TIME COMMITMENT:	½ -1 hour session
CONFIDENTIALITY:	*Your results will be confidential: you will not be identified by name in any study reports. Test results will be stored in a secure computer account accessible only to the experimenters.*

You understand that the experimenters will ANSWER ANY QUESTIONS you have about the instructions or the procedures of this study. After participating, the experimenter will answer any other questions you have about this study.

Your participation in this study is entirely voluntary and you may refuse to participate or withdraw from the study at any time without jeopardy. Your signature below indicates that you have received a copy of this consent form for your own records, and consent to participate in this study.

If you have any concerns about your treatment or rights as a research subject, you may contact the Research Subject Info Line in the UBC Office of Research Services at 604-822-8598.

Version 1.0 / August 10, 2009

B.3 Experiment 2

B.3.1 Post-Experiment Questionnaire

When asked to mirror the creature

I was able to easily mirror the creatures breathing.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I was aware of the creatures pulse.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I was comfortable with the creature on my lap.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I was aware of my own breathing.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I was aware of my own heart rate.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I found the noise of the creature distracting.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*

While sitting still with the creature

I was aware of the creatures breathing.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I was aware of the creatures pulse.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I noticed changes in the creatures breathing.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I noticed changes in the creatures pulse.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I was aware of my own breathing.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I was aware of my own heart rate.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I was comfortable with the creature on my lap.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*

During the reading assignment

I was aware of the creatures breathing.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I was aware of the creatures pulse.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I noticed changes in the creatures breathing.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I noticed changes in the creatures pulse.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I was aware of my own breathing.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I was aware of my own heart rate.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I was comfortable with the creature on my lap.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I found the creatures motion distracting.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*

In general during the experiment

The creature made me more aware of my own breathing.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
The creature made me more aware of my own heart rate.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*
I enjoyed interacting with the creature.	*(strongly disagree)* 1 2 3 4 5 *(strongly agree)*

B.3.2 Data Tables

Table B.4: Table of results from Experiment 2 questionnaire (1 = strongly disagree, 5 = strongly agree), n = 10.

1	**2**	**3**	**4**	**5**	
5	2	2		1	It was easy to recognize the creature mirroring my breathing.
1	1				I found the creature mirroring my breathing comforting (if noticed).
	2	1	2		I found the creature mirroring my breathing disturbing (if noticed).
2	2		2	4	The creature's breathing made me more aware of my own breathing.
6	1	1	1	1	It was easy to recognize the creature mirroring my pulse.
	1	1	8		I found the creature mirroring my pulse comforting.
1		2	2	5	I found the creature mirroring my pulse disturbing.
5	2	1	2		The creature's pulse made me more aware of my own heart rate.
		1	8	1	I found the creature comfortable on my lap.
3	1	3	3		I was startled by the activation of the creature.
3	4	3			I found the creature's motion disturbing.
3	4	3			I found the noise of the creature distracting

Table B.5: Results for two-tailed unequal variance t-test between series of interbeat intervals for each subject between all stages. 'Y' indicates a significant difference between the two stages.

	subject								
	1	2	3	4	5	6	7	8	9
baseline-training	0.108	0.014	0.000	0.000	0.000	0.000	0.000	0.008	0.018
baseline-task	0.466	0.001	0.001	0.012	0.000	0.103	0.004	0.000	0.023
baseline-no task	0.000	0.040	0.000	0.000	0.000	0.000	0.000	0.000	0.000
baseline - 70bpm	0.723	0.146	0.205	0.778	0.000	0.965	0.001	0.571	0.158
task-70bpm	0.732	0.057	0.794	0.421	0.032	0.581	0.012	0.415	0.297
no task-70bpm	0.840	0.226	0.042	0.553	0.221	0.899	0.003	0.864	0.436

Table B.6: Questionnaire results from Experiment 2 post-experiment survey (1 = strongly disagree, 5 = strongly agree).

When asked to mirror creature:

1	**2**	**3**	**4**	**5**	
	1		4	4	I was able to easily mirror the creature's breathing
	2		1	6	I was aware of the creature's pulse
			5	4	I was comfortable with creature on my lab
				9	I was aware of own breathing
	6	3			I was aware of own heartrate
	4		4	1	I found noise of creature distracting

While sitting with active creature:

1	**2**	**3**	**4**	**5**	
			2	7	I was aware of the creature's breathing
	1	1	1	6	I was aware of the creature's pulse
	1	1	4	3	I noticed changes in the creature's breathing
	6		1	2	I noticed changes in the creature's pulse
	1	2	4	2	I was aware of my own breathing
3	4	2			I was aware of my own heart rate
		1	4	4	I was comfortable with creature on my lap

During reading task:

1	**2**	**3**	**4**	**5**	
	1	1	5	2	I was aware of the creature's breathing
1	4	3	1		I was aware of the creature's pulse
1	4	1	1	2	I noticed changes in the creature's breathing
4	4	1			I noticed changes in the creature's pulse
	4	3	2		I was aware of my own breathing
6	2	1			I was aware of my own heart rate
	1	2	5	1	I was comfortable with creature on my lap
1	3	1	3	1	I found creature's motion distracting

Overall:

1	**2**	**3**	**4**	**5**	
		1	4	4	creature made me more aware of breathing
1	6	2			creature made me more aware of heart rate
		2	7		enjoyed interacting

B.3.3 Sample Data

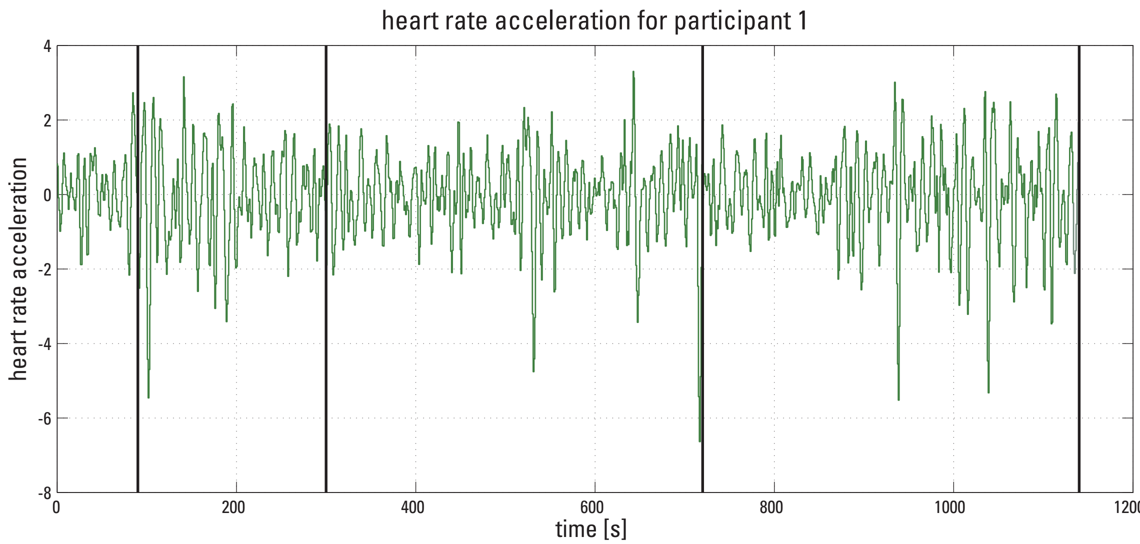

Figure B.33: Heart rate acceleration for a participant during Experiment 2. Black lines delineate experiment stages i, ii, iii, and iv as listed in Figure 4.14.

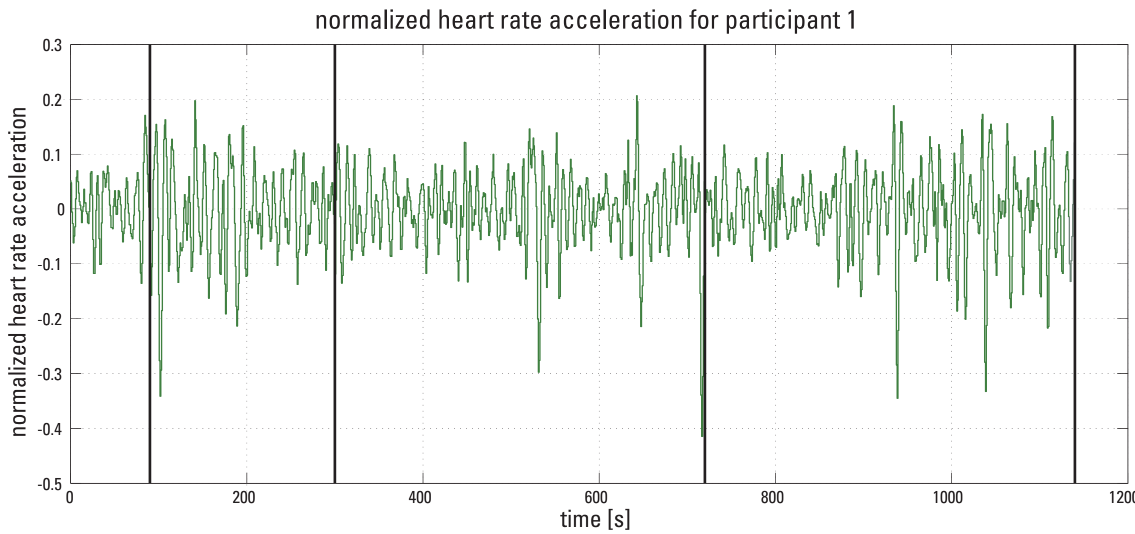

Figure B.34: Normalized heart rate acceleration for a participant during Experiment 2. Black lines delineate experiment stages i, ii, iii, and iv as listed in Figure 4.14.

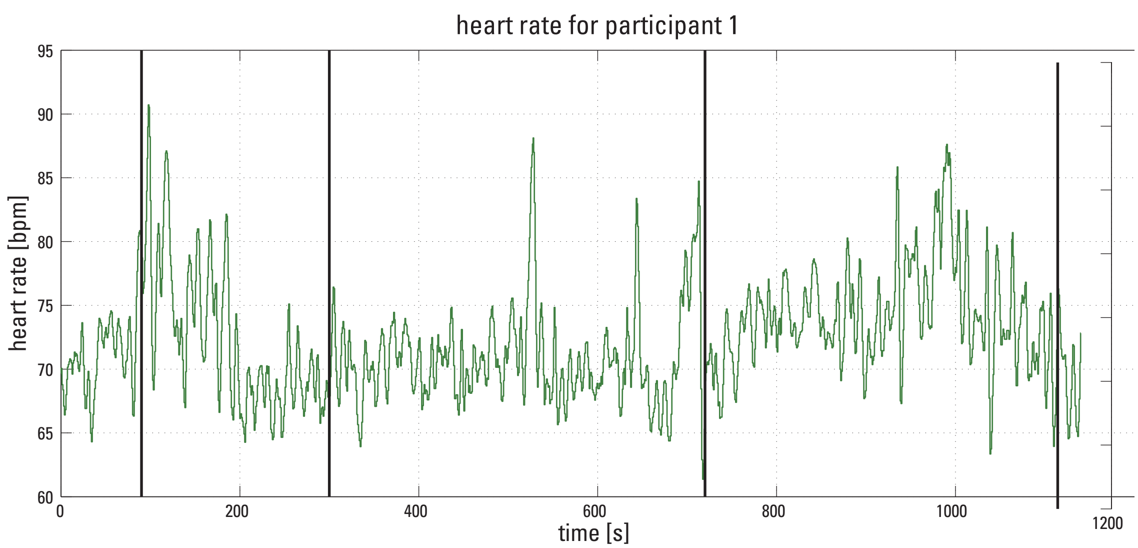

Figure B.35: Heart rate for a participant during Experiment 2. Black lines delineate experiment stages i, ii, iii, and iv as listed in Figure 4.14.

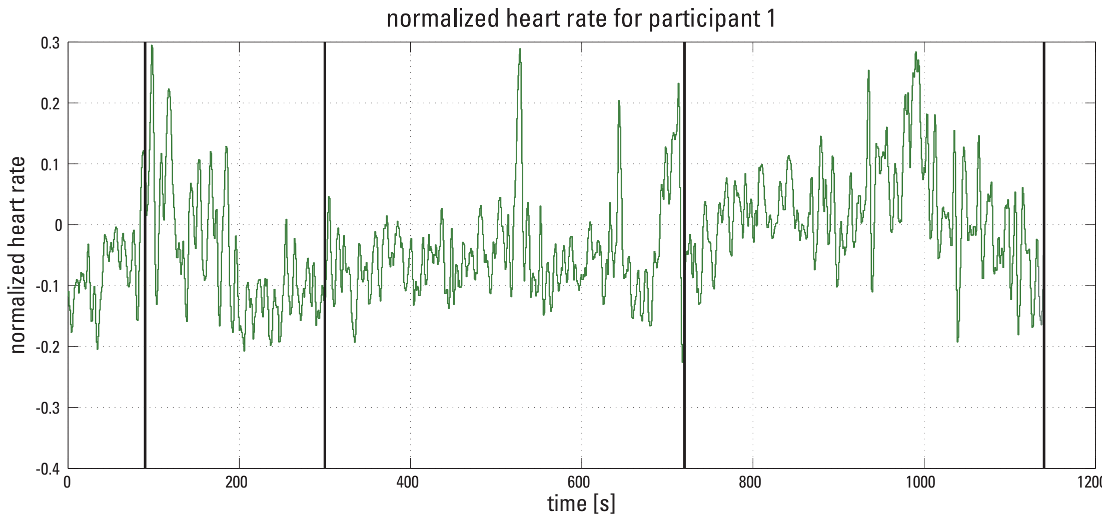

Figure B.36: Normalized heart rate for a participant during Experiment 2. Black lines delineate experiment stages i, ii, iii, and iv as listed in Figure 4.14.

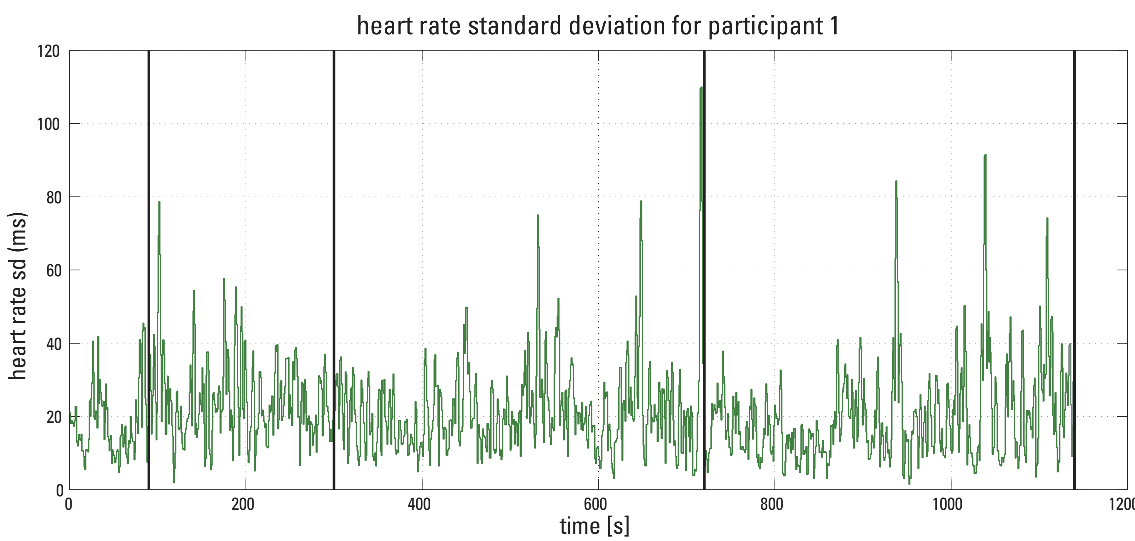

Figure B.37: Normalized heart rate standard deviation for a participant during Experiment 2. Black lines delineate experiment stages i, ii, iii, and iv as listed in Figure 4.14.

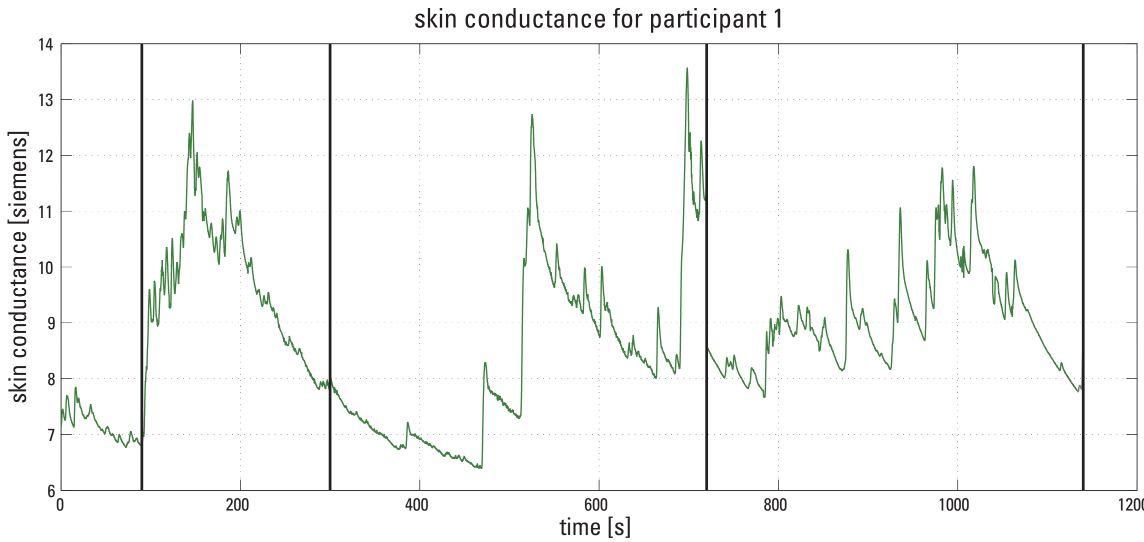

Figure B.38: Skin conductance response for a participant during Experiment 2. Black lines delineate experiment stages i, ii, iii, and iv as listed in Figure 4.14.

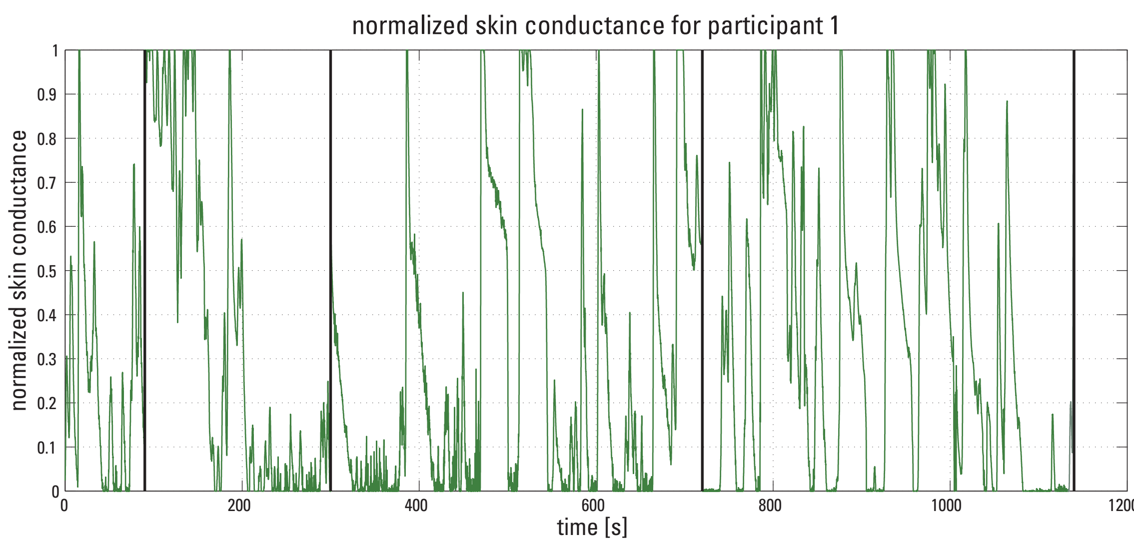

Figure B.39: Normalized skin conductance for a participant during Experiment 2. Black lines delineate experiment stages i, ii, iii, and iv as listed in Figure 4.14.

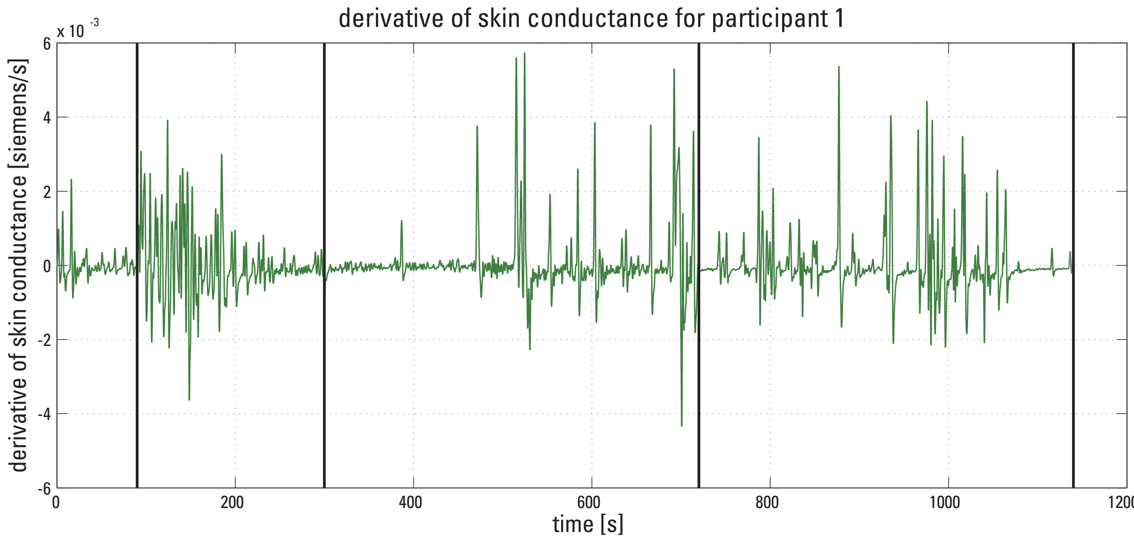

Figure B.40: Skin conductance derivative for a participant during Experiment 2. Black lines delineate experiment stages i, ii, iii, and iv as listed in Figure 4.14.

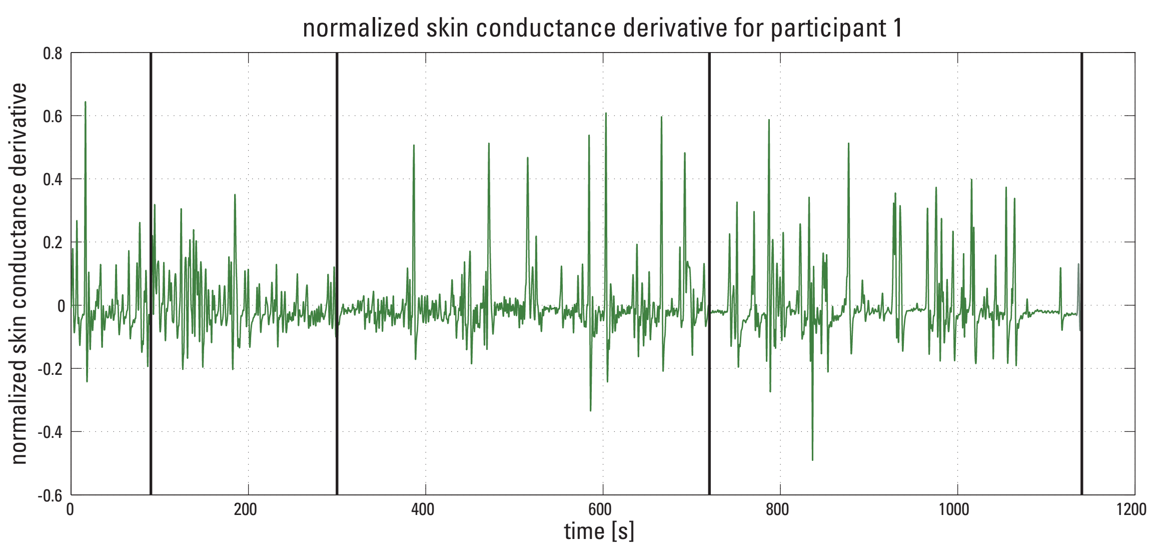

Figure B.41: Normalized skin conductance derivative for a participant during Experiment 2. Black lines delineate experiment stages i, ii, iii, and iv as listed in Figure 4.14.

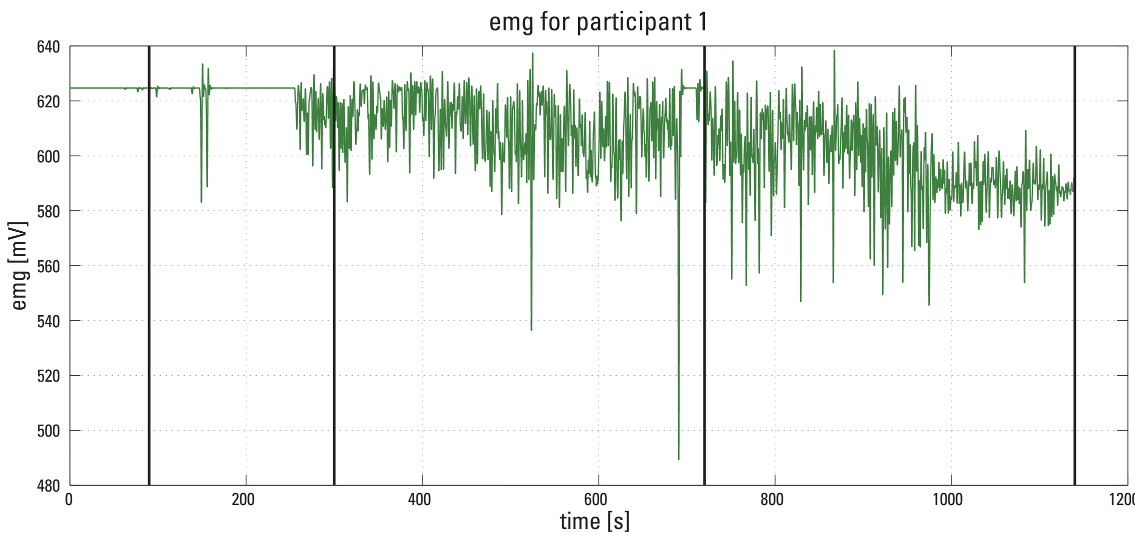

Figure B.42: EMG for a participant during Experiment 2. Black lines delineate experiment stages i, ii, iii, and iv as listed in Figure 4.14.

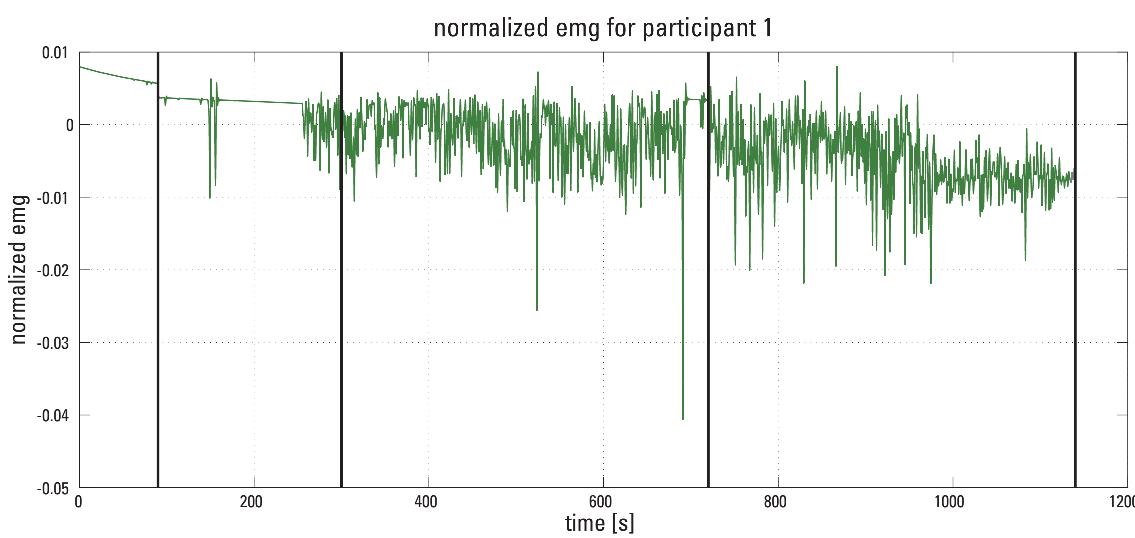

Figure B.43: Normalized EMG for a participant during Experiment 2. Black lines delineate experiment stages i, ii, iii, and iv as listed in Figure 4.14.

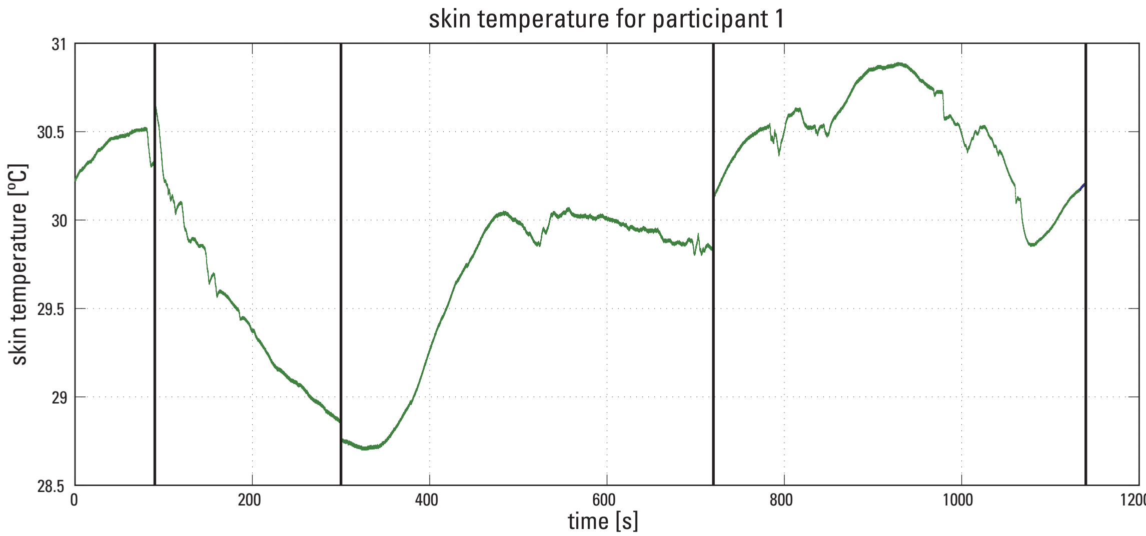

Figure B.44: Skin temperature for a participant during Experiment 2. Black lines delineate experiment stages i, ii, iii, and iv as listed in Figure 4.14.

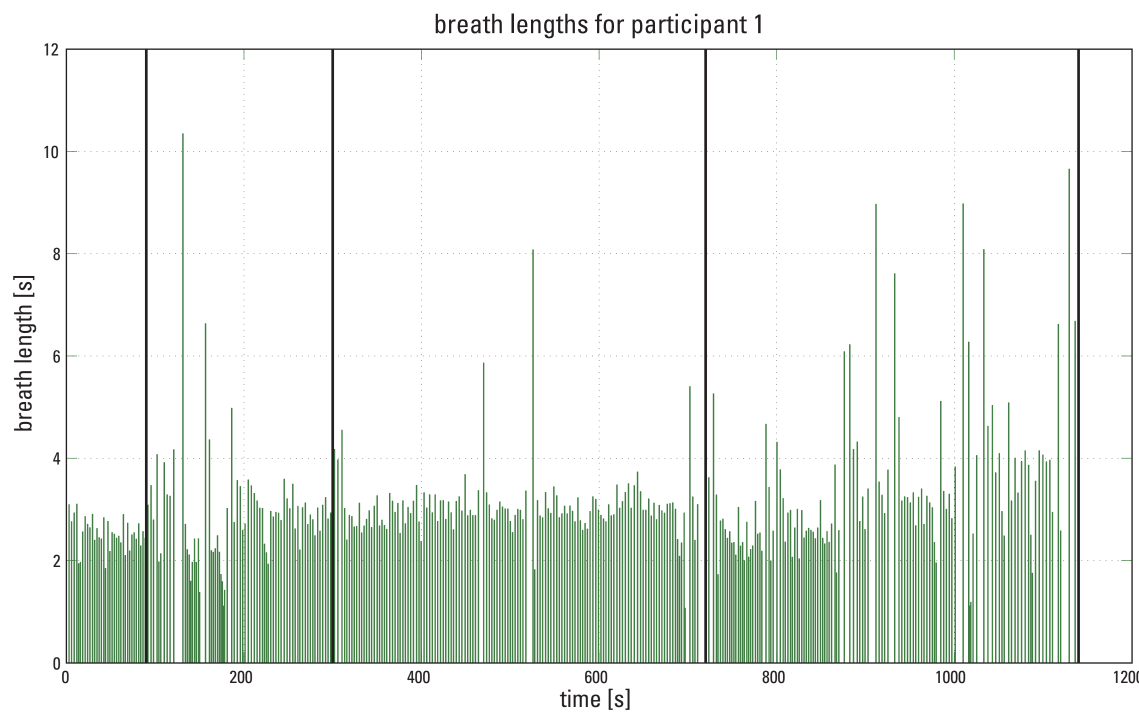

Figure B.45: Breath lengths for a participant during Experiment 2. Black lines delineate experiment stages i, ii, iii, and iv as listed in Figure 4.14.

B.3.4 Sample Comparisons

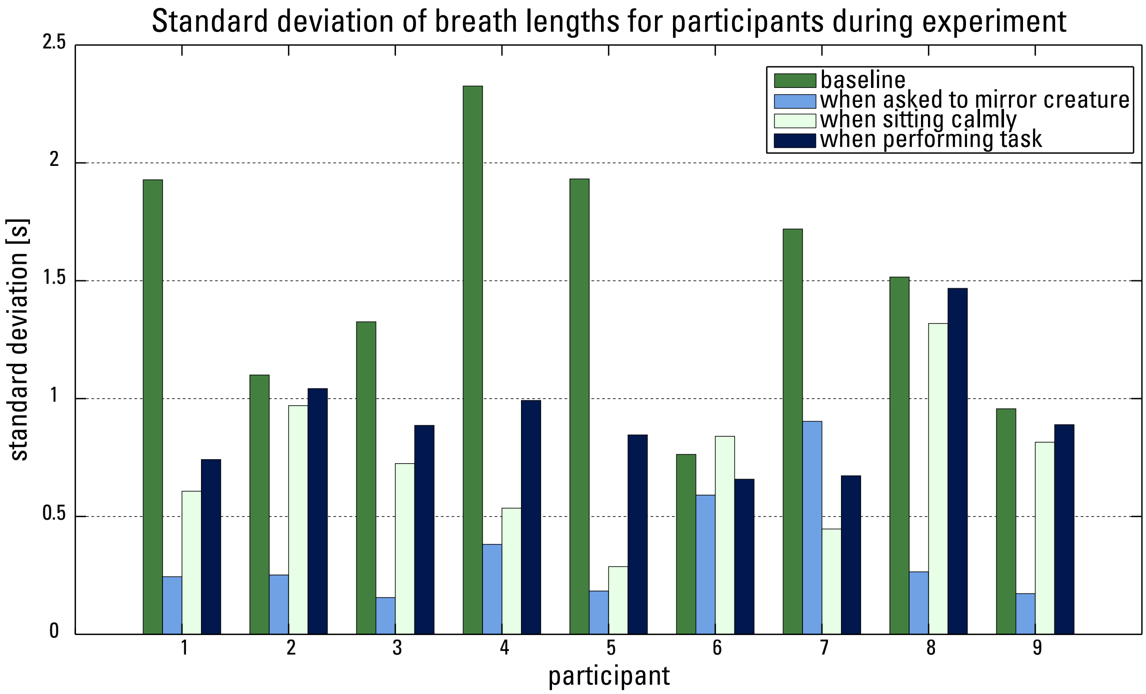

Figure B.46: Standard deviation of breath lengths for all participants during Experiment 2.

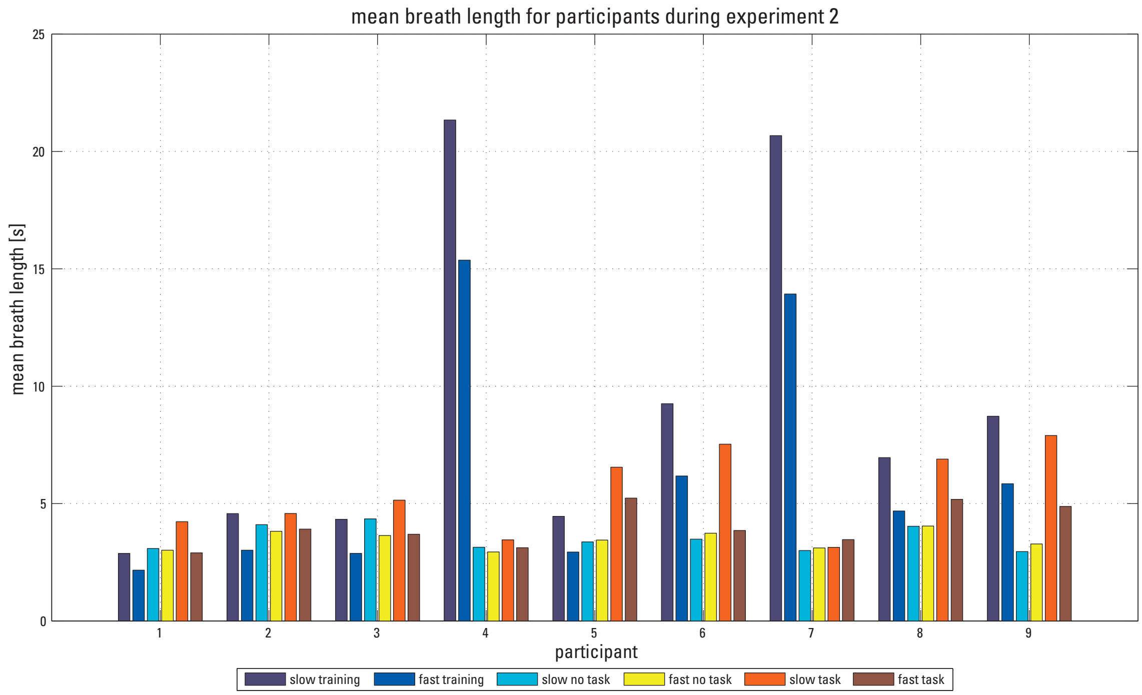

Figure B.47: Mean breath length for all participants during Experiment 2.

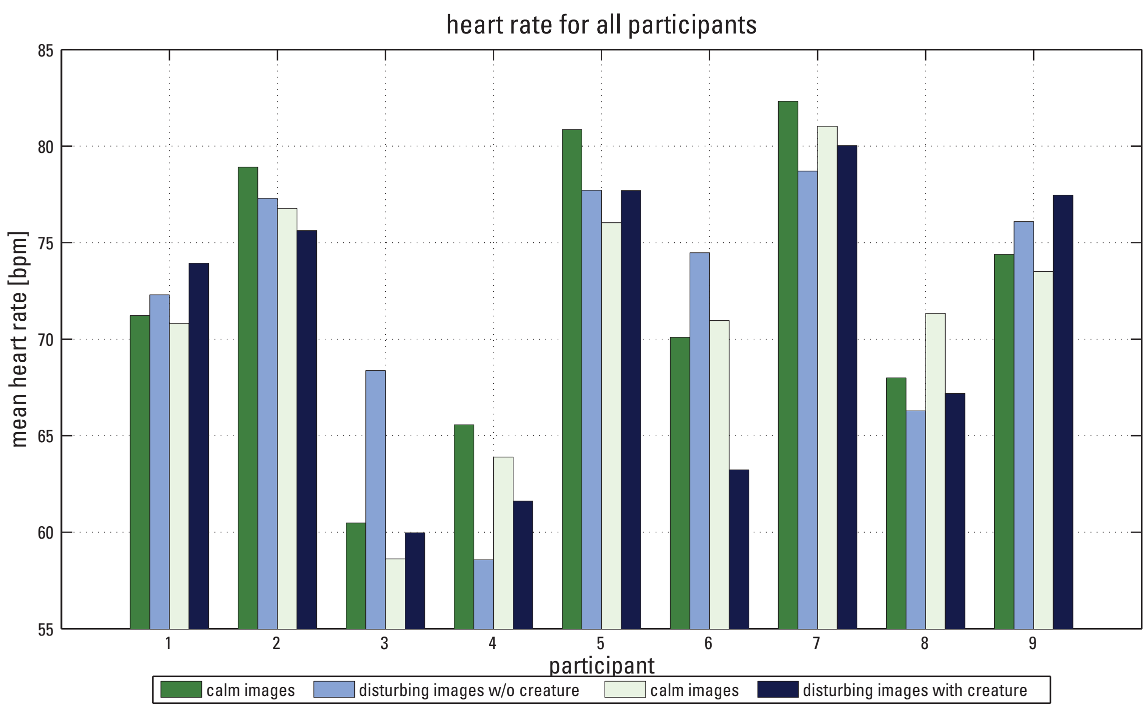

Figure B.48: Mean heart rate for participants during Experiment 2.

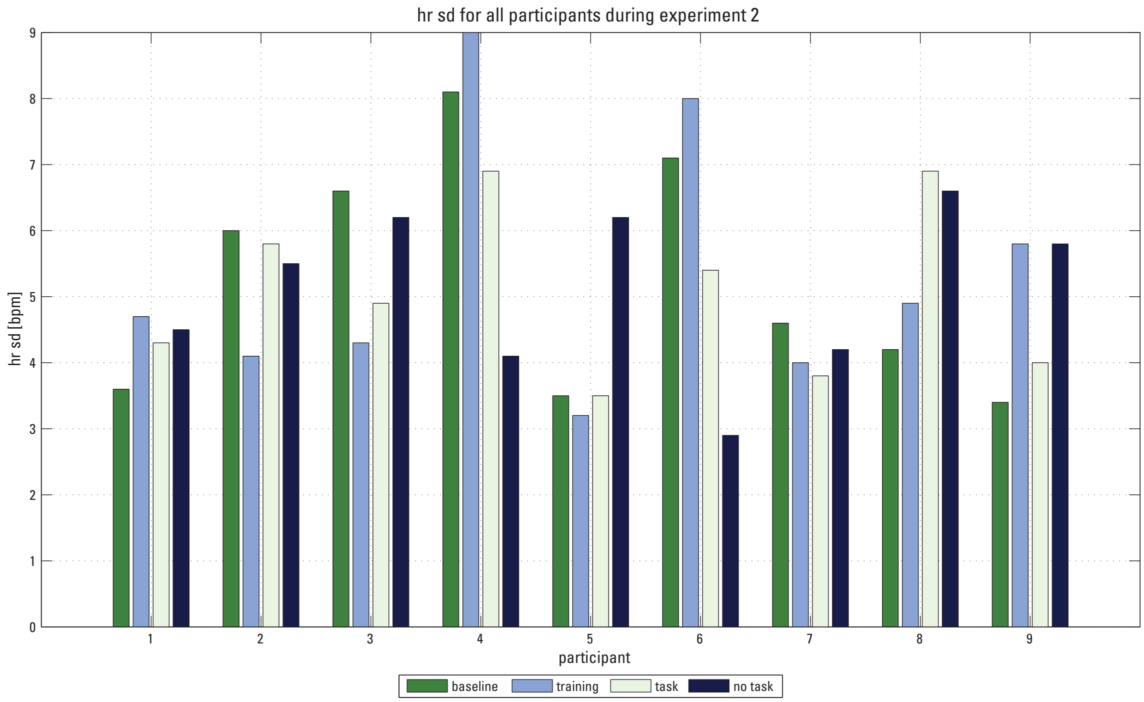

Figure B.49: Mean heart rate standard deviation for participants during Experiment 2.

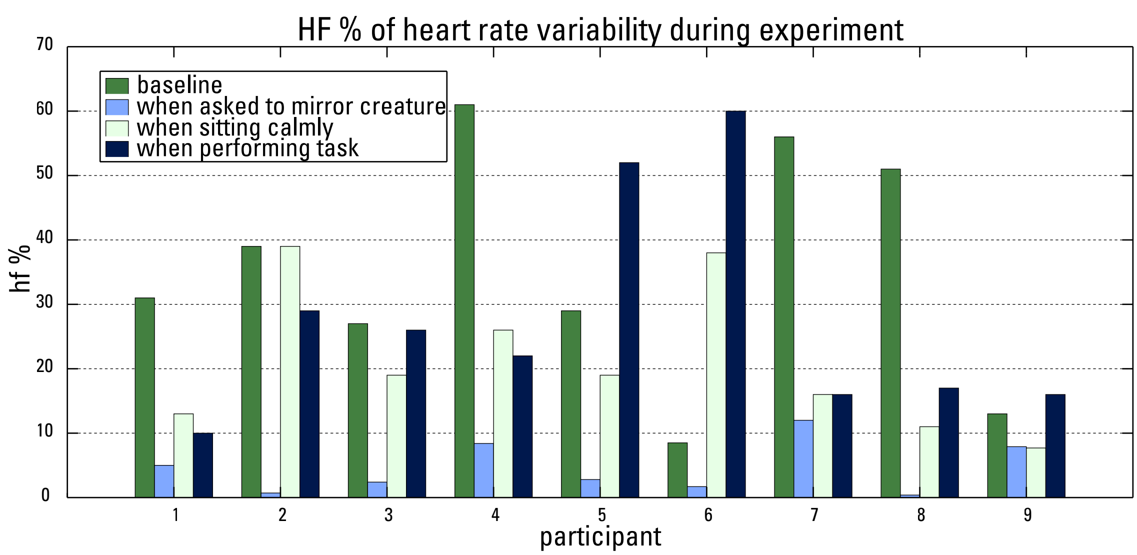

Figure B.50: High frequency component of heart rate variability during Experiment 2 for all participants for all stages.

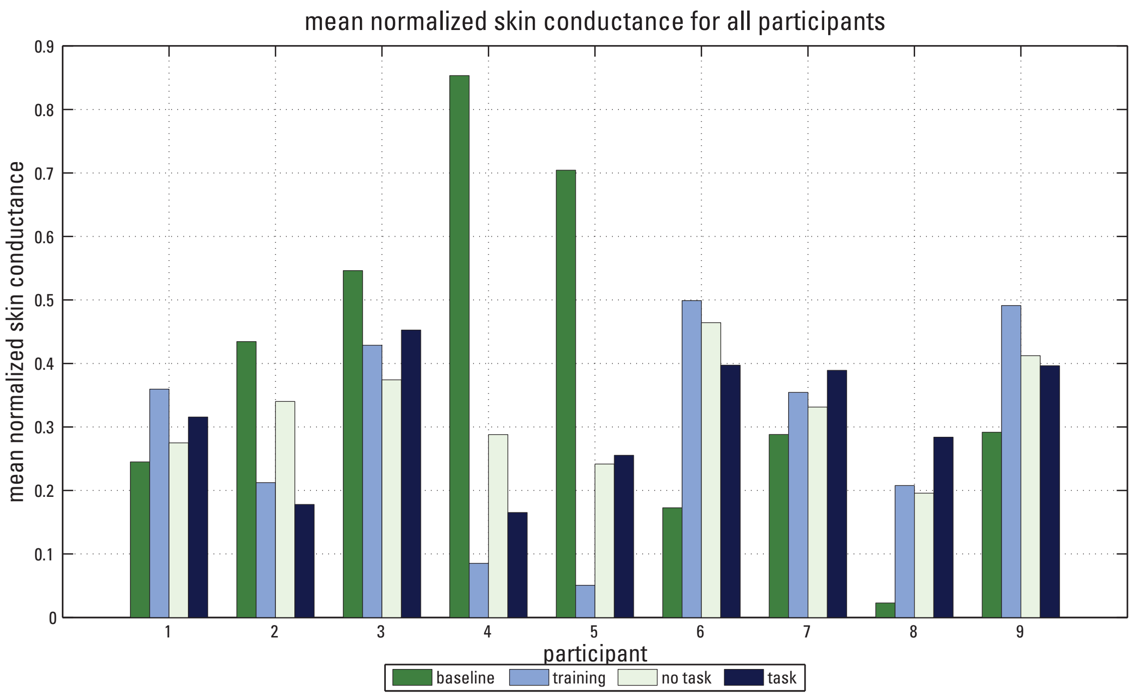

Figure B.51: Mean skin conductance for participants during Experiment 2.

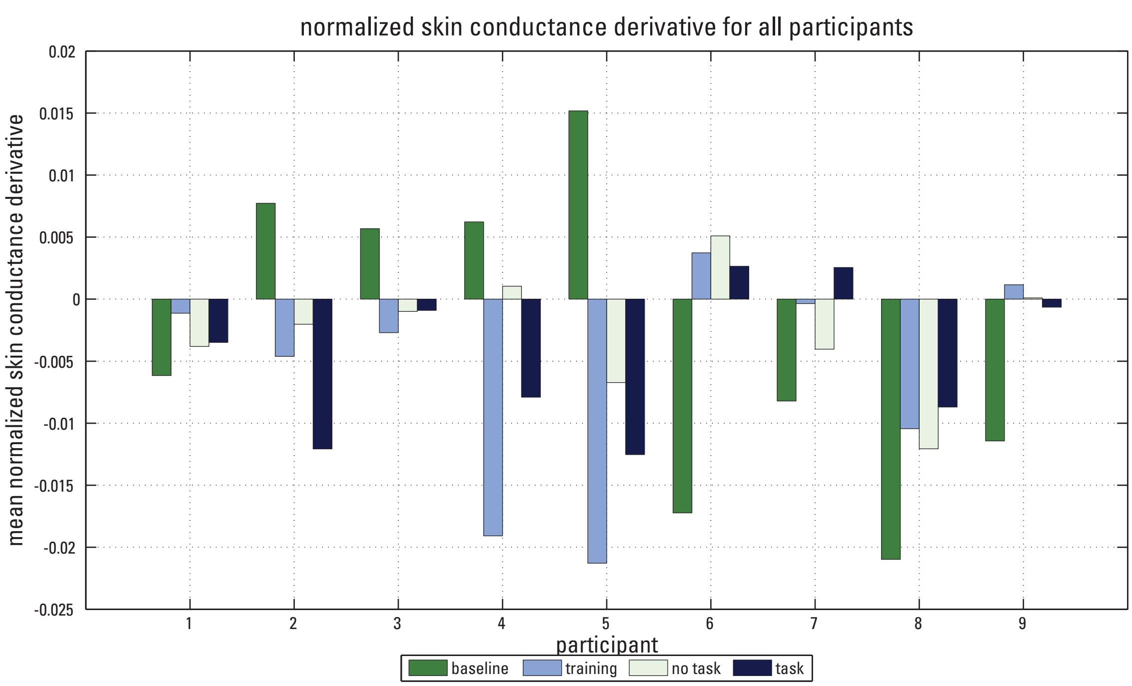

Figure B.52: Mean derivative of skin conductance for participants during Experiment 2.

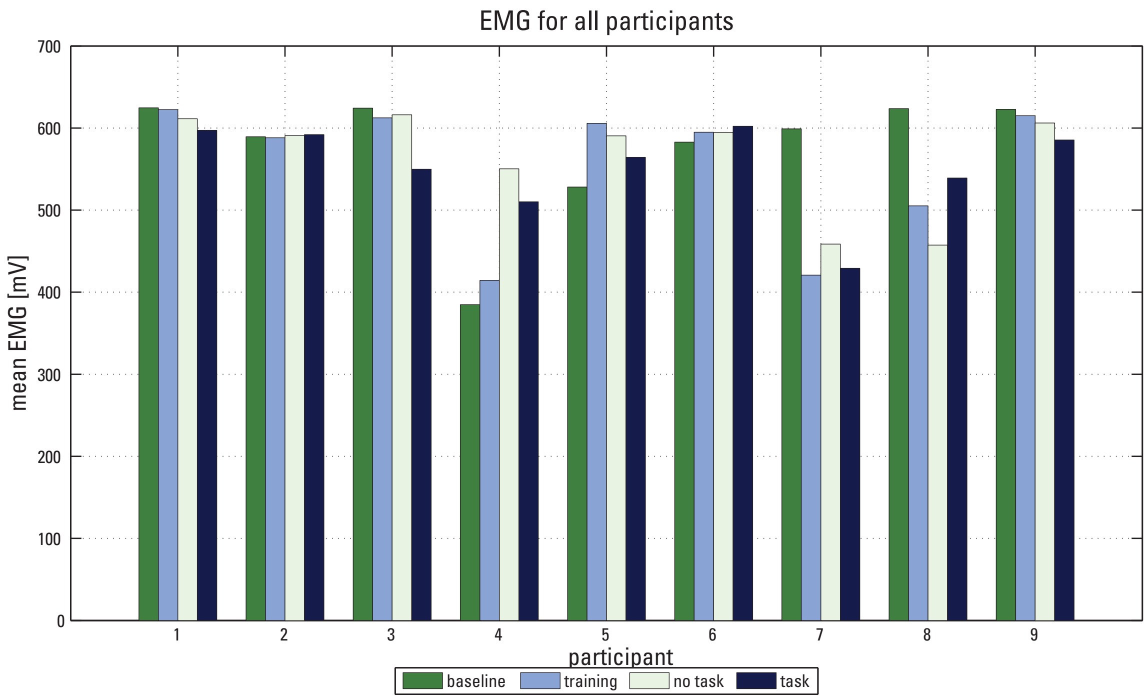

Figure B.53: Mean EMG for participants during Experiment 2.

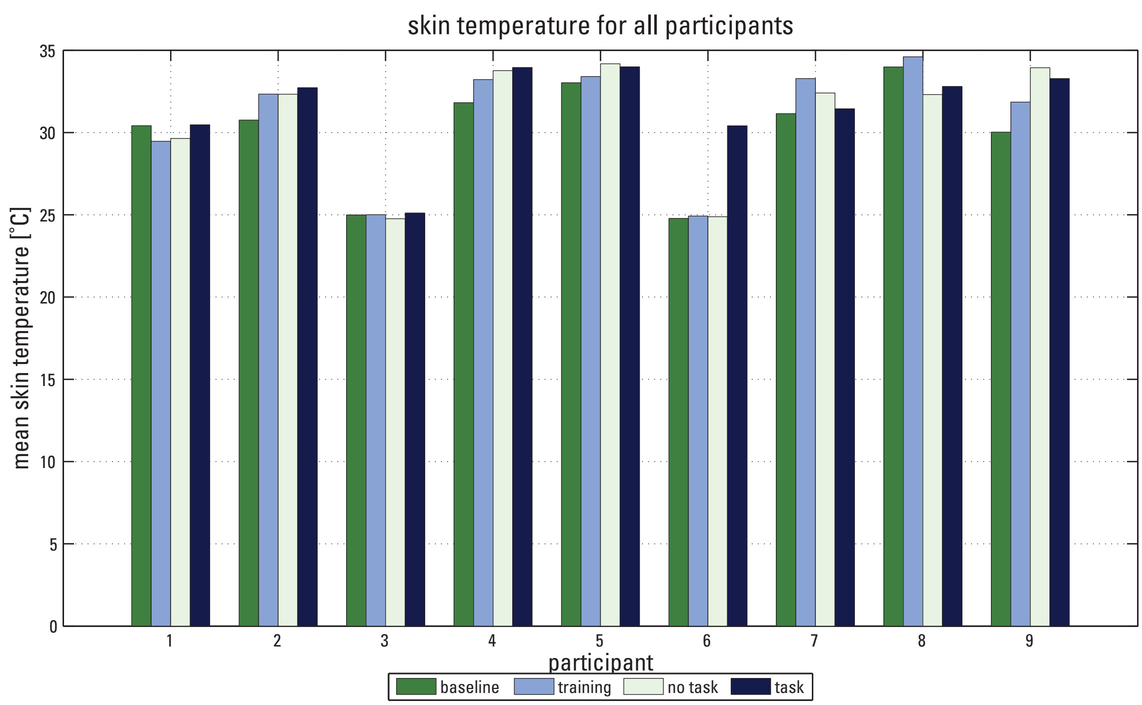

Figure B.54: Mean skin temperature for participants during Experiment 2.

B.3.5 Participant Consent Form

THE UNIVERSITY OF BRITISH COLUMBIA

Department of Computer Science
2366 Main Mall
Vancouver, B.C. Canada V6T 1Z4
tel: (604) 822-3061
fax: (604) 822-4231
(PARTICIPANT'S COPY CONSENT FORM)

Project Title: Investigation of haptic-affect loop through the haptic creature

(UBC Ethics #B01-0470)

Principal Investigators: Dr. Karon MacLean, Department of Computer Science, 604-822-8169

Dr. Elizabeth Croft, Department of Mechanical Engineering, 604-822-6614

Student Investigator: Joseph P. Hall III, Department of Mechanical Engineering, *jphiii@interchange.ubc.ca*

The purpose of this study is to examine your reaction to interaction through touch with a robotic pet.

You will be asked to hold and touch a small robot that may gently move. You will be asked to wear external (i.e. non-invasive) sensors that collect some basic physiological information such as heart rate, respiration rate, some muscle activity, and perspiration. Please tell the experimenter if you find the sensors uncomfortable and adjustments will be made. You will be asked to answer questions in a questionnaire as part of the experiment.

If you are unsure about any instructions, do not hesitate to ask.

TIME COMMITMENT: $\frac{1}{2}$ -1 hour session

CONFIDENTIALITY: *Your results will be confidential: you will not be identified by name in any study reports. Test results will be stored in a secure computer account accessible only to the experimenters.*

You understand that the experimenters will ANSWER ANY QUESTIONS you have about the instructions or the procedures of this study. After participating, the experimenter will answer any other questions you have about this study.

Your participation in this study is entirely voluntary and you may refuse to participate or withdraw from the study at any time without jeopardy. Your signature below indicates that you have received a copy of this consent form for your own records, and consent to participate in this study.

If you have any concerns about your treatment or rights as a research subject, you may contact the Research Subject Info Line in the UBC Office of Research Services at 604-822-8598.

Version 1.1 / December 2, 2009

B.4 Experiment 3

B.4.1 Sample Data

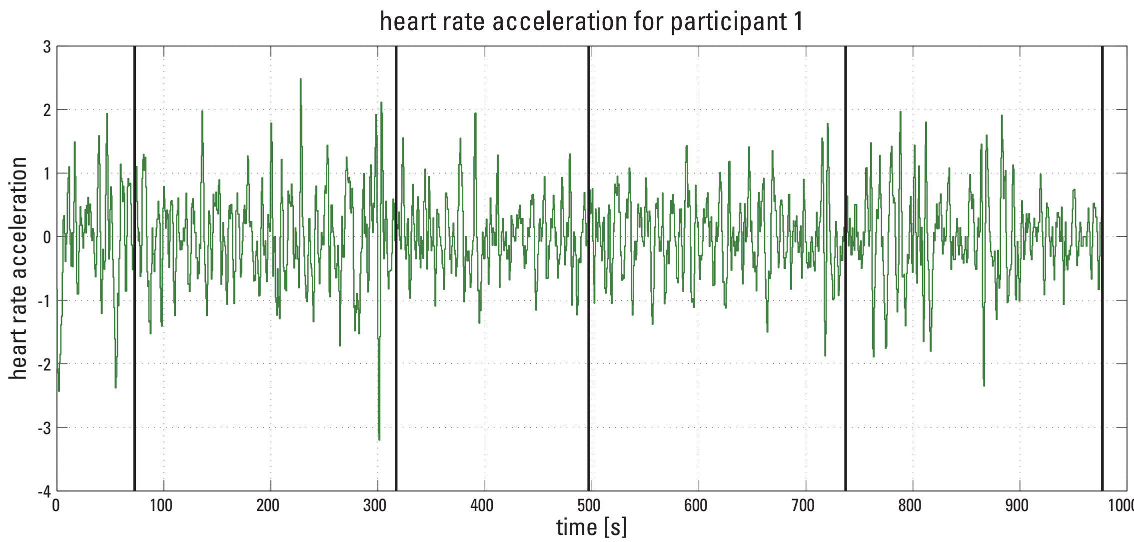

Figure B.55: Heart rate acceleration for a participant during Experiment 3. Black lines delineate experiment stages as listed in Figure 4.22.

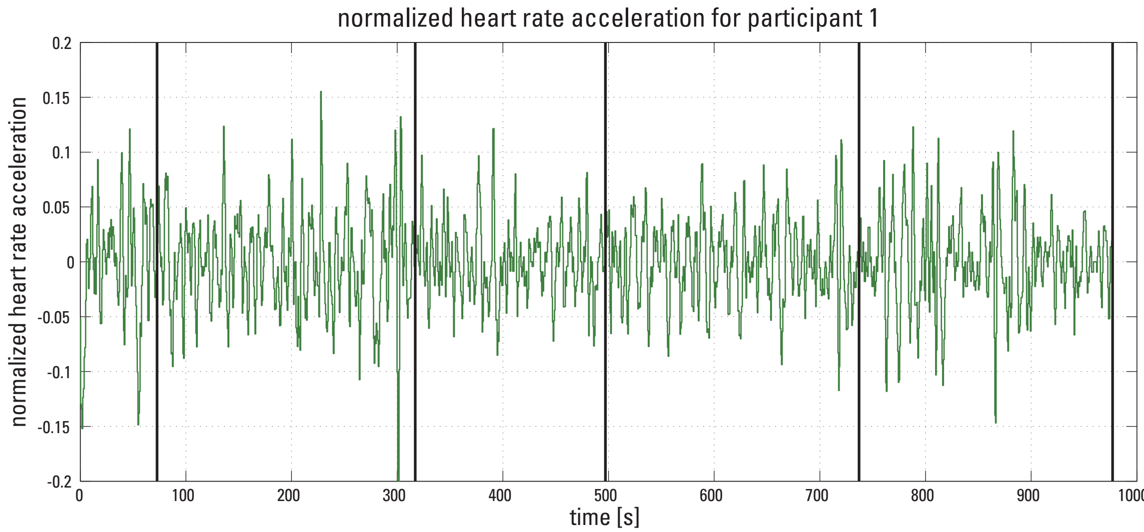

Figure B.56: Normalized heart rate acceleration for a participant during Experiment 3. Black lines delineate experiment stages as listed in Figure 4.22.

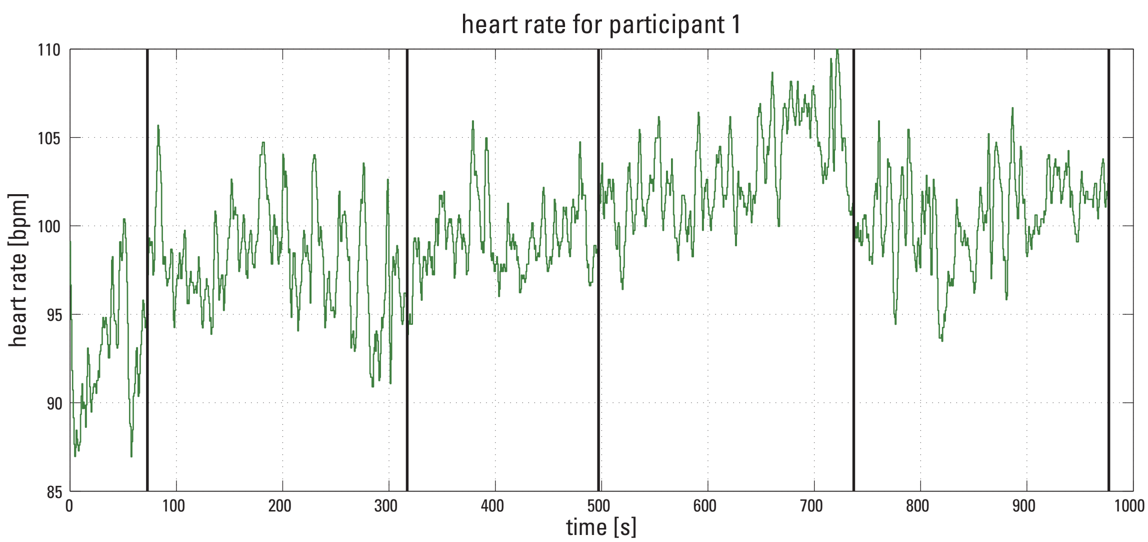

Figure B.57: Heart rate for a participant during Experiment 3. Black lines delineate experiment stages as listed in Figure 4.22.

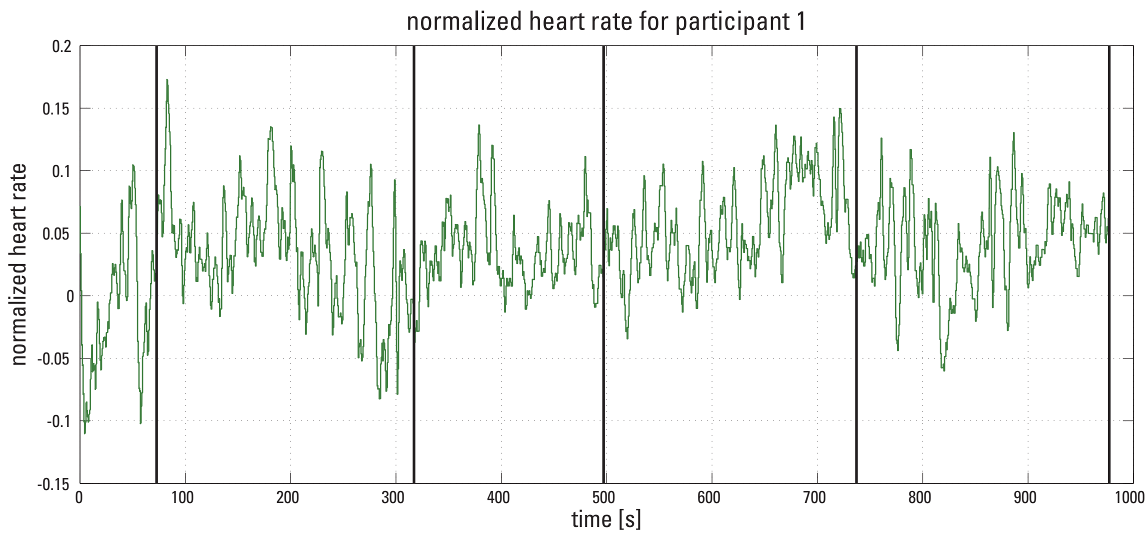

Figure B.58: Normalized Heart Rate for a participant during Experiment 3. Black lines delineate experiment stages as listed in Figure 4.22.

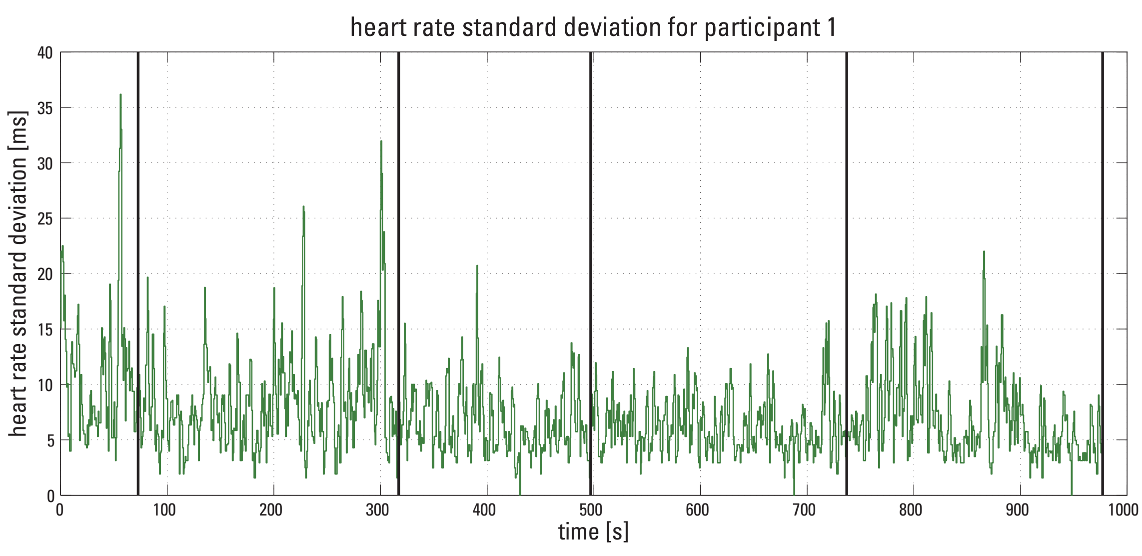

Figure B.59: Normalized heart rate standard deviation for a participant during Experiment 3. Black lines delineate experiment stages as listed in Figure 4.22.

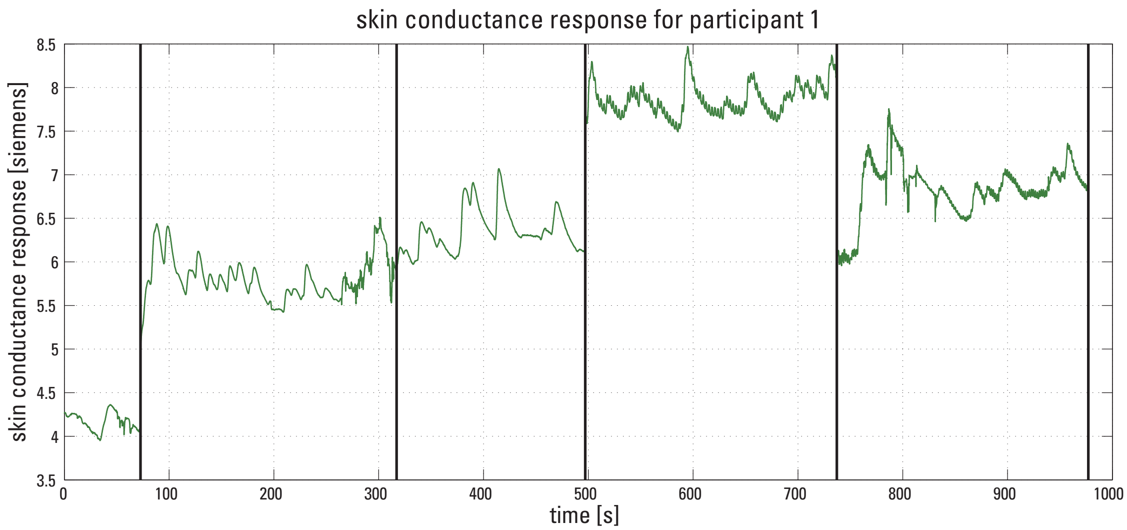

Figure B.60: Skin conductance response for a participant during Experiment 3. Black lines delineate experiment stages as listed in Figure 4.22.

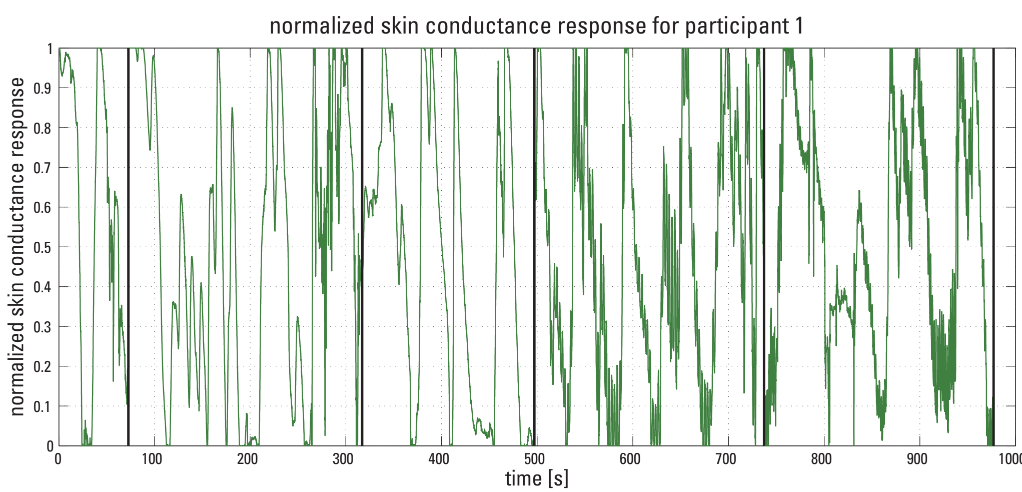

Figure B.61: Normalized skin conductance for a participant during Experiment 3. Black lines delineate experiment stages as listed in Figure 4.22.

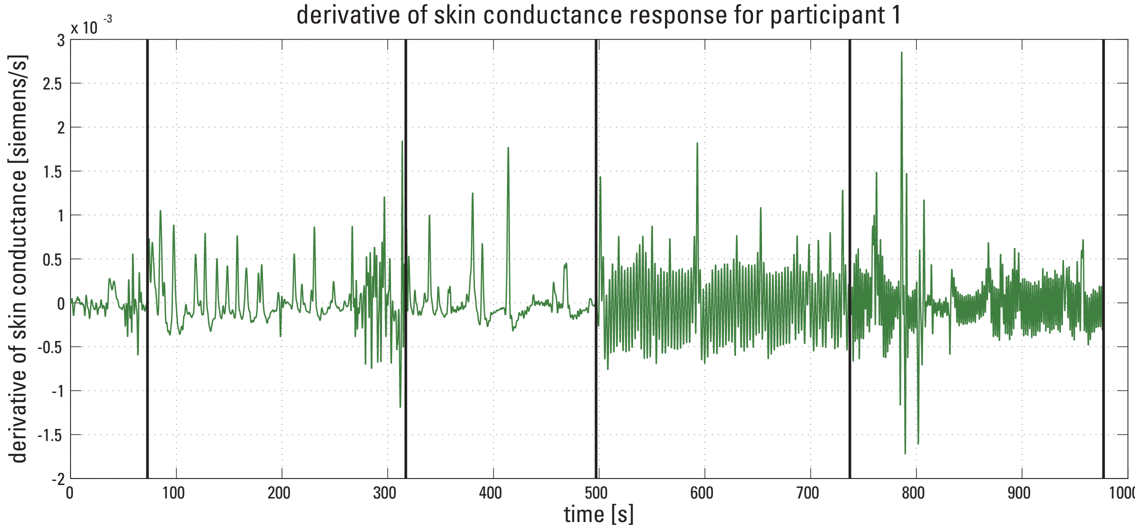

Figure B.62: Skin conductance derivative for a participant during Experiment 3. Black lines delineate experiment stages as listed in Figure 4.22.

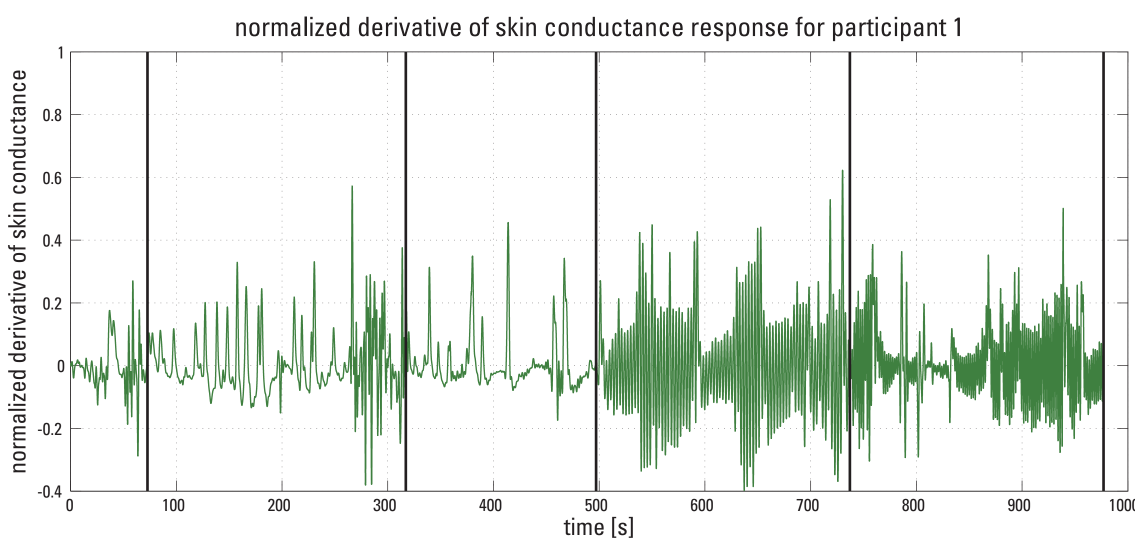

Figure B.63: Normalized skin conductance derivative for a participant during Experiment 3. Black lines delineate experiment stages as listed in Figure 4.22.

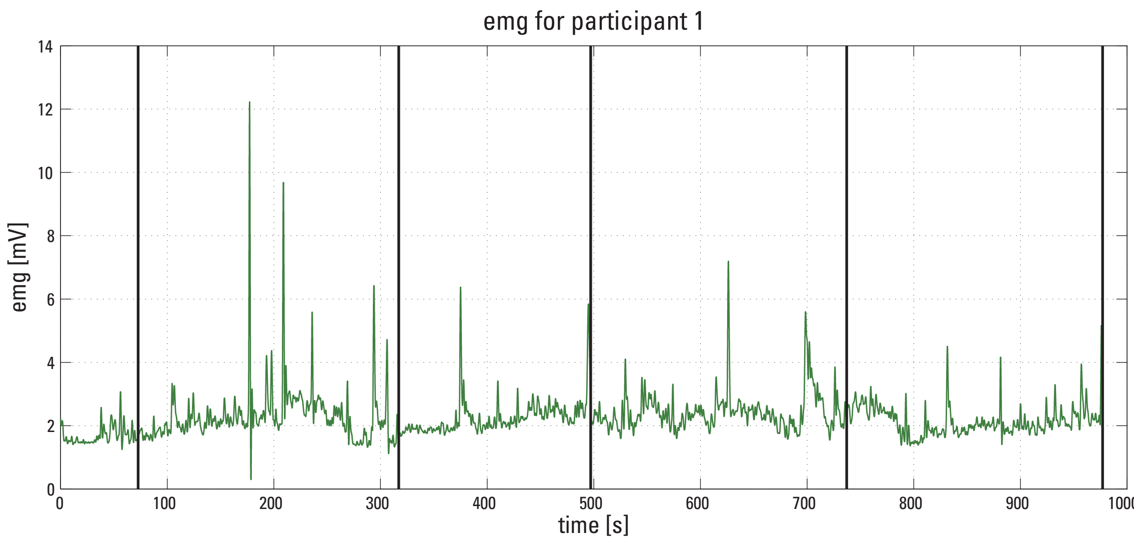

Figure B.64: EMG for a participant during Experiment 3. Black lines delineate experiment stages as listed in Figure 4.22.

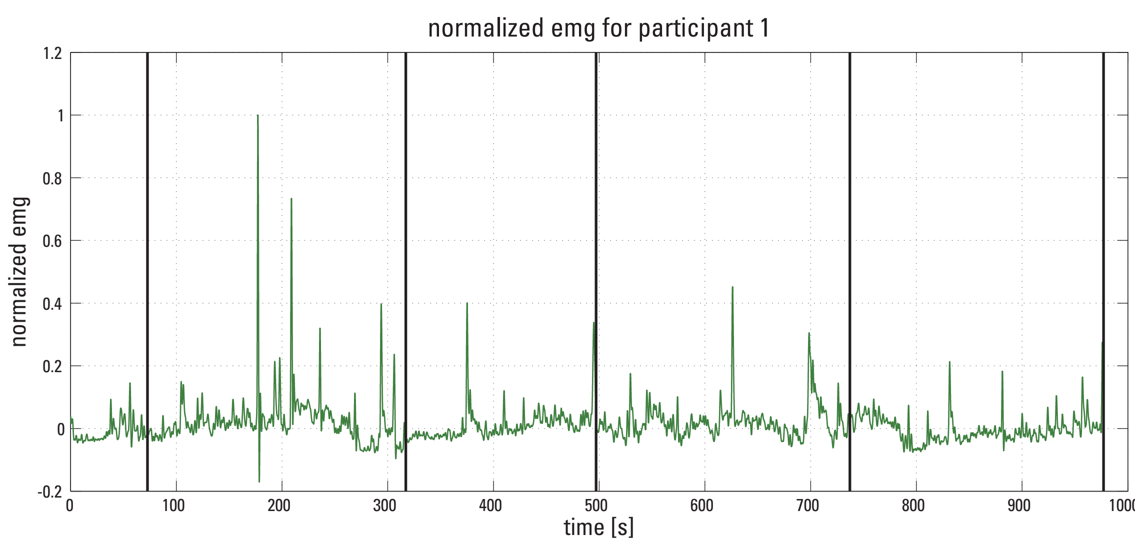

Figure B.65: Normalized EMG for a participant during Experiment 3. Black lines delineate experiment stages as listed in Figure 4.22.

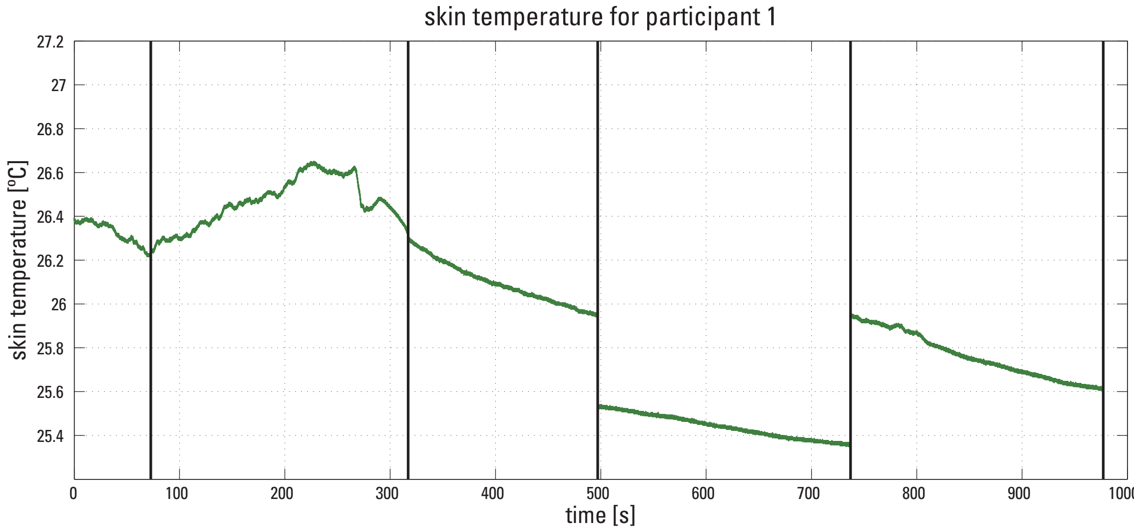

Figure B.66: Skin temperature for a participant during Experiment 3. Black lines delineate experiment stages as listed in Figure 4.22.

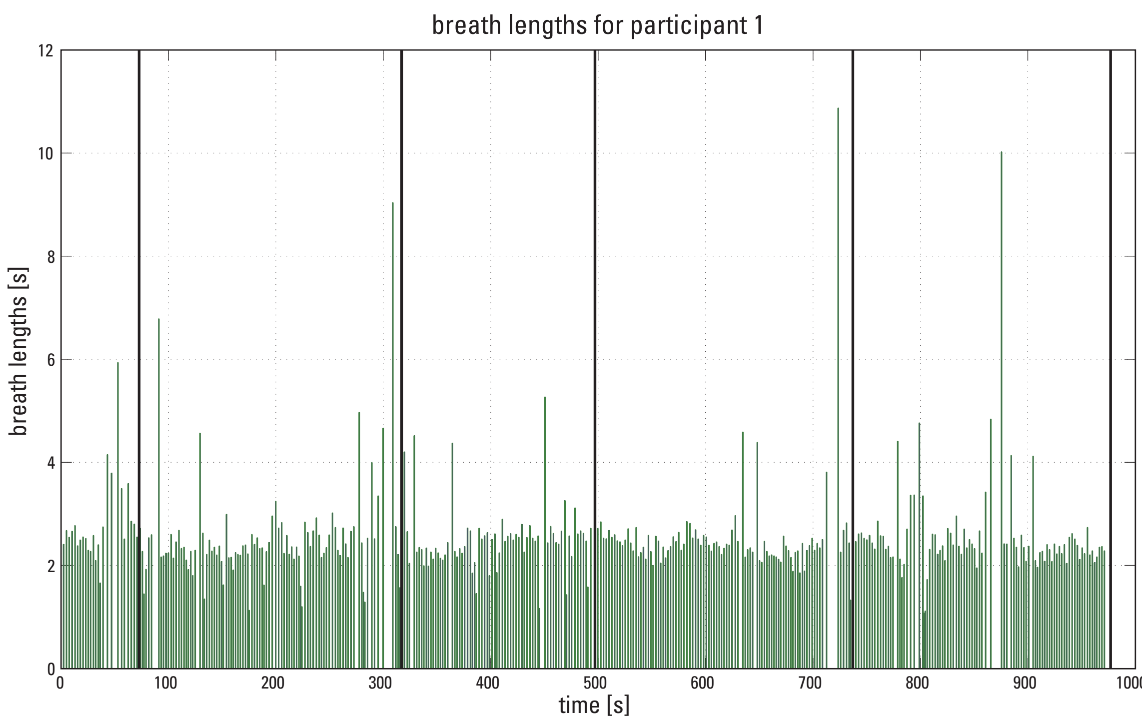

Figure B.67: Breath lengths for a participant during Experiment 3. Black lines delineate experiment stages as listed in Figure 4.22.

B.4.2 Sample Comparisons

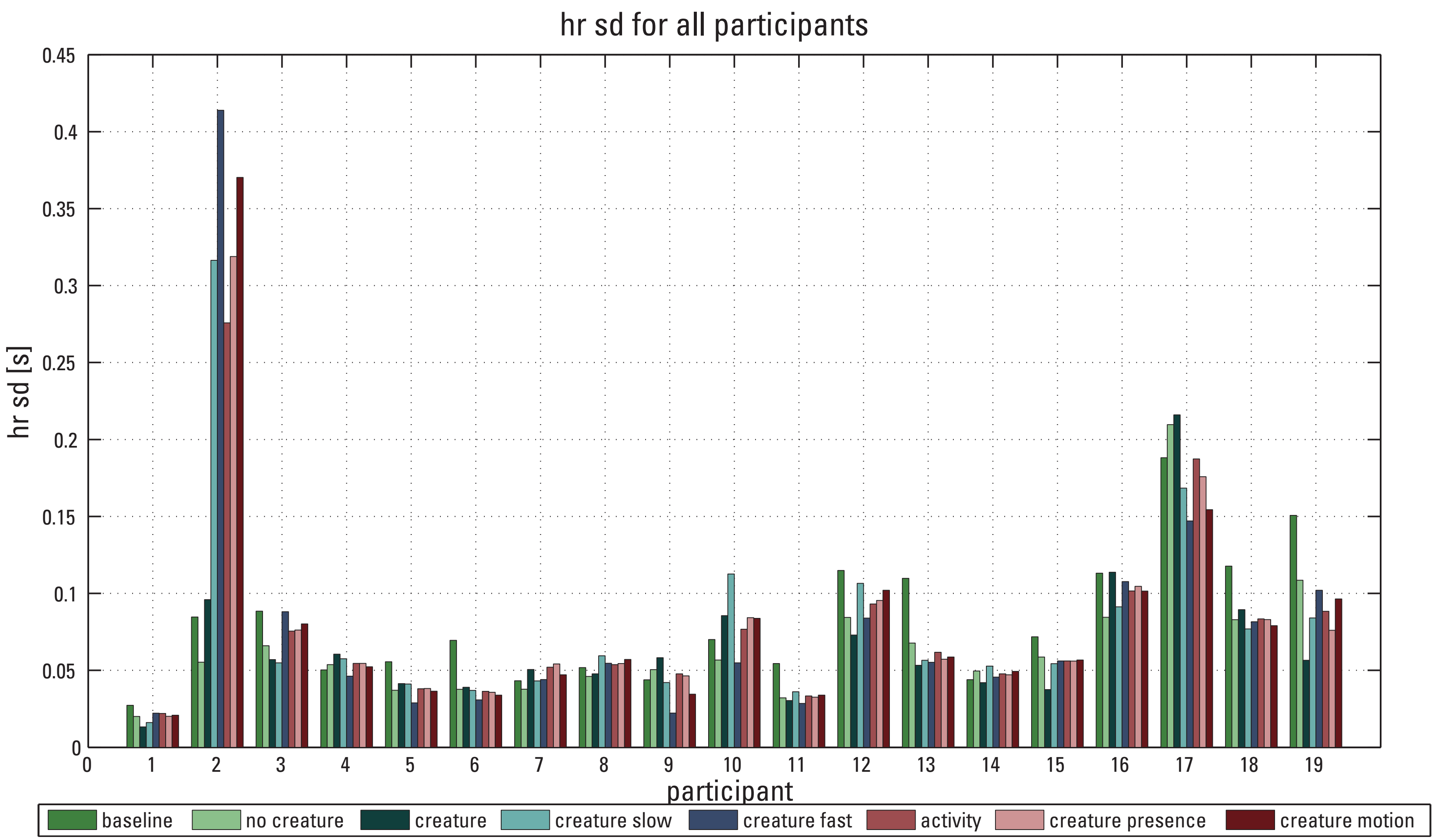

Figure B.68: Mean heart rate standard deviation for participants during Experiment 3.

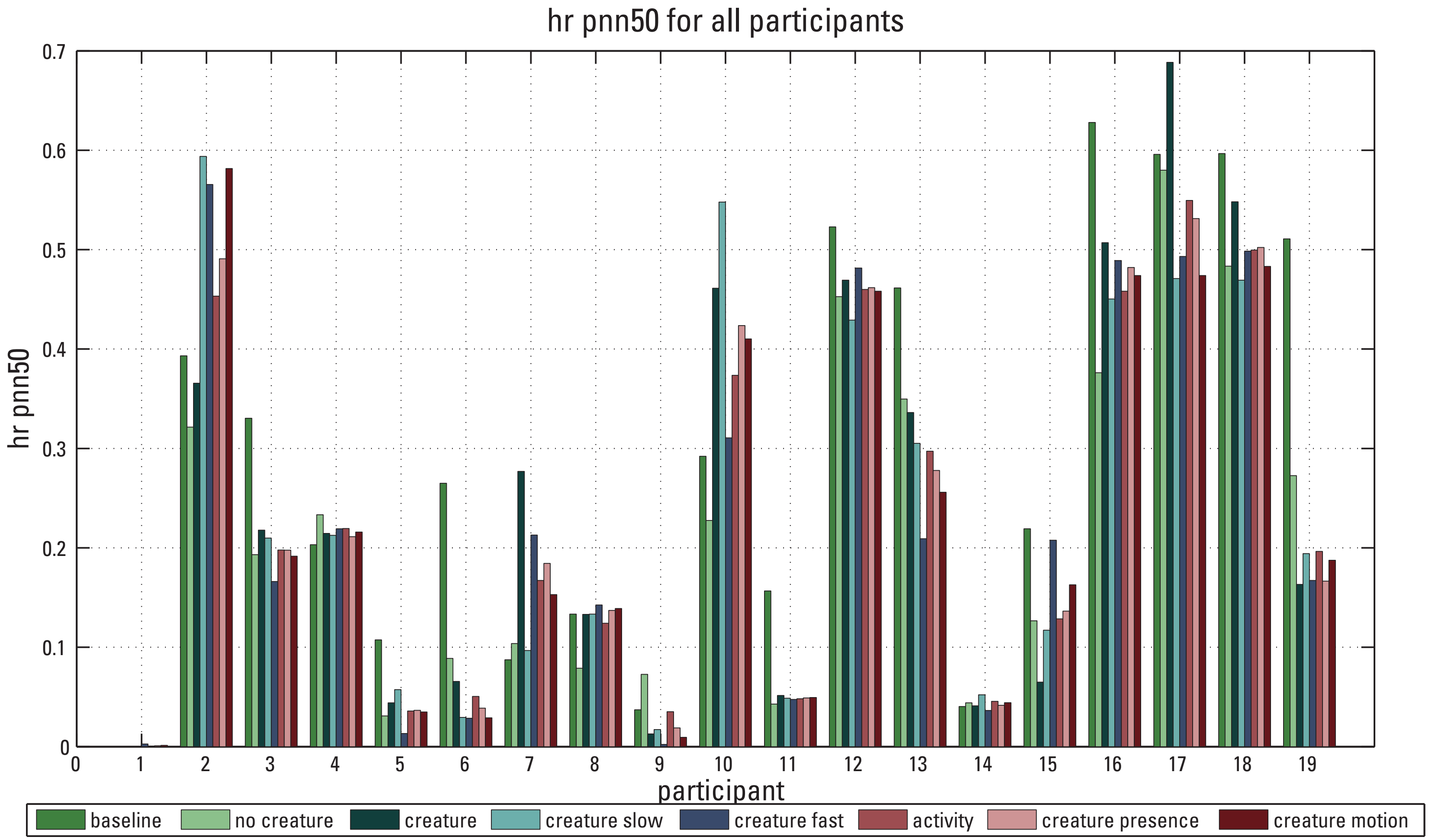

Figure B.69: Mean heart rate pnn50 for participants during Experiment 3.

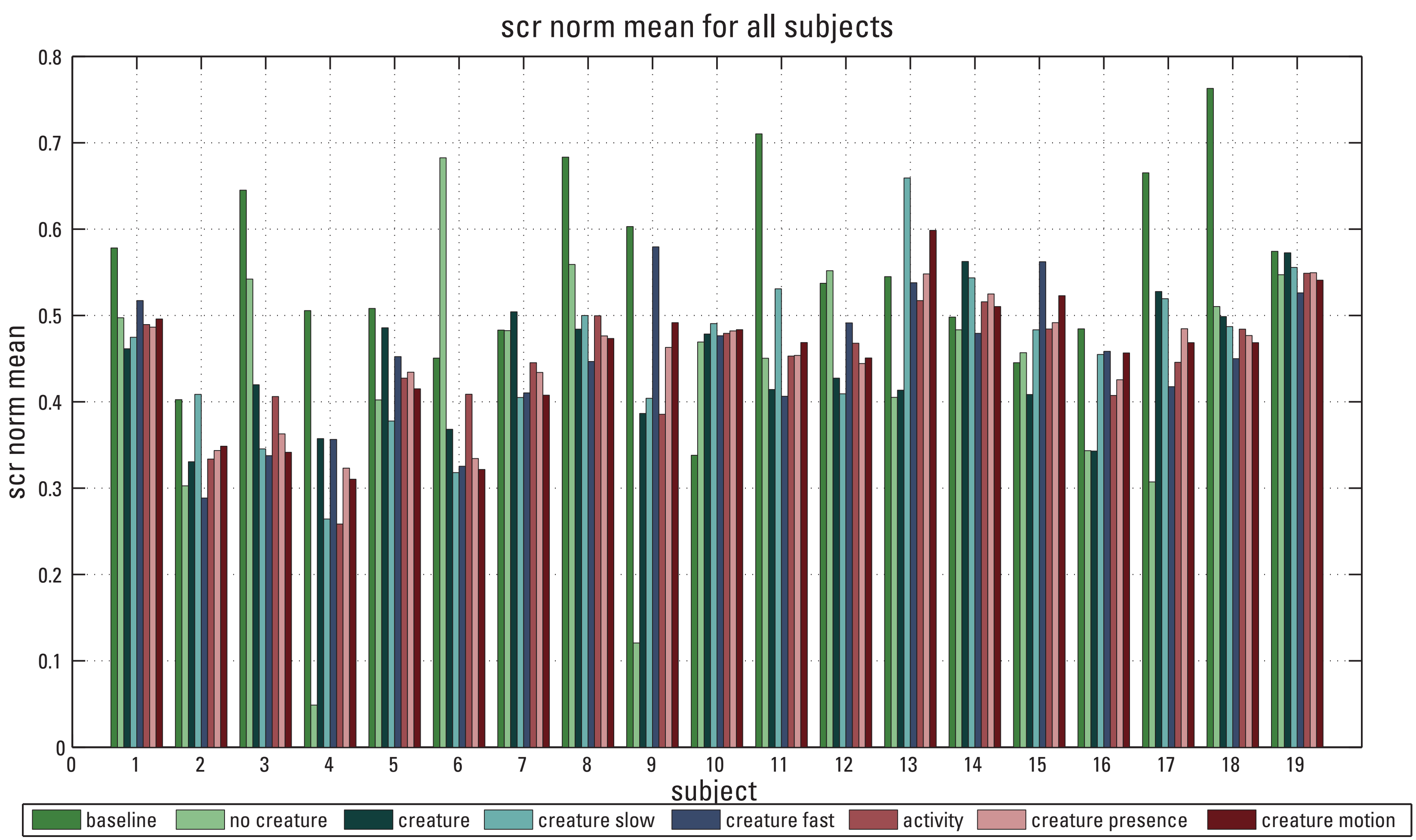

Figure B.70: Mean skin conductance for participants during Experiment 3.

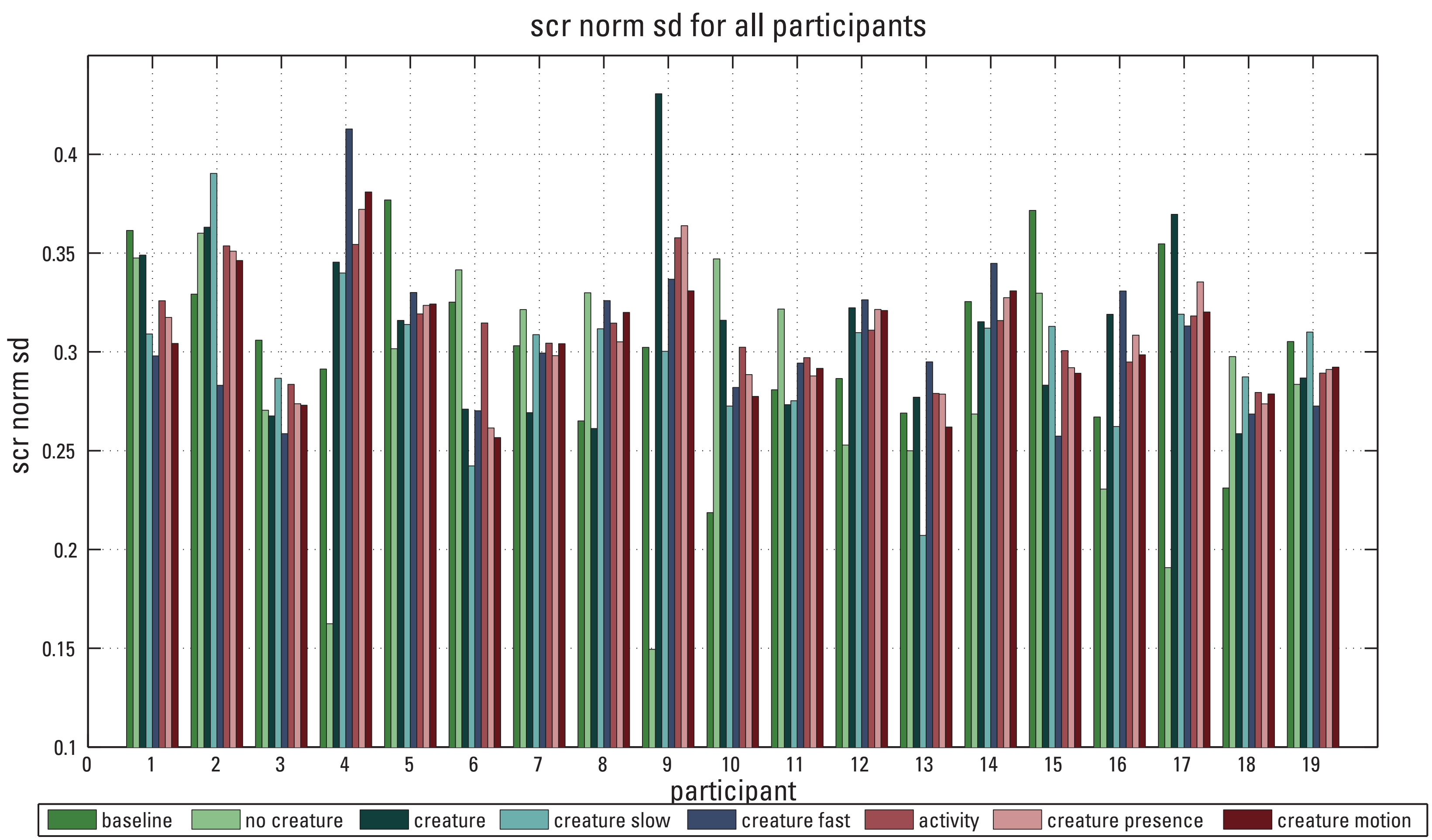

Figure B.71: Mean skin conductance standard deviation for participants during Experiment 3.

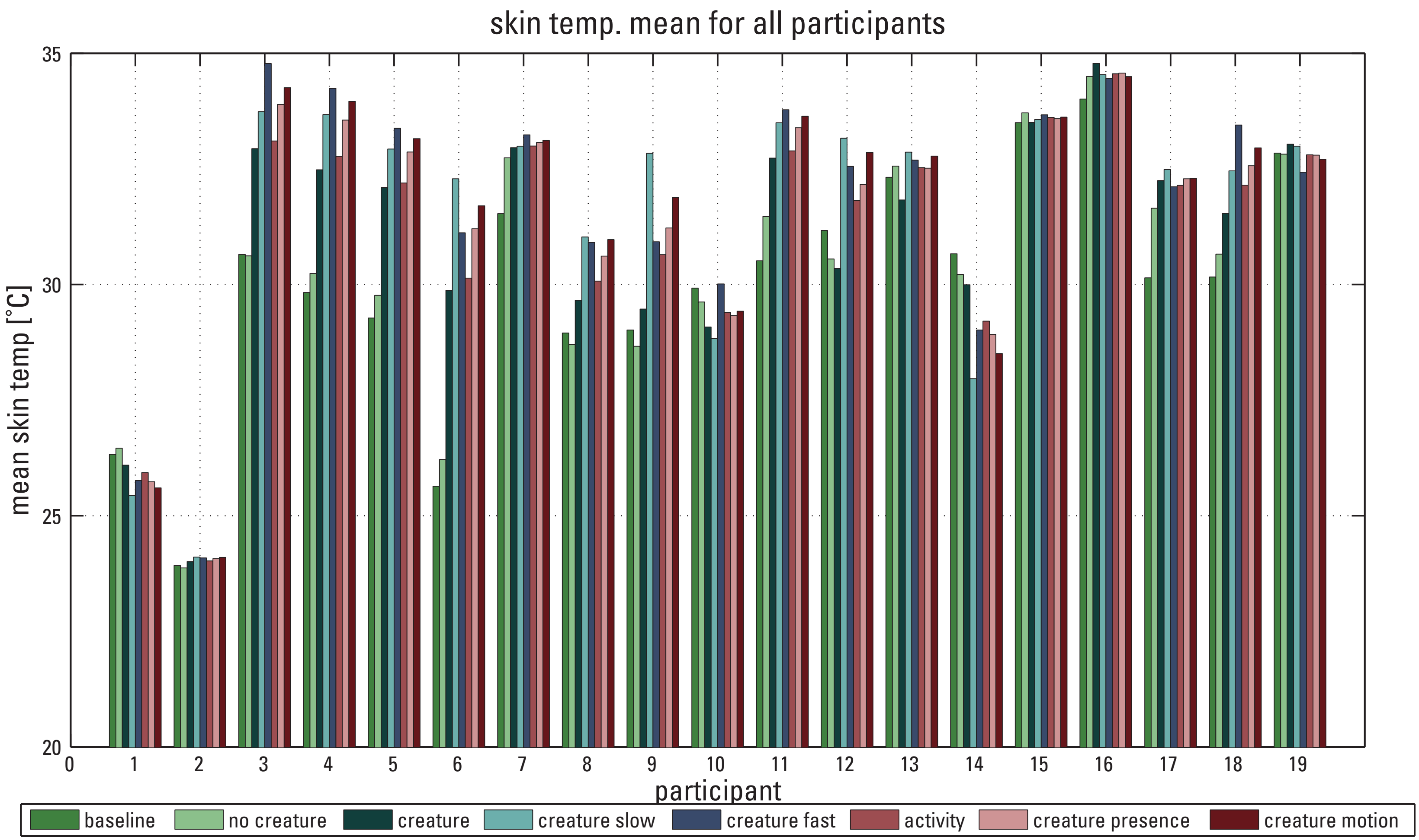

Figure B.72: Mean skin temperature for participants during Experiment 3.

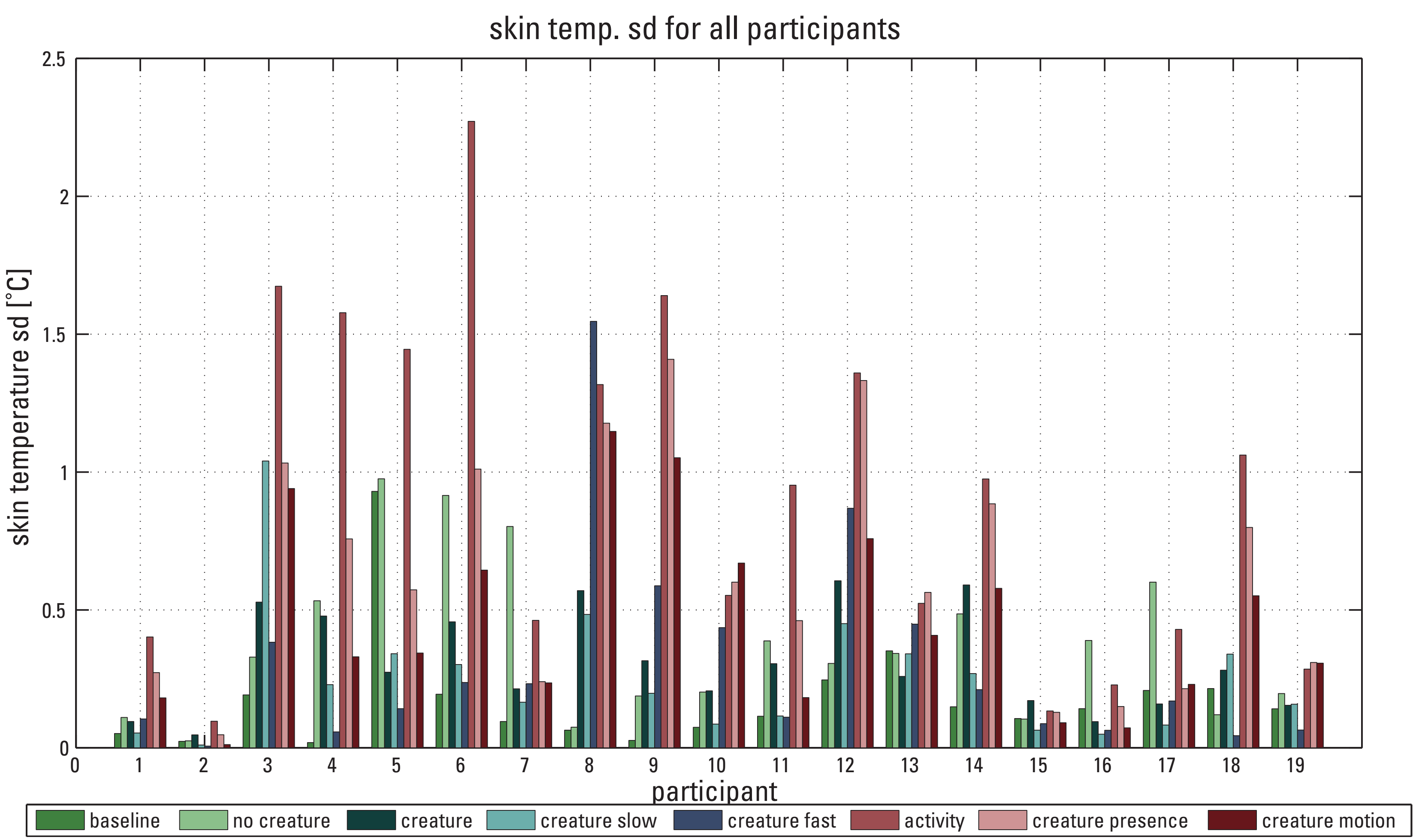

Figure B.73: Mean skin temperature standard deviation for participants during Experiment 3.

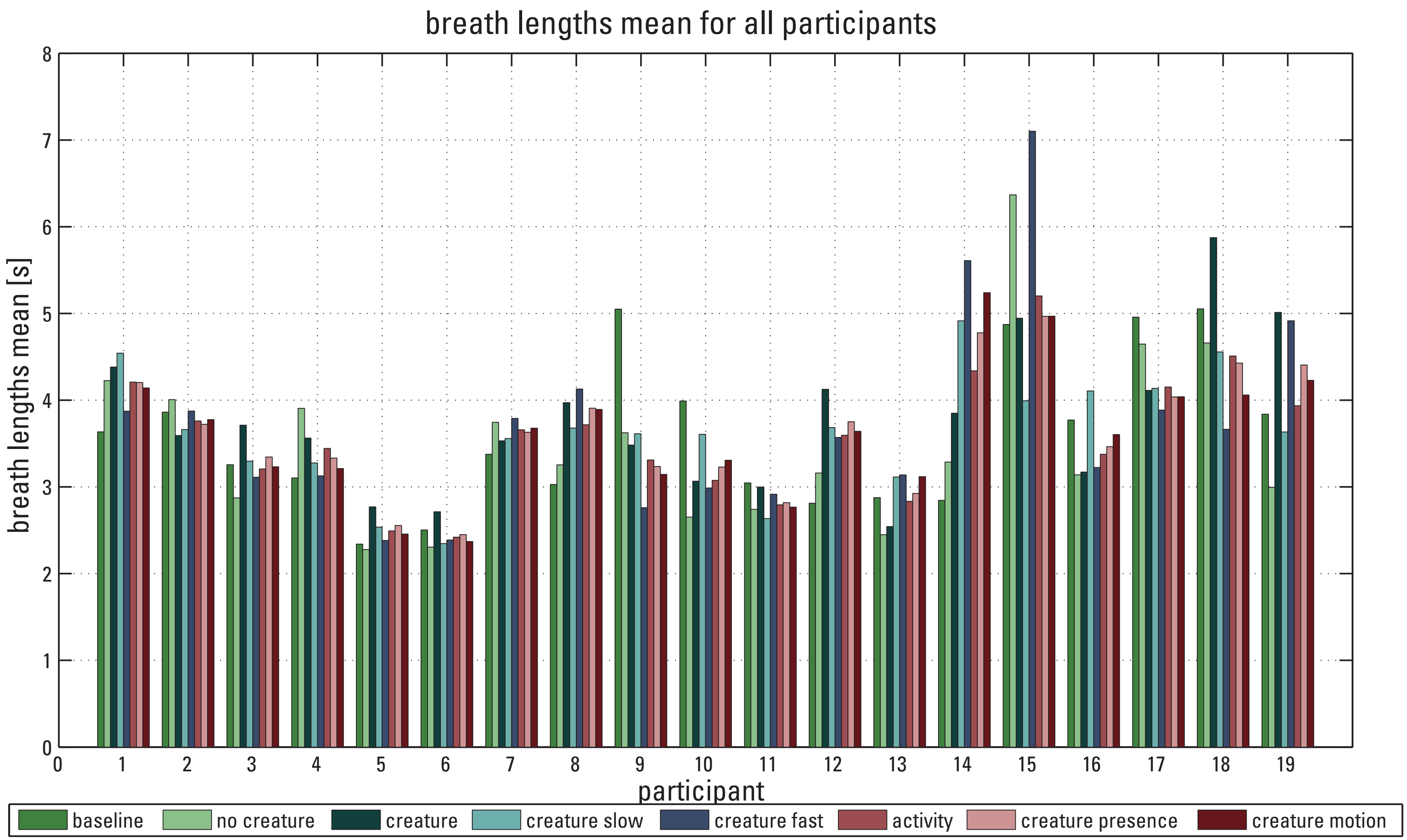

Figure B.74: Mean breath length for participants during Experiment 3.

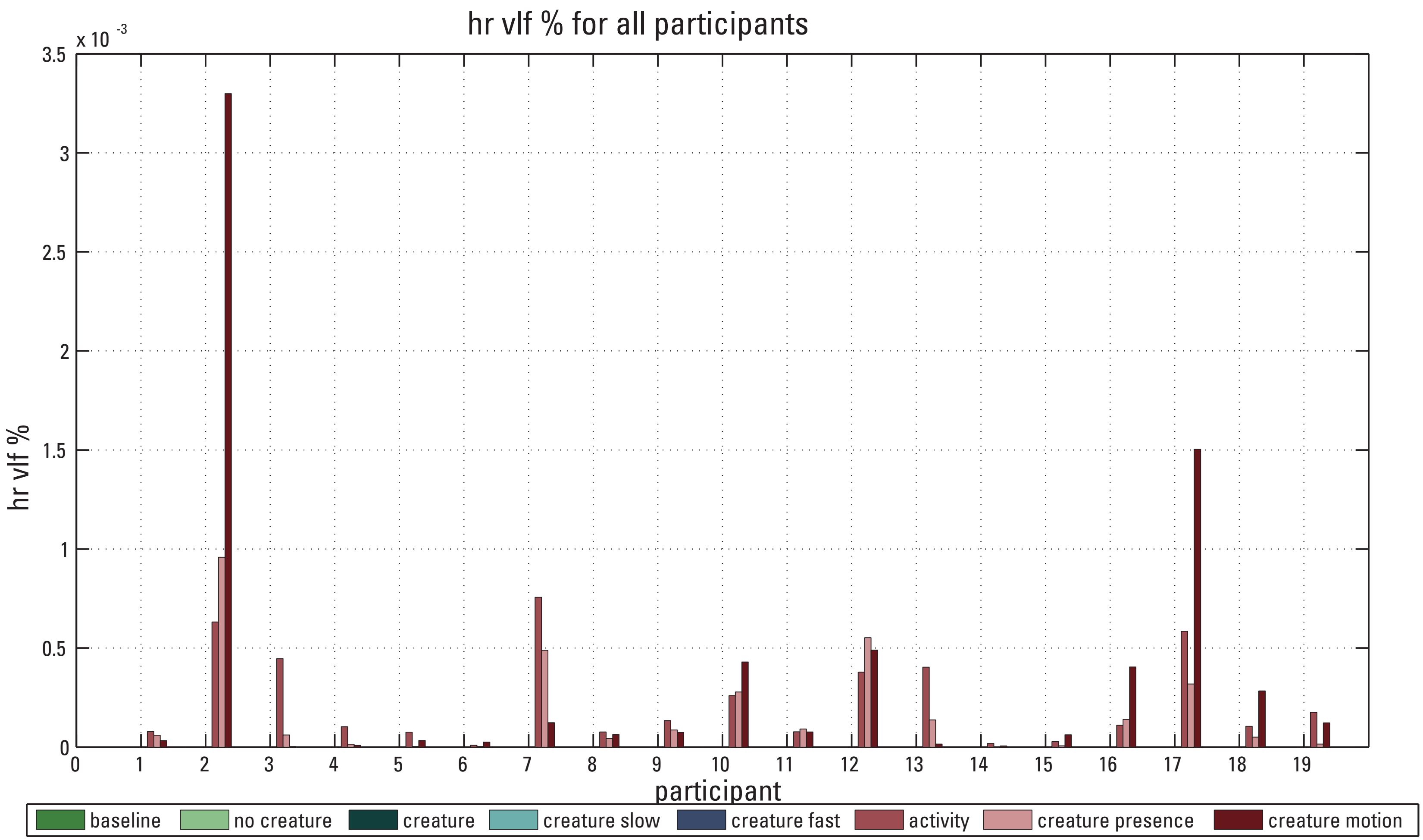

Figure B.75: Heart rate vlf% for participants during Experiment 3.

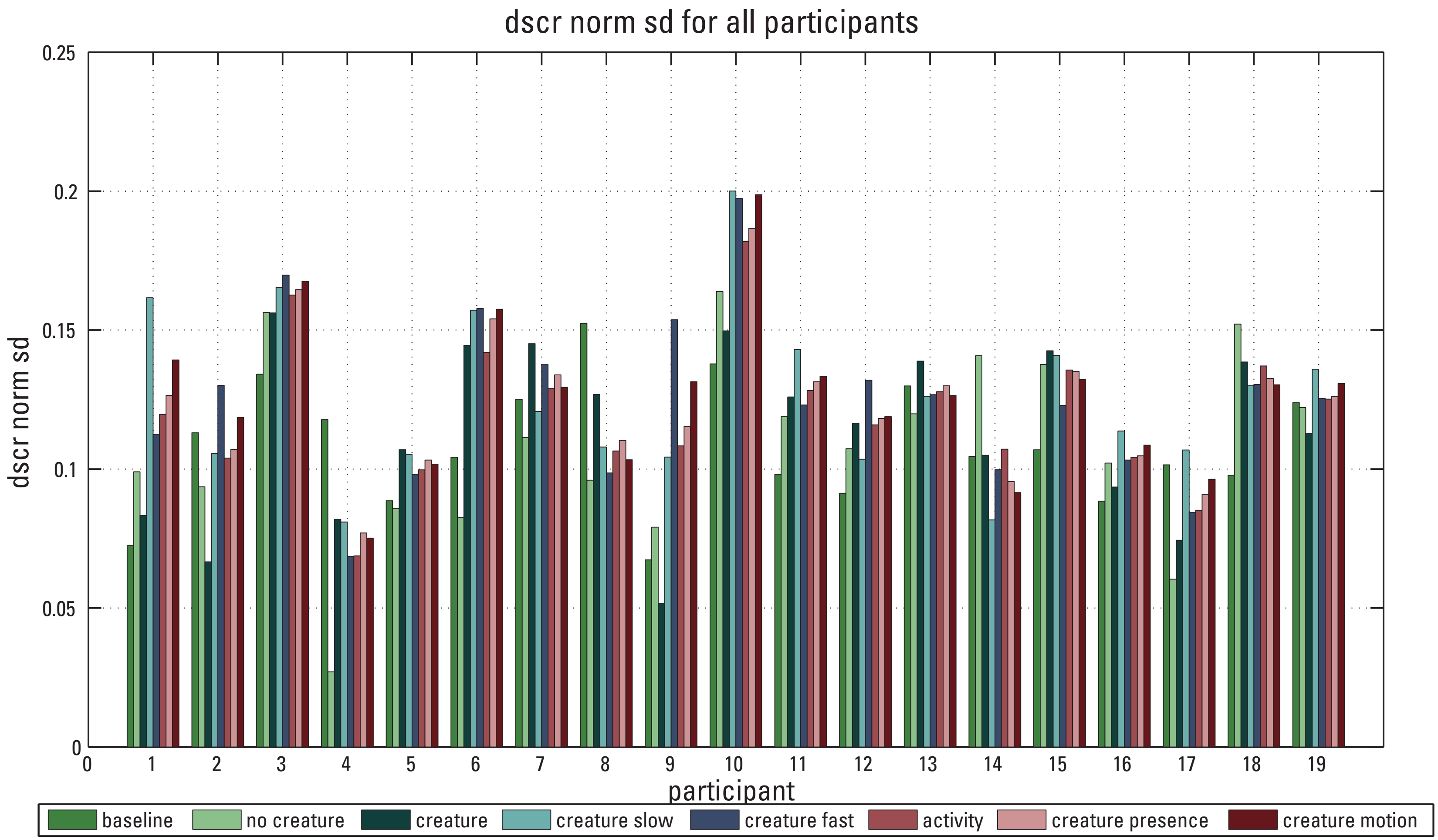

Figure B.76: Mean derivative of skin conductance standard deviation for participants during Experiment 3.

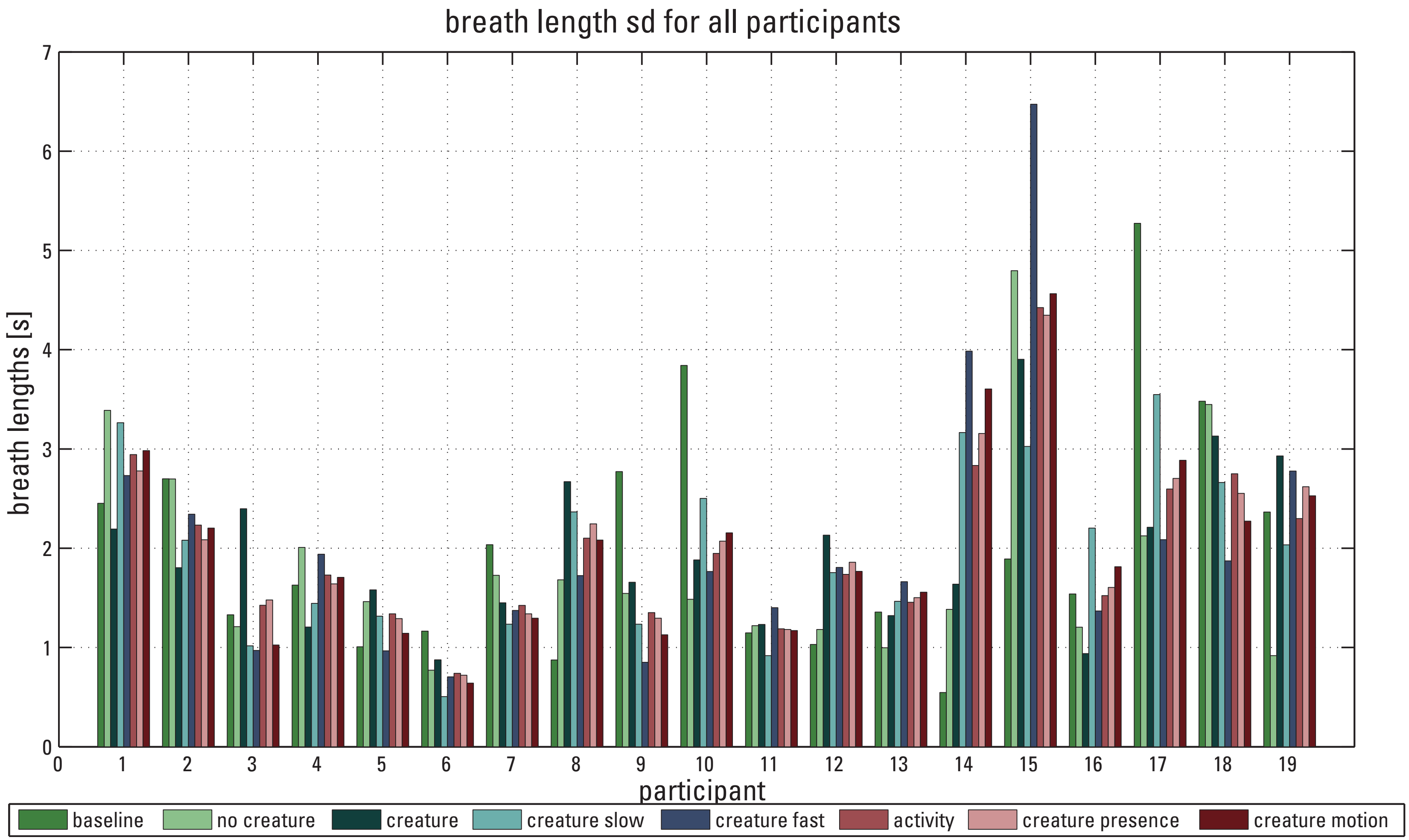

Figure B.77: Mean breath length standard deviation for participants during Experiment 3.

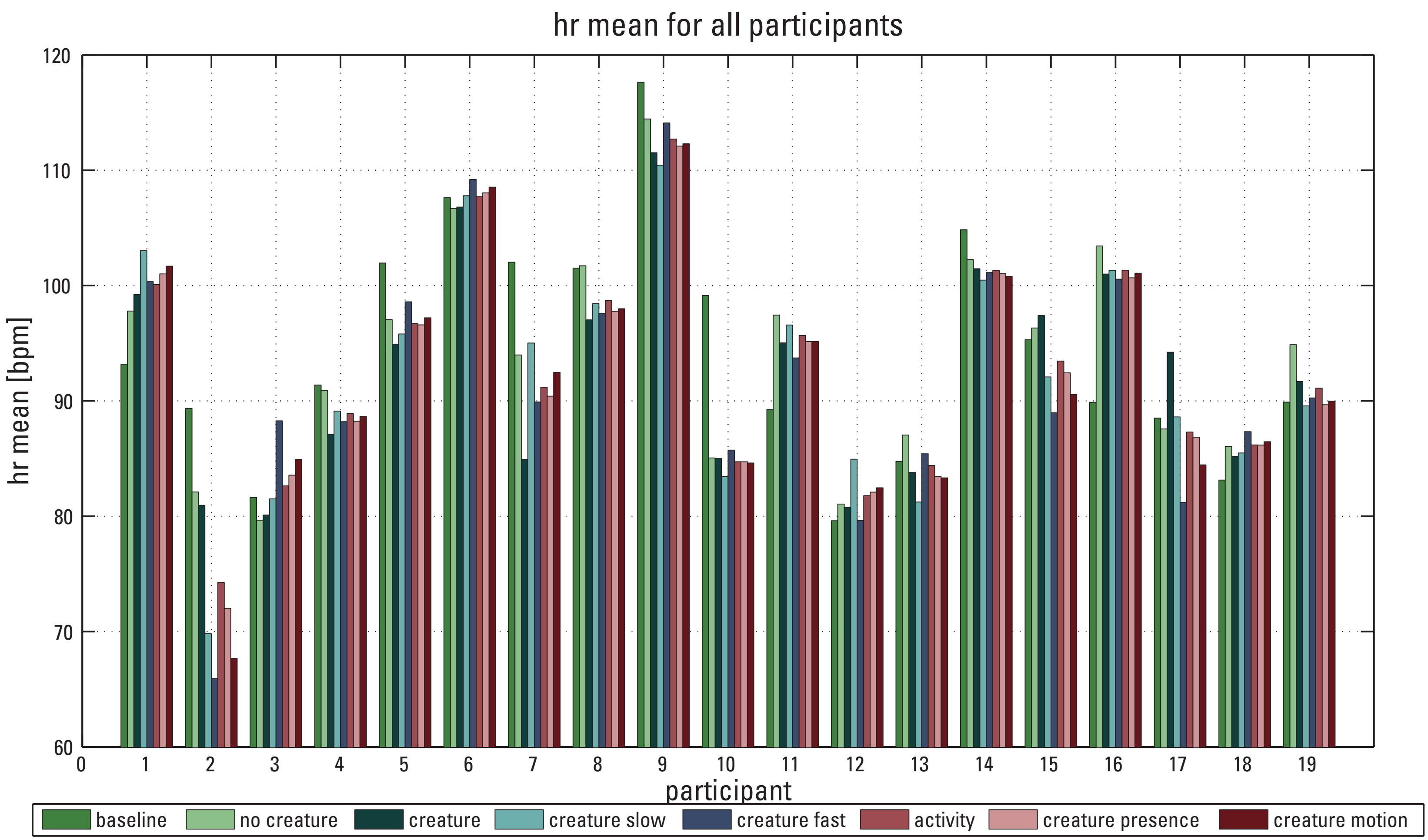

Figure B.78: Mean heart rate for participants during Experiment 3.

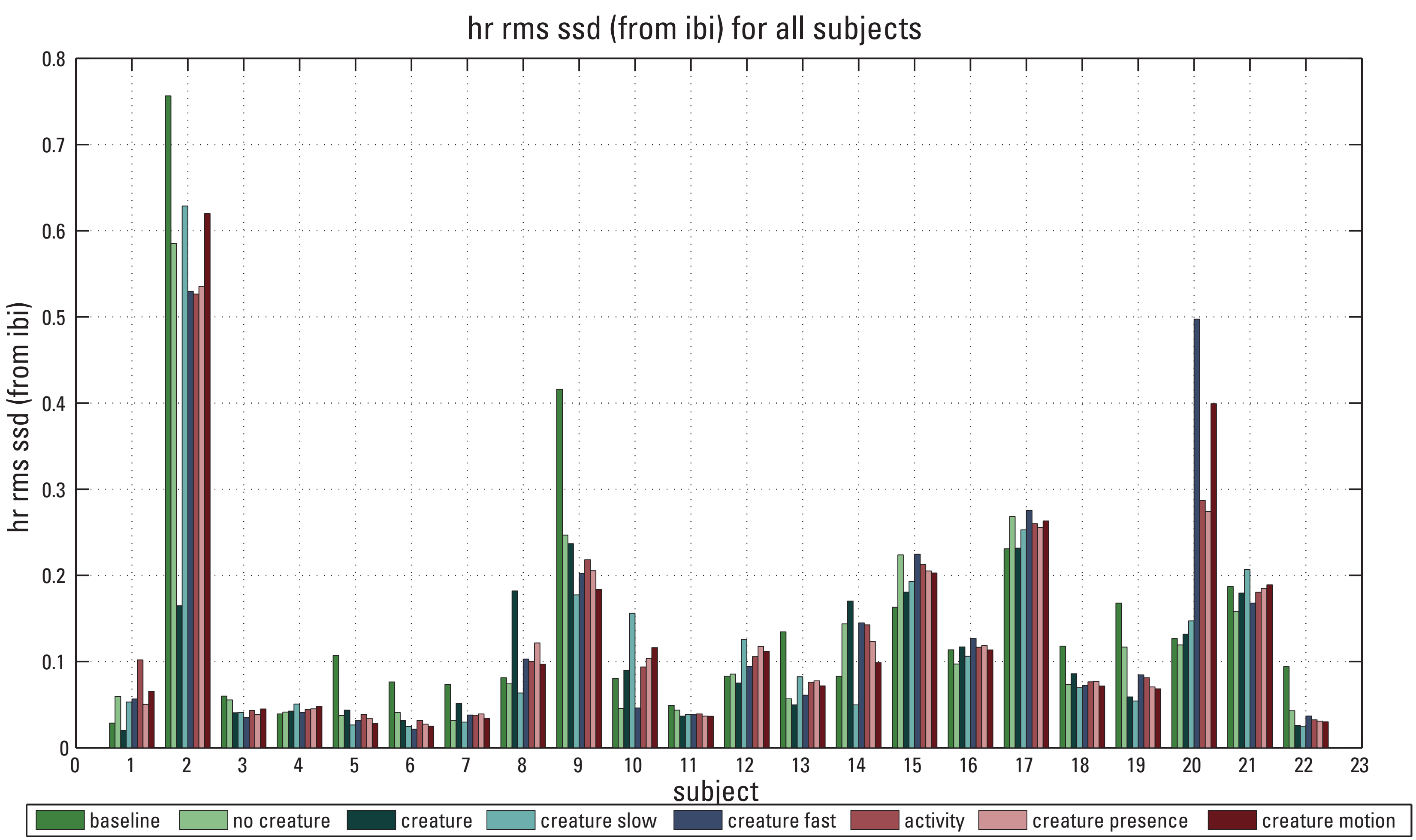

Figure B.79: Mean heart rate rms standard deviation for participants during Experiment 3.

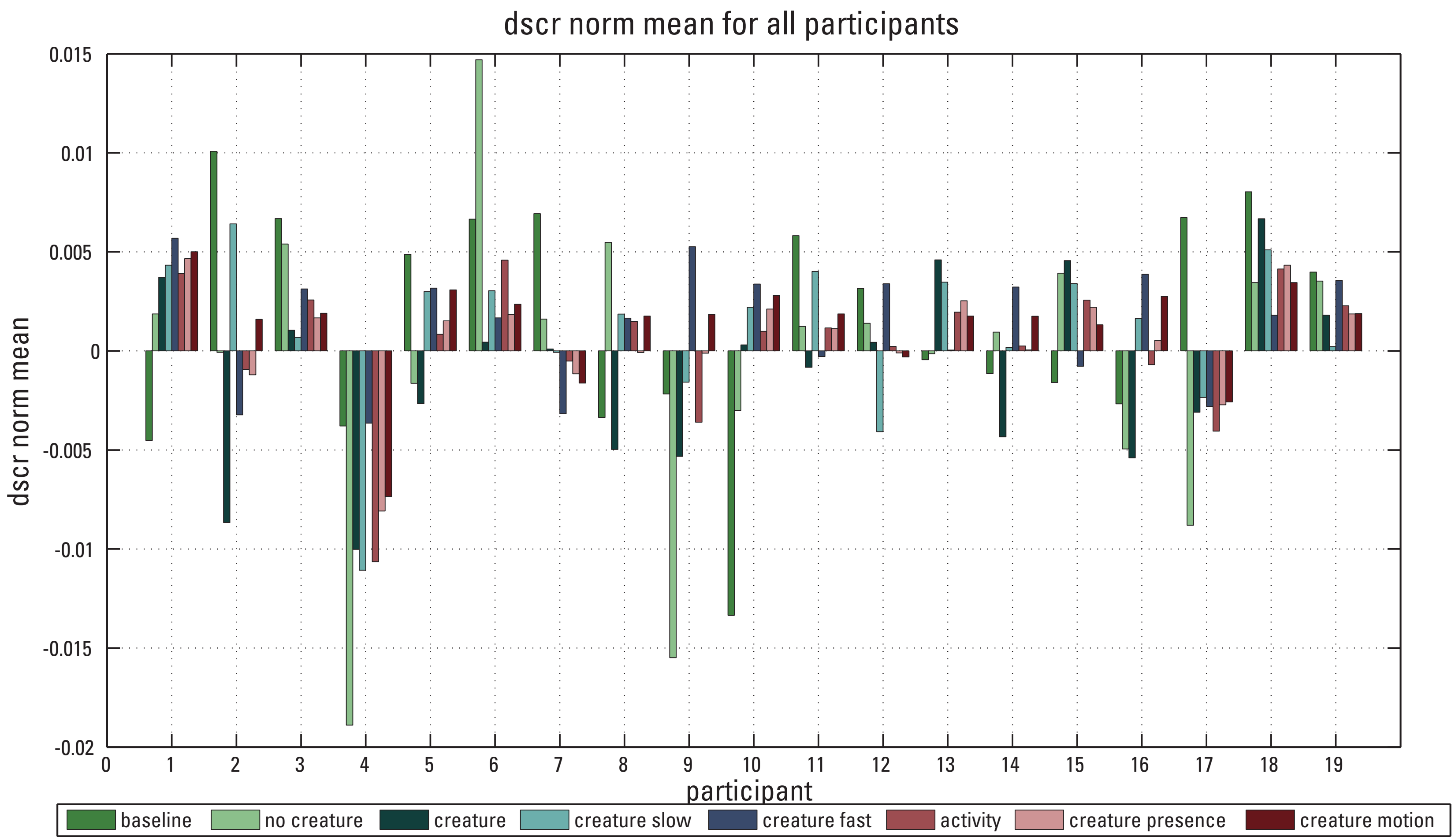

Figure B.80: Mean derivative of skin conductance for participants during Experiment 3.

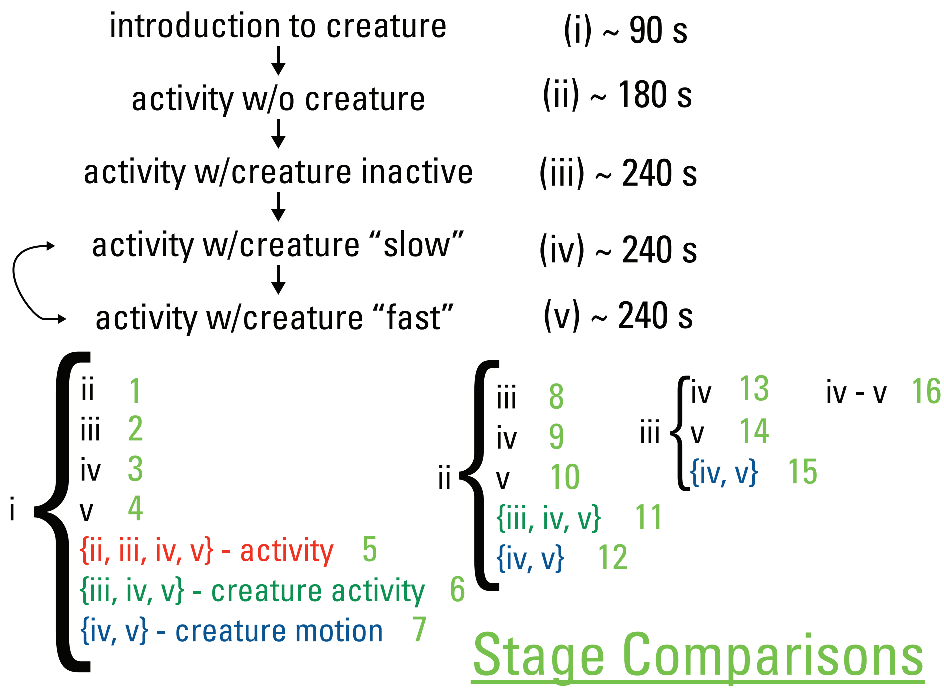

Figure B.81: Summary of comparisons made during Experiment 3.

Table B.7: Summary of results from Experiment 3. Investigated columns in green, significant results are in bold. See Figure B.81 for comparisons.

unit		comparison 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	unit
ibi mean	*p*	0.263	0.181	0.200	0.160	0.178	0.174	0.175	0.513	0.635	0.377	0.476	0.458	0.944	0.578	0.746	0.406	s
	mean	0.011	0.014	0.014	0.020	0.014	0.015	0.017	0.004	0.003	0.009	0.005	0.006	0.000	0.006	0.003	0.006	
	sd	0.046	0.050	0.051	0.067	0.048	0.054	0.058	0.026	0.031	0.049	0.032	0.039	0.029	0.048	0.037	0.035	
ibi sd	*p*	**0.000**	**0.016**	0.465	0.543	0.320	0.608	0.658	0.531	0.272	0.481	0.242	0.311	0.242	0.524	0.295	0.828	s
	mean	-0.022	-0.018	-0.008	-0.010	-0.009	-0.006	-0.006	0.004	0.013	0.012	0.015	0.015	0.010	0.008	0.012	-0.001	
	sd	0.022	0.034	0.054	0.077	0.044	0.060	0.068	0.027	0.058	0.081	0.062	0.072	0.040	0.063	0.053	0.031	
hr mean	*p*	0.308	0.168	0.185	0.157	0.168	0.156	0.161	0.308	0.428	0.366	0.312	0.354	0.893	0.805	0.912	0.642	
	mean	-1.286	-2.019	-1.915	-2.299	-1.838	-2.060	-2.118	-0.733	-0.628	-1.013	-0.774	-0.832	0.105	-0.280	-0.099	-0.385	
	sd	6.042	6.952	6.859	7.707	6.328	6.883	7.172	3.443	3.813	5.377	3.667	4.308	3.787	5.479	4.356	4.004	
hr sd	*p*	**0.000**	**0.003**	**0.004**	**0.002**	**0.004**	**0.005**	**0.002**	0.916	0.156	0.893	**0.037**	0.091	0.070	0.985	0.097	0.275	
	mean	422	410	285	407	148	255	275	-11.7	-137	-14.4	-85	-146	-125	-2.63	-135	122	
	sd	418	597	441	560	329	405	394	542	456	519	260	406	322	666	381	535	
hr skewness	*p*	0.859	0.349	0.703	0.575	0.533	0.656	0.753	0.232	0.556	0.494	0.529	0.631	0.293	0.853	0.232	0.725	
	mean	-0.042	0.298	0.119	0.233	0.176	0.141	0.096	0.340	0.161	0.275	0.183	0.138	-0.179	-0.065	-0.202	0.113	
	sd	1.144	1.526	1.517	2.001	1.361	1.524	1.472	1.357	1.324	1.933	1.398	1.385	0.812	1.714	0.808	1.556	
hr rms ssd	*p*	**0.001**	**0.029**	0.371	0.512	0.229	0.473	0.531	0.830	0.575	0.684	0.529	0.596	0.500	0.662	0.540	0.988	
	mean	-0.024	-0.022	-0.015	-0.015	-0.015	-0.013	-0.013	0.002	0.009	0.009	0.011	0.011	0.008	0.008	0.009	0.000	
	sd	0.030	0.047	0.078	0.108	0.060	0.085	0.098	0.040	0.081	0.110	0.086	0.102	0.055	0.083	0.074	0.041	
hr *p*nn50	*p*	**0.013**	0.072	**0.025**	**0.014**	**0.009**	**0.017**	**0.013**	0.820	0.784	0.552	0.803	0.643	0.549	0.368	0.409	0.750	
	mean	-0.054	-0.049	-0.060	-0.066	-0.065	-0.059	-0.063	0.005	-0.006	-0.012	-0.005	-0.009	-0.012	-0.017	-0.014	-0.005	
	sd	0.099	0.127	0.123	0.120	0.104	0.112	0.114	0.113	0.109	0.094	0.091	0.093	0.093	0.090	0.083	0.081	
hr vlf %	*p*	**0.019**	0.064	0.165	**0.037**	**0.004**	**0.001**	**0.003**	0.267	0.648	0.943	**0.001**	**0.003**	0.630	0.247	0.053	0.398	
	mean	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
	sd	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
hr lf %	*p*	0.098	0.142	0.232	0.399	0.268	0.217	0.275	0.932	0.134	0.275	0.115	0.182	0.091	0.222	0.139	0.553	
	mean	0.000	0.000	0.001	0.001	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.000	
	sd	0.001	0.001	0.004	0.004	0.002	0.003	0.004	0.001	0.004	0.004	0.003	0.004	0.003	0.004	0.004	0.002	
hr mf %	*p*	0.051	0.185	0.941	0.624	0.634	0.894	0.706	0.228	0.246	0.324	0.276	0.303	0.295	0.361	0.347	0.425	
	mean	-0.001	-0.001	0.000	0.001	0.000	0.000	0.001	0.000	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.001	
	sd	0.002	0.002	0.004	0.009	0.003	0.005	0.007	0.001	0.004	0.009	0.005	0.007	0.003	0.008	0.006	0.005	
hr hf %	*p*	**0.015**	**0.010**	0.591	0.720	0.623	0.987	0.900	0.601	0.618	0.460	0.501	0.497	0.405	0.389	0.390	0.408	
	mean	-0.001	-0.001	-0.001	0.001	0.000	0.000	0.000	0.000	0.001	0.002	0.001	0.001	0.001	0.002	0.001	0.001	
	sd	0.002	0.002	0.005	0.012	0.004	0.007	0.009	0.001	0.005	0.012	0.007	0.009	0.004	0.011	0.008	0.008	

Continued. . .

unit		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	unit
scr norm mean	p	**0.002**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	0.874	0.842	0.845	0.967	0.993	0.577	0.890	0.839	0.434	
	mean	-0.121	-0.123	-0.112	-0.126	-0.120	-0.120	-0.119	-0.004	0.007	-0.007	-0.001	0.000	0.011	-0.003	0.004	-0.013	
	sd	0.170	0.123	0.125	0.133	0.117	0.117	0.122	0.119	0.155	0.168	0.143	0.156	0.089	0.101	0.086	0.081	
scr norm sd	p	0.057	0.286	**0.034**	0.695	0.584	0.456	0.357	0.271	0.451	0.156	0.141	0.162	0.242	0.476	0.738	0.098	
	mean	-0.028	-0.012	-0.021	-0.005	-0.005	-0.007	-0.009	0.018	0.009	0.025	0.023	0.021	-0.009	0.007	0.003	0.016	
	sd	0.069	0.051	0.044	0.057	0.043	0.046	0.047	0.077	0.056	0.082	0.071	0.068	0.036	0.046	0.035	0.044	
dscr norm mean	p	0.195	0.067	0.336	0.198	0.155	0.159	0.245	0.443	0.917	0.899	0.816	0.984	0.208	0.359	0.240	0.657	
	mean	-0.002	-0.003	-0.002	-0.002	-0.002	-0.002	-0.002	-0.001	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000	
	sd	0.008	0.007	0.008	0.007	0.006	0.007	0.007	0.008	0.007	0.008	0.007	0.007	0.005	0.005	0.005	0.004	
dscr norm sd	p	0.434	**0.028**	**0.006**	**0.012**	**0.010**	**0.005**	**0.006**	0.270	**0.011**	**0.023**	**0.011**	**0.008**	0.095	0.214	0.101	0.553	
	mean	0.006	0.014	0.024	0.022	0.019	0.022	0.023	0.007	0.017	0.014	0.015	0.016	0.010	0.007	0.009	-0.003	
	sd	0.036	0.029	0.039	0.038	0.032	0.033	0.037	0.027	0.029	0.027	0.024	0.026	0.028	0.028	0.026	0.022	
emg norm mean	p	0.420	0.630	0.424	0.512	0.739	0.471	0.464	0.207	0.182	0.252	0.195	0.214	0.595	0.750	0.669	0.417	
	mean	0.022	-0.012	-0.024	-0.019	-0.008	-0.019	-0.021	-0.035	-0.047	-0.042	-0.042	-0.044	-0.012	-0.007	-0.010	0.005	
	sd	0.133	0.113	0.140	0.135	0.108	0.121	0.136	0.128	0.163	0.171	0.149	0.166	0.108	0.108	0.107	0.029	
emg norm sd	p	0.053	**0.011**	**0.009**	**0.007**	0.067	**0.014**	**0.010**	0.148	**0.047**	0.052	0.242	0.078	0.406	0.283	0.745	0.916	
	mean	-0.035	-0.062	-0.074	-0.073	-0.031	-0.052	-0.066	-0.027	-0.039	-0.038	-0.017	-0.030	-0.012	-0.011	-0.003	0.002	
	sd	0.085	0.108	0.124	0.118	0.076	0.094	0.111	0.086	0.090	0.088	0.068	0.079	0.070	0.047	0.049	0.067	
skin temp. mean	p	0.069	**0.001**	**0.001**	**0.000**	**0.001**	**0.000**	**0.000**	**0.002**	**0.002**	**0.001**	**0.001**	**0.001**	**0.032**	**0.008**	0.011	0.870	°C
	mean	0.273	1.167	1.699	1.727	1.180	1.570	1.714	0.879	1.411	1.439	1.232	1.426	0.532	0.560	0.547	0.028	
	sd	0.702	1.508	2.102	1.951	0.739	1.825	1.987	1.186	1.908	1.708	1.671	1.764	1.117	0.925	0.942	0.800	
skin temp. sd	p	**0.019**	0.814	0.890	0.722	**0.000**	**0.002**	**0.016**	0.056	0.080	0.344	**0.032**	0.308	0.856	0.763	0.091	0.719	°C
	mean	0.124	0.015	0.008	0.033	0.739	0.344	0.221	-0.114	-0.121	-0.096	0.257	0.092	-0.007	0.019	0.206	0.025	
	sd	0.239	0.296	0.281	0.444	0.621	0.463	0.405	0.271	0.315	0.474	0.507	0.423	0.171	0.294	0.235	0.332	
resp rate mean	p	0.260	0.239	0.132	0.081	0.091	0.075	0.100	0.968	0.974	0.829	0.907	0.898	0.993	0.865	0.930	0.369	s
	mean	36.0	38.9	38.6	45.2	40.4	41.1	41.9	1.37	1.08	7.65	3.61	4.38	-0.29	6.28	3.01	6.57	
	sd	153	154	118	118	102	106	117	164	159	167	146	162	152	175	163	34.4	
resp rate sd	p	**0.039**	**0.021**	**0.029**	**0.009**	0.450	0.171	**0.017**	0.664	0.861	0.337	0.099	0.778	0.650	0.298	0.520	0.331	s
	mean	-29.8	-27.2	-33.7	-44.9	-8.3	-16.7	-34.9	3.9	-2.6	-13.9	14.4	-3.8	-6.5	-17.7	-7.7	-11.2	
	sd	66.8	52.5	69.3	75.2	52.0	56.7	64.8	42.3	71.3	67.7	64.6	64.3	67.8	49.4	56.6	54.2	
breath lengths mean	p	0.261	0.130	0.096	0.101	0.070	0.092	0.092	0.886	0.597	0.222	0.743	0.632	0.311	0.335	0.414	0.496	s
	mean	1.565	1.363	2.058	2.416	0.789	1.868	1.956	-0.202	0.493	0.851	0.303	0.391	0.695	1.053	0.593	0.359	
	sd	6.649	4.248	5.816	6.919	1.540	5.208	5.450	6.852	4.504	3.323	4.467	3.941	3.287	5.241	3.488	2.537	
breath lengths sd	p	0.255	0.251	0.202	0.118	0.155	0.129	0.121	0.096	0.185	0.099	0.114	0.110	0.443	0.116	0.182	0.339	s
	mean	-0.580	0.588	1.230	1.808	1.371	1.207	1.353	1.168	1.810	2.388	1.787	1.933	0.642	1.220	0.764	0.578	
	sd	2.431	2.450	4.589	5.451	4.562	3.753	4.109	3.292	6.484	6.801	5.333	5.689	4.027	3.660	2.720	2.902	

Continued...

unit		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	unit
scr mean	p	0.859	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.002**	**0.002**	**0.001**	0.875	S
	mean	0.032	0.901	1.510	1.485	1.040	1.341	1.498	0.849	1.458	1.433	1.288	1.446	0.609	0.584	0.597	-0.025	
	sd	0.865	0.970	1.353	1.505	1.108	1.247	1.381	0.743	1.060	1.109	0.900	1.018	0.819	0.799	0.718	0.746	
scr sd	p	0.740	0.933	0.516	0.594	**0.000**	**0.002**	**0.045**	0.994	0.433	0.542	**0.000**	**0.017**	0.240	0.468	**0.005**	0.138	S
	mean	0.015	0.004	0.043	-0.026	0.433	0.243	0.142	0.000	0.039	-0.030	0.239	0.138	0.039	-0.030	0.137	-0.069	
	sd	0.222	0.245	0.313	0.229	0.393	0.325	0.319	0.202	0.235	0.231	0.275	0.256	0.154	0.196	0.213	0.215	
dscr mean	p	**0.029**	**0.043**	0.054	**0.034**	**0.029**	**0.032**	**0.038**	0.672	0.937	0.659	0.716	0.773	0.720	0.995	0.847	0.560	S
	mean	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
	sd	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
dscr sd	p	**0.020**	0.680	0.115	0.352	0.496	0.192	0.161	**0.003**	**0.001**	**0.000**	**0.000**	**0.000**	0.113	0.449	0.154	0.356	S
	mean	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
	sd	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	

B.4.3 Participant Consent Form

THE UNIVERSITY OF BRITISH COLUMBIA

Department of Computer Science
2366 Main Mall
Vancouver, BC Canada V6T 1Z4
Phone: (604) 822-3061
Fax: (604) 822-4231

PARTICIPANT & PARENT INFORMATION AND CONSENT FORM

Tamer: `Touch-guided Anxiety Management via Engagement with a Robot Pet`

Principal Investigator: Associate Professor Karon MacLean, PHD
Department of Computer Science
University of British Columbia
(604)-822-8169

Sponsor: Name(s) of industry sponsor or granting agency

INTRODUCTION
You (or your child) are being invited to take part in this research study because we feel that your participation and feedback will greatly assist us in developing anxiety-reducing robotic devices.

YOUR PARTICIPATION IS VOLUNTARY
Your participation is entirely voluntary, so it is up to you to decide whether or not to take part in this study. Before you decide, it is important for you to understand what the research involves. This consent form will tell you about the study, why the research is being done, what will happen to you during the study and the possible benefits, risks, and discomforts.

If you wish to participate, you will be asked to sign this form. If you do decide to take part in this study, you are still free to withdraw at any time and without giving any reasons for your decision.

If you do not wish to participate, you do not have to provide any reason for your decision not to participate. Please take time to read the following information carefully.

WHO IS CONDUCTING THE STUDY?
The study is being conducted/funded by the National Science and Engineering Research Council of Canada (NSERC). The Principal Investigator has received funds from this agency to compensate subjects for participating in this study. You are entitled to request any details concerning this compensation from the Principal Investigator.

BACKGROUND
This project's goal is to advance a novel tool and technique to help young children attain independent anxiety regulation skills. Engagement will be utilize to give children access to cognitive training by interacting with an expressive animatronic pet. This robot will be programmed to respond physically to a combination of a child's pattern of touch and biometrically sensed emotional state in a way that rewards patience and progress.

WHAT IS THE PURPOSE OF THE STUDY?

The purpose of this study is to examine the role of haptic (touch sense) feedback on anxiety levels. This study investigates your reaction to a small robotic creature that is touch-sensitive and can breath, purr and stiffen its ears.

WHO CAN PARTICIPATE IN THE STUDY?

This study is open to children from ages 5-17, particularly those who may have been diagnosed with mild anxiety or learning disorders, as well as adult subjects between the ages of 17-50. We expect to enroll approximately 20 children and 10 adults in this experiment.

WHAT DOES THE STUDY INVOLVE?

You will be asked to wear external (i.e., non-invasive) sensors that collect some basic physiological information such as the heart rate, respiration rate, some muscle activity, and perspiration. We request that you tell the experimenter if you find the sensor positioning uncomfortable, and adjustments will be made. You will be invited to answer questions in two questionnaires as part of the experiment. The study will be viewed by the experimenters in a separate room via a webcam. It will not be recorded. The time commitment required for this session will range from one to three hours.

Image 1: User demonstrating possible physiological sensors: respiration rate (a), blood volume pulse (b), skin conductance (c), ECG (d).

Image 1 shows a photo of a child attached to the physiological sensors that will be used during these experiments. There are four primary sensors that will be used during these experiments:

a. Respiration Rate: A Velcro band is worn around the abdomen outside of the clothing. Expands and contracts with the abdomen to measure respiration rate, waveform, and amplitude.

b. Blood Volume Pulse: also known as a photoplethysmograph (PPG) sensor. A small black box attaches to the distal end of a finger with a Velcro strap. Measures heart rate.

c. Skin Conductance: Two electrodes attach to Velcro straps, each in turn attached to the distal end of two fingers on the same hand. Measures galvanic skin response (GSR), the electrical resistance of the skin.

d. ECG: Three electrodes attach to the upper right and left sides of the chest and the lower abdomen. Measures heart electrical activity.

IF YOU DECIDE TO JOIN THIS STUDY: SPECIFIC PROCEDURES

After being fitted with the sensors, you will be invited to hold the creature in your lap. The creature may move during this experiment. You will then complete a questionnaire about your interaction during this experiment. If you are not sure about any instructions, do not hesitate to ask.

WHAT ARE THE POSSIBLE HARMS AND SIDE EFFECTS OF PARTICIPATING?

There are no expected harms or side effects from participating in this experiment. Nothing will be done to impose stress or anxiety on you. The biosensors that are worn are non-intrusive, and FDA-approved safe for medical uses.

WHAT ARE THE BENEFITS OF PARTICIPATING IN THIS STUDY?
No one knows whether or not you will benefit from this study. There may or may not be direct benefits to you from taking part in this study. We hope that the information learned from this study can be used in the future to benefit others.

WHAT HAPPENS IF I DECIDE TO WITHDRAW MY CONSENT TO PARTICIPATE?
Your participation in this research is entirely voluntary. You may withdraw from this study at any time. If you choose to enter the study and then withdraw at a later time, all data collected about you during your enrolment in the study will be retained for analysis. By law, this data cannot be destroyed.

WHAT WILL THE STUDY COST ME?
You are not expected to incur any personal expenses as a result of your participation in this study. You will be compensated $5 for each 1/2-hour study session.

WILL MY TAKING PART IN THIS STUDY BE KEPT CONFIDENTIAL?
Your confidentiality will be respected. No information that discloses your identity will be released or published without your specific consent to the disclosure. Research records identifying you may be inspected in the presence of the Investigator or his or her designate by representatives of Health Canada and the UBC Research Ethics Board for the purpose of monitoring the research. However, no records which identify you by name or initials will be allowed to leave the Investigators' offices.

WHO DO I CONTACT IF I HAVE QUESTIONS ABOUT THE STUDY DURING MY PARTICIPATION?
If you have any questions or desire further information about this study before or during participation, you can contact **Karon Maclean** at (604)-822-8169.

WHO DO I CONTACT IF I HAVE ANY QUESTIONS OR CONCERNS ABOUT MY RIGHTS AS A SUBJECT DURING THE STUDY?
If you have any concerns about your rights as a research subject and/or your experiences while participating in this study, contact the Research Subject Information Line in the University of British Columbia Office of Research Services by e-mail at RSIL@ors.ubc.ca or by phone at 604-822-8598.

B.4.4 Participant Assent Form

THE UNIVERSITY OF BRITISH COLUMBIA

Department of Computer Science
2366 Main Mall
Vancouver, BC Canada V6T 1Z4
Phone: (604) 822-3061
Fax: (604) 822-4231

SUBJECT ASSENT FORM

Tamer: Touch-guided Anxiety Management via Engagement with a Robot Pet

INVITATION
I am being invited to be part of a research study. A research study tries to find better treatments to help children like me. It is up to me if I want to be in this study. No one will make me be part of the study. Even if I agree now to be part of the study, I can change my mind later. No one will be mad at me if I choose not to be part of this study.

WHY ARE WE DOING THIS STUDY?
We are doing this study to investigate how a robot may help reduce my anxiety levels. We want to see my reactions to a robot that purrs, breathes, and moves on my lap.

WHAT WILL HAPPEN IN THIS STUDY?

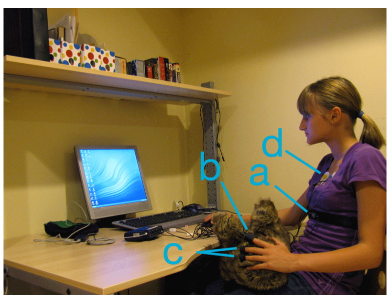

Image 1: User demonstrating possible physiological sensors: respiration rate (a), blood volume pulse (b), skin conductance (c), ECG (d).

During this experiment you will be asked to wear physiological sensors as shown in Image 1 on your hands and chest. These will allow us to record your heart rate, pulse, breathing rate, and skin conductance (how sweaty you are). If at any time these are uncomfortable please let us know, and we will adjust them for you.

We are investigating your reaction to a small robotic creature is touch-sensitive and can breath, purr and stiffen its ears. You will be asked to hold the creature in your lap while you complete some schoolwork. The creature may move during this experiment.

WHO IS DOING THIS STUDY?
Karon Maclean and other investigators from the UBC Computer Science Department will be doing this study. They will answer any questions I have about this study. I can also call them at **604-822-8169**, if I am having any problems or if there is an emergency and I cannot talk to my parents.

CAN ANYTHING BAD HAPPEN TO ME?
There is nothing in this study that should cause anything bad to happen to me.

Version 1.0 – September 22, 2009 10:23 PM

WHO WILL KNOW I AM IN THE STUDY?
Only the people who are involved in the study will know I am it. When the study is finished, the investigators will write a report about what was learned. This report will not say my name or that I was in the study. My parents and I do not have to tell anyone I am in the study if we don't want to.

WHEN DO I HAVE TO DECIDE?
I have as much time as I want to decide to be part of the study. I have also been asked to discuss my decision with my parents. If I put my name at the end of this form, I agree to be in the study.

SUBJECT'S ASSENT TO PARTICIPATE IN RESEARCH
I have had the opportunity to read this consent form, to ask questions about my participation in this research, and to discuss my participation with my parents/guardians. All my questions have been answered. I understand that I may withdraw from this research at any time, and that this will not interfere with the availability to me of other health care. I have received a copy of this consent form. I assent to participate in this study.

___________________________	___________________________	___________
PRINTED NAME OF SUBJECT	SIGNATURE	DATE

B.5 Experiment Equipment

Figure B.82 shows the command and control scheme used during the experiments. During the experiment the host computer was an IBM Thinkpad T400P with an Intel Core 2 Duo T9400 processor and 2 gigabytes of RAM, running Windows XP. Communications between the sensors and host computer was by USB. Communication of touch data and hardware state from the Creature to the host computer was by Bluetooth radio, and of creature commands from the host computer to the Creature by the XBee wireless radio system.

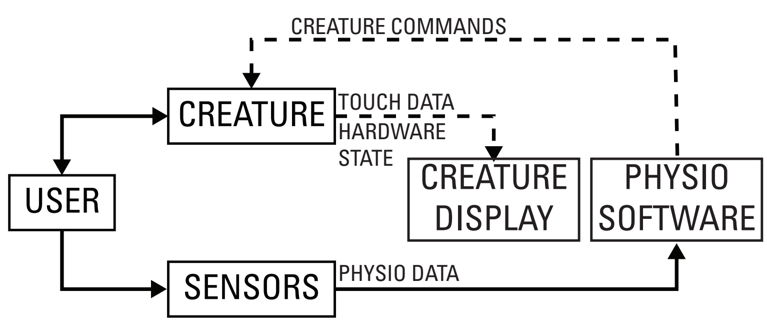

Figure B.82: Diagram of TAMER command and control scheme. Arrows represent communications links between system components, dashed arrows identify the connections that are typically wireless.

Appendix C

Schematics

C.1 Radio Base Station Schematics

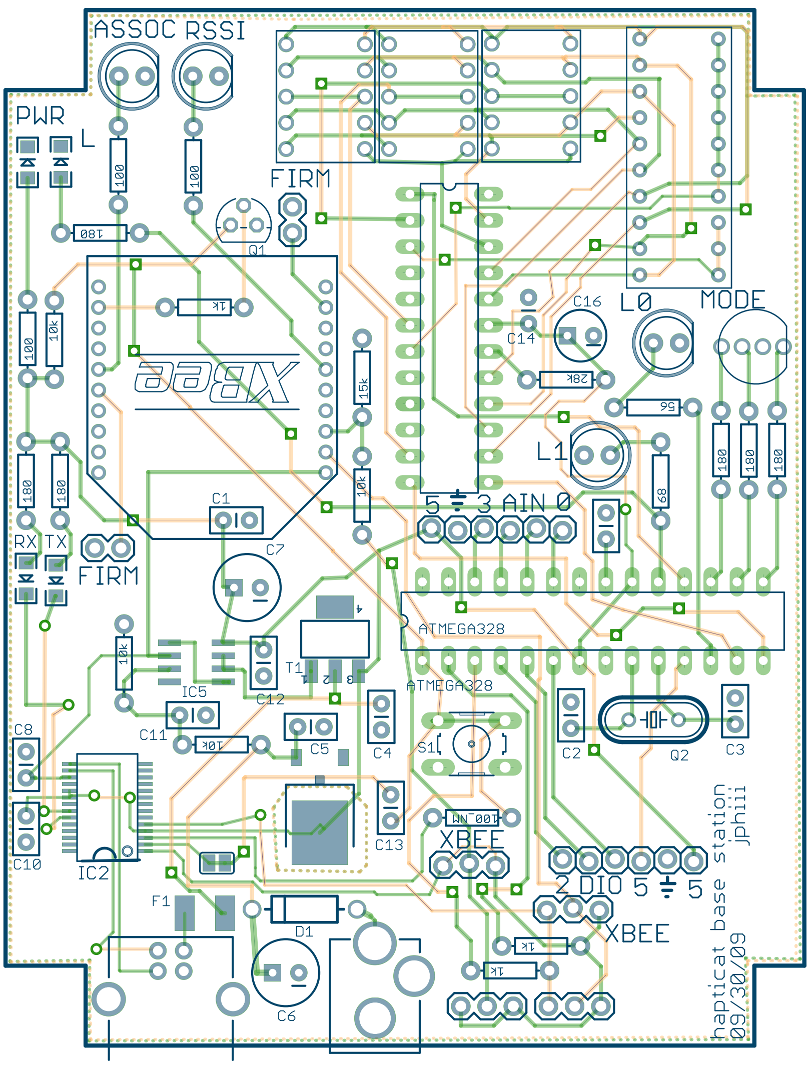

Figure C.1: The radio base station board.

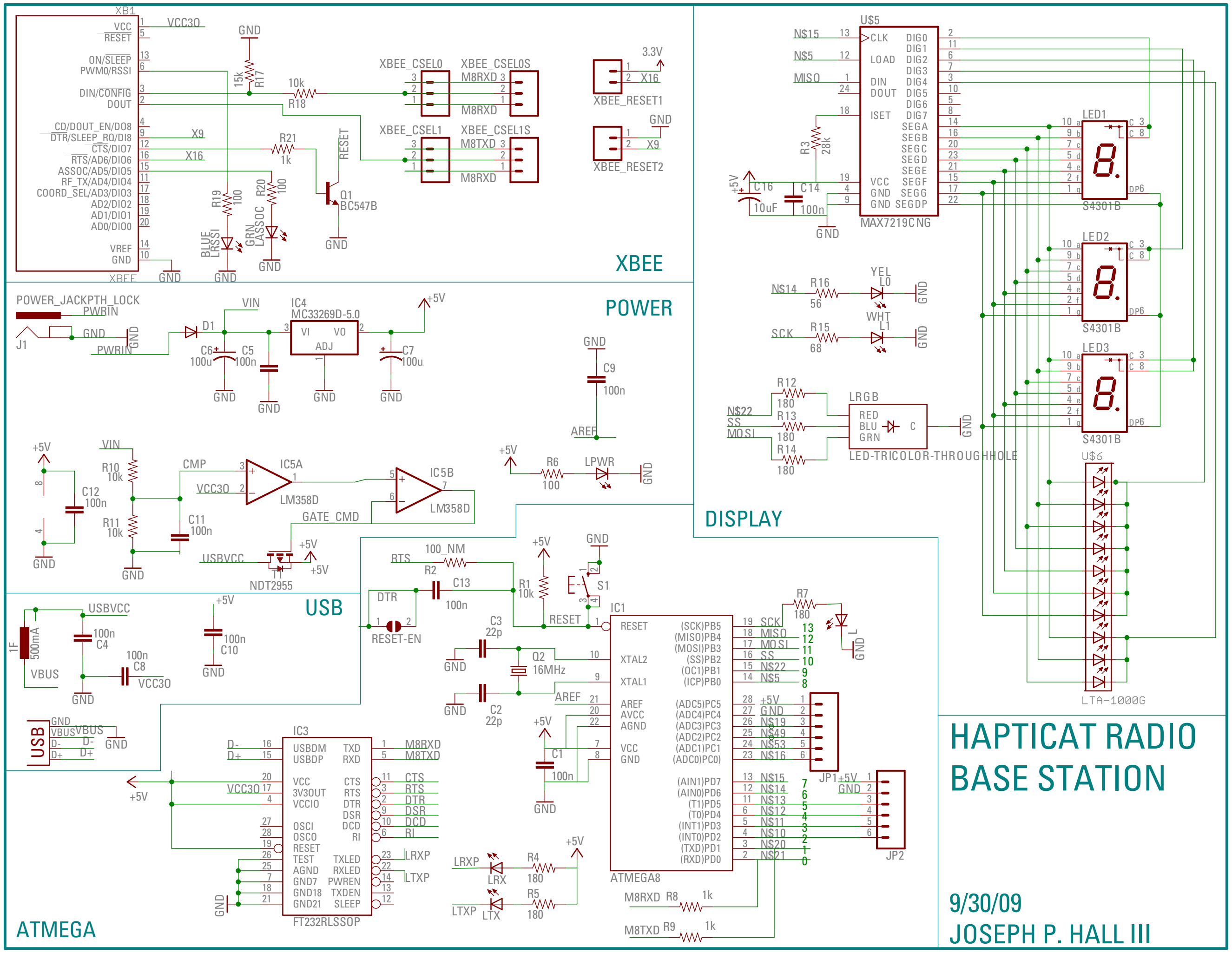

Figure C.2: The radio base station schematic.

Part	Value	Device	Form Factor	Source	Part No.
C1	100n	Ceramic Capacitor	.1" Through-hole	Digikey	PCC1828CT-ND
C10	100n	Ceramic Capacitor	.1" Through-hole	Digikey	PCC1828CT-ND
C11	100n	Ceramic Capacitor	.1" Through-hole	Digikey	PCC1828CT-ND
C12	100n	Ceramic Capacitor	.1" Through-hole	Digikey	PCC1828CT-ND
C13	100n	Ceramic Capacitor	.1" Through-hole	Digikey	PCC1828CT-ND
C14	100n	Ceramic Capacitor	.1" Through-hole	Digikey	PCC1828CT-ND
C16	10uF	Electrolytic Capacitor	Radial	Digikey	P975-ND
C2	22p	Ceramic Capacitor	.1" Through-hole	Digikey	445-4763-ND
C3	22p	Ceramic Capacitor	.1" Through-hole	Digikey	445-4763-ND
C4	100n	Ceramic Capacitor	.1" Through-hole	Digikey	PCC1828CT-ND
C5	100n	Ceramic Capacitor	.1" Through-hole	Digikey	PCC1828CT-ND
C6	100u	Electrolytic Capacitor	Radial	Digikey	vP12924-ND
C7	100u	Electrolytic Capacitor	Radial	Digikey	P12924-ND
C8	100n	Electrolytic Capacitor	Radial	Digikey	PCC1828CT-ND
C9	100n	Electrolytic Capacitor	.1" Through-hole	Digikey	PCC1828CT-ND
D1	-	DIODE-1N4001	SparkFun	Digikey	1N4001FSCT-ND
F1	500mA	Resettable Fuse	SMD	Digikey	MF-MSMF030- 2CT-ND
IC1	-	ATMEGA8	DIL28-3	Sparfun	
IC3	-	FT232RL USB to Serial Converter	SSOP28DB	Digikey	768-1007-1-ND
IC4	-	MC33269D-5.0	DPACK		
IC5	-	LM358D Low Dropout OpAmp	SO08	Digikey	LM358DR2GOSCT-ND
J1	-	Power Jack		Sparkfun	
JP1	-	Front Header Pins		Digikey	
JP2	-	Front Header Pins		Digikey	
L	WHT	Indicator Light	1206 SMD	Digikey	160-1737-1-ND
L0	YEL	LED	5MM Radial	Digikey	365-1190-ND
L1	WHT	LED	5MM Radial	Digikey	67-1695-ND
LASSOC	GRN	LED	5MM Radial	Digikey	C503B-GCN-CY0C0791-ND
LED1	-	LED Bar Graph		Digikey	160-1068-ND
LED2	-	LED Bar Graph		Digikey	160-1068-ND
LED3	-	LED Bar Graph		Digikey	160-1068-ND
LPWR	ORG	Power Light	1206 SMD	Digikey	350-2049-1-ND
LRGB	-	Tricolor LED	5MM Radial		
LRSSI	BLUE	LED5MM	5MM Radial	Digikey	C503B-BAN-CY0C0461-ND
LRX	BLUE	LED-1206	1206 SMD	Digikey	
LTX	BLUE	LED-1206	1206 SMD	Digikey	
Q1	-	BC547B	TO92		BC547B
Q2	16MHz	Crystal Oscillator	HC49/S		CRYTALHC49S
R1	10 kOhm	Resistor	AXIAL-0.3	Digikey	P10.0KCACT -ND

Continued…

Part	Value	Device	Form Factor	Source	Part No.
R10	10 kOhm	Resistor	AXIAL-0.3	Digikey	P10.0KCACT -ND
R11	10 kOhm	Resistor	AXIAL-0.3	Digikey	P10.0KCACT -ND
R12	180 Ohm	Resistor	AXIAL-0.3	Digikey	P180CACT-ND
R13	180 Ohm	Resistor	AXIAL-0.3	Digikey	P180CACT-ND
R14	180 Ohm	Resistor	AXIAL-0.3	Digikey	P180CACT-ND
R15	68 Ohm	Resistor	AXIAL-0.3	Digikey	
R16	56 Ohm	Resistor	AXIAL-0.3	Digikey	
R17	15 kOhm	Resistor	AXIAL-0.3	Digikey	P15.0KCACT -ND
R18	10 kOhm	Resistor	AXIAL-0.3	Digikey	P10.0KCACT -ND
R19	100 Ohm	Resistor	AXIAL-0.3	Digikey	P100CACT-ND
R2	100 Ohm	Resistor	AXIAL-0.3	Digikey	P100CACT-ND
R20	100 Ohm	Resistor	AXIAL-0.3	Digikey	P100CACT-ND
R21	1 kOhm	Resistor	AXIAL-0.3	Digikey	P1.00KCACT -ND
R3	28 kOhm	Resistor	AXIAL-0.3	Digikey	P28.0KCACT -ND
R4	180 Ohm	Resistor	AXIAL-0.3	Digikey	P180CACT-ND
R5	180 Ohm	Resistor	AXIAL-0.3	Digikey	P180CACT-ND
R6	100 Ohm	Resistor	AXIAL-0.3	Digikey	P100CACT-ND
R7	180 Ohm	Resistor	AXIAL-0.3	Digikey	P180CACT-ND
R8	1 kOhm	Resistor	AXIAL-0.3	Digikey	P1.00KCACT -ND
R9	1 kOhm	Resistor	AXIAL-0.3	Digikey	P1.00KCACT -ND
RESET-EN	-	SJ	jumper		
S1	-	6mm Tactile Switch	6mm	Digikey	SW793-ND
T1	NDT2955	PMOSSOT223	SOT223		
U$5		MAX7219CNG	DIL24-3		MAX7219CNG
U$6	LTA-1000G	LTA-1000G	LTA-1000G		
X1	USBPTH	USBPTH	USB-B-PTH		
XB1	-	Xbee Radio	-	Digikey	XB24-AWI-001-ND
XBEE_CSEL0	-	Xbee RX/TX Jumper Pins	SparkFun		
XBEE_CSEL0S	-	Xbee RX/TX Jumper Pins	SparkFun		
XBEE_CSEL1	-	Xbee RX/TX Jumper Pins	SparkFun		
XBEE_CSEL1S	-	Xbee RX/TX Jumper Pins	SparkFun		
XBEE_RESET1	-	Xbee Reset Jumper Pins	SparkFun		
XBEE_RESET2	-	Xbee Reset Jumper Pins	SparkFun		

C.2 Creature Board Schematics

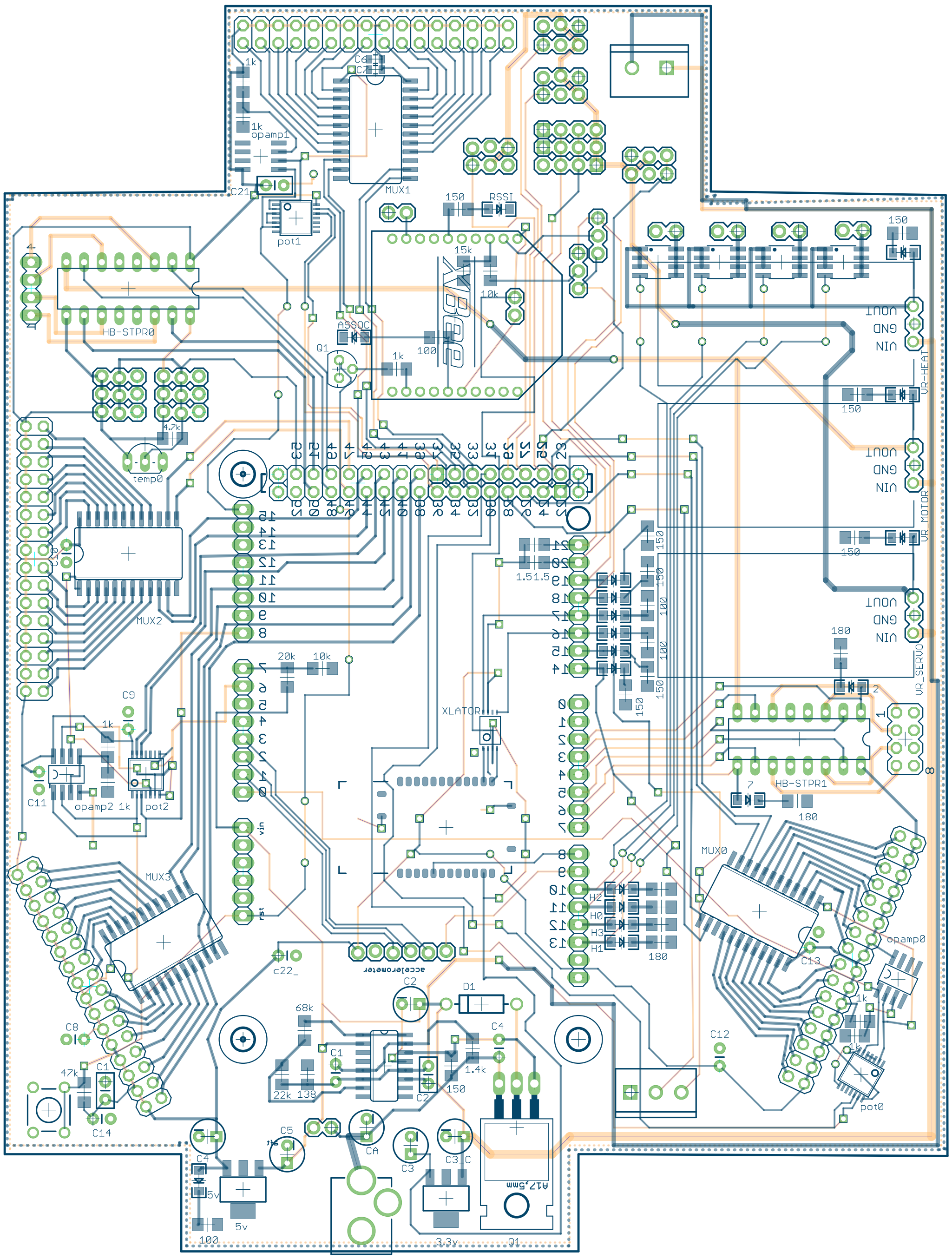

Figure C.3: The Creature board board.

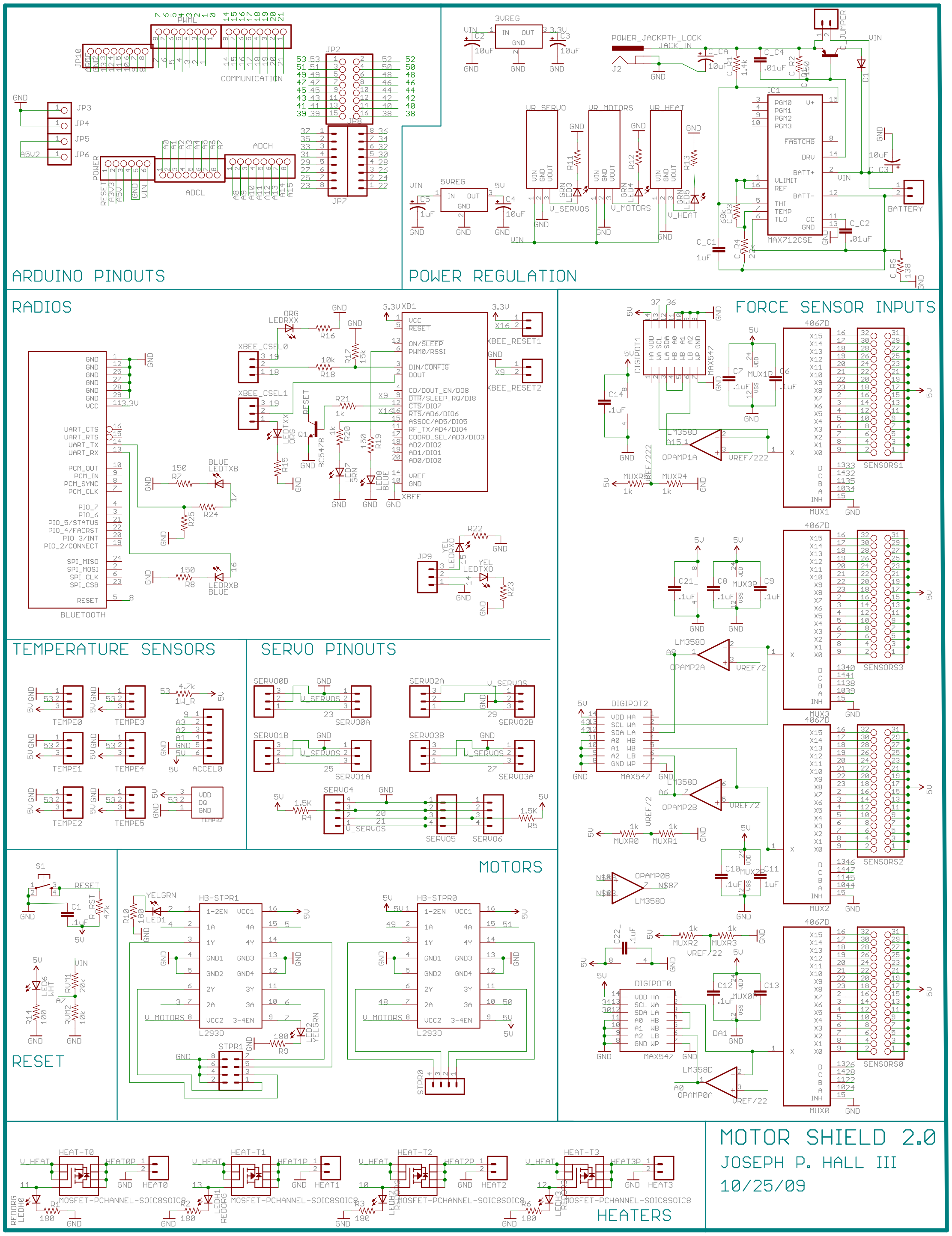

Figure C.4: The Creature board schematic.

Part	Value	Name	Number
1W_R	4.7k	RES 4.70K OHM .25W 1% 1206 SMD	RHM4.70KFRCT-ND
3VREG		IC LDO REG W/SD 3.3V SOT223-3	LT1129CST-3.3#PBF-ND
5VREG		IC LDO REG W/SD 5V SOT223-3	LT1129CST-5#PBF-ND
Bluetooth		Bluetooth SMD Module - Bluegiga	WRL-08771
C_C1	.1uF	CAP .10UF 50V CERAMIC X7R 10%	BC1084CT-ND
C_C2	.01uF	CAP .01UF 50V 10% CER RADIAL	399-4148-ND
C_C3	10uF	CAP ELECT 10UF 25V KS RADIAL	P975-ND
C_C4	.01uF	CAP .01UF 50V 10% CER RADIAL	399-4148-ND
C_CA	10uF	CAP ELECT 10UF 25V KS RADIAL	P975-ND
C_Q1		TRANS PNP PWR GP 7A 50V TO220AB	2N6109GOS-ND
C_R1	1.4k	RES 1.40K OHM 1/4W 1% 1206 SMD	RHM1.40KFCT-ND
c_R2	150	RES 150K OHM 1/4W 1% 1206 SMD	RHM150KFRCT-ND
C_R3	68k	RES 68.0K OHM 1/4W 1% 1206 SMD	RHM68.0KFRCT-ND
C_R4	22k	RES 22.0K OHM 1/4W 1% 1206 SMD	RHM22.0KFRCT-ND
C_RS	138	RES 137 OHM 1/4W 1% 1206 SMD	RHM137FCT-ND
C1	.1uF	CAP .10UF 50V CERAMIC X7R 10%	BC1084CT-ND
C10	.1uF	CAP .10UF 50V CERAMIC X7R 10%	BC1084CT-ND
C11	.1uF	CAP .10UF 50V CERAMIC X7R 10%	BC1084CT-ND
C12	.1uF	CAP .10UF 50V CERAMIC X7R 10%	BC1084CT-ND
C13	.1uF	CAP .10UF 50V CERAMIC X7R 10%	BC1084CT-ND
C14	.1uF	CAP .10UF 50V CERAMIC X7R 10%	BC1084CT-ND
C2	10uF	CAP ELECT 10UF 25V KS RADIAL	P975-ND
C21_	.1uF	CAP .10UF 50V CERAMIC X7R 10%	BC1084CT-ND
C22_	.1uF	CAP .10UF 50V CERAMIC X7R 10%	BC1084CT-ND
C3	10uF	CAP ELECT 10UF 25V KS RADIAL	P975-ND
C4	10uF	CAP ELECT 10UF 25V KS RADIAL	P975-ND
C5	10uF	CAP ELECT 10UF 25V KS RADIAL	P975-ND
C6	.1uF	CAP .1UF 25V CERAMIC X7R 0805	PCC1828CT-ND
C7	.1uF	CAP .1UF 25V CERAMIC X7R 0805	PCC1828CT-ND
C8	.1uF	CAP .10UF 50V CERAMIC X7R 10%	BC1084CT-ND
C9	.1uF	CAP .10UF 50V CERAMIC X7R 10%	BC1084CT-ND
D1		DIODE GEN PURPOSE 50V 1A DO41	1N4001FSCT-ND
DIGIPOT0	100k	IC DGTL POT DUAL 256-TAP 14TSSOP	MAX5479EUD+-ND

Continued...

Part	Value	Name	Number
DIGIPOT1	100k	IC DGTL POT DUAL 256-TAP 14TSSOP	MAX5479EUD+-ND
DIGIPOT2	100k	IC DGTL POT DUAL 256-TAP 14TSSOP	MAX5479EUD+-ND
HB-STPR0		IC QUAD HALF-H DRVR 16-DIP	296-9518-5-ND
HB-STPR1		IC QUAD HALF-H DRVR 16-DIP	296-9518-5-ND
HEAT-T0		MOSFET P-CH 12V 8.9A 8-SOIC	IRF7433PBFCT-ND
HEAT-T1		MOSFET P-CH 12V 8.9A 8-SOIC	IRF7433PBFCT-ND
HEAT-T2		MOSFET P-CH 12V 8.9A 8-SOIC	IRF7433PBFCT-ND
HEAT-T3		MOSFET P-CH 12V 8.9A 8-SOIC	IRF7433PBFCT-ND
IC1		IC BATT FASTCHRG NICD/NIMH16SOIC	MAX712CSE+-ND
LED1	YEL/GRN	LED ALINGAP YW/GN CLEAR 1206 SMD	350-2052-1-ND
LED2	YEL/GRN	LED ALINGAP YW/GN CLEAR 1206 SMD	350-2052-1-ND
LED3	GRN	LED ALINGAP GREEN CLEAR 1206 SMD	350-2053-1-ND
LED4	GRN	LED ALINGAP GREEN CLEAR 1206 SMD	350-2053-1-ND
LED5	GRN	LED ALINGAP GREEN CLEAR 1206 SMD	350-2053-1-ND
LED6	WHT	LED WHITE YELLOW 260MCD 1206	160-1737-1-ND
LED7	GRN	LED ALINGAP GREEN CLEAR 1206 SMD	350-2053-1-ND
LED8	BLUE	LED INGAN BLUE CLEAR 1206 SMD	350-2055-1-ND
LEDH0	RED/ORG	LED ALINGAP RD/OR CLEAR 1206 SMD	350-2048-1-ND
LEDH1	RED/ORG	LED ALINGAP RD/OR CLEAR 1206 SMD	350-2048-1-ND
LEDH2	RED/ORG	LED ALINGAP RD/OR CLEAR 1206 SMD	350-2048-1-ND
LEDH3	RED/ORG	LED ALINGAP RD/OR CLEAR 1206 SMD	350-2048-1-ND
LEDRXB	BLUE	LED INGAN BLUE CLEAR 1206 SMD	350-2055-1-ND
LEDTXB	BLUE	LED INGAN BLUE CLEAR 1206 SMD	350-2055-1-ND
MUX0		IC MUX/DEMUX 1X16 24SOIC	568-4591-5-ND
MUX1		IC MUX/DEMUX 1X16 24SOIC	568-4591-5-ND
MUX2		IC MUX/DEMUX 1X16 24SOIC	568-4591-5-ND
MUX3		IC MUX/DEMUX 1X16 24SOIC	568-4591-5-ND
MUXR0	1k	RES 1.00K OHM 1/4W 1% 1206 SMD	RHM1.00KFRCT-ND
MUXR1	1k	RES 1.00K OHM 1/4W 1% 1206 SMD	RHM1.00KFRCT-ND
MUXR2	1k	RES 1.00K OHM 1/4W 1% 1206 SMD	RHM1.00KFRCT-ND
MUXR3	1k	RES 1.00K OHM 1/4W 1% 1206 SMD	RHM1.00KFRCT-ND
OPAMP0		IC OP AMP LOW PWR DUAL 8-SOIC	497-1591-1-ND
OPAMP1		IC OP AMP LOW PWR DUAL 8-SOIC	497-1591-1-ND
OPAMP2		IC OP AMP LOW PWR DUAL 8-SOIC	497-1591-1-ND

Continued. . .

Part	Value	Name	Number
POWER_JACK			
Q1	BC547B	TRANS NPN 45V 100MA TO-92	BC547BTACT-ND
R/A HEAD			
R_RST	47k	RES 47.0K OHM 1/4W 1% 1206 SMD	RHM47.0KFRCT-ND
R1	180	RES 180 OHM 1/4W 1% 1206 SMD	RHM180FRCT-ND
R10	180	RES 180 OHM 1/4W 1% 1206 SMD	RHM180FRCT-ND
R11	150	RES 150 OHM 1/4W 1% 1206 SMD	RHM150FRCT-ND
R12	150	RES 150 OHM 1/4W 1% 1206 SMD	RHM150FRCT-ND
R13	150	RES 150 OHM 1/4W 1% 1206 SMD	RHM150FRCT-ND
R14	100	RES 100 OHM 1/4W 1% 1206 SMD	RHM100FRCT-ND
MUXR5	1k	RES 1.00K OHM 1/4W 1% 1206 SMD	RHM1.00KFRCT-ND
MUXR4	1k	RES 1.00K OHM 1/4W 1% 1206 SMD	RHM1.00KFRCT-ND
R17	15k	RES 10.0K OHM 1/4W 1% 1206 SMD	RHM10.0KFRCT-ND
R18	10k	RES 15.0K OHM 1/4W 1% 1206 SMD	RHM15.0KFRCT-ND
R19	150	RES 150 OHM 1/4W 1% 1206 SMD	RHM150FRCT-ND
R2	180	RES 180 OHM 1/4W 1% 1206 SMD	RHM180FRCT-ND
R20	100	RES 100 OHM 1/4W 1% 1206 SMD	RHM100FRCT-ND
R21	1k	RES 1.00K OHM 1/4W 1% 1206 SMD	RHM1.00KFRCT-ND
R3	180	RES 180 OHM 1/4W 1% 1206 SMD	RHM180FRCT-ND
R4	1.5k	RES 1.50K OHM 1/4W 1% 1206 SMD	RHM1.50KFRCT-ND
R5	1.5k	RES 1.50K OHM 1/4W 1% 1206 SMD	RHM1.50KFRCT-ND
R6	180	RES 180 OHM 1/4W 1% 1206 SMD	RHM180FRCT-ND
R7	100	RES 100 OHM 1/4W 1% 1206 SMD	RHM100FRCT-ND
R8	100	RES 100 OHM 1/4W 1% 1206 SMD	RHM100FRCT-ND
R9	180	RES 180 OHM 1/4W 1% 1206 SMD	RHM180FRCT-ND
RVM1	20k	RES 20.0K OHM 1/4W 1% 1206 SMD	RHM20.0KFRCT-ND
RVM2	10k	RES 10.0K OHM 1/4W 1% 1206 SMD	RHM10.0KFRCT-ND
S1		SWITCH TACT 6MM 260GF H=4.3MM	SW793-ND
TEMPB2		IC THERM MICROLAN PROG-RES TO-92	DS18B20+PAR-ND
U$9		IC VOLT-LVL TRANSL 2BIT BI SM8	296-21978-1-ND
VR_HEAT		Dimension Engineering 10W Adjustable Switching Regulator	
VR_MOTORS		Dimension Engineering 10W Adjustable Switching Regulator	
VR_SERVO		Dimension Engineering 10W Adjustable Switching Regulator	
XBEE		MODULE ZIGBEE 100MW W/CHIP ANT	XBP24-ACI-001-ND

Continued...

Part	**Value**	**Name**	**Number**
XBPINS		2mm 10pin XBee Socket	
LEDTXX	ORG	LED ALINGAP ORN CLEAR 1206 SMD	350-2049-1-ND
LEDRXX	ORG	LED ALINGAP ORN CLEAR 1206 SMD	350-2049-1-ND
R15	150	RES 150 OHM 1/4W 1% 1206 SMD	RHM150FRCT-ND
R16	150	RES 150 OHM 1/4W 1% 1206 SMD	RHM150FRCT-ND
LEDRXO	YEL	LED ALINGAP YLW CLEAR 1206 SMD	350-2050-1-ND
LEDTXO	YEL	LED ALINGAP YLW CLEAR 1206 SMD	350-2050-1-ND
R22	150	RES 150 OHM 1/4W 1% 1206 SMD	RHM150FRCT-ND
R23	150	RES 150 OHM 1/4W 1% 1206 SMD	RHM150FRCT-ND

Appendix D

Code

Herein is code used for the experiments in thesis. Creature accepts incoming serial byte at 9600bps from XBee radio. If that byte is 0-252, value mapped to breathing servo. If that byte is 253, pulse triggered. Heat, ears, and purr all deactivated. The most recently received value and serial port is sent out via Bluetooth.

Table D.1: Haptic Creature communications protocol.

	Input to Creature
f	Pulse out ten steps
d	Pulse in ten steps
a	Pulse out one step
s	Pulse in one step
r	Start reporting temperature sensor data
t	Stop reporting temperature sensor data
	Output from Creature
R.	Current respiration servo position
T.	Output of breathing servo temperature sensor
U.	Output of anterior temperature sensor
V.	Output of electronics board temperature sensor

Listing D.1: Haptic Creature Mirroring Code

```
/****  Arduino code for Haptic Creature to allow mirroring of breathing and pulse ****
 *      Joseph P. Hall III
 *      03/27/10
 *
 *      Accepts incoming serial byte at 9600bps
 *      If that byte is 0-252, value mapped to breathing servo
 *      If that byte is 253, pulse triggered
 *      heat, ears, and purr off
 *
 *      Use with new electronics board:
 *        - Sends data out via bluetooth, in via XBee
 *
 * */

//Connection Definitions, pretty much self-explanatory
```

```
#define STEPPER_PIN1 48
#define STEPPER_PIN2 49
#define STEPPER_PIN3 50
#define STEPPER_PIN4 41
#define LIMIT_SWITCH_PIN 25
#define PULSE_LS 25

#define BREATH_PIN 23
#define SEAR_PIN 27
#define PEAR_PIN 29

#define PURR_ENABLE_PIN 7
#define PURR_DIR1_PIN 5
#define PURR_DIR2_PIN 6

// OneWire for temperature readings
#include <OneWire.h>
OneWire ds(53); // start onewire on pin 53
//OneWire and temperature processing variables
byte present = 0; // 1 if sensors present
byte data[12]; // data read from sensors
byte addr[8];  // address of sensor from which to read
int HighByte, LowByte, TReading, SignBit, Tc, Tc_100, Whole, Fract; //vars for converting data to degrees F
byte tempsense1[8] = {40, 136, 25, 15, 2, 0, 0, 15}; //address of temperature sensor in decimal, breathing servo
byte tempsense2[8] = {40,  81, 22,  2, 2, 0, 0, 175}; //address of temperature sensor in decimal, on board
byte tempsense3[8] = {40,  35, 65,  2, 2, 0, 0, 157}; //address of temperature sensor in decimal, creature anterior
boolean t2sflag = false; // True when we should print a temperature reading
int t2s = 0; // temperature to be sent over serial
byte senstoread = 0; // the next temperature sensor to read, typically 1-3

// Stepper motor for pulse
#include <Stepper.h>
Stepper Pulse(200, STEPPER_PIN1, STEPPER_PIN2, STEPPER_PIN3, STEPPER_PIN4); // 200 pulse per rotation stepper
int Pulse_dir = 1;  // Direction of next pulse step
boolean pulseflag = false; // True when pulse command sent until pulse completed
byte pulsecount = 0;  //  Number of steps into pulse we are
// Pulse limit switch is attached to pins 43 and 45, is high on depress
boolean pulse_ls_read = true; //  Pulse limit switch reading;

// Servo variables
#include <Servo.h>
Servo Breathing;
Servo SEar;
```

```
Servo PEar;


//Timer Library (Just to use the temperature sensors :-\)
#include <MsTimer2.h>

// loop index variables
int j = 0;
int i = 0;

void setup() {
    //Set timer to fifteen seconds
    MsTimer2::set(15000, readtemp);
    MsTimer2::start();

    //Serial communication channels
    Serial.begin(9600);  // USB
    Serial1.begin(9600); // XBee
    Serial2.begin(9600); // Bluetooth
    //Serial3.begin(9600); //tail wire

    //Setup Limit switch power and receiver
    pinMode(LIMIT_SWITCH_PIN, INPUT);
    digitalWrite(LIMIT_SWITCH_PIN, LOW);

    //Attach Servos
    Breathing.attach(BREATH_PIN);
    SEar.attach(SEAR_PIN);
    PEar.attach(PEAR_PIN);

    //Set purring motor direction, turn purring motor off
    pinMode(PURR_DIR2_PIN, OUTPUT);
    pinMode(PURR_DIR1_PIN, OUTPUT);
    digitalWrite(PURR_DIR1_PIN, LOW);
    digitalWrite(PURR_DIR2_PIN, HIGH);
    pinMode(PURR_ENABLE_PIN, OUTPUT);
    analogWrite(PURR_ENABLE_PIN, 0); //purr speed to 0

    //Initiate and zero stepper motor
    Pulse.setSpeed(5); //Slow down the speed for initiation
    //Run until pulse depressed
    for (i = 0; i < 50; i++) {
        if(digitalRead(PULSE_LS) != 1) {
            Pulse.step(Pulse_dir);
            delay(50);  //wait for debounce
        }
    }
    //take two additional steps to be sure it is depressed
    Pulse.step(Pulse_dir);
    Pulse.step(Pulse_dir);

    //Restore speed
```

```
    Pulse.setSpeed(25);

    //deactivate heaters
    for (j = 10; j < 13; j++) {
        pinMode(j, OUTPUT);
        digitalWrite(j, HIGH);
    }

    //Zero servos
    Breathing.write(0);
    SEar.write(0);
    PEar.write(0);

    //Start temperature reading
    tempPreparetoRead();
}

byte inByte = 0; // byte read from serial port
byte btarget = 0; // breathing amplitude to achieve
byte boldtarget = 0; // previous breathing amplitude to achieve

int bvalue = 50; // filtered breathing amplitude to achieve
int millisold = 0; // previous time respiration command received
int diff = 0;  // amount of time since previous respiration command was received
int interval = 10; // milliseconds between respiration commands

int pulseinterval = 0; // amount of time since previous pulse command was received
int pulseold = 0;  // time previous pulse command was received

void loop() {
    // Communication and Control through USB Port
    if (Serial.available() > 0) {
        inByte=Serial.read();
        switch (inByte) {
            case 'f':
        Pulse.step(10);
        break;
            case 'd':
        Pulse.step(-10);
        break;
            case 'a':
        Pulse.step(1);
        break;
            case 's':
        Pulse.step(-1);
        break;
            case 'r':
        // read tail sensor
        MsTimer2::start();
        break;
```

```
            case 't':
        MsTimer2::stop();
        break;
        }
        inByte = 0;
    }

    // Breathing and pulse commands through XBee Radio
    if (Serial1.available() > 0) {
        boldtarget = btarget; // store the previous commanded breathing servo value
        inByte=Serial1.read();
        Serial2.print("R."); // print the new respiration rate
        Serial2.println(inByte, DEC);
        if (inByte == 253) { //253 = pulse command
            pulseinterval = millis() - pulseold; // make sure we're not receiving these too quickly
            pulseold = millis();
            if (pulseinterval > 50) {
                pulseflag = true;
      } else{
                btarget = boldtarget;
            }
    }
    if (inByte < 253) {
            btarget = inByte;
        }
        millisold = millis();
    }

    // Now what we pass through every iteration:
    // Send proper command to breathing servo
    diff = millis() - millisold;
    //Updates are received every ~60 microseconds
    /*if (diff < interval) {
   bvalue = boldtarget + ((btarget - boldtarget) * diff) / interval;
   } else {
   bvalue = btarget;
   }
   if (bvalue < 0) { // sanity check, this happened once or twice
   bvalue = 0;
   }
   */
    Breathing.writeMicroseconds(map(btarget,0,253,950,1400));

    // Pulse if necessary
    if (pulseflag == true) {
        if (pulsecount < 5) { // To pulse go three steps forward
            Pulse.step(3*Pulse_dir);
            pulsecount=6;
        }
        else if (pulsecount > 5 && pulsecount < 10) {
```

```
            Pulse.step(-3*Pulse_dir); // Then three steps back
            pulsecount=11;
        }
        else {
            pulseflag = false;
            pulsecount = 0;
        }
    }
}

/*************************** */
// To read temperature sensors first we select sensor, then wait for
// conversion, then read sensor.  Some of this code from arduino ↩
    onewire guide
void tempPreparetoRead() {
    if (senstoread < 4) { // number of temperature sensors + 1
    senstoread = 1;
    }

    switch(senstoread) {
        case 1:
      for ( i = 1; i<9; i++) {
        addr[i]=tempsense1[i];
      }
      break;
        case 2:
      for ( i = 1; i<9; i++) {
        addr[i]=tempsense2[i];
      }
      break;
        case 3:
      for ( i = 1; i<9; i++) {
        addr[i]=tempsense3[i];
      }
      break;
    }


    ds.search(addr);
    // Send the command to read
    ds.reset();
    ds.select(addr);
    ds.write(0x44,1);
    MsTimer2::start(); // start timer for conversion
}

void readtemp() {
    MsTimer2::stop();
    present = ds.reset();
    ds.select(addr);
    ds.write(0xBE);

```

```
    for (i = 0; i<9; i++) {
        data[i] = ds.read();
    }

    // Convert to Fahrenheit and send
    LowByte = data[0];
    HighByte = data[1];
    TReading = (HighByte << 8) + LowByte;
    SignBit = TReading & 0x8000;
    if (SignBit) { //negative
        TReading = (TReading ^ 0xffff) + 1; // 2's compliment
    }
    Tc_100 = (6 * TReading) + TReading / 4;
    Tc = Tc_100;

    if (SignBit) {
        Tc = -1 * Tc;
    }
    t2sflag=true;
    t2s=Tc*9/5+3200;

    // If temperature flag set, read the sensrs.
    if (t2sflag) {
        if (senstoread ==1) {
            Serial2.print("T.");
        } else if(senstoread ==2) {
            Serial2.print("U.");
        } else if (senstoread == 3) {
            Serial2.print("V.");
        }
        Serial2.println(t2s);
        t2sflag = false;
    }

    tempPreparetoRead();
}
```