The Impact of Social Robots on Young Patients' Socio-emotional Well-being in a Pediatric Inpatient Care Context

by

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BSc. Electrical Engineering and Computer Science, MIT (2014)
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School of Architecture and Planning
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Abstract

In this thesis, I explore how interactive technologies can positively impact human wellness and flourishing. I investigate this in the context of pediatric inpatient care. Children and their parents may undergo challenging experiences when admitted for inpatient care at pediatric hospitals. While most hospitals make efforts to provide socio-emotional support for patients and their families during care, gaps still exist between human resource supply and demand. The Huggable project aims to close this gap by creating a social robot able to mitigate stress and anxiety and to promote positive affect and physical activity in pediatric patients by engaging them in playful interactive activities. We ran a randomized controlled trial study at a local pediatric hospital to study how three different interactive mediums (a plush teddy bear, a virtual agent on a screen and a social robot) affects the child patient's physical activity, affect, joyful play, stress and anxiety. In this thesis, I analyze the social, emotional, linguistic and physical behaviors of the patients, caretakers and medical staff with the video data collected during the Huggable study. Results from the behavioral analyses show that a social robot promotes more physical movement, more emotional verbal expressions, and more dynamic patient-caretaker-medical staff interaction than the virtual character and the plush interventions. Then, I extend the findings from the in-hospital experiment and develop an autonomous virtual avatar mobile application that provides personalized positive psychology interventions. A three-week longitudinal study with smartphone users showed that the interactive virtual avatar resulted an immediate improvement on people's affect and the users' engagement with the avatar increased over time due to the personalization algorithm implemented in the system. The findings from the randomized clinical trial in the pediatric hospital and the longitudinal study with smartphone users suggest the potential benefit of an autonomous and personalized social robot in pediatric inpatient-care contexts on young patients' social and emotional wellbeing.

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The following people served as readers for this thesis:

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1. Introduction

1.1 The Problem

Many children do not like to be at a hospital. During hospital stays, they may experience painful, invasive procedures and may need to have intrusive medical devices attached to their bodies. Often times, children who are hospitalized are stressed, anxious, and in pain. This impacts a number of important challenges hospitals and clinical staff face. When a child refuses to cooperate with a medical procedure, clinical service becomes less efficient, patient throughput increases and recovery rate decreases. The negative affect during hospital stay influences patient satisfaction. It not only affects patients and their caregivers, but also the hospital as an institution with its cost management and customer care.

Most pediatric hospitals in the U.S and in Canada have child life programs that use developmental interventions and therapeutic play to reduce anxiety in children and to psychologically prepare patients and their families for upcoming procedures and clinical care (Wilson, 2006). Certified child life specialists (CCLS) engage and support patients and their families to create a less intimidating and more comfortable healthcare experience. CCLS use various activities in order to distract children from anxiety or pain and to promote positive emotion and physical activities. However, there is still a gap between the supply and demand for CCLS support for children and their families. In order to address these issues, the Huggable project developed a social robot that can extend the reach of the human staff by playfully interacting with children and can enhance patients' wellness in an inpatient care context (Jeong, Santos, Graca, & Connell, 2015).

The Huggable research team ran a randomized clinical trial at Boston Children's Hospital to study the effect of a plush bear (current standard practice), a virtual agent on an Android tablet device, and a social robot in mitigating pediatric inpatients' anxiety and stress and promoting physical activity, positive affect and engagement with clinical staff through playful interactions (Jeong, Graca, Connell, Anderson, & Goodenough, 2015). Developing interactive technologies for pediatric inpatient care is a challenging task because the technology needs to engage a diverse population of children with different ages, medical conditions, physical/emotional states, etc. Thus, we aim to understand how these factors of pediatric patients impact the nature of these interventions needed for each child in a hospital. The result of this research will gain new knowledge on the efficacy and potential application of a social robot, a virtual agent and a plush bear in enhancing pediatric inpatients' socio-emotional well-being.

During the study, we observed that children were highly engaged with the interventions. Children were asked to play with the provided intervention as long as they would like, and most of the interaction

sessions lasted 5 to 20 minutes. During the interactions, children smiled, laughed, touched the intervention and moved their bodies. Based on these observations, this thesis deeply investigates the effects of each intervention by analyzing the behaviors of child patients, family members, and medical staff before, during and after the interaction session. Through these analyses, this thesis offers better understanding of the potential efficacy of both virtual and robotic agents on pediatric patients' social and emotional wellbeing in an inpatient-care context, and how those effects could influence patient-family-clinical staff relationships and interactions.

1.2 Research Questions

This thesis explores development of interactive agents that are designed to engage young pediatric in-patients and the evaluation of these technologies through a randomized clinical trial at a local pediatric hospital. The three interactive agents studied each has different level of physical and social interactivity. A social robot can interact both physically and socially, while a virtual avatar is socially interactive but lacks physical embodiment, and a plush toy is physically embodied but cannot engage children socially on its own. A plush toy has physical embodiment that children can touch but cannot provide social support as a robot or a virtual avatar could. I hypothesize that a social robot that has both physical embodiment and sociability could make an interesting platform to augment and extend CCLS in pediatric inpatient care. Based on the video footage collected from the experimental study, I perform detailed analyses of children's, parent's, and medical staff's behavior during their interaction with one of three different agents in pediatric inpatient care context, and aim to address the following research questions:

- How do patients engage with a plush bear, a virtual agent and a social robot differently?
- What is the impact of the physical embodiment of the social robot for young patients in a pediatric hospital?
- Based on the difference in these agents, what are the design implications for serving the needs of patients, families and clinical staffs?
- Would a social robot be more effective in improving all pediatric patients' wellbeing than a virtual agent?
- Would one group of pediatric patients benefit more from a social robot and another group benefit more from a virtual agent?

The behavioral analyses done in this thesis investigate social robots' effect on pediatric patients' physical movements and social and emotional well-being in an inpatient-care context. Furthermore, my thesis work offers insights on how these effects influence the patient-family-clinical staff relationship and interactions in child patients' hospital bed space. The effect of social robots and virtual agents on children in relation to their medical condition and baseline affective state is explored in this thesis.

However, if these interactive agents become autonomous and repeatedly meet children at the hospital, what would those interaction look like? In order to be deployed in the real-world, the agents need to be able to develop longitudinal and personalized relationships with each child based on repeated interactions. Therefore, I aim to address the following research questions through a pilot study that explores how an emotionally intelligent Huggable avatar that is always present on a mobile device can promote smartphone users' psychological wellbeing through longitudinal and personalized interactions:

- Can an emotionally intelligent virtual avatar improve people's affect and emotional wellbeing?
- What is the impact of personalized interaction on people's engagement?
- What is the benefit of being an easily accessible and always present interactive agent from the user's perspective?

By addressing these questions, I hope to gain interesting insights into further design guidelines for social and interactive technologies.

1.3 Contributions

The core contributions of this thesis are as following. First, I develop interactive technologies (a social robot, a virtual avatar and their teleoperation interface) that are designed to interact with young children by bedside in a pediatric hospital. Second, in collaboration with other members of the Huggable research team, I ran an experimental study that investigates the application of these companion-like agents as part of pediatric in-patient care context. Third, I conduct behavioral analyses on recorded video footage and verbal utterance transcriptions to investigate the impact of a social robot, a virtual avatar and a plush toy on the social engagement and emotion of young patients and co-present family. Fourth, based on the findings from the in-hospital experimental study, I develop an always-present virtual avatar mobile applications that provides personalized positive psychology interventions to improve psychological wellbeing of smart phone users. Lastly, based on the findings from the two studies, I propose guidelines for interactive technologies as an interface that fits into a professional context and promotes children's wellness.

1.4 Thesis Overview

This thesis is composed of three main parts. Part I (section 2-7) discusses the development of interactive technologies and the evaluation of these prototyped technologies through a series of experimental studies. Section 2 discusses the related works and theoretical background that motivated the hypotheses. Section 3 summarizes the mechanical and electrical design revision made in the Huggable v5 robot platform and its tele-operation interface that were used for the in-hospital experimental study. The

detailed descriptions of the robot design and software infrastructure are provided in Jeong's M.Eng thesis (Jeong, 2014). Section 4 describes the first between-subject randomized clinical trial ran at Boston Children's Hospital with three interactive agents (a plush toy, a virtual Huggable avatar and a Huggable social robot) and the results of behavioral analyses from the study. Part II (section 8-9) describes a longitudinal pilot study that was run with an autonomous virtual Huggable avatar on mobile phones that provides personalized positive psychology interventions to improve smartphone users' psychological well-being. While this study was not done with pediatric patients, it offers insights into ways to make the Huggable robot autonomous with personalized and emotionally intelligent behaviors in the pediatric in-patient care context in the future. Part III (section 10-11) reports the work-in-progress status of the new technologies (the upgraded Huggable v6 robot, virtual avatar platform and their teleoperation interface) that will be used for the new within-subject experimental study and proposes a within-subject experimental study to follow up the first study in Section 3. The new proposed study aims to compare the effects on children's affective/physiological response and preference in a more controlled manner, while the first between-subject study was more exploratory and aimed to observe natural playing behaviors of pediatric patients with each interactive agent. Finally, Section 11 summarizes the findings and contributions of this thesis, and offers design guidelines for creating interactive technologies in a pediatric inpatient care context.

Part I

Improving Young Pediatric Patients' Socio-emotional Wellbeing with Interactive Technologies

2. Related Works

2.1 Distraction from Pain, Stress and Anxiety

In order to develop interactive technologies that supports young patients with severe illness and high level of pain and stress, it is important to understand the non-pharmacologic interventions currently used in pediatric hospitals. Currently, medical professionals use various methods for young pediatric patients' pain management. Many interventions aim to distract children from the physical pain by engaging children with various activities or media, e.g. bubble blowing (French, Painter, & Coury, 1994), video games (Suzuki & Kato, 2003), plush toys (Ullan et al., 2014) or music (Robb, Nichols, Rutan, Bishop, & Parker, 1995), while other methods are various types of behavioral therapies, such as guided imagery, breathing exercise and positive self-statement reflection that aim to improve children's self-efficacy in managing their pain (Tsao & Zeltzer, 2005; van Tilburg et al., 2009).

How does distraction reduce perceived level of pain? Although researchers still do not have conclusive agreement on how distraction alters pain, there are several theories that pose possible mechanisms of distraction on pain mitigation. The first physiology-based theory is the gate control theory (Melzack and Wall, 1967). According to the gate control theory, non-painful stimuli provided by a distraction intervention closes or modulates the connectivity, or the "gates," between the perception of painful stimuli and the central nervous system. Empirically, Valet et al. (2004) found evidence through an fMRI study that distraction modulates the connectivity between the cingulo-frontal cortex and the midbrain in a top–down maner to gate pain perception.

There are two theories that are posed to explain the mechanism of distraction in pain mitigation by viewing attention as a cognitive resource: the limited attentional capacity theory (McCaul and Malott, 1984) and the multiple attentional resource theory (Wickens, 1991). McCaul and Malott (1984) argues that one has limited capacity available for focusing attention on stimuli, and stimuli provided by distraction requires a non-automatic process. Based on these assumptions, the limited attentional capacity theory states that (1) distractions will be more effective than placebo, (2) distraction interventions that require more attentional capacity will be more effective, (3) distraction will have higher effect on low level of pain, and (4) distraction will be more effective than sensation redefinition for mild pain stimuli, but the reverse will be true for intense pain stimuli. The multiple attentional resource theory is similar to the limited attentional capacity theory but claims that that there are three separate domains of information-processing capacity (perceptive, spatial and somatic) instead of one attentional resource (Wickens, 1984). Based on the multiple attentional resource theory, Johnson et al. (1998) suggests that

distraction interventions that use perceptual and spatial processors will be most effective in alleviating pain.

2.2 Socio-emotional Support and Health Outcomes

Effects of socio-emotional support on patient's stress and health outcome are actively being studied as well. A meta-analysis of 122 studies done by DiMatteo (DiMatteo, 2004) shows that positive and constructive social support has significant effects on patient's adherence. Social support from mothers was also found to help young girls report less pain than a control group (Chambers, 2002). Patients can also benefit from interacting with other agents. Pet therapies have been shown to improve pediatric patient's mood and to decrease self-reported pain level (Braun, Stangler, Narveson, & Pettingell, 2009; Kaminski, Pellino, & Wish, 2002; Sobo, Eng, & Kassity-Krich, 2006). Virtual agents have been used to engage young pediatric patients with a storytelling activity. Cassell et al. explored the efficacy of a storytelling activity with virtual agents on pediatric patient's self-disclosure and emotion narration (Bers, Ackermann, & Cassell, 1998). Bickmore et al. developed virtual nurses that assist a patient with discharge instruction (Bickmore, Pfeifer, & Jack, 2009). Often times, hand puppets are used by CCLS to gain information on children's social, emotional and relational issues (Ringoot, Jansen, Graaff, & Measelle, 2013). These approaches are used because children often are more engaged by the playful interactions and find animals or toys less intimidating than hospital staff. Robotic platforms are also being studied as a tool to decrease children's distress during intravenous injection procedure. Researchers are starting to use a social robot as a platform to distract young patients from stress and anxiety (Beran et al., 2013; Greczek & Matari, 2015).

Cohen and Wills (1985) have first theorized the link between social support, perceived stress and health outcomes based on their buffering model, which claims that social support provides resource that protects, or "buffers," persons from stressful events that could lead to poor health outcomes. The buffering model is supported by the work of Uchino, Cacioppo and Kiecolt-Glaser (1996) that found evidence on beneficial effects of social support on the cardiovascular, endocrine, and immune systems. Their finding on positive impact on social support on these physiology suggest that providing patients with good quality and quantity of socio-emotional support could lead to better health outcomes. Later on, Lakey and Cohen (2000) further adds two more perspectives in addition to the buffering theory by arguing that social support directly influences health by promoting self-esteem and self-regulation, regardless of the presence of stress (social constructionist perspective) and that health effects of social support co-occur with relational support, such as companionship, intimacy, and low social conflict (relationship perspective).

2.3 Child Life Program and Play

How are the distraction and social support methodology incorporated in the child life program? A certified child life specialist uses play as the primary modality to distract pediatric patients from pain, anxiety and stress, and promote children's well-being during their hospital experience. Play is a fundamental part of young children's development and have been shown to make the health care experience less intimidating and more comfortable (Council, 2006). When children play, they concentrate on the playing task and are distracted from painful or stressful stimuli, both external and internal. Furthermore, the social interactions between a child and a CCLS during the play provides socio-emotional support for the child, which positively impacts the patient's health outcome.

Child life program provides age-appropriate play for each children. They often engage young children with make-believe play, whereas school-aged children are provided with games with rules. Other activities a CCLS engages young patients with include creative or expressive arts, such as music therapy, art therapy, drama, video work, and creative writing to help children feel the normalcy at the hospital. In order to address children's negative feelings and anxiety over medical procedures, a child life specialist often uses health care play or “medical play.” During a child-directed medical play, a patient often gets to explore medical equipment, dramatic or dress-up play, games or puzzles depicting medical themes, and the creation of artwork using health care materials, such as bandage strips, tongue depressors, and syringes (Thompson & Stanford, 1981; Brown, 2001, Solnit, 1984; McGrath, 2001; Zahr, 1998; McCue, 1998). Such activities allow pediatric patients to familiarize with the overall hospital experience and to gain a sense of control and mastery of their environment.

2.4 Socially Assistive Robotics

In this thesis, I propose developing a social robot to augment the work currently provided by child life program. Then why would a social robot be an interesting tool for improving young pediatric patients' socio-emotional wellbeing and extending the service provided by child life specialists? Socially assistive robots (Feil-Seifer & Mataric, 2005) assist people “through social rather than physical interaction.” SAR have been actively developed to help diverse demographic groups including children, the elderly, and those with disabilities in the healthcare domain. Beran et al. (Beran, Ramirez-Serrano, Vanderkooi, & Kuhn, 2013) investigated the efficacy of a small humanoid robot MEDi in providing distraction from pain for young children receiving a vaccination procedure. Their work focused on relieving short-term pain and anxiety for relatively healthy children. A robotic baby seal Paro is widely used in the world in order to mitigate the symptoms of dementia and Alzheimer's disease in nursing homes residents. Paro was found to reduce stress, to increase the social and emotional engagement among the elders and their caregivers (Kidd, Taggart, & Turkle, 2006; K. Wada, Shibata, Saito, & Tanie, 2004;

Kazuyoshi Wada & Shibata, 2005). ALIZ-E (Adaptive Strategies for Sustainable Long-Term Social Interaction) project shows how social robots can motivate and persuade diabetic children to maintain a healthier lifestyle, and emotionally and socially engage and connect with children to increase self-efficacy and self-confidence (Greeff & Henkemans, 2014; van der Drift, Beun, Looije, & Henkemans, 2014). However, there has been not much work done on how socially assistive robots could assist children with critical health conditions in an inpatient care context. Most of the robots in earlier research were developed to help children without severe stress or pain. On the other hand, the Huggable project (Jeong, Graca, et al., 2015) investigates a socially assistive robot's effectiveness in mitigating stress and anxiety and promoting positive affect and physical interactions in patients with complex medical issues, who often require long or repeated hospitalizations and are frequently associated with chronic pain and other distressing.

2.5 Physical Embodiment and Engagement

The previous section discussed supporting evidence that a socially assistive robot could positively impact patients through social interactions. However, does it need to be a physically embodied robot? If it is the social interaction between the agent and the human that provides the core intervention impact, can the same interaction be carried on a virtually embodied agent instead? Various studies comparing a virtual agent and a robot showed that physically present and embodied robots are more positively perceived and more effective at persuading people than a virtual agent (Fasola & Mataric, 2011; Li, 2013, 2015; Wainer, Feil-Seifer, Shell, & Matarić, 2006). Why is this so? Li (2015) suggests that when both physically present, the lack or existence of physical embodiment could possibly alter the realism of the interactive agent in the interacting human's psychological processing. A study done by Han et al. (2005) found that an area of the brain that represents of the mental states of others gets activated when watching video clips of real-world humans, while an area of the brain related to attention to actions is activated when watching video clips of virtual-world humans. Li (2015) suggests that "the mere recognition that an entity has a physical form in the real world – even though that form is not present – influences human perception."

An alternative theory that could possibly explain the different level of engagement on a physical robot and a virtual agent is construal level theory. Construal level theory describes the relation between psychological distance and the level of perceived abstractness or concreteness on objects or events (Trope, Y., and Liberman, N., 2010). In other words, the more distant an object is from the individual, the more abstract it will be thought of, while the closer the object is, the more concretely it will be thought of. Various dimensions, such as temporal, spatial, social and hypothetical distance, are considered to contribute to the psychological distance. Based on this theory, a virtual agent could perceived as farther

from the self in the here and now in hypotheticality dimension. An animated digital agent on a two-dimensional screen may seem less real or less probable, and not in the real world but only existing on a flat screen.

3. Experimental Testbed

This section describes the design and implementation of the Huggable hardware and software systems that were used as experimental testbed and deployed at a local pediatric hospital for a randomized clinical study. The Huggable agent was brought to life in two forms: a social robot with physical embodiment and a virtual avatar on a flat smart tablet device. These two forms of Huggable agent were both remotely controlled by a CCLS through a custom teleoperation interface in an identical maner. The Huggable v5 system used with real patients, by a non-technical novice user and at a dynamically changing pediatric hospital setting. In order to conduct a successful randomized clinical trial study, the system needed to be robust, e.g. not break when a child pulls or pushes the robot's joint against its target position, and easy to use for a novice user. Huggable v5's hardware and software systems were modified based on those of Huggable v4 (Santos, 2012) to meet these needs for an in-hospital experimental study. In addition, the interaction data during the study session was collected with several cameras in a systemic way for time-synchrony.

3.1 The Robot

Huggable v5 was used for the first experimental study in this thesis. The Huggable robot has a long history of design iterations. Stiehl et al. (Stiehl et al., 2005) developed the first version of Huggable robot. The initial prototype was bulky and required multiple computers, one desktop and two laptops, in order to run the robot. In 2012, Dos Santos in collaboration with a Chinese manufacturing company Jetta made a drastic change to the mechanical and electrical design and developed Huggable v4 that adapted an Android smartphone as the core computing processor for the robot (Santos, 2012). However, Huggable v4 did not have enough mechanical stability and robustness to endure interactions with children in an experimental study.

3.1.1 Mechanical Design

Thus, some of the mechanical components of Huggable v4 were redesigned, and Huggable v5 was made in 2014 (Jeong, 2014). The new robot platform was designed to aesthetically look the same as the previous version. Huggable v5 has a form of a teddy bear and is generally perceived as a cute, friendly and unintimidating interaction partner (Figure 1). The overall contour is in a round and curvy bean shape,

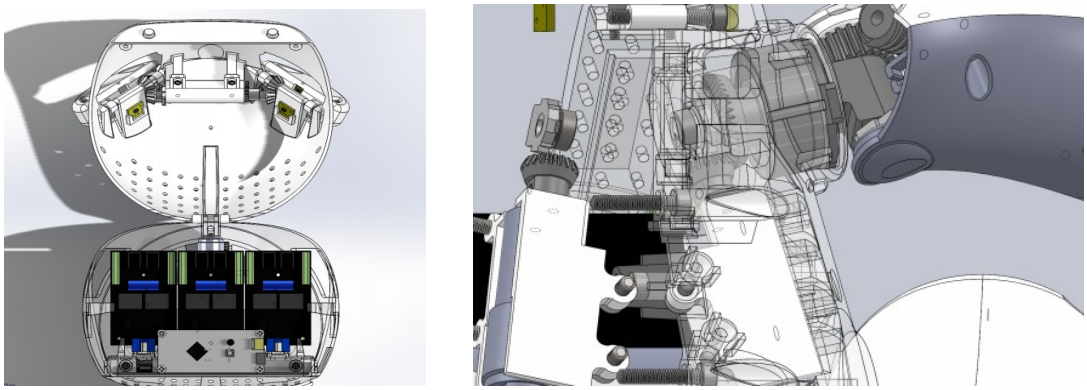
similar to the body of a young child, and the robot's big head and large eyes intensify its juvenile appearance. Huggable v5's twelve degrees of freedoms (DOFs) are able to perform animate and expressive motions: three for the head, two for each shoulder, one for each elbow, one for the waist, one for the muzzle and one for each ear. The head can rotate, nod and tilt. The arms can rotate and lift at the shoulders and can bend at the elbows. The ears and the waist can move forward and backward. The muzzle moves up and down when the robot talks.

Figure 1. The Huggable v5 in Simulation Suite at Boston Children's Hospital.

One of the biggest change from Huggable v4 to Huggable v5 was that the new robot was designed to be much more modular. The outward shells for Huggable v4 had to be vertically put together. As a result, opening up the torso or the head of Huggable v4 led to displacement of several internal components, e.g. motor boards, gears, potentiometers, etc. Figure 2 shows the vertical assembly design of Huggable v4. On the other hand, Huggable v5's head was designed to be opened up like a clam shell (Figure 3a), which required only the 3D printed top shell to be moved for accessing the motor boards and the internal components of the robot's head. The torso still had to be vertically aligned but the team made the Huggable v5's arms easily removable by connecting them to the torso with two pins (Figure 3b). Detailed explanations on technical changes made in Huggable v5 can be found in Jeong's M.Eng thesis (Jeong, 2014). The modularity of Huggable v5 allowed much more efficient testing and troubleshooting workflow for the Huggable team, and even the team at Boston Children's Hospital could be trained to replace gears or motors in the robot's arm without much technical background. Furthermore, ball bearings were attached to the joints in order to lessen friction between the plastic components and to smooth the overall movement.

Furthermore, Huggable v5 used slip clutch mechanisms in order to protect three arm joints (shoulder up/down, shoulder rotate and elbow) to prevent damage on gears and motors in case children manually move the robot's arms during the interaction (Figure 4). The flower shaped flexure inside the gear allows the shaft to spin when the joints are over-torqued due to a child's manipulation without back-driving the gearboxes and motors.

Figure 2. Huggable v4 shells were vertically aligned for its assembly.



(a) (b)

Figure 3. (a) Huggable v5's head opens up like a clam shell, and (b) the robot's arms are designed to be modular for easy replacement and troubleshooting.

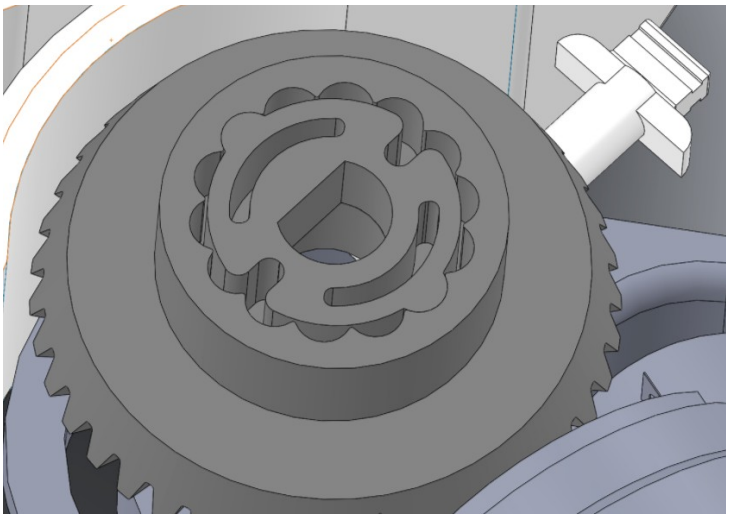


Figure 4. The flower shaped flexure in the arm joints prevents damaging gears and motors when over-torqued by external force.

In addition, we designed Huggable's fur to be easily removable and washable in order to comply with the infection control policy at pediatric hospitals. We kept several duplicates of the fur pieces of the robot in sealed plastic bags at Boston Children's Hospital and put freshly machine washed fur on the robot right before bringing the robot into a child patient's bed space. The fur cover was made in seven pieces to minimize the hindrance in the robot's physical motions and to simplify the clothing and unclothing processes.

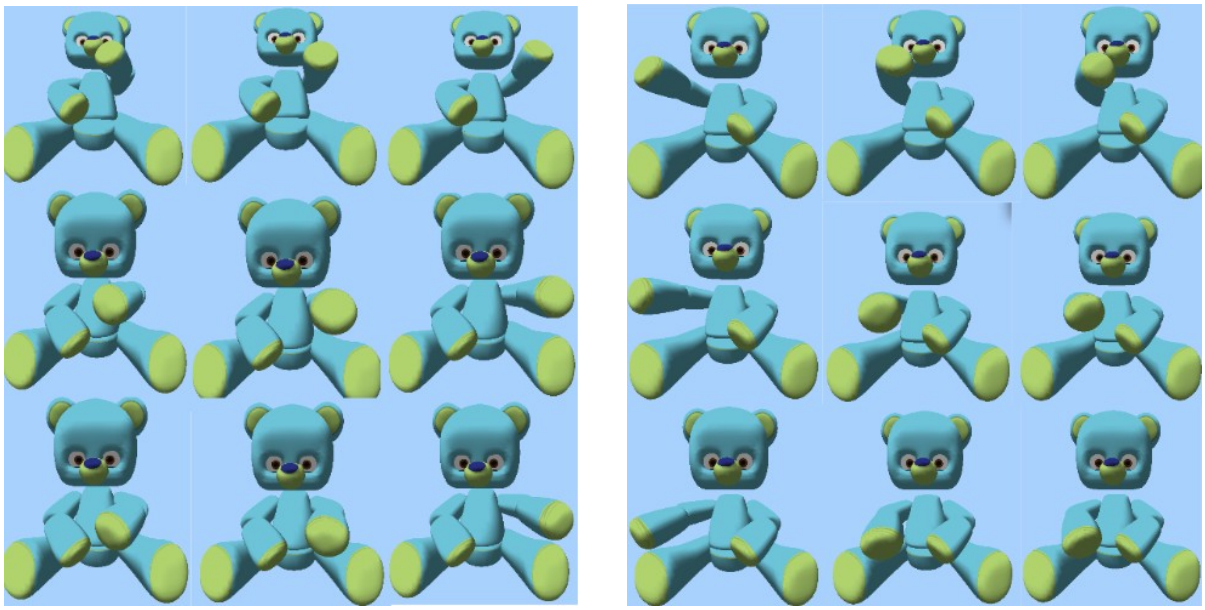
3.1.2 Electrical Design

Huggable v5 used an HTC Vivid smart phone for its core processor and sensors (microphone, front-faced camera and speaker). SparkFun's IOIO board interfaced the communication between the Android smart phone and a stack of MCBMini motor controller boards so that the robot controller Android application could set direct target positions for each joint. As a result, the smart phone could leverage the phone's internal sensors and wirelessly communicated data from the teleoperation interface while controlling the physical movement of the robot's joints as well. The screen of the phone displayed the eyes of the Huggable robot, and the eye animations were synchronized with the robot's body animations. Each of Huggable's eyes comprises a pupil and two upper and lower eyelids. The circular pupils can expand or shrink its size, and the eyelids can change their positions and closeness to the pupils to create more expressive animations.

3.1.3 Software Design

The Huggable robot's behavior controller was created with the Personal Robot Group's internal code base, *r1d1*. The *r1d1* code base enables playing pre-programmed facial and gestural animations while blending them with idle breathing behavior and procedural look-at/point-at behaviors. The look-at and point-at behavior blends look/point animations for 9 different (x, y) coordinate with normalized weights in order to enable looking/pointing at any coordinate in the 2D vector space for the robot's field of view. Figure 5 and Figure 6 show the nine poses for look-at, right point-at and left point-at that were used for blending. The robot's look-at system was also used additively with other canned animations. This additive look-at behavior allowed the Huggable robot to nod while looking at its left side. This feature enables the robot to show a joint attention when interacting with children and to make the social interaction more fluid, especially when it was playing an I Spy game with the child. With the twelve DOFs along with animated eyes on the Android smart phone screen, the Huggable robot is able to express various emotions and nonverbal cues (Figure 7).

Figure 5. Nine eye pose animations were blended together for procedural look-at behavior.



(a) (b)

Figure 6. Nine pose animations for (a) the right point-at and (b) the left point-at behavior.

Figure 7. The Huggable v5 robot can express various gestures and facial expressions.

The *r1d1* Huggable robot/avatar controller application runs on a HTC Vivid smart phone, which wirelessly communicates with the teleoperation interface. External sensory data and motor control information are sent to the Huggable controller application on the Android smart phone via IOIO board, and the controller application utilizes the internal phone sensors and features to communicate with the teleoperation interface. An external camera sends a black and white video stream of the robot/avatar's field-of-view to the teleoperation interface. The Realtime Voice Stream module takes in an audio steram of the Huggable operator's voice, modulates the pitch of the incoming voice into a higher one and then sends the transformed audio data to the Huggable robot/avatar controller application on the Android phone. The pressure level of the transformed audio is translated into the target position for the muzzle

joint and the motor gets actuated accordingly. As a result, the muzzle position changes dynamically when the robot operator is talking in an energetic manner, and moves less when the operator talks calmly. Figure 8 illustrates the system diagram of how external sensors, the smart phone and other modules for the Huggable robot communicate with one another.

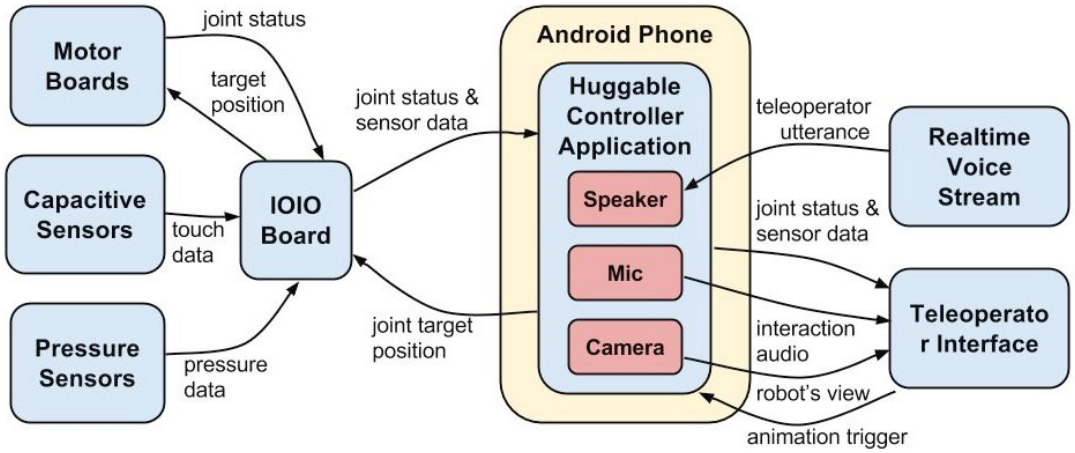


Figure 8. The system diagram of the Huggable v5 software architecture.

3.2 The Virtual Avatar

The Huggable virtual avatar had the exact same aesthetics and features the Huggable robot had (Figure 8). The 3D CAD model of virtual Huggable avatar was exported into a 3D animation model that could be used in Autodesk Maya, a commercial software that is frequently used by professional animators. The imported maya model is processed in order to be exported again in .x file that is used by *r1d1* code base. The .x model contains information of each joint and its range of movement as well as the geometric mesh for the skin. Various movements of the robot/avatar can be implemented in Autodesk Maya environment, and then can be exported into .iy files that are used in the *r1d1* system. The .iy animation files contain timestamped target positions for each joint. The mesh for Huggable avatar was designed to assimilate the fur skin of Huggable robot as well.

The same set of animations and 3D agent model was used for both Huggable robot and Huggable avatar. The appearance of the Huggable virtual avatar is exactly equivalent to the Huggable robot, and the motions of the virtual Huggable avatar had the same quality and speed as those of the Huggable robot. The custom Maya-to-r1d1 export feature allows a professional animator who is not familiar with the *r1d1* system to create smooth and natural animations for Huggable robot/avatar, and enables the researchers in Personal Robots Group to easily integrate the animations into the agent system. This system allowed the only difference between the robot and the virtual avatar to be the lack or the existence of physical

embodiment. Furthermore, the virtual avatar was controlled with a teleoperation interface in the exact same manner the social robot was controlled.

For the in-hospital experimental study, the virtual Huggable Android application was installed on Samsung Galaxy Tab 2 10 in device. The tablet was placed on a tablet stand so that children could interact with the Huggable avatar without holding the device. An external speaker was connected to the tablet device to amplify the remote controller's pitch-shifted voice, and the internal tablet microphone collected the audio data of the child and her surrounding and sent to the teleoperator interface. In addition, a narrow transparent acrylic pad was attached at the bottom of the tablet device in order to prevent children from accidentally closing the Huggable avatar application during the interaction.

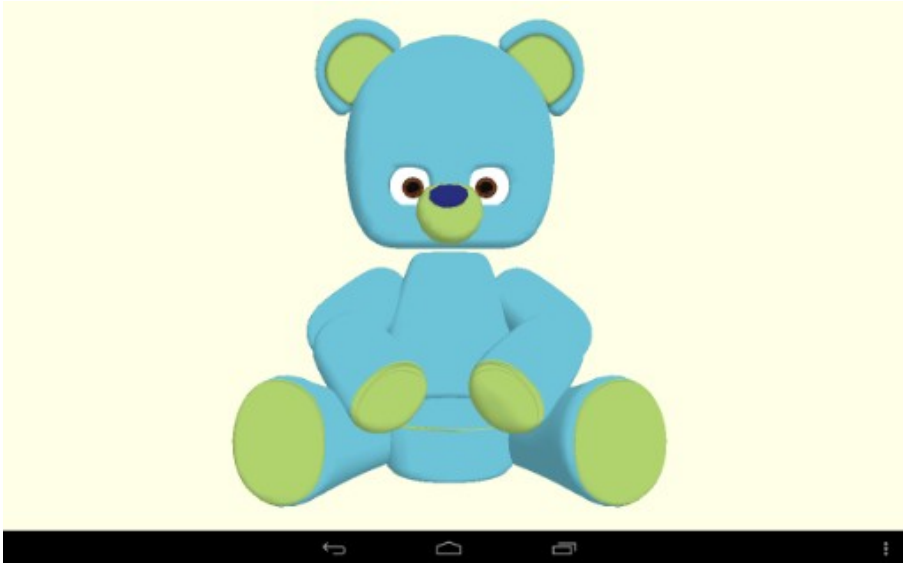


Figure 9. The virtual Huggable avatar on an Android tablet device.

3.3 Teleoperation Interface & Real-time Pitch Shift

The Huggable v5 teleoperation interface was developed to be used by three certified child life specialists (CCLS) at Boston Children's Hospital. The interface allows a remote operator to trigger various facial expression and gesture animations for the Huggable robot/avatar and to perceive the Huggable agent's surrounding environment via video and audio streams. The virtual representation of the Huggable character in the lower left corner of the interface visualizes the movement of the Huggable agent, either robotic or virtual, in real time. In addition, the tele-operator can make the Huggable robot or the avatar look at or point at certain objects or locations in its field of view via a left-click (look-at) or a right-click (point-at). Further details on the tele-operation interface can be found in (Jeong, 2014).

The teleoperation interface was installed on a 15- inch MacBook Pro, and had various features for controlling the behaviors of Huggable robot/avatar: canned animations trigger, sound clip mute/un-mute function, look-at and point-at by left/right click, and open/close type for canned animations. Light pastel tone of sky blue, green and yellow colors were used in the interface to match the colors of the Huggable, which is bright sky blue and light yellow green, and to create user-friendly atmosphere. Given that all three child life specialists using the interface are right-handed, the list of action buttons and emotional state diagram were placed on the right side of the interface for ease of use.

With the teleoperator interface, the CCLS can trigger twenty canned animations that are coupled with short sound clips. The animations composed of gestures for generic interaction behavior, such as greetings, agreement/disagreement, backchannels, etc., and could be used either with or without the pre-recorded sound clips. In addition to utterance-based gestures, the teleoperator interface allowed the remote control to trigger various short facial expressions based on the arousal-valence emotion model. However, instead of using the two dimensional arousal-valence graph, the interface used a gradient color scheme on a circular graph for triggering 16 emotion expression. The color around each emotion trigger button was chosen to intuitively match with the impression of the emotion. For example, “Alert” was matched with red, “Depressed” with dark blue, and “Happy” with light yellow. Positive arousal emotions were associated with bright and warm colors and negative arousal emotions with cold colors.

Each animation had an open and a closed version. The open animations had bigger body movements and were more animated while the closed animations were minimal and less expressive. Creating two different versions of each animation was suggested by the CCLS during the Huggable operating practice sessions because the CCLS was concerned some of the big animations could scare or overwhelm some children who are timid or shy. In the randomized controlled study, the closed animations were frequently used at the beginning of the interaction session.

The teleoperator interface visualizes the joint position of the robot’s twelve DOFs in the lower right corner. If Huggable robot is being controlled by the interface, the raw potentiometer reading data are sent to the interface, are translated to the joint position for the 3D agent model and then get displayed on the interface. If Huggable avatar is being controlled by the interface, the positions of Huggable avatar's virtual joints are sent to the interface for the real time joint status display.

The teleoperator's voice was pitch-shifted in real time and sent through Huggable robot/avatar. The distortion of remote operator's voice prevented children interaction with Huggable robot/avatar from realizing that a familiar CCLS is talking through the Huggable agent, and amplified the peer-like character of Huggable robot/avatar.

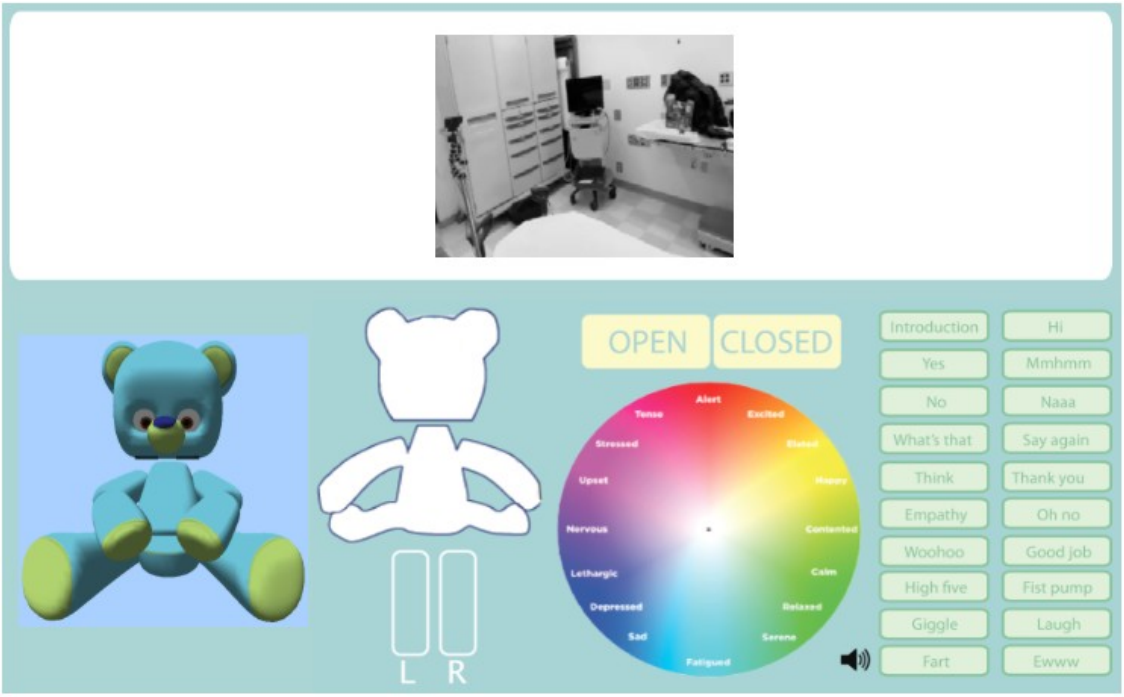


Figure 10. The tele-operation interface for the Huggable robot and the virtual avatar.

3.4 Data Collection

Several camera devices were installed in the patient room in order to collect the child-Huggable interaction data. Children were encouraged to sit in one place during the interaction with Huggable but often changed their sitting position and locations. Thus, many camera devices were placed in order to capture children's behavior regardless of where they were in the room.

Three external USB web cameras and two GoPro cameras were used to collected the video footage of the child-Huggable interaction. Two USB cameras, facing the child's patient bed, were placed on a wall connected to a MacBook Pro and simultaneously recorded the child's behavior before, during and after the interacting with Huggable agent, using EvoCam software. The third USB camera was placed at the mobile bedside table the Huggable agent was placed on. The camera feed from this camera was streamed to the teleoperation interface for a remote operator to view Huggable agent's surrounding. One GoPro cameras was placed at the foot of patient's bed. This device was placed in order to best capture children's facial expressions during the interaction in order to analyze children's affect in comparison to the electro-dermal activity level collected from the Q sensor. The other GoPro device was placed next to the child, facing the Huggable. The stream from this camera was viewed on an iPad device so that a remote operator can have a better look at the patient room when the child played an I Spy game with Huggable.

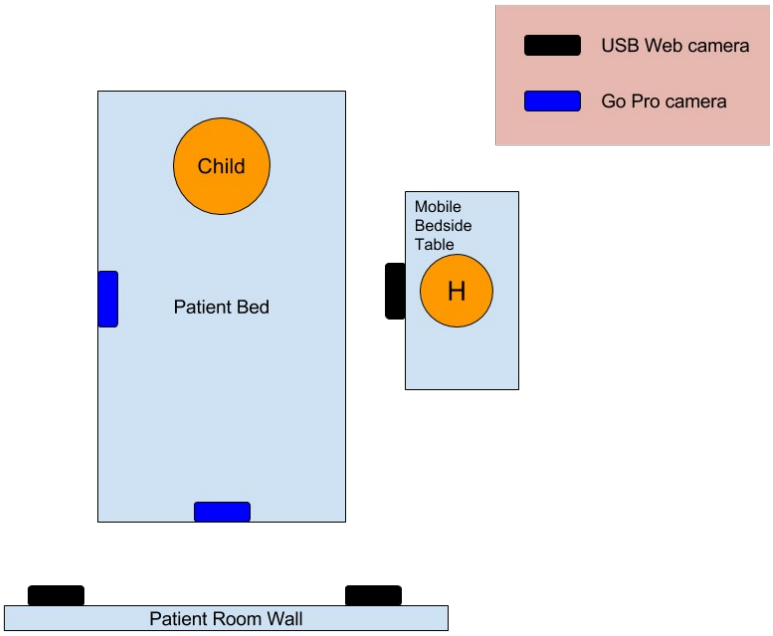


Figure 11. Layout of camera installation in patient room.

4. Randomized Clinical Trial Study

4.1 Hypotheses

The Huggable research team ran a randomized clinical trial study at Boston Children's Hospital using the Huggable v5 robot and avatar system. This thesis aims to test the following hypotheses by conducting deep behavioral analyses based on the video and audio recordings collected during the study.

- **H1**: The robotic Huggable promotes more physical movements from children.
- **H2**: The robotic Huggable promotes more affect expressions from children.
- **H3**: Children interact longer with the robotic Huggable than the virtual Huggable and the plush bear.
- **H4**: The robotic Huggable requires less CCLS assistance for the interaction than the plush bear and the virtual Huggable.
- **H5**: Family and medical staff are more likely to participate in the interaction with the robotic Huggable than with the virtual Huggable or a plush bear.
- **H6**: CCLS will have a positive impression of social robots in pediatric inpatient care context at the end of the study.
- **H7**: Each of the three interventions has different impact on the children's affect and physical movements depending on their medical condition and baseline affective state.

4.2 Method

4.2.1 Participants

We recruited 54 inpatients aged 3-10 (33 male and 21 female, age M = 6.09, SD = 2.33) staying for at least 48 hours at Boston Children's Hospital. Out of the total 54, twenty children were in the Inpatient Surgical Unit, one in the Medical Surgical Intensive Care Unit (MSICU), twenty-four in the Hematology/Oncology Unit and nine in the Bone Marrow Transplant Unit. Demographically, parents of thirty-six children reported White, three reported Asian, three reported Black, five reported Hispanic, one reported Native American, four reported Biracial, and one reported Other. All except two participants were typically developing children. The recruitment criteria was included wide ranges of children's ages and medical conditions. This was intentional because the Huggable research team aimed to identify opportunities for each interactive agent through this first exploratory in-hospital study.

4.2.2 Interactive Agents

Figure 12 shows the three agents used in our study. All three interventions were introduced as "Huggable" to the participant. Both the virtual Huggable and the robotic Huggable ran on Android devices, a tablet and a smartphone respectively, and could be teleoperated by a remote child life specialist. The teleoperator could trigger various facial expressions and body actions, and talk through the Huggable agent in a pitch-shifted voice. The remote operator could see and hear the participant and his/her surroundings via a camera feed.

Figure 12. Three interventions used in the Huggable study: plush bear, virtual agent and social robot

4.2.3 Procedure

The study had a between-subjects design with three conditions (*Robot* × *Avatar* × *Plush*). In order to ensure the balance across three experimental conditions, we applied block random assignment with

participants' age and gender as nuisance factors. We assigned children between age 3-5 year-old into the *Young* block and children between age 6-10 year-old into the *Old* block. Participants were then grouped into one of four blocks: age {*Young* vs. *Old*} × gender {*Male* vs. *Female*}. Within each of the four blocks, children were randomly assigned to interact with one of the three interventions: a plush Huggable, a virtual Huggable character on an Android tablet device or a Huggable social robot.

All study procedures were undertaken in participants' bed spaces. We set up the experiment equipment appropriately to accommodate each participant's bed space and asked the participants and their caregivers to act as they would normally. For infection control, all the equipment, including the Huggable robot's fur, was wiped down and washed between every study session.

We recorded a thirty-minute video of our study participants. Each child also wore a Q sensor from Affectiva Inc. (http://www.affectiva.com/) that measures electrodermal activity (EDA) data on their wrist in order to assess their baseline affective and physical state. The Q sensor was placed on a wrist that the child preferred and gel electrodes were used in the study. We also administered developmentally appropriate surveys to measure participants' self-reported levels of anxiety, pain, and affect, as follows. All participants were administered the Facial Affective Scale (FAS) (Nilsson, Finnström, Mörelius, & Forsner, 2014) and the Faces Pain Scale – Revised (FPS-R) (Hicks, von Baeyer, Spafford, van Korlaar, & Goodenough, 2001), which are both picture-based and commonly used in pediatric hospitals. Older children ages 6-10 were administered additional questionnaires: the Positive and Negative Affect Schedule (PANAS) (Watson, Clark, & Tellegen, 1988), the State-Trait Anxiety Inventory for Children (STAIC) (Spielberger & Edwards, 1973), and the Numeric Pain Rating Scale (NRPS), which has been shown to be valid for use in young children (von Baeyer, 2009).

After the thirty-minute observation, a certified child life specialist (CCLS) brought and introduced the intervention agent to the participant. The intervention was put on a mobile bedside table and placed next to the participant's bed for the interaction (Figure 11). Each participant was asked to freely interact and play with the intervention agent as long as she liked. The CCLS leveraged the intervention as she would normally do as her standard care for patients, and loosely guided the interaction for safe and proper usage of the intervention. For the *Robot* and the *Avatar* conditions, the virtual and the robotic Huggable were tele-operated by an additional CCLS outside the patient bed space. The virtual and the robotic Huggable engaged participants by conversing about their likes/dislikes, singing nursery rhymes, and playing an "I Spy" game. All child life specialists, both remotely operating the Huggable and the one sitting in the patient's bed space as well as all participants were blinded to the specific hypotheses regarding physical movement and affect valence. When the interaction ended, we administered the same self-report questionnaires on anxiety, pain, and affect to the participant, and recorded an additional 30-minute video of the participant. The pre- and post-interactions were video recorded without audio, and the participants' interactions with the intervention were video recorded with audio.

During the interaction and observation phase of our study, we asked the patients, their family, and other medical staff to act as they typically would. We hoped to test the effect of our three interventions in a natural setting in order to study how each agent would fit in the pediatric inpatient care routine.

At the end of the study, we asked the CCLS who were involved in the experiment to fill out a paper questionnaire about their views on social robots in the pediatric care routine. We wanted to better understand potential opportunities for social robots in a pediatric care context from the hospital staff's perspective. The main questions in the questionnaire were:

- How do you think Huggable (*Robot*/*Avatar*/*Plush*) in the hospital room could impact the hospital experience for a child?
- What do you think children could gain from interacting with Huggable (*Robot*/*Avatar*/*Plush*) during their hospital stay?
- What could Child Life gain from having Huggable (*Robot*/*Avatar*/*Plush*) as part of patient care, if anything?
- In what ways would a fully autonomous Huggable robot be useful?
- During what aspects of a child's hospital experience do you think Huggable (*Robot*/*Avatar*/*Plush*) would be most helpful?
- Does Huggable (*Robot*/*Avatar*/*Plush*) offer benefits that cannot be provided to patients through other means?

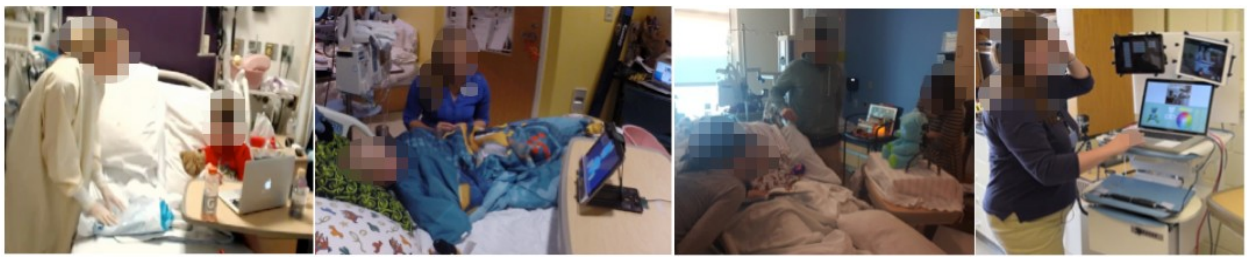


Figure 13. Children interact with a plush Huggable, a virtual Huggable on an Android tablet device or a robotic Huggable in their patient bed space (from left to right). For the virtual and the robotic Huggable, a remote operator controls the Huggable's behavior (first right).

4.2.4 Data Analysis

Many of the participants became very fatigued after the interaction and failed to fill out the post-questionnaires. Out of 54 recruited children, 11 did not complete the Facial Pain Scale-Revised (FPS-R) and 10 failed to answer the Facial Affect Scale (FAS). Also, 29 older children (6-10 years old) were asked to fill out longer, more tedious questionnaires on their affect and anxiety, and 8 out of 29 failed to answer the Positive and Negative Affect Schedule (PANAS) and 3 failed to answer the State-Trait Anxiety Inventory for Children (STAIC).

We extracted child patients' verbal and physical behavioral data from videos. Video recordings of six participants were lost due to technical issues; thus, we measured children's interaction length from 48 videos. Children's interaction videos were transcribed to analyze interaction participants' verbal utterances. A professional HIPPA-compliant vendor transcribed the audio clips processed from video footage. Three interaction audio clips were excluded from transcription due to their poor audio quality to be transcribed and were excluded from the transcription data analysis. The transcription data identified each speaker into one of the four categories: *Patient*, *Huggable*, *Moderator* and *Other*. *Patient* indicates the child study participant, *Huggable* indicates the Huggable intervention, *Moderator* indicates the CCLS assisting the interaction by the patient bedside and *Other* indicates family members who were in the room.

The sentiment of total and patient utterances was also analyzed with IBM Watson's Tone Analyzer (Mostafa, Crick, Calderon, & Oatley, 2016). The Tone Analyzer tool attempts to label five emotions (anger, fear, joy, sadness and disgust) and the Big Five personality traits (agreeableness, conscientiousness, extraversion, neuroticism and openness) for given text input in range of [0, 1]. Among these ten metrics, joy, agreeableness, extraversion and sadness scores were measured for each utterance sentence and were averaged for each participant's session. Agreeableness score measures how much compassionate, cooperative, trusting and helpful the utterances are rather than suspicious, antagonistic, competitive or challenging. Extraversion score measures how much outgoing and energetic the utterances are rather than reserved, reflective, aloof or self-absorbed. Joy, extraversion and sadness scores were calculated for the total utterance and agreeableness scores calculated for the patient's utterance. When analyzing the joy scores, children were divided into two groups based on their report of the Facial Affect Scale during the pre-test: children who reported minimum score (the most positive affect) on the Facial Affect Scale (FAS) during the pre-test vs. children who did not report the most positive affect on the FAS during pre-test. Also, 18 children in the MSICU (Medical Surgical Intensive Care Unit) and Hema-Onc (Hematology and Oncology) units were removed from the patient utterance analysis because the patients in those two units did not produce enough utterances to have their sentiment analyzed.

Children's arousal level was coded by one annotator [-2: Very low, -1: Low, 0: Neutral, 1: High, 2: Very high]. Children's valence level was coded by two annotators [-2: Very low, -1: Low, 0, Neutral, 1: High, 2: Very high]. During the video annotation training session, the annotators were given an instruction document that explains the arousal-valence emotion model and were provided with short sample video clips for each level of arousal and valence. For instance, a short clip of a child crying and screaming was shown to annotators as an example of -2 (very low) level of valence and 2 (very high) level of arousal, and a clip of a child bouncing up and down with excitement was given as an example of 2 (very high) level of valence and 2 (very high) level of arousal. Two random videos were selected to test the inter-rater reliability. Cohen's kappa for inter-rater reliability on the two sample videos showed that the two video

annotators had fair agreement on their valence annotation, $\kappa = 0.255$. The inter-rater reliability was rather low and I plan to re-annotate the valence for each video again in the future.

Two video coders annotated children's gaze behavior during the interaction. The video annotator coded children's gaze at one of the three choices: at *Huggable*, at *Moderator* (the CCLS inside the room) and at *Others*. Two random videos were selected for the reliability sample and each coder also independently coded an additional 23 videos. Cohen's kappa for inter-rater reliability on the two sample videos showed that the two video annotators had high agreement on their annotation, $\kappa = 0.837$. Children's touch behavior with Huggable was annotated by one video coder [0: Not touching, 1: Touching]. Children's physical movement during the interaction was annotated on a continuous scale between 0 [no movement] – 1 [active body movement] using a joystick device. The annotator watched the recorded video footage in real time and moved the joystick up/down to indicate the level of children's physical movement for each video frame. We segmented each child's interaction into three sections and calculated the mean level of physical movement for each section. Children who were too fatigued to interact physically and showed a very low level of physical movement (below 0.2) throughout all three sections were excluded from the analysis.

5. Results: Huggable-Patient Interaction

A generalized linear model (McCullagh & Nelder, 1989) was applied to predict various measurements of engagement (interaction duration, total utterances, patient's utterances, intervention agent's utterances, interaction moderator's utterances and family member' utterances based on the type of intervention offered to the patient. The predictor variable was contrast-coded (Davis, 2010) as ordered values [-1 0 1], *Robot*, *Avatar* and *Plush* respectively for interaction duration and verbal utterances data. For gaze and touch data, the predictor variable was contrast-coded (Davis, 2010) as [-1 0 1] for *Plush*, *Robot* and *Avatar*, respectively.

5.1 Interaction Duration

A generalized linear model was calculated to predict the duration of children's interaction with the intervention they were given. A contrast-coded generalized linear regression model showed a statistically significant trend of increase found in the lengths of children's interaction with the given agent across the three experimental condition (*Robot* > *Avatar* > *Plush*) based on the regression model, $F(1, 46) = 18.2$, $p < 0.001$. A one-way ANOVA also showed a statistical difference in interaction lengths across the three conditions, $F(2, 45) = 9.911$, $p < 0.001$. Figure 12 shows the mean lengths of children's interactions with each intervention agent.

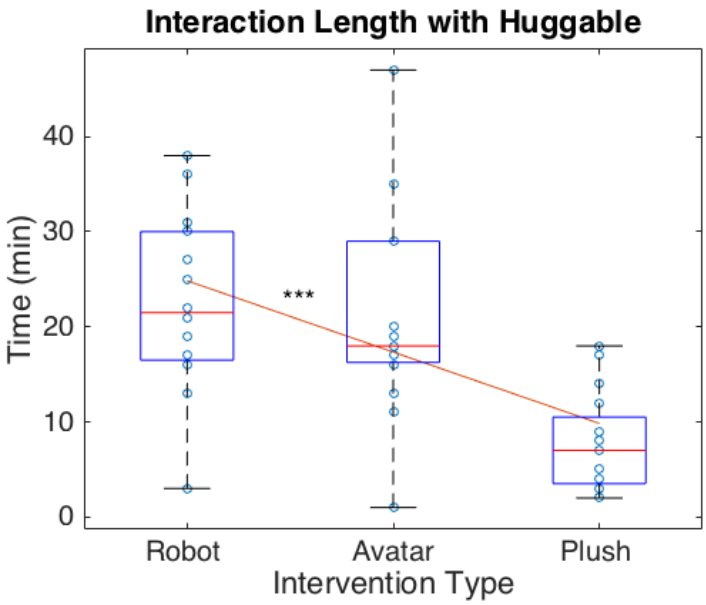


Figure 14. The lengths of children's interaction showed a statistically significant increase over the three experimental conditions (*Robot* > *Avatar* > *Plush*), $p < 0.001$.

5.2 Emotion

Children's mean arousal level in each condition was 0.550 (SD 0.708), 0.856 (SD 0.704), 0.582 (SD 0.669) for *Robot*, *Avatar* and *Plush*, respectively. An one-way ANOVA was conducted to compare the effect of three interactive agents on children's arousal level. An analysis of variance showed that children's arousal level in the three experimental conditions did not show any statistically significant difference, $F(2, 45) = 0.911$, $p = 0.410$. A contrast-coded generalized linear regression analysis also showed that there was no statistically significant trend in children's arousal level across the three conditions, $F(1, 46) = 0.024$, $p = 0.877$.

Children's mean valence level in each condition was 0.033 (SD 0.112), -0.001 (SD 0.364) and -0.034 (SD 0.141) for *Robot*, *Avatar* and *Plush*. A one-way ANOVA on children's valence level failed to show a statistically significant difference across the three experimental conditions, $F(2, 45) = 0.361$, $p = 0.699$. A contrast-coded generalized linear regression model also did not show any significant trend, $F(1, 46) = 0.051$, $p = 0.394$.

Joy scores computed on all the utterances with children who did not report the highest positive affect on the Facial Affect Scale during pre-test, showed a statistically significant trend of increase across the three agents (*Robot* > *Avatar* > *Plush*), $F(1, 20) = 11.2$, $p = 0.003$. On the other hand, joy scores of total utterance with children who reported the most positive affect during pre-test failed to show any significant trend across the three conditions, $F(1, 25) = 0.001$, $p = 0.979$. Agreeableness scores of Bone

Marrow Transplant and Surgical units patients' utterances showed a statistically significant trend of increase (*Robot* > *Avatar* > *Plush*), F(1, 25) = 13.6, p = 0.001. There were statistically significant trends of increase in the extraversion score of total utterance across the three agents (*Robot* > *Avatar* > *Plush*), F(1, 25) = 6.46, p = 0.015. Lastly, the sadness score for the total utterances showed a statistically significant trend of decrease across the conditions (*Robot* < *Avatar* < *Plush*), F(1, 43) = 5.35, p = 0.026.

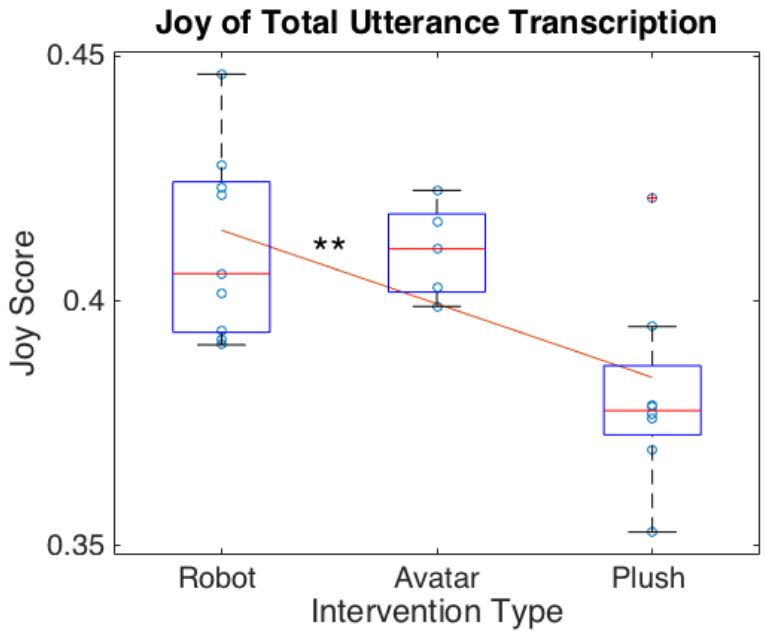


Figure 15. The joy scores of total utterances showed a statistically significant trend of increase over the three experimental condition (*Robot* > *Avatar* > *Plush*) after excluding sessions of children who reported the maximum positive affect in the Facial Affect Scale in the pre-text, p =0.003.

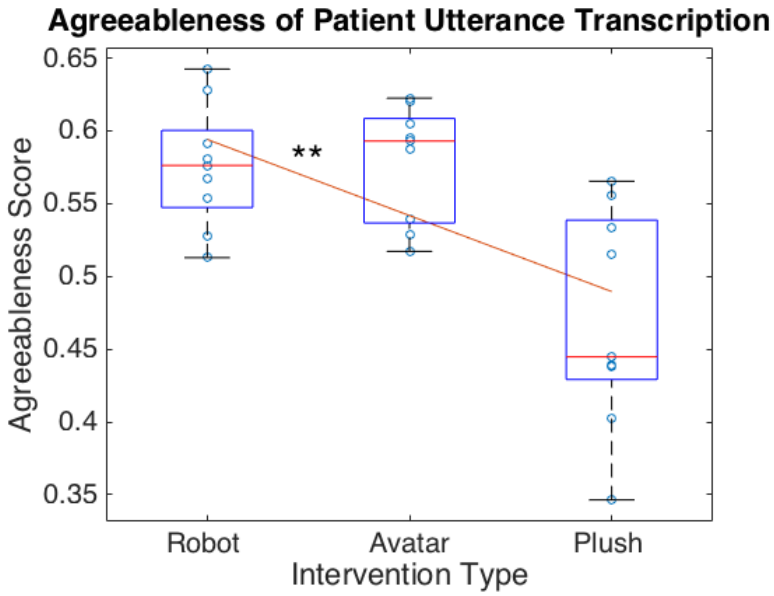


Figure 16. The agreeableness scores of the utterances made by patients in Bone Marrow Transplant and Surgical units showed a statistically significant trend of increase over the three experimental condition, (*Robot* > *Avatar* > *Plush*), p = 0.001.

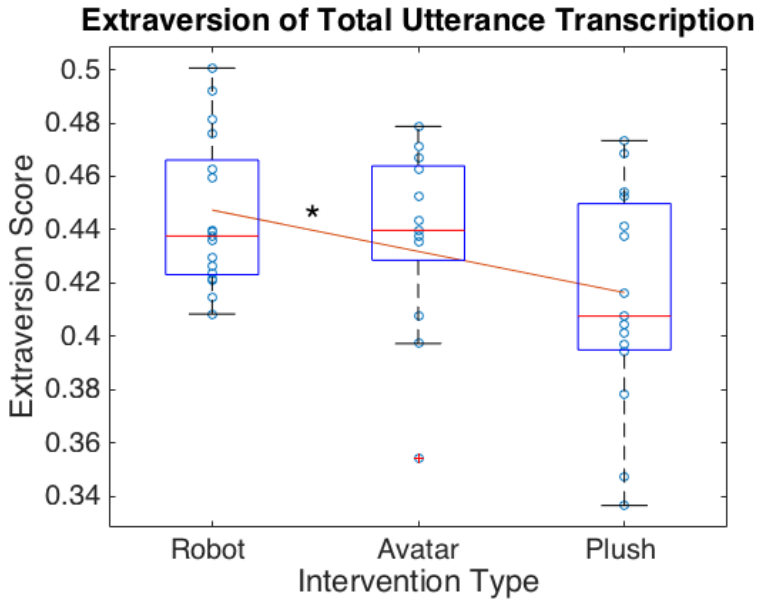


Figure 17. The extraversion scores of total utterances showed a statistically significant trend of increase over the three experimental condition, (*Robot* > *Avatar* > *Plush*), p = 0.015.

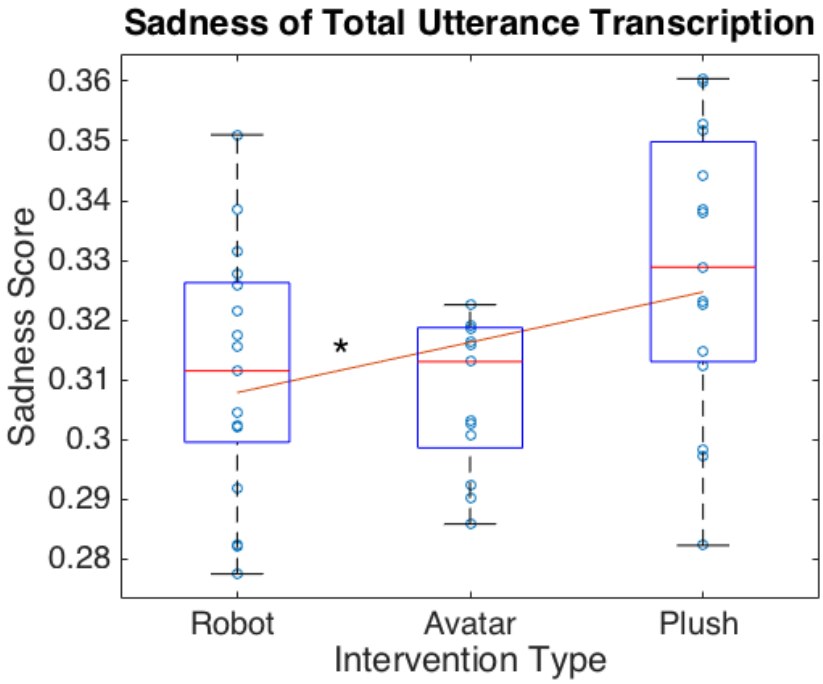


Figure 18. The sadness scores of total utterances showed a statistically significant trend of decrease over the three experimental condition, (*Robot* < *Avatar* < *Plush*), p = 0.026.

One-way ANOVA tests on the sentiment scores of Huggable's and the Moderator's utterances to the three conditions were conducted to check whether Huggable or the CCLS in the room talked with same or different sentiment in the three conditions. The analysis results show that the sentiment scores of Huggable's utterances were consistent across the three experimental conditions. The sentiment scores of the Moderator's utterance did not show statistically significant difference for most of the sentiment metrics, except for the sadness and the conscientiousness scores. Pairwise post-hoc Tukey's tests showed that sadness scores and consciousness scores in the *Avatar* were significantly higher than in the *Plush* condition (sadness: p = 0.024, consciousness: p = 0.036), while the other pairs (*Robot-Avatar* and *Robot-Plush*) did not. Table 1 reports the detailed result from the one-way ANOVA analyses.

	Huggable		Moderator	
	F statistic	p value	F statistic	p value
Joy	F(2, 28) = 0.565	0.575	F(2, 42) = 2.073	0.139
Sadness	F(2, 28) = 0.646	0.532	F(2, 42) = 3.755	**0.032 ***
Anger	F(2, 28) = 1.568	0.226	F(2, 42) = 1.021	0.369
Fear	F(2, 28) = 0.552	0.582	F(2, 42) = 1.097	0.343
Disgust	F(2, 28) = 0.852	0.438	F(2, 42) = 0.445	0.644
Agreeableness	F(2, 28) = 1.289	0.291	F(2, 42) = 5.550	0.007
Extraversion	F(2, 28) = 0.717	0.497	F(2, 42) = 0.878	0.423
Conscientiousness	F(2, 28) = 1.475	0.246	F(2, 42) = 3.606	**0.036 ***
Openness	F(2, 28) = 1.026	0.372	F(2, 42) = 1.529	0.229

Table 1. One-way ANOVA analyses on sentiment scores of Huggable's and the Moderator's utterances.

5.3 Relational Behavior

The proportion of time children spent gazing at Huggable showed a statistically significant trend of increase in the order of *Plush* < *Robot* < *Avatar*, $F(1, 46) = 7.65$, $p = 0.008$. On the other hand, the proportion of time children spent gazing on Others showed a statistically significant trend of decrease in the order of *Avatar* < *Robot* < *Plush*, $F(1, 46) = 7.69$, $p = 0.008$.

The proportion of time children spent gazing on Moderator (the CCLS in the patient room) failed to show a statistically significant difference or trend. The generalized linear regression analysis did not show any trend of increase, $F(1, 46) = 0.00627$, $p = 0.937$. A one-way ANOVA for the proportion of time children gazed on the CCLS resulted $F(2, 45) = 0.65$, $p = 0.527$.

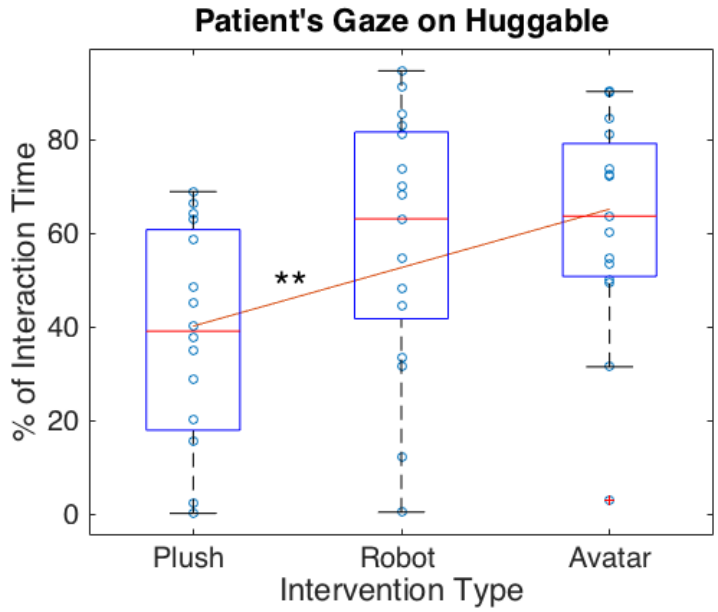


Figure 19. The proportion of interaction time patients spent gazing at Huggable showed statistically significant trends of increase over the three experimental conditions (*Plush* < *Robot* < *Avatar*), p = 0.008.

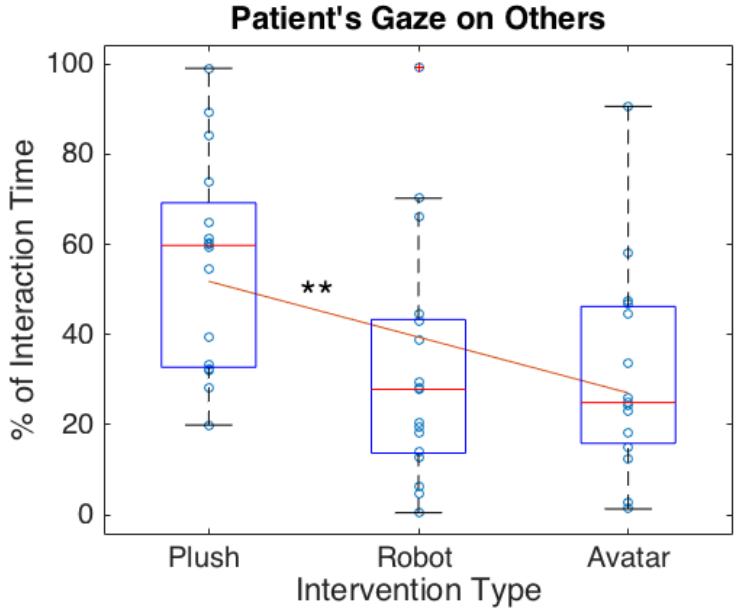


Figure 20. The proportion of interaction time patients spent on gazing on others (not Huggable or CCLS) showed statistically significant trends of increase over the three experimental conditions (*Plush* > *Robot* > *Avatar*), p = 0.008.

The time patients spent touching Huggable also showed a significant trend of decrease in the order of *Plush* > *Robot* > *Avatar*, $F(1, 46) = 5.58$, $p = 0.022$. A one-way ANOVA also showed a statistically significant difference in the duration of children's touch on Huggable across the three experimental conditions, $F(2, 45) = 22.04$, $p < 0.001$.

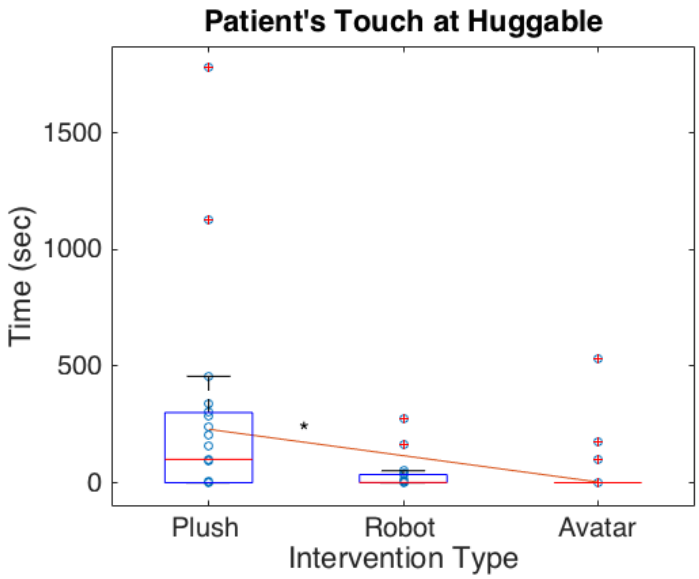


Figure 21. The time spent touching Huggable by the patient showed statistically significant trends of increase over the three experimental conditions (*Plush* > *Robot* > *Avatar*), p = 0.022.

5.4 Verbal Utterance

A contrast-coded generalized linear regression model showed a statistically significant trend of increase in the total number of utterances made across the three experimental condition (*Robot* > *Avatar* > *Plush*) based on the generalized linear regression model, F(1, 43) = 11.7, p = 0.001. There were statistically significant trends of increase in the utterances produced by the child patient across the three agents (*Robot* > *Avatar* > *Plush*), F(1, 43) = 6.35, p = 0.016. The number of utterances produced by the patient's family members showed a statistically significant trend of increase across the conditions (*Robot* > *Avatar* > *Plush*), F(1, 43) = 11.7, p = 0.001.

A one-way ANOVA was conducted to compare the effect of experimental condition on the verbal utterances produced by all participants, by patient only and by family members. We found statistically significant effects of experimental condition on the number of total utterances, F(2, 42) = 5.75, p = 0.006; the number of utterances made by the child patient, F(2, 41) = 3.3, p = 0.047; and the number of utterances made by the patients family members, F(2, 41) = 6.03, p = 0.005.

On the other hand, the number of utterances produced by the Huggable agent failed to show a statistically significant trend of increase, F(1, 43) = 1.33, p = 0.257. In the Plush condition, we considered the CCLS's utterances as the Huggable's utterances The number of utterances produced by the CCLS by the patient bedside also did not show any statistically significant trend of increase, F(1, 43) = 3.42, p = 0.071. Figure 21, 22 and 23 show the mean number of utterances produced by all members of the interaction participants (*Total*), by patient only and by family members who were not directly invited for the interaction (*Others*).

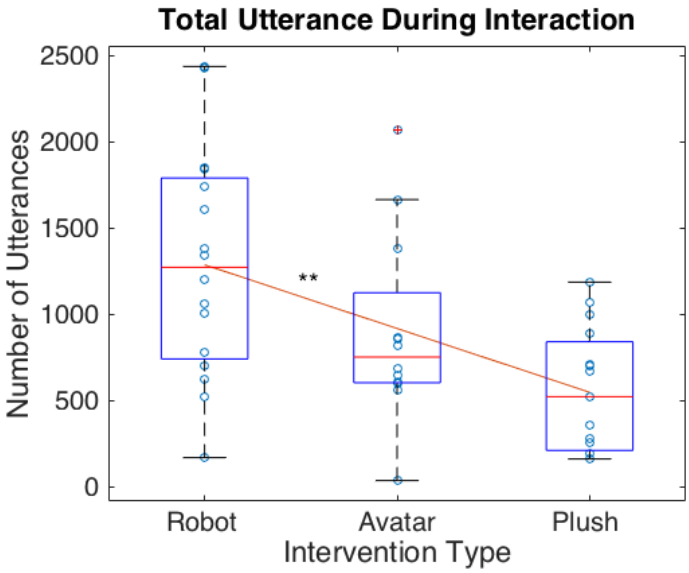


Figure 22. The number of utterances produced in total showed statistically significant trends of increase over the three experimental conditions (*Robot* > *Avatar* > *Plush*), p = 0.001.

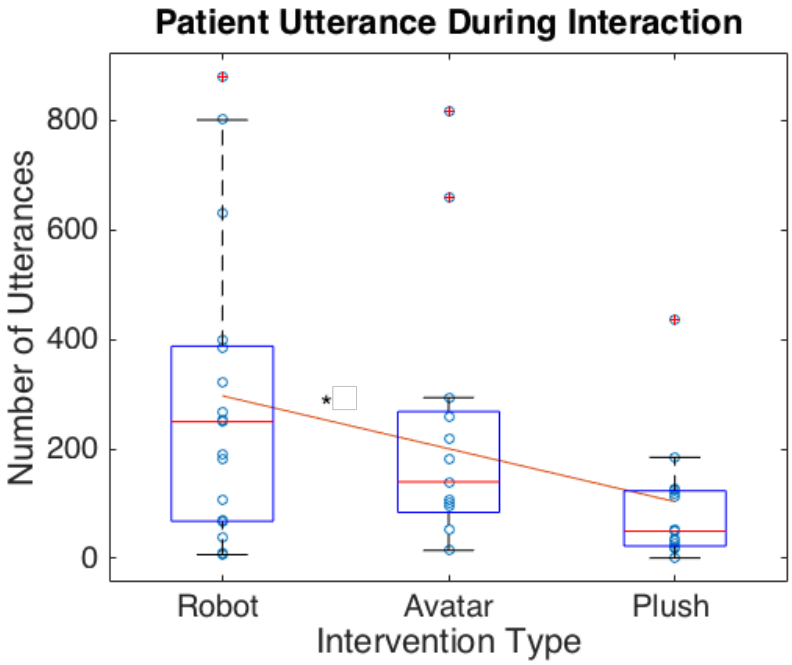


Figure 23. The number of utterances produced by patients showed statistically significant trends of increase over the three experimental conditions (*Robot* > *Avatar* > *Plush*), p = 0.016.

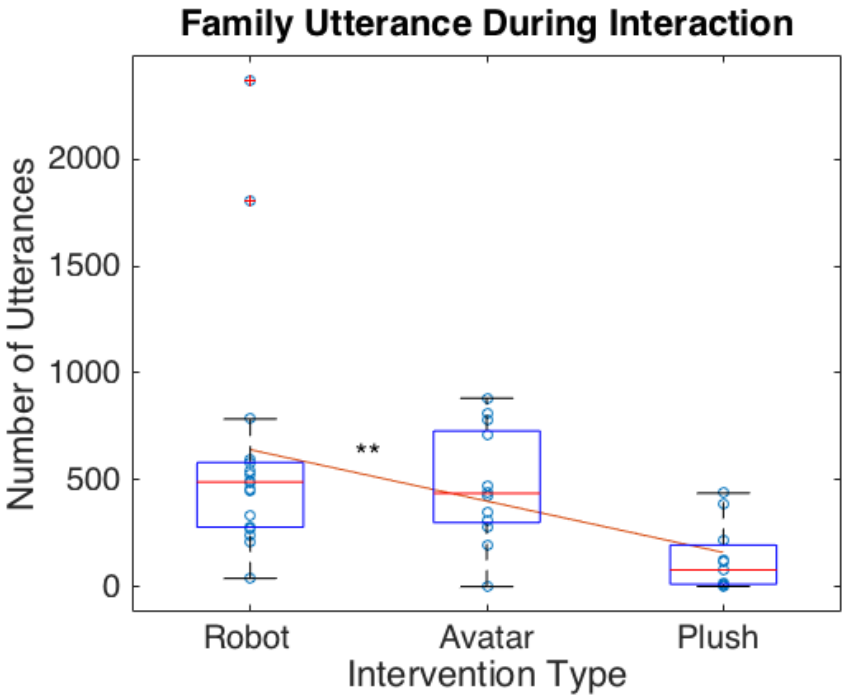


Figure 24. The number of utterances produced by others (family members who were not directly involved in the experimental study) showed statistically significant trends of increase over the three experimental conditions (*Robot* > *Avatar* > *Plush*), p = 0.001.

5.5 Physical Movement

For *Robot* condition, the mean levels of children's physical movement were 0.027 (SD 0.018), 0.097 (SD 0.054) and 0.385 (SD 0.182) for the first, second and third section of the interaction, respectively. For *Avatar* condition, the mean levels of children's physical movement were 0.334 (SD 0.25), 0.314 (SD 0.159) and 0.369 (SD 0.051). For *Plush* condition, the mean levels of children's physical movement were 0.316 (SD 0.136), 0.319 (SD 0.171) and 0.272 (SD 0.091).

A two-way Repeated-Measures ANOVA was conducted to compare the effect of experimental condition and time on the levels of children's physical movement at first, second and third section of the interaction. We found a statistically significant effect of time on children's physical movement throughout the interaction, $F(2, 16) = 3.673$, $p = 0.049$. We also found a statistically significant condition-time interaction, $F(4, 16) = 4.372$, $p = 0.014$. Figure 23 shows the mean levels of physical movement children produced during each stage of the interaction with each intervention agent.

A one-way ANOVA was conducted for a pairwise comparison of children's physical movement during three interaction sections for each experimental condition. Children's physical movement did not show any statistically significant change over time for *Avatar* and *Plush* conditions, $p = 0.839$ and $p = 0.967$ respectively. For *Robot* condition, a post-hoc Tukey's test on the physical movement level showed

that children's physical movement in the third section was statistically significant different from the first and the second, p = 0.0013 and p = 0.0059.

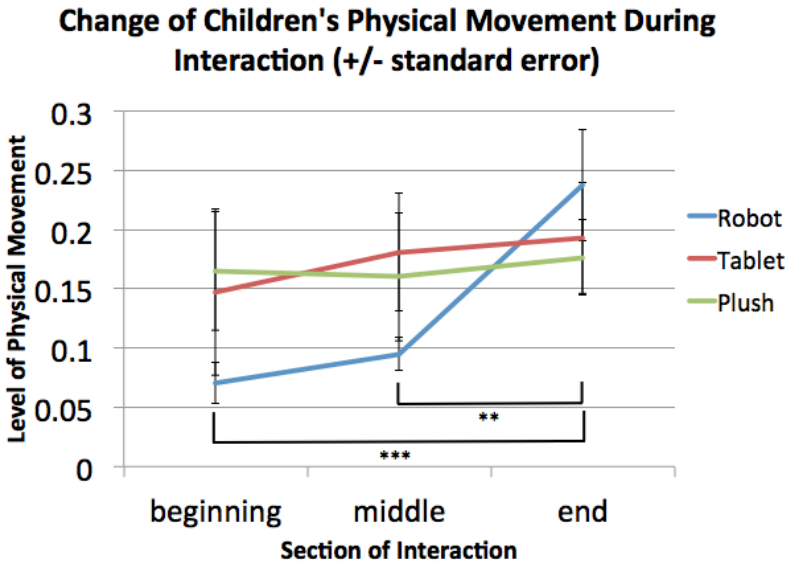


Figure 25. Children in the *Robot* condition showed statistically significant higher level of physical movement in the end of the interaction than in the beginning and in the middle, p = 0.001 and p = 0.006.

6. Results: CCLS Perspective

We reviewed the responses of the three CCLS on their views and perspective on social robots in pediatric care setting after using each Huggable intervention with the children who participated in our study. In general, CCLS did not perceive a critical difference between the robotic and the virtual Huggable in their effect on children's engagement and affect. They noted that "the robot and the tablet [compared to the plush] caught their [children's] attention and kept it for longer periods of time," especially "for children with a little more energy overall but who are fatigued and stressed at being in the hospital." However, they viewed the plush Huggable to be more appropriate and effective for children who are extremely fatigued and do not have enough energy for social interaction.

Regarding opportunities for social robots in a pediatric inpatient care context, the three CCLS's projected extending their care using the Huggable robot in three ways: education, diversion, and companionship. First, one CCLS reported in the questionnaire that she "would love to have him [the Huggable robot] be part of medical play, preparation, and support as a partner to a child life specialist or psychologist, etc." Another CCLS noted, "An autonomous social robot could be part of the perioperative experience for general preparation and continuity." Second, all CCLS agreed that a social robot could be effective in diverting child patients from their stress, anxiety, pain and discomfort through playful games

and activities. One CCLS reported, “The novelty and social engagement can be a benefit to providing diversion from the situation and potentially discomfort.” Another thought a social robot could potentially “cue or remind patient about necessary tasks,” or provide “encouragement or support to patients in medical tasks and daily activities, i.e. physical therapy.” Lastly, CCLS saw opportunities for social robots to provide longitudinal and personalized companionship for young patients. One responded “Huggable could really enhance a patient’s stay in the hospital especially for patients who are away from their parents/caregivers/families for extended periods of time… it may help decrease feeling of loneliness and isolation, promote a sense of fun and provide a welcome distraction from being in the hospital, and decrease stress and anxiety.” Another CCLS responded that the Huggable robot would be more beneficial if it were able to offer longitudinal and repeated care for the child patient, “Repeated exposures to Huggable would be ideal for patients who are in the hospital long-term. If patients were alone at bedside, it would be great to have the opportunity to allow them time with the Huggable each day.”

7. Results: Usability of the Teleoperation Interface

At the end of the study, a partial set of the Networked Mind Social Presence Scale and the Software Usability Measurement Inventory (SUMI) were applied to the three CCLS who teleoperated the robotic and the virtual Huggable to evaluate the usability and effectiveness of the teleopration interface. The Network Mind Social Presence scale measures the self-reported level of social presence, the sense of being together with another in a mediated environment (Biocca & Harms, 2003), and the SUMI measures the quality of a software user experience from the end user's point of view (Kirakowski & Corbett, 1993).

The results from Networked Mind Social Presence Scale showed that the remote operators were well aware of the child's presence in the room and often felt as if they were in the same room with the child. They thought that the child was also very aware of their co-presence as the Huggable agent in the room. Through the interface, the child and the operators were able to pay close attention to each other. They somewhat agreed that when the operator was happy/sad, the child tended to be happy/sad. The CCLS reported that they were not able to communicate their intentions and thoughts clearly to the child, and it was also difficult to understand what the child meant. However, it was reported that the remote operator's actions were often dependent on or in direct response to the child's actions, and their actions affected the child's actions as well.

The three CCLS all agreed that the teleoperation interface responds to slowly to inputs and has stopped unexpectedly at times. They also reported that they sometimes did not know what to do next with the interface, preferred when using a few familiar functions and have experienced tense moments while using the interface. However, they all agreed enough information was displayed on the screen when needed.

8. Discussion

This study investigated how a social robot, a virtual character, and a plush toy could influence young pediatric inpatients socio-emotional well-being in a hospital setting. While the analysis of questionnaire data did not find any statistical significant changes of children's self report of affect, pain, or anxiety after interacting with the intervention, the behavioral analyses of verbal transcriptions and video data showed that the three interactive agents engage and affect young pediatric patients differently through playful social interactions in a hospital setting.

Children interacted longer and talked more when given a social robot than when given a virtual character or a plush toy. In addition, family members who were not explicitly invited or prompted to participate in the interaction produced higher verbal utterances when a robot was present than when the other two intervention agents were present. The analysis of verbalized utterances showed evidence that a social robot is most effective in inducing socially energetic conversations (extraversion score). Furthermore, the analysis of children's physical movement during the interaction suggests that a social robot can promote young patients to engage in higher physical activity *over time* during the interaction. A virtual character and a plush toy could maintain a high level of physical activity if children were already moving their bodies but did not have effect on increasing their physical movement any further.

These findings are noteworthy because they show that a social robot can significantly impact a pediatric patient's verbal and physical interactions and engagement with others. Many young children in a hospital suffer psychological distress from isolation and loneliness. The negative affect often leads to uncooperative behavior toward medical staff and poor health outcomes. The results from the behavioral analyses suggest that a social robot could promote social and physical interactions for patients and potentially lessen the feeling of loneliness by facilitating interactions between a child and her family members. The impact of a social robot on children's physical movement also opens another opportunity for social robots in the pediatric care context because perioperative exercise and physical therapy can play a huge role in the patient's' recovery and health outcome.

The impact of three interactive agents on children's affect was investigated by analyzing the recorded video footage and sentiment of transcribed verbal utterances. Children's arousal and valence levels rated by human coders looking at the video data did not show any statistically significant difference or trend across the three experimental conditions. This could be due to fact that a human specialist was engaging the patient alongside the interactive agent for all three experimental conditions. The child life specialists using each agent were making best efforts to engage the children as they would normally do as part of their clinical service. However, the sentiment analysis of verbalized utterances showed evidence that a social robot is more effective in producing positively valenced verbal utterances (joy score) from children who are not feeling well, i.e. patients who did not report minimum score on the Facial Affective

Scale, than a virtual avatar and a plush toy. Patients in the Surgical units and in the Bone Marrow Transplant units, i.e. children who are feeling relatively less ill, produced the most cooperative (agreeable score) verbal utterances when the robot was in the room as well. The type of agent given also influenced the sadness level of conversation. Conversations during the interaction were least sad when a social robot was present (sad score) in the room. In other words, when a child is already feeling positive, the type of agent given might not make a difference on the emotional level of children's utterances. However, for a child not in a positive mood, a social robot could make the greatest impact on children's verbal interactions by making them more joyful, less sad and more cooperative. These results are surprising because in each condition a CCLS using the interactive agent is doing their best to engage the patient. The manipulation check was done by comparing the number and various sentiment metrics of utterances made by the CCLS moderating the interaction. The results for this manipulation check show that the CCLS in the room was consistent in their social and verbal behavior regardless of the intervention she was using.

Lastly, children's relational behavior with the Huggable agent was investigated by analyzing their gaze and touch behavior. Children in the *Avatar* condition gazed on Huggable the most and least at others (not at Huggable nor at Moderator) than children in *Robot* or *Plush* condition. The proportion of interaction children gazing on the CCLS moderating the play did not show any statistically significant difference for the three conditions. In some sense, children's gaze behavior with the plush Huggable was not interesting; most of the children given a plush put the toy on their lap or on their side. As noted earlier, a social robot produced more voluntary participation from family members in the interaction than the virtual avatar or a plush toy. Perhaps, children in the *Robot* condition naturally got to distribute their gaze to more of the family members, which caused relatively lower gaze proportion at Huggable agent than children in the *Avatar* condition.

Previous findings on people's gaze and social interaction when a screen device supports the behaviors found on children in the *Avatar* condition. It was shown that a person who is tasked to negotiate with another person while using the information from a screen-based kiosk spent most of the time looking at the screen device not only when speaking to the kiosk system but also when negotiating with the other person (Bakx, Turnhout, & Terken, 2003). Furthermore, the time a child spends interacting with family members was found to be negatively impacted by the time a child spends on a screen-based device even with parents or siblings (Vandewater, 2006).

Alternatively, children's different gaze behaviors with a social robot and a virtual avatar could be explained by how the children perceive or treat each interactive agent. Some of the children showed signs of shyness, e.g. covering the face with a toy, avoiding direct gaze, etc., when interacting with a social robot. Perhaps, a social robot was perceived more like a social other than a virtual avatar, and thus children in the *Robot* condition gazed less proportion of time at Huggable during the initial familiarization phase of the interaction.

The analysis of children's touch behavior showed that patients touched the plush toy the most, which is not surprising. However, it is difficult to make conclusive interpretations from this result because the instructions given to children in the three experimental conditions were not consistent. Children in the *Robot* condition were told they were allowed to touch the robotic Huggable only if they were being gentle and careful in order to protect the robot from being damaged. However, children in the *Plush* or the *Avatar* were not told any specific instructions on touching Huggable. Most of the children who were given a plush toy held it on their lap or by their side. Between the robotic and the avatar Huggable, the types of touches children made with the robot and the avatar were different. Children in the *Robot* condition touched the robotic Huggable by tickling, caressing or high-fiving. On the other hand, most of the touches made in the *Avatar* condition were made when children were holding the Android tablet device to take a better look, or when they were tapping the tablet screen repetitively as they would normally do when playing a videogame with a tablet device. Further analysis on the different nature of touches made in *Robot* and *Avatar* conditions could potentially reveal better understanding on how children treat Huggable agents in existence or lack of physical embodiment.

Surprisingly, the different effects of three interactive agents were not entirely reflected in the CCLS post-study questionnaire. The three child life specialists' responses mostly reported a major difference between *Plush* vs. *Avatar* and *Plush* vs. *Robot* but they provided similar reports for their perceived effect of a social robot and a virtual avatar on children's engagement and emotion. It is noteworthy that both children's self-reported questionnaire responses and clinical staff's perceived effect on three interactive agents failed to show any significant difference on the impact of the three interactive agents, and yet the results from detailed behavioral analyses suggest otherwise. The discrepancy between perceived or self-reported questionnaire responses and behavioral analysis results shows the complexity of designing and evaluating new interactive assistive technologies for pediatric in-patient care.

Nonetheless, the child life specialists reported that social robots could be used as a part of the clinical care team. The robots could promote better socio-emotional wellbeing for children and induce better engagement with clinically necessary activities, either by diverting them from pain and stress or by motivating them to actively participate. Furthermore, the CCLS perceived social robots as another channel to communicate with children. Young patients in pediatric hospitals do not have many opportunities to interact and play with peers, and sometimes do not respond well to clinical staff. One CCLS noted, "children may feel more comfortable opening up/trusting a robot versus sharing with a hospital staff member." The various behavioral analyses conducted in this thesis align with the three child life specialists' thoughts and provide substantial evidence for socially assistive robots' potential role in extending the child life service by promoting young patients' socio-emotional well-being in pediatric inpatient care context.

Part II

Improving Smartphone Users' Socio-emotional Wellbeing with Longitudinal and Personalized Interventions

9. From Teleoperation to Standalone Mobile App

The experimental study described in previous sections investigate how three different interactive agents engage young in-patients with playful interactions and promote their socio-emotional well-being. By Wizard-of-Oz controlling the virtual and robotic Huggable agents, the research team could observe an ideal and optimal interaction between a robot and a child patient. The behavioral analyses of the interactions from the first study provide insights into the nature and characteristics of interactions between a child and a socially assistive robot in a pediatric hospital setting. However, the ultimate goal for the Huggable project is to develop an autonomous social agents that can interact with child patients solo, without a remote operator, and can complement the service human specialists provide in a pediatric hospital setting. Furthermore, these agents need to be able to develop longitudinal and personalized relationships with each child based on repeated interactions.

In this section, I present a pilot study that explores how a Huggable avatar could autonomously interact with people over three weeks and improve their affect via personalized positive psychology interventions. A virtual Huggable avatar was used instead of the physical Huggable robot in this study because the Huggable robot was not fit to be deployed in people's home for several weeks. However, studying people's interaction with a virtual avatar on their personal mobile devices could potentially provide another interesting insight into further design guidelines for social and interactive technologies.

9.1 Related Works

9.1.1 Mobile Health Applications

Mobile devices are easily accessible and can be a useful tool to collect data of people's behavior and to infer about their wellbeing. Studies from the SNAPSHOT project explored using data from mobile wearable devices, such as call, SMS, location, Internet usage and screen-on time, to predict college students' academic performance and happiness, and to provide advice (Jaques et al., 2015.; Sano et al., 2015; Sano, Yu, et al., 2015; Sano, Johns, & Czerwinski, 2015). Other mobile health applications have been developed to support patients of alcohol use disorder (Bernhardt et al., 2009; Freedman, Lester, et al., 2006), post-traumatic syndrome disorder (Department of Veterans Affairs, 2011), chronic pain (Palermo, Eccleston, et al., 2010), bipolar disorder (Gigaram Technologies, 2011), severe mental illness (Depp et al., 2010), etc. Most of the mobile health applications target patients who already have been diagnosed with a mental disorder and focus on monitoring their mental and/or physiological states, or

providing guidance for CBT. Likewise, a socially interactive agent can leverage data collected via mobile devices to personalize and improve its interaction with the user.

9.1.2 Positive Psychology

The Huggable avatar on the mobile device developed for this study engages smartphone users with positive psychology interventions that were shown to reduce depressive symptoms and to increase psychological well-being (Jeong & Breazeal, 2016). Positive psychology is "the scientific study of optimal human functioning that aims to discover and promote the factors that allow individuals and communities to thrive" (Seligman, 2004). Research in positive psychology aims to understand factors that are present in psychologically healthy individuals — well-being, personal strengths, wisdom, psychological health, creativity and flow. Seligman (2010) proposed the PERMA (Positive Emotion, Engagement, Relationships, Meaning and Accomplishment) model to define five core elements of well-being and happiness. Based on this model, Seligman and others have developed various interventions and therapy methods that reduce depressive symptom levels for those diagnosed with major depressive disorder, and increase subjective and psychological wellbeing for patients with depression as well as for people who are not diagnosed with any mental disorder (Asgharipoor et al., 2012; Bolier et al., 2013; Gander et al., 2013; Seligman et al., 2005; Seligman et al., 2006).

9.1.2 Personalization

In order to provide a more personalized intervention for each user, Huggable avatar monitors the smartphone user's affect throughout the day and learns to select interventions that are likely to result in the most positive impact on users' affect and engagement over repeated interactions. Seligman et al. studied the effect of one positive psychology intervention at a time but the Huggable avatar aims to personalize the most effective set of interventions for each individual based on their mood and immediate affect. But why does personalization matter in human-agent interactions?

Fan and Poole (2006) suggests that personalization could benefit computer-human interactions it could make people focus on their unique identity instead of identifying themselves as a member of a social group. The identification of the self, whether as a unique individual or as a member of a group, could potentially change the user's perception of the computer agent and the task they are working on. Furthermore, the Media Equation theory (Reeves & Nass, 1996) claims that people tend to treat computers and other media as if they were either real people or real places. If people perceive an interactive as if it is a real person and the agent personalizes its interaction with them, this will decrease the social distance (Brewer, 1979; Kramer & Brewer, 1984) between the user and the agent. The

decreased social distance could further increase people's engagement with the agent and amplify the effect of the intervention it provides.

9.2 Hypotheses

A three-week longitudinal study was run in order to evaluate the efficacy of the system, and all of the verbal interactions were audio recorded for qualitative analysis. This study aims to test the following hypotheses through a longitudinal human-avatar interaction study.

- **H1**: Interacting with the Huggable avatar would improve smartphone users' psychological wellbeing over the three-week.
- **H2**: Interacting with the Huggable avatar would result an immediate improvement of smartphone users' affect.
- **H3**: User's engagement with the Huggable avatar application will increase over time due to personalized intervention selection.

9.3 Method

9.3.1 Participants and Procedure

Nine participants (three male and six female, age M=28.33, SD=6.58) who own Android devices with API 4.1 or higher were recruited from the MIT campus via email advertisements. Once consented, the participants filled out the pre-survey and had the Huggable avatar application installed on their mobile device for the study. Participants were asked to interact with the Huggable avatar at least once a day for three weeks. The application showed a pop-up notification to remind participants to interact with the Huggable avatar at 9PM every day. However, the participants were not given any specific instruction on when and how long to interact.

Over the three-week study period, participants were asked to fill out pre-, mid- and post-questionnaires: Brief Mood Introspection Scale (BMIS) (Mayer & Gaschke, 2001), Perceived Stress Scale (Cohen, Kamarck, & Mermelstein, 1983), Affect Balance Scale [Bradburn, 1969] and Ryff's Psychological Well-Being Scales (Ryff & Keyes, 1995). The pre-questionnaire also included a mobile version of Signature Strength Survey (Peterson & Seligman, 2004). The Signature Strength survey is a self-report questionnaire that uses 5-point Likert-scale items to identify an individual's profile of character strengths. There are six categories of strength (wisdom and knowledge; courage; humanity; justice; temperance; and transcendence) and in total 24 individual signature strengths (creativity, bravery, love, teamwork, forgiveness, appreciation of beauty, etc.) The Signature Strength survey app on participants' mobile phone recorded which signature strength the participant and provided examples of

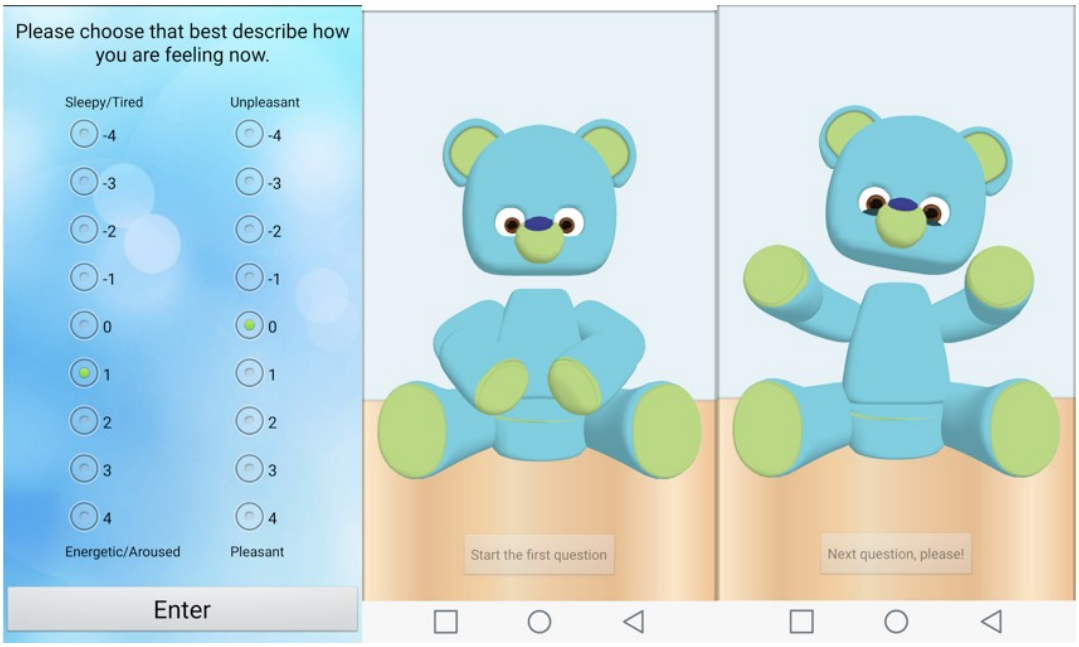
using the identified signature strength in daily lives. This result of the Signature Strength survey was later used for the participant's interaction with Huggable when the avatar asked "How did you use your signature strength today?"

The pre-questionnaire was applied at the beginning of the study before the journaling application was installed on the participant's device. The mid-questionnaire was applied after one week, and the post-questionnaire was applied at the end of the three-week study.

9.3.2 Huggable Avatar Application

Eleven positive psychology interventions (Table 2) were framed as questions and were categorized into one of the three groups (positive, neutral and negative). For each session with the app, the personalization algorithm selected one of the positive, neutral and negative intervention categories. Three positive psychology interventions within the selected category were randomly chosen. Huggable avatar prompted each of the selected three interventions in a question format and prompted the participant to verbally answer the question. The Huggable avatar was not presented as a conversational partner but rather as a facilitator and a helper for users to reflect and verbally journal about their day with the positive psychology intervention prompts provided by the Huggable avatar.

Before and after the journaling session, the participant was asked to self-report her arousal and valence levels in numeric scores [-4, 4] (Figure 38a). Huggable avatar had a simple greeting behavior, e.g. *"Hi! Nice to see you again. Are you excited for the questions?"* that varied per session. The participant could presse a button on the screen to receive the first question from Huggable avatar. During the participant's response, the Huggable avatar occasionally responded with neutral comments, such as "Hmm", "Uh-huh", "I see", "Oh", etc., when a pause was detected via Android microphone input. Once the participant was finished with her response, she could press the button again to receive the next question from Huggable avatar. When all three intervention questions were answered, the Huggable avatar thanked the participant for the response and said goodbye to end the interaction. The self-report arousal/valence screen (Figure 38a) appeared again and the app closed upon the user's response.



(a) (b) (c)

Figure 26. (a) Arousal and valence assessment screen for pre- and post-interaction with the interactive journaling application, (b) virtual character at idle position, (c) virtual character animated.

Interventions	Questions
Positive	(1) What are three good things that happened today? (2) Is there someone you feel gratitude to? (3) Tell me about one kind act you did today. (4) Tell me three funny things that you experienced today.
Neutral	(1) How did you use yours signature strengths in a new way today? (2) Is there anything you'd like to talk about? (3) How did you use your "gift" of time to someone today? It could be helping someone, sharing meal, etc.
Negative	(1) Was there anything that made you angry today? (2) Is there someone you need to forgive? (3) Tell me about a moment today when something bad turned into something good.

Table 2. Questions used for each positive psychology intervention in the Huggable avatar application.

9.3.3 Affect Detection with Affdex and SentiStrength

The Huggable avatar application measured smartphone users' affect via two modalities: facial expression detection with the phone's front-faced camera and SMS sentiment analysis. The Affdex mobile SDK (affectiva.com) was used to measure users' affect through their facial expressions. Affdex takes camera images from the mobile device and can detect 34 FACS (Facial Action Coding System) units

(Kring & Sloan, 1991) along with 9 emotions (joy, anger, disgust, contempt, engagement, fear, sadness, surprise and valence) and 15 expressions (attention, brow furrow, brow raise, chin raise, eye closure, inner brow raise, lip corner depressor, lip press, lip pucker, lip suck, mouth open, nose wrinkle, smile, smirk and upper lip raise). Among these, the engagement and valence features were used in this system. Engagement score has range [0, 100] and valence score has range [-100, 100].

While the smartphone was turned on, the application ran the facial expression capture process and captured facial emotional data from any visible face from the front-faced camera of the mobile device. The facial expression capture process silently started every five minutes and captured data for 10 seconds at each run. If no face was found during the ten second period, the system did not record any data. When the user was interacting with the Huggable avatar, the facial expression capture process ran continuously at 0.5 fps until the interaction ended.

The sentiment of smartphone users' incoming and outgoing text messages was also analyzed in order to infer their emotional state throughout the day. SentiStrength tool (Thelwall, Buckley, & Paltoglou, 2012) evaluates the sentiment of the text message content with both positive and negative scores. The positive score ranges between [1, 5] and the negative score ranges between [-5, -1]. SentiStrength is able to take account of widely used emoticons, such as :), :(or <3, and the usage of all capitalized words for sentiment analysis. For example, a message "Cool cool. also turns out Dustin has to work :[so I'm brining my friend Sam if that's OK with you" results with a positive score of 2 and a negative score of -2, and the message "Aww, that is so sweet! Sure. I can hold onto the tickets until then. :]" produces a positive score of 3 and a negative score of -1. The application retrieved the content of the text message whenever there is an incoming or outgoing SMS message. The positive and negative scores for a single SMS was added and then multiplied by 20 to have the same scale with the valence score from Affdex.

Mood is a collective and aggregate metric of continuous affect and emotions over time. Thus, both previous mood score and the most current valence score contribute to the daily mood score with a decay effect over time. The mood score was estimated as below:

$$m_{new} = m_{old}\lambda^{\Delta t} + v_{new}(1 - \lambda^{\Delta t})$$

The variable m and v are the mood and valence scores respectively, while λ is the decay rate (0.95) and Δt is the elapsed time since the last mood score update time in hours. The mood score was updated whenever a new affect data was available, either by capturing facial expression information through Affdex or by analyzing the sentiment of a text message via SentiStrength.

9.3.4 Personalization

Markov Decision Process (MDP) (Puterman, 1994) and State-Action-Reward-State-Action (SARSA) (Rummery & Niranjan, 1994) algorithms were used to learn the intervention selection policy that maximizes its positive effect. The intervention selection behavior was modeled as a Markov Decision Process (MDP). The policy on the MDP model was formulated as a *Q(s, a)* matrix, where *s* represents the user's mood and affect state and *a* represents the selection of the intervention type. The state space consisted of three dimensions: daily mood, current valence and current engagement. The daily mood state was discretized to three values:

$$s_{\text{mood}} = \{Negative, Neutral, Positive\} = \{[-100, 0), 0, (0, 100]\}$$
$$s_{\text{valence}} = \{Negative, Neutral, Positive\} = \{ -100, 0 , 0, 0, 100 \}$$
$$s_{\text{engagement}} = \{Low, High\} = \{[0, 0.91), [0.91, 100]\}$$

In total, the state space consisted of 3 × 3 × 2 = 18 states. The action space consisted of 3 actions, *a = {Negative, Neutral, Positive}*. The action selection was made when the user launches the interactive journaling application for the journaling activity. Once the intervention type has been chosen, three questions within the selected intervention category were randomly selected for the session The initial policy represented an equally random distribution over three possible actions. A reinforcement-learning algorithm was implemented in order to personalize the intervention selection policy to each user. In order to achieve this, a standard SARSA (State-Action-Reward-State-Action) algorithm was used. In our algorithm, the reward was calculated as a weighted sum of the valence score, engagement score and the duration of the journaling session:

$$r = 0.15(s_{val} + 100) + 0.3s_{eng} + 0.66(t_{end} - t_{start})$$

Let t_{start} and t_{end} be the start and end time of the journaling session in the unit of seconds. This reward function aims to maximize engagement and valence scores and the duration of user's journaling activity. In order to control for the exploration and exploitation of the MDP model, an ε-greedy algorithm was implemented. The exploration probability ε was set to decrease with each successive session $\varepsilon_1 = 0.75$, $\varepsilon_2 = 0.5$, and $\varepsilon_i = 0.25$, for $i >= 3$. The learning rate α also decreased: $\alpha_1 = 0.5$, $\alpha_2 = 0.4$, $\alpha_3 = 0.3$, $\alpha_4 = 0.2$ and $\alpha_i = 0.1$ for $i >= 5$.

9.3.5 System Architecture

The SMS Sentiment Analyzer, Facial Expression Analyzer and the data manager service inside the Huggable avatar application run as background processes as long as the Android device was powered on. The Huggable avatar app's data manager service stored new affect information whenever it became available, and stored the numeric scores of SMS sentiment, engagement and valence scores from the Facial Expression Analyzer service. The raw data (the text content of SMS and the image from the camera) were only used for extracting the numeric affect scores but did not get stored to be reviewed by the author. The timestamped affect information were stored in the Android device's internal SD card along with the personalization algorithm parameters, audio recordings of the interactions and other data of the Huggable-user interactions (interaction start/end time, session duration and self-reported arousal/valence scores, audio recordings of the interaction).

When the user started the Huggable avatar app to interact with the agent, the data manager service read the most updated mood score and personalization parameters. Based on these information, the personalization algorithm chose the positive psychology interventions for the session, and started the interaction session with the user.

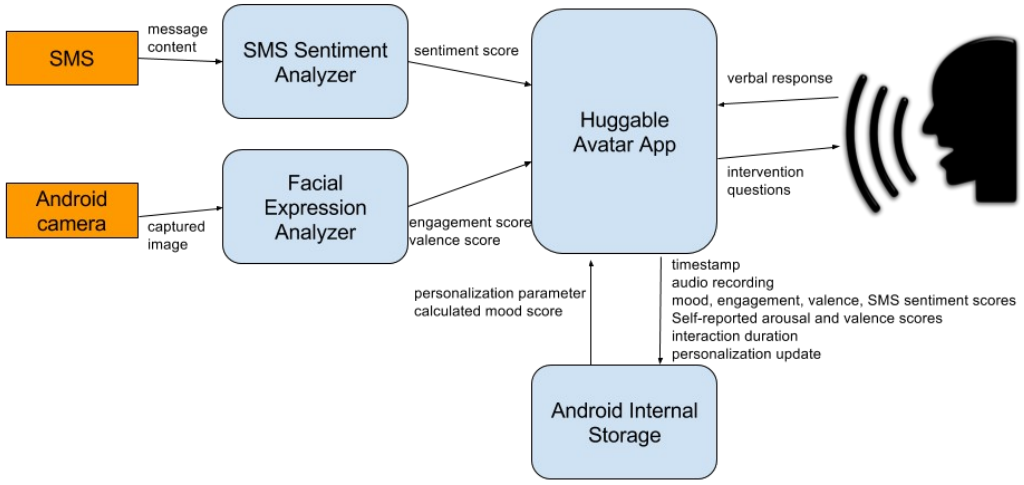


Figure 27. A system architecture of the Huggable avatar application.

9.4 Results

9.4.1 Personalized Intervention Selection Policies

Each participant developed a different intervention selection policy. Figure 39 shows Euclidean distances between participant's final intervention selection policies. The learning algorithm has

personalized to each participant and the smart phone users ended up with drastically different policies. The policies did not converge after 3 weeks but this was not surprising since there were many state spaces and not enough learning interactions.

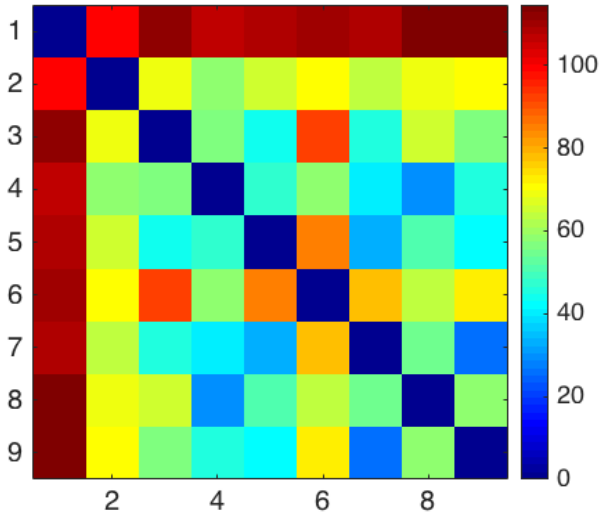


Figure 28. A distance matrix for nine participants' final intervention selection policy after three weeks.

9.4.2 Immediate Effect on Self-reported Arousal and Valence

A paired t-test showed that interacting with the Huggable avatar elicits a statistically significant change in study participant's self-reported arousal level, $t(136) = -2.339$, $p = 0.021$. The mean arousal level was -0.591 (SD 2.038) before and -0.387 (SD 2.023) after the interaction, out of [-4, 4] range. A paired t-test on participant's self-reported valence level also showed that interacting with Huggable avatar elicits a statistically significant change, $t(136) = -2.974$, $p = 0.004$. The mean valence level was 0.526 (SD 1.902) before and 0.825 (SD 1.870) after the interaction with Huggable, out of [-4, 4] range.

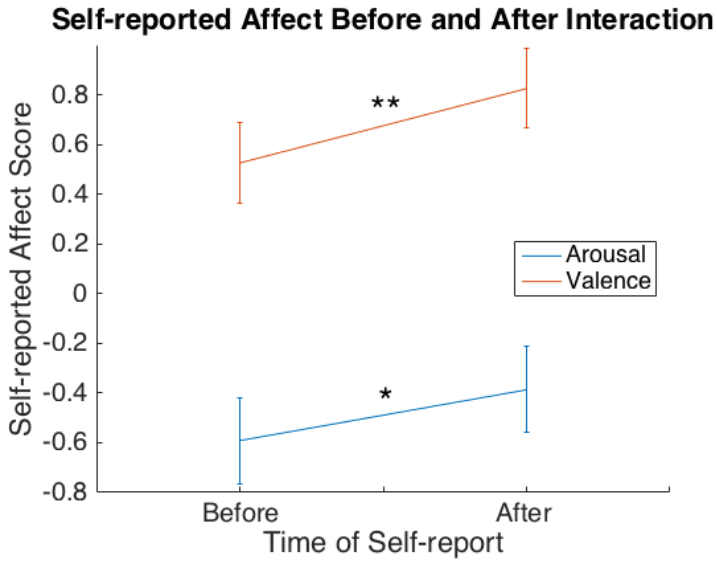


Figure 29. Both self-reported arousal and valence levels showed a statistically significant increase after participants interacted with the Huggable avatar.

9.4.3 Long-term Effect on Psychological Well-being

Participants' mood, perceived stress, affect balance and psychological well-being level did not show any statistical significant change based on pre-, mid- and post-questionnaires. However, a Friedman's test on participants' self-acceptance levels in Ryff's Psychological Well-Being scale showed a trend of difference, χ^2 (2, 16) = 4.563, p=0.102. A post-hoc Tukey's test on self-acceptance levels among pre-, mid- and post-questionnaires failed to reject the null hypothesis at $p<0.05$ significance level but a trend of increase was found between the mid-test to the post-test, p=0.08.

9.4.4 Interaction Duration per Question

An independent-samples t-test was conducted to compare participant's response duration for each intervention question. There was a significant difference between the interaction duration per intervention question for the first 10 days of the study (M 24.617, SD 22.455) and the latter 11 days of the study (M 31.590, SD 33.874), t(1352) = -4.464, $p < 0.001$.

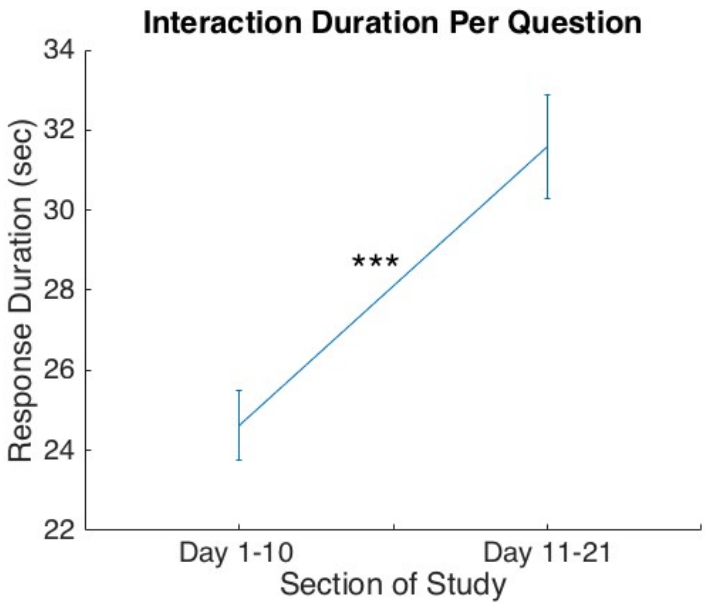


Figure 30. Interaction length per question increased in the second half period of study.

9.4.5 Interaction Contents

All except for one participant's interactions were audio-recorded and were transcribed by a professional vendor. The transcribed interaction contents revealed that the topics of participants' responses ranged from talked about very intimate and personal matters to the Huggable avatar. Although the questions asked by Huggable avatar were about specific events or actions, the participants often expanded their responses to more of a self-reflection thought process *("I usually try to have positive attitudes," "I get irritated really easily," "I am the unhealthiest person in the world,"* etc.)

When asked the gratitude question, one participant told Huggable that she was not sure whether to feel "gratitude" for the friendship that she and her friend shared since a friendship is supposed to be a "mutual thing" and therefore it felt "weird" to say that she was grateful that her friend likes her. She continued by saying that she probably thought this way because she was an "insecure" person. However, in one of the later interactions, the same participant expressed appreciation for her friends listening to her despite the fact that "all [she does] is complaining." Another participant reported that she realized through this study that small acts, such as preparing a nice warm meal for her family or friends, could be considered as a "kind act" and she found meanings in her daily chores that she used to consider trivial by repeatedly answering the "three kind acts" questions at the end of the study. Below is a transcription of one interaction made in the study. *H* represents the Huggable avatar and *P* indicates the participant's response.

H: How did you use your signature strength in a new way today?

P: (clears throat) I don't remember what my signature strength is, I think it's "appreciation" ... maybe? Uhm ... what did I do today? I fell asleep during class ... lunch ... oh okay, so, yeah, last night my friend came up, uhh, to basically ... to basically just talk about, like, random stuff. But, uhm, we ended up talking for, like, an hour-and-half about ... my life, and my ... and I don't know, it got kind of deep? Like my character, or my world views and how maybe there are things that I can work on, which I agree with (clears throat). And then I talked to my roommate about some more, sort of like ... views on change, or how ... I was very, like, interesting conversations.

Uhm, and then it's something that I've been thinking about a lot and so I kind of ... this is more like the gratitude question, I guess. But I'm grateful that they took time out of their day to listen to me. I feel like all I do is complain, which is another thing I'm working on. And so it was nice that ... I really did ... I really did appreciate that they were there and that they listened to what I had to say and they made time for me and ...

H: (Excited) Oh! Tell me anything you would like to talk about.

P: Uhm ... I guess just generally I feel like ... getting ... getting better, I guess, or ... ? Maybe closer to who I was before, and the next step is for me to let go of all these negative thoughts and feelings that I still have. I don't know why, unconsciously or subconsciously, clinging to these thoughts (clears throat). Like I feel like I have to be ... or it's not that I feel like I have to be, I feel like ... I have this weird idea that my natural state is negative. And I feel like that's not true ... because ...

H: (Excited) Mmm!

P: I feel like things have changed ... and I want to change them back. Because I liked who I was as a person more before I sort of entered this storm of negativity. Uhm, I'm going to do my writing exercise tonight and I think since writing is a good way to sort out your thoughts and explore ... deeper what you truly believe, to organize these things that you have, I'll probably use that time to kind of figure out how I'm feeling about who I am ... and sort of the way that I've been acting lately.

H: How did you use your gift of time to someone today? It could be helping someone, sharing a meal, or anything like that.

P: Uhm, I shared a meal with the [sports] team today. I kind of wanted to just dream box and come back to my room and watch T.V. and ... eat (laughter) by myself ... because sometimes I'm antisocial. But (clears throat), I ended up eating with the team and an old teammate that came back to visit us this week and it was nice ... talking to them. And I feel like the fact that I think it was nice, or maybe even just some part of me ... means that I'm moving in the right direction because like if you asked me a month ago I probably would have been insufferable and I feel like yeah it's the whole ... vicious cycle thing, like my negativity is making me act a certain way, people are reacting accordingly and then I'm just sort of like "This is terrible". But ... I don't know, that was a positive thing that happened today, I guess.

H: Thank you for sharing. It was good to hear your stories. See you!

Three of the nine study participants were mothers of young children. Occasionally, the recorded interactions showed that the participant's child joined the interaction. In most of these cases, both the participant and the child responded to Huggable avatar's questions. During this process, the participant will often help the child find answers or articulate the details and they discussed among themselves. Below is one of the examples of a triadic parent-child-avatar interaction:

H: **Hi! My name is Huggable. I will be helping you reflect about your day for three weeks.**

Child: Can I do that?

H: **Each day, I am going to ask three questions. I am so excited to hear about your day.**

Child: My name is-

H: **I'm ready to start. Are you?**

P: Okay, I'll press this, then it will ask the first question. Okay? Can you please close that off? Now listen to the-

H: **How did you use your gift of time to someone today? It could be helping someone, sharing a meal, or anything like that.**

Child: Um-

P: Did you share a meal, help someone, today?

Child: Hmm. I didn't. My, only my father asked me helped me get my jacket on how to, but my, and so my jacket, into the laundry because they had to do, because they was having a little trouble.

P: Okay.

Child: Can I press that?

P: No, not yet. Uh ... did I in any way help you or Dad today? I made delicious food for you guys. Anything else that I do to help you guys?

Child: Um, yeah. Yeah, because you ... can I press the-

P: Yes, you can press the next question.

H: **Tell me anything you would like to talk about.**

P: You would like to talk about something?

Child: Hmm. I have, I have, um, one, two, three, four, five, six, seven, eight, nine, 10, 11 ... 11 games on my iPad.

P: Nothing much. We got good news from the families today. We spoke to our family back home in [place], so there was good news from both sides. That's what we like.

H: **How did you use your signature strength in a new way today?**

Child: What does that mean, Mommy?

P: Signature strength, like mine is fairness. I am fair to other people. Now, how was I fair to you or your dad today?

Child: I-

P: Because you are the only people who I met today. Well, I was patient with you.

Child: And I-

P: I gave you time to look, to watch TV, then I took turns with you.

Child: Yes, and I let you watch something [inaudible 00:02:36] so many animals.

P: So we were all fair to each other today, right?

Child: I let Papa sleep while I play, and then woke up!

P: Great.

At the end of the study, two of these participants with young children reported that they had used the Huggable avatar application with their children several times and the experience helped them learn more about the children's days and thoughts. One mother said "[child name] never talks about what happened at school or how his day was. He just says "I don't know" all the time... I like this app because [child name] talks to the bear and I get to hear it. Sometimes I even get to talk about it with [child name]."

9.5 Discussion

This study investigated how a virtual avatar could engage with smartphone users on their personal mobile devices and influence their affect and psychological well-being. Although, no statistical significant change in participants' psychological well-being level over the three-week was found, the smartphone user's interactions with Huggable avatar showed a promising positive impact on improving their emotion. The analysis of self-reported arousal and valence level showed evidence that interacting with the Huggable avatar immediately make the smartphone users more aroused and valenced than before interacting with the avatar. In addition, it was shown that the users interacted with the Huggable avatar longer as they used the application over a three-week period. This finding is noteworthy because most of the mobile applications that are developed for behavior change have a high dropout rate and the engagement does not sustain over time. This could have resulted from unique intervention selection policies that the reinforcement algorithm learned for each user over time. However, an alternative hypothesis also exists; the increased engagement and interaction length could be due to the participants' increased familiarity with the interaction with the Huggable avatar and that they learned to express themselves better with the application. Since there was no control group that used the application without the personalization algorithm, it is difficult to strictly conclude that the personalization of intervention selection directly contributed to the change of interaction length over time. In addition, although not statistically significant, the self-acceptance factor in the Ryff's Psychological Well-being scale showed a trend of increase between the mid-test and the post-test.

The interaction transcriptions showed that participants reflected about themselves, which could have led this trend of increase in self-acceptance level. This is intriguing because the intervention

questions provided by the Huggable avatar did not contain questions on self-reflections. However, the participants voluntarily expanded their responses and reflected about themselves.

This pilot study has some limitations. There were only nine study participants in the study and there was no control group to compare the effect of personalization algorithms. A follow-up study that compares the effect of physical embodiment and the personalization algorithm could further inform how interactive agents (a virtual avatar and a social robot) could use emotionally intelligent interactions to improve people's affect and overall psychological well-being. Yet, despite some weaknesses, the system successfully engaged users for three weeks and the engagement with the application even increased over time. Many of the participants found the Huggable avatar application helpful in reflecting about themselves and their daily lives, and this work could complement existing psychological interventions and enable people to have more frequent and easy access to interventions that improve human wellbeing.

Part III

Improving Interactive Agents for Future In-hospital Study

10. Huggable v6

Huggable v5 was designed in 2014 and was used for the randomized clinical trial at Boston Children's Hospital until 2016. During the two years, some of the hardware components of Huggable v5 have become obsolete, e.g. Sparkfun's IOIO board for Android and HTC Vivid smartphone, and the robot platform physically was worn down. Thus, the Huggable research team decided to redesign and update significant parts of the robot for higher robustness and performance for future research experiments. The hardware issues found during the clinical trial study were compiled by the whole team and addressed in the new robot design. The software system was also upgraded to utilize newly available technologies and to be compatible with the changes made in hardware components.

The robot development team at MIT consulted with a local engineering consulting firm, Cooper Perkins Inc., to redesign and prototype Huggable v6. The key goal for the redesign was to maintain the aesthetics and appearance of the Huggable robot while strengthening the mechanical robustness and upgrading electrical components for higher performance. The software system was also updated based on the changes in the electrical system and the state-of-the-art ROS (Robot Operating System) infrastructure.

10.1 Electrical Design Change

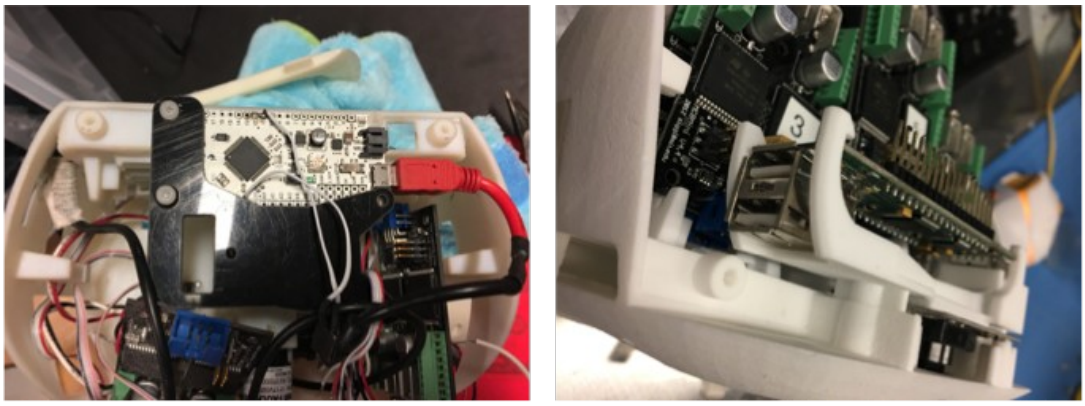
Huggable v6 had several major changes in its electrical design from Huggable v5. First, Huggable v6 was designed to use a Samsung Galaxy S7 phone, which has much higher processing power than the previously used HTC Vivid phone. The Galaxy S7 phones have a USB On-The-Go (OTG) feature that allows Android devices to host other USB devices, such as keyboards, mice or USB flash drives. With the OTG feature, Huggable v6 can directly receive video streams from a wide-angle camera installed on the robot's head. Second, Sparkfun's IOIO board for Android became obsolete and was replaced with a FTDI USB Hi-speed Serial/Hub Module (Figure 24). The USB Hub module not only connects the Android device with a wide-angle camera (Figure 25) but also interfaces the serial communication between the Android phone and the MCBMini boards (Aðalgeirsson, 2008) for the robot's motor control. The wide-angle external camera is newly installed inside the head of Huggable v6 whereas Huggable v5 was designed to use the smartphone's front-facing camera. The stronger computation power of Samsung Galaxy S7 allows capturing images from the external camera at 20-30 fps and streaming them to a remote machine for post-processing, such as face recognition and identification. Several ports on the hub module also allows adding another sensor, e.g. an external microphone or speaker, that can be accessed and controlled by the phone. Lastly, Huggable v5's SEED power board designed by Setapen (Setapen, 2012) was replaced to a custom power distribution board (PDB). The new

PDB takes 14.4V from the battery pack or the power charging supply, and then distributes appropriate voltages to each component. Figure 28 shows the PDB connected to the MCBMini boards, FTDI USB serial/hub module, Samsung Galaxy S7 phone, etc. The phone directly receives visual data from a wide-angle external USB camera. Table 3 shows the summary of how each component changed from Huggable v5 to Huggable v6.

The changes in electronic system required a new bracket to hold and fixate all of the components in the head, which was already crowded in the Huggable v5 design. In order to address the spacing issue, the robot's head brackets were redesigned and the dual USB port was removed from the FTDI USB serial/hub module. Further details on the head shell and inner bracket are described in the next section.

Component	Huggable v5	Huggable v6
Android-MCBMini interface	Sparkfun's IOIO board	FTDI USB Serial/Hub Module
Smartphone	HTC Vivid	Samsung Galaxy S7
Visual perception	External USB camera off the robot	Wide angle camera on the robot
Torso movement	Hip joint	Removed
Head floor	3D printed material	Aluminum plate
Arm support	3D printed material	Metal plate and steel bearings

Table 3. Major changes in Huggable v6 hardware components in comparison to Huggable v5



(a) (b)

Figure 31. (a) The IOIO board interfaced in Huggable v5 was replaced, (b) FTDI USB serial hub in Huggable v6.

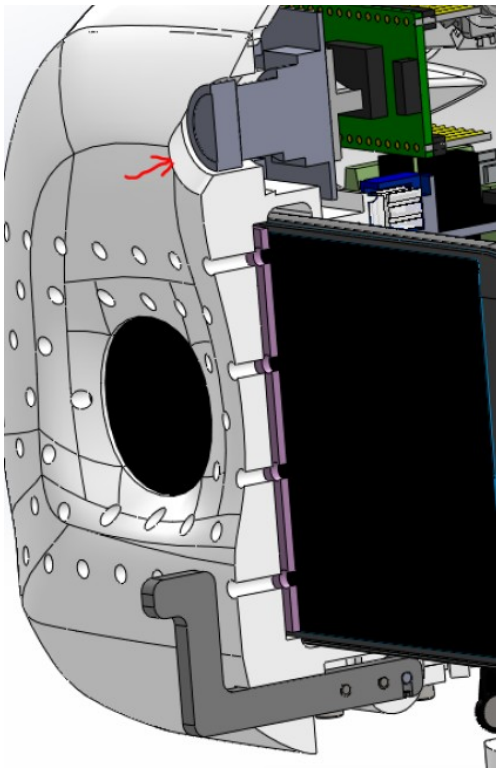


Figure 32. A wide-angle external camera is installed inside the Huggable v6's headshell.

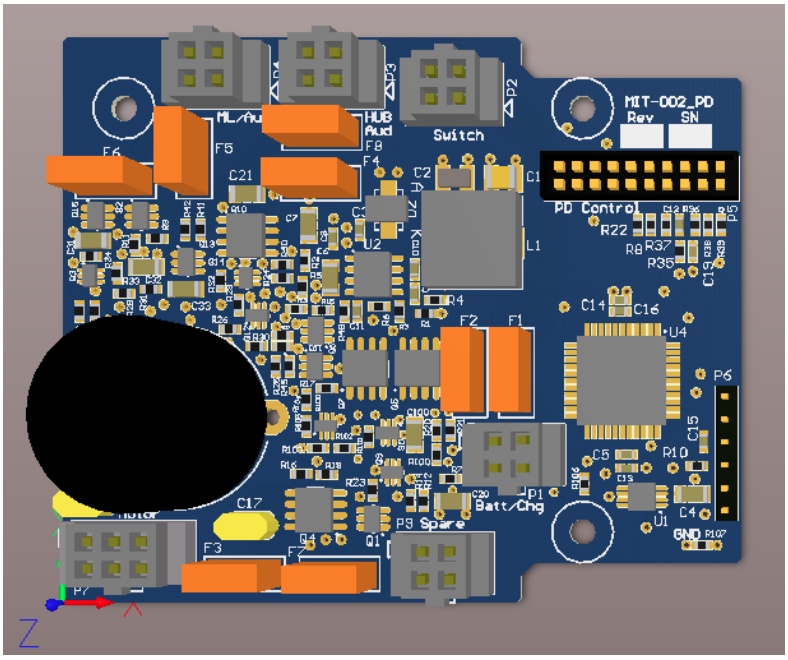


Figure 33. The 3D snapshot of the Huggable v6 Power Distribution Board (PDB)

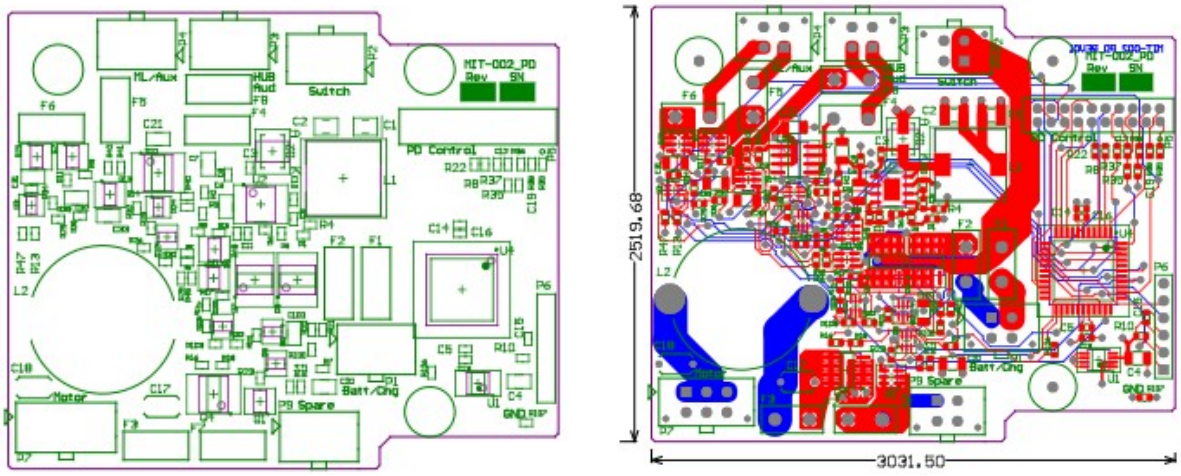


Figure 34. The assembly and the trace diagram for the Huggable PDB

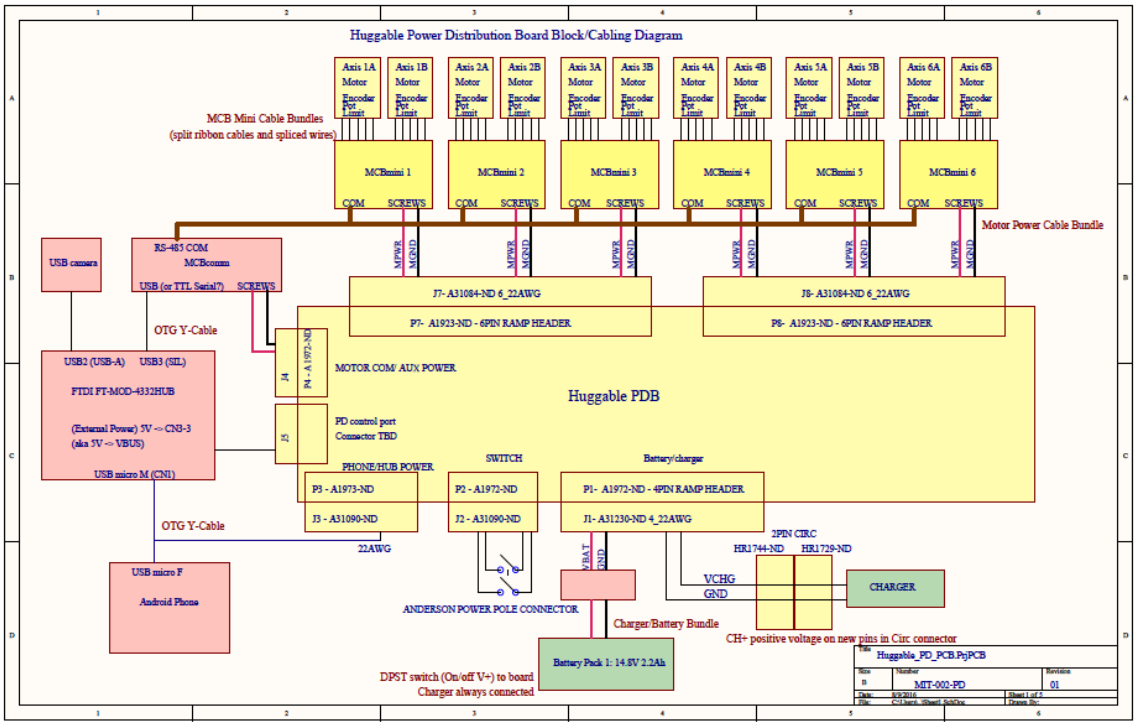


Figure 35. The wire diagram for the Huggable PDB and other electrical components.

10.2 Mechanical Design Change

During the first randomized clinical trial, the Huggable team found several mechanical design issues with the Huggable v5. Most of the mechanical structures in Huggable v5 were made via 3D printing ABS (Acrylonitrile-Butadiene-Styrene) plastic. While 3D printing allowed an easier and cheaper prototyping process, the additive manufacturing is innately more brittle than metal or other material with

a stronger chemical bond to concentrated force. 3D prints are especially more vulnerable when an external force is applied along its additive layer. Thus, repeated interactions with children who grab, pull and hold the robot caused 3D printed shells of Huggable v5 to crack (Figure 29), and some of the components that were tightly fit during the assembly loosened over time.

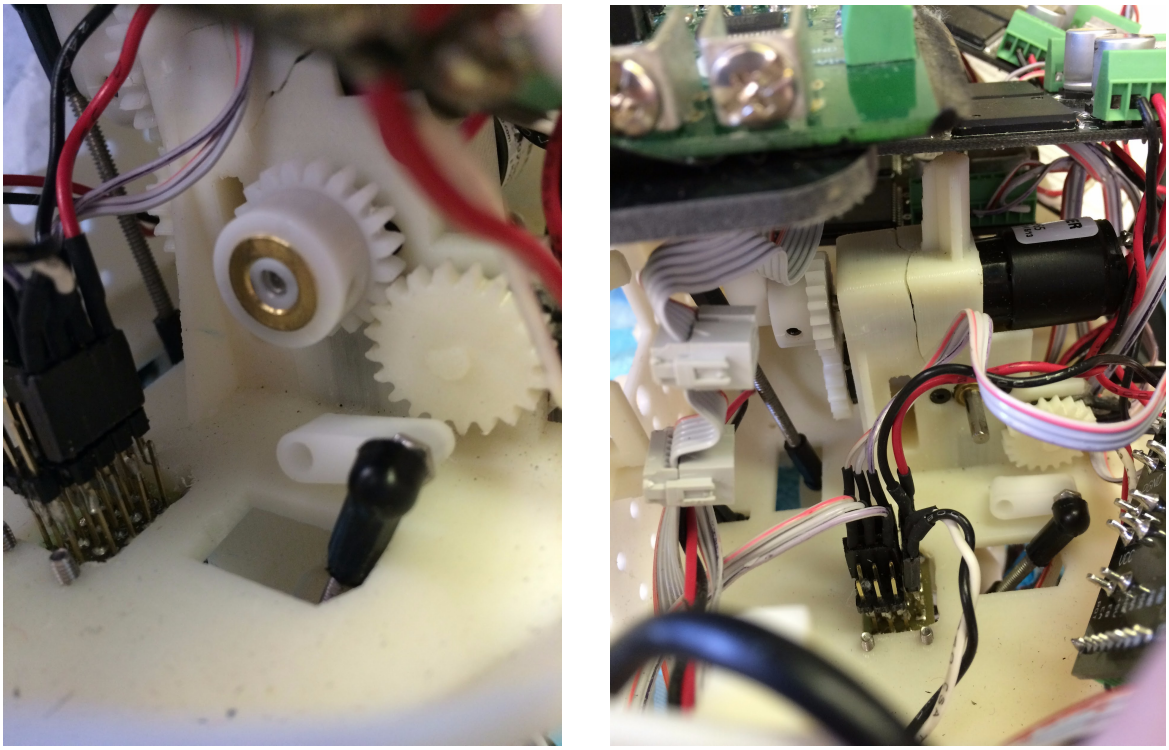
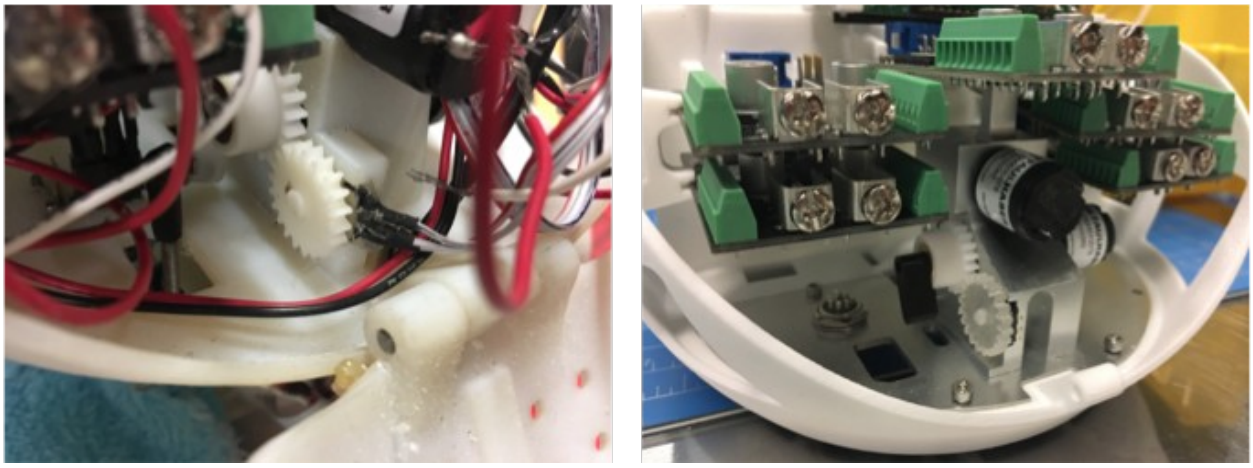


Figure 36. The 3D printed head structure in Huggable v5 cracked after repeated usage and external force.

In order to address this issue, metal support structures were added in the arm and the head of Huggable v6. The metal gear housing in the robot's head and the aluminum head floor in Huggable v6 are designed to distribute external force across the entire head floor instead of creating a small weak point in the head structure. The metal head floor would also prevent screw threads from stripping and strengthen the fixture.



(a) (b)

Figure 37. (a) The 3D printed head floor cracked when external force, e.g. a child pressing the robot's head during a hug, was repeatedly applied. (b) The new head floor was made in aluminum plate to bear any extra stress and force on the neck joint.

In addition, the overall size and inner structure of the head were modified to adapt the bigger smartphone and the wide-angle external camera. Samsung Galaxy S7 is slightly longer than HTC Vivid and thus the head of Huggable v6 is a bit wider than that of Huggable v5 (Figure 31). Furthermore, adding a wide-angle external camera and a FTDI USB serial/hub module complicated the positioning and fixating of these components inside the head structure. After considering several options, the team decided to have the smartphone slide into the side of the head with a thin delrin plate to hold the fur pieces down. Then a lock latch will hold the phone from moving out of the head shell. Figure 32 illustrates how the Samsung Galaxy S7 phone will be installed inside the Huggable v6 head structure. This solution allows the external camera to be held with a housing so that it will not move its position when the robot is actuated.

(a) (b)

Figure 38. The original head shell (a) was slightly enlarged in the Huggable v6 (b) due to the bigger size of the Samsung Galaxy S7 phone. Huggable v6's head shell also has a hole for the wide-angle camera.

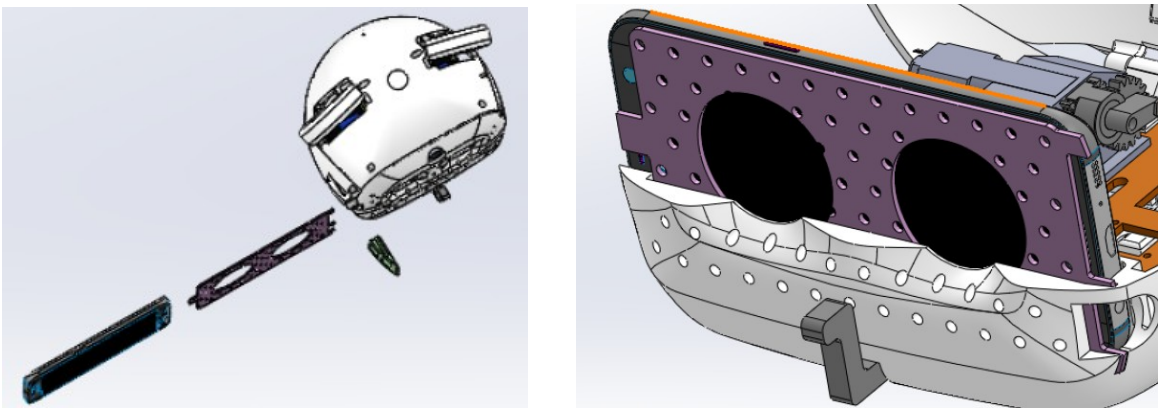
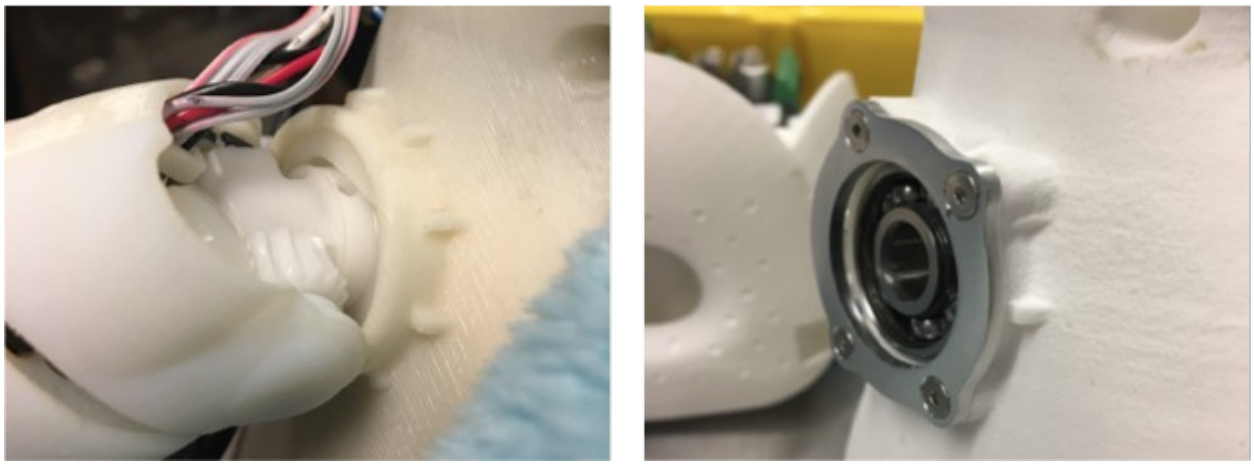


Figure 39. The Samsung Galaxy S7 slides into the head shell from the side. The delrin plate holds (purple) and the clutch (green) fixates the phone from moving inside the shell.

The arm joints were also found to be vulnerable to external force based on our experimental study. Many children were naturally drawn to hold the robot's paw and wanted to move them manually as if they would with a plush teddy bear. Some children also wanted to do a high-five or fist bump with the robot. In order to prevent gear teeth from stripping through these kinds of back-driving behavior, Huggable v5 had the flexure rachet mechanism inside the arm joints to allow the gears to slip. This mechanism successfully protected the motor and the gear in Huggable v5 but unfortunately still left the 3D printed arm shells to loosen its fixture from the torso. In Huggable v6, we added modified geometry of supports and added metal plate and steel bearings in the arm-torso interface to create more reliable engagement between arm gears. Also, we are testing four different flexure shapes to compare their performance in Huggable v6 (Figure 34).



(a) (b)

Figure 40. The 3D printed arm support and plate (a) in Huggable v5 were replaced with metal plate and (b) steel bearings for higher robustness and reliability in Huggable v6.

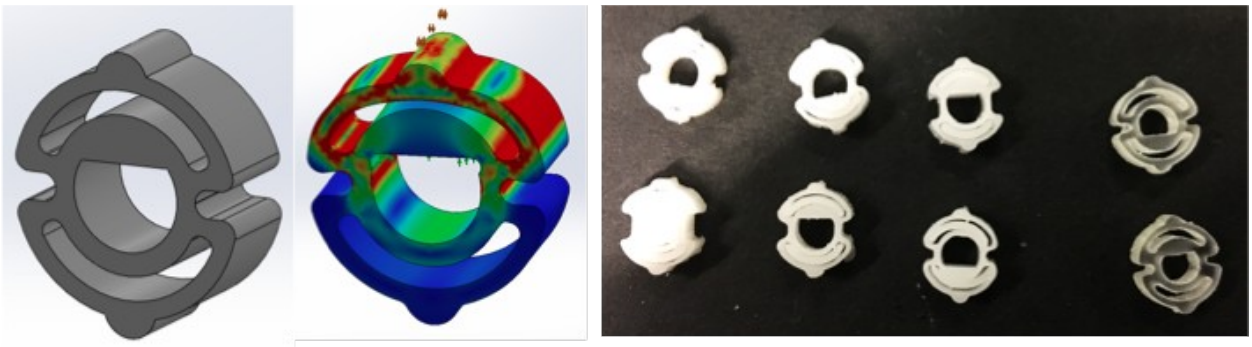


Figure 41. Various models of the flexures were cut to be tested on the new Huggable v6.

Huggable v5 had a hip joint that moved the entire torso forward and backward. However, it was found that the entire upper body of the robot had too much mass and the mechanical structure in the joint could not reliably provide enough torque to actuate the hip movement. The screw that connects the gear to the motor shaft continuously loosened after a few runs and let the motor spin without engaging the gear. The team decided to remove the hip joint completely since there was no clear solution to address this issue without making drastic changes into the mechanical structure in the torso. Instead, it was decided that the torso would have a spring installed so that the torso would move fluidly with the forward/backward movement of the head. However, the legs of Huggable v5 had ball bearings installed that allow very smooth and fast rotation at the hip. The hip joint is not strictly actuated and with the freely moving legs, if could potentially allow the robot to fall forward or backward with a drastic head movement. In order to prevent this, the ball bearings were removed from the legs and the base was directly attached to the leg. Two detent mechanisms were installed to restrict overall travel in the surrounding space and increase the overall friction in the interface between the leg and the base of robot's torso.

The upgraded Huggable v6 has not been fully assembled and tested yet but this section reports the changes made so far.

Figure 42. Partially assembled Huggable v6.

10.3 Software Design Change

Huggable v6's software system was built with the *r1d1_action* codebase and the Robot Operating System (ROS). The *r1d1_action* is a lighter and more efficient version of the original *r1d1* codebase and ROS is widely used in the robotics community. ROS is agnostic to programming language and the component's operating system. The ROS bag system also enables time-synchronized data logging and playback, which is beneficial for post data processing and analysis.

The Huggable robot controller application built upon *r1d1_action* runs on the Android smartphone (for *Robot* condition) or the tablet device (for *Avatar* condition). The overall app architecture remained very similar to that of Huggable v5. The robot controller app for Huggable v6 uses the same motor system and can be controlled remotely through the commands sent from the teleoperator interface running on a Ubuntu 14.04 computer. The laptop that runs the teleoperator interface also runs the real-time voice stream module and sends pitch shifted voice audio data to the Huggable controller application. Huggable v5 software system required an OSX machine for the teleoperation interface and a Windows virtual machine for the voice stream module. However, the Huggable v6 system only requires a Ubuntu

14.04 environment to run both the teleoperator interface and the voice stream module, which decreases the workload for the setup process.

The new voice stream module was written in JAVA instead of C++, and allows more intuitive and user-friendly control of pitch shift parameters (Figure 36). The first section allows the user to select the source of audio input for the pitch shifting process. With the slider in the second section, the operator can control how much the voice would be pitch shifted (100% meaning the original pitch). With the slider in the third section, the operator can control the volume of the processed audio stream.

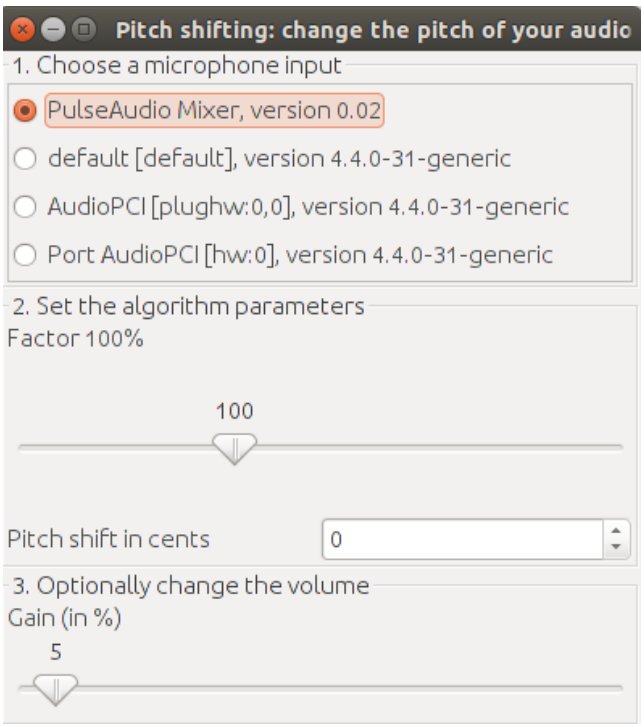


Figure 43. The screen capture of the real-time pitch shift interface. The operator can control the degree of pitch distortion and the loudness of the streamed voice.

The GUI of the Huggable v6 teleoperator interface was simplified for better ease of use. First of all, many of the animations were renamed based on the CCLS feedback. In the Huggable v5 system, the animations were named based on the audio clips coupled with them, e.g. “Hi!” or “What’s that?.” The coupled audio clips were removed in the Huggable v6 system except for the fart animation, and the rest of the animations were renamed based on the gestures, e.g. “nod_big,” “bow_big,” etc. Some of the animations and features not used in the experimental study were removed from the interface. The pressure bar and the touch indicator section were removed because the new within-subject experimental study will not need such information. The color-based emotional wheel was also replaced with simple rectangular

buttons. The new look of the teleoperator interface was reviewed by the CCLS for their feedback and the CCLS were satisfied at the simplicity of the control procedure.

A few new features were added to the teleoperator interface upon the CCLS's requests. The first new added feature is the sleeping animation. The CCLS wanted the Huggable to be asleep until the child "wakes" it up at the beginning of the interaction. Also, the high five and fist bump animations were modified so that the Huggable avatar/robot will hold its paw high until the CCLS triggers Huggable to return back to its idle position. In the previous study, we saw many children not being able to quickly do high fives or fist bumps with Huggable because the animation was too fast. The camera stream from the robot is displayed with color in the new teleoperator interface.

Furthermore, the Huggable v6 software system no longer uses IRCP (Inter-Robot Communication Protocol) system, which is an internal communication protocol developed by the Personal Robots Group. The new system leverages the open-source ROS architecture that is widely used by the general robotics community. All of the sensor data stream and robot status will be stored as a ROSbag format. ROSbag makes it easy to record and replay camera/audio streams, robot animation trigger messages and robot joint status with timestamps.

Figure 44. The updated teleoperator interface for Huggable v6. The buttons for animation triggers had been simplified and renamed for easier control based on the CCLS's feedback.

11. Within-Subject Experimental Study

The Huggable research team at MIT Media Lab, Boston Children's Hospital and Northeastern University are planning a new within-subject experiment to follow up the study discussed in section 6. The new study will again compare the impact of three interactive agents (*Robot*, *Avatar* and *Plush*) on changing pediatric patients' affect, pain and anxiety. However, the new study will test the effects in a more controlled manner via a within-subject experimental study protocol whereas the first between-subject study was more exploratory. Also, each child participant will interact with all three interventions in a randomized order in the new within-subject study. Thus, the overall study session will be much longer than that of the first between-subject study.

11.1 Participants

For this follow-up study, the Huggable team will recruit thirty children of age 6-10 who are staying in a PICU, medical, or post-surgical unit for more than two consecutive days. The new recruitment criteria will exclude patients who are 3-5 year-olds or who are staying in an oncology unit. The team decided to exclude children in these two conditions because we observed in the first between-subject study that many of the oncology patients were too fatigued to interact with any of the intervention, and the new study protocol considered too strict and lengthy for 3-5 year-olds.

11.2 Proposed Procedure

Once recruited, the study participant will be administered a Q sensor on one wrist 10-20 minutes prior to the start of the intervention. At the beginning of the study, the child participant will fill out the Facial Affective Scale (FAS); the Numeric Rating Scale for Pain (NRSP); and the Positive and Negative Affect Scales for Children – Brief version (PANAS-C) to measure the child's baseline present affective state. Prior to interacting with each intervention, the child participant will watch a relaxing video for 2.5 minutes to neutralize her affective state. Then, the study participant will interact with all three interventions in a randomized order for 10 minutes each. The robotic and the virtual Huggable will be teleoperated by a CCLS outside the patient's bed space as in the original study. After each intervention, the study participant will complete the Facial Affective Scale (FAS), the Positive and Negative Affect Scales for Children – Brief version (PANAS-C) and an Engagement subscale of the Intrinsic Motivation Survey. At the end of the study, the parent and child will be asked to complete a brief interview and a survey questionnaire regarding experience with the three interventions. The entire intervention will be video recorded and other biometrics already gathered for the patient will also be recorded (heart rate,

blood pressure, respiratory rate, if clinically monitored). The virtual and the robotic Huggable intervention will be equipped with an internal camera and the participant's behavior will also be recorded via the Huggable agent itself.

11.3 Data Analysis Plan

Video data will be annotated for the child's affective state, reactions to and engagement with each of the interventions. The biometric data (electrodermal activity from Q sensors, heart rate, respiratory rate, blood pressure) will be time synchronized and labeled with affect according to the video highlights. We plan to use this annotated data set to train a computational model for automatic and continuous anxiety and stress detection, using supervised machine learning techniques.

12. Conclusion

This thesis presents the development of interactive technologies and an experimental study that investigates the application of these companion-like agents as part of pediatric in-patient care context. The design process of these technologies actively involved the CCLS to ensure the usability of the Huggable robot/avatar system in a pediatric hospital setting. With the developed system, a randomized clinical study was conducted to study the impact of a social robot, a virtual avatar and a plush toy on social and emotional engagement between the patient, the child life specialist and co-present families, as well as patient's physical activity. The behavioral analyses on recorded video footage and verbal utterance transcriptions found that over time, a social robot promotes physical and verbal engagement and positive conversations from young patients and co-present family more effectively than a virtual character and a plush toy. The post-study CCLS questionnaire responses also suggest that social robots could potentially play a significant role in improving young patients hospital experience, helping to entertain and educate, as well as to help reduce feelings of isolation through providing various types of playful social interactions, both of which are associated with positive patient outcomes.

These findings provide an important foundation to guide the ongoing development of effective pediatric-companion technologies for hospitalized children and their families to augment CCLS and to improve patient's socio-emotional well-being. Based on the first exploratory experimental study, a new within-subject experimental study is proposed, and the technologies to support the new experiment have been developed. The new interactive agent systems address the issues found in the first randomized clinical trial and improved the robustness of both electro-mechanical and software systems.

Lastly, a pilot study was conducted to study the efficacy of a virtual avatar on mobile devices in improving smartphone users' psychological well-being. This was conducted to explore the opportunities

of autonomous interactive technologies that can be deployed in people's home. Although the last study was not conducted on pediatric patients, the outcome from the pilot study offers insights on how personalized longitudinal human-agent interactions could be used to improve people's psychological well-being.

I plan to continue investigating the nature of interaction between young pediatric patients and the three interactive agents by further analyzing the behavior children exhibit during the interaction, e.g. types of touch, cause of gaze aversion, etc. The prosodic features, such as pitch, loudness and musicality, of interaction participants' utterances will also be studied as a measure of arousal, as well as children's facial expressions and their skin conductance level during the interaction. Understanding how these sensory data features are related to children's affective state and physical/medical conditions can assist building a personalized computational model that will intelligently assess and detect when and how to engage young pediatric patients by their bedside.

I will also collaborate with the rest of the Huggable research team to finish developing the Huggable v6 system and run the proposed within-subject study to further understand the impact of a social robot, a virtual avatar and a plush toy on children's affect, perception of pain, and mitigation of stress and anxiety based on factors such as patient's initial affect, age group, medical condition and gender. This will provide additional insights as to how different companion-like interventions can provide value to different groups of pediatric patients. The knowledge and insights from future analyses shall also inform the further development of the robot pediatric companion toward greater autonomy and patient personalization to support professional care teams, patients, and their families.

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