Designing and Deploying Robotic Companions to Improve Human Psychological Wellbeing

by
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I will join the Purdue Computer Science Department as a tenure-track Assistant Professor in Fall 2023. If you are interested in developing interactive technologies for people's lives, please reach out!

My research focuses on designing and deploying interactive AI agents that can improve people's lives by providing personalized support based on each user's needs, traits and behaviors. I deploy these agents "in-the-wild" to evaluate how they build relationship/rapport with people over time and improve their wellbeing, health and learning. I believe relational technologies can be more than just tools and become helpful companions for people by continuously adapting themselves to help users achieve their health goals. Some of my research interests are in Human-Computer/AI Interaction, Social Robotics, Affective Computing, Applied Machine Learning, and Digital Health.

I received a S.B. and a M.Eng. from the Department of Electrical Engineering and Computer Science (EECS) at MIT, and a S.M. and a Ph.D in Media Arts and Sciences from MIT Media Lab. My doctoral dissertation was advised by Prof. Cynthia Breazeal who directs the Personal Robots Group.

Currently, I am a T32 Postdoctoral Fellow at the Center for Behavioral Intervention Technologies in Northwestern University Feinberg School of Medicine.

Abstract

Globally, **more than 264 million people of all ages are affected by depression**, which has become a leading cause of disability. Several interactive technologies for mental health have been developed to make various therapeutic services more accessible and scalable. However, most are designed to engage users only within therapy and in tervention tasks. **This thesis presents social robots that deliver interactive positive psychology interventions and build rapport with people over time as helpful companions to improve psychological wellbeing.** Two long-term deployment studies explored and evaluated how these robotic agents could improve people's psychological wellbeing in real-world contexts. In Study 1, **a robotic coach provided seven positive psychology interventions for college students** in on-campus dormitory settings and showed significant association with **improvements in students' psychological wellbeing, mood,and motivation to change**. In Study 2, we deployed our robots in **80 people's homes across the U.S. during the COVID-19 pandemic and evaluated the efficacy of a social robot that delivers wellbeing interventions as a peer-like companion rather than an expert coach**. The companion-like robot was shown to be the most effective in building a positive therapeutic alliance with people and resulted in enhanced psychological wellbeing, improved readiness for change, and reduced negative affect. We further explored how traits, such as personality and age, influence the intervention outcomes and participants' engagement with the robot. The two long-term in-the wild studies offer valuable insights into **design challenges and opportunities for companion AI agents that personalize mental health interventions and agent behaviors based on users' traits and behavioral cues for better mental health outcomes**.

Introduction

The prevalence of **mental health problems has increased and affects people of different ages**, with **depression** being one of the leading causes of disability. The COVID-19 pandemic has exacerbated the problem, tripling the prevalence of mental health issues due to stressors. Older adults have experienced extreme isolation and concerns about contracting **COVID-19**, resulting in worse psychological and functional problems, while sudden school closures have resulted in transitioning out of employment for working mothers. Higher education institutions have mandated relocation for students who experience loneliness and anxiety. **Systemic and personal barriers, such as social stigma, cost of treatment, and limited resources, still hinder people from seeking and receiving help for their mental health conditions.**

Introduction

The development of interactive technologies aimed at improving the **scalability and accessibility of mental health resources.** Unlike human therapists and clinicians, who typically meet with patients at limited times and places, digital health technologies can be with us at all times. Mobile and wearable devices can monitor and track our health conditions through in-the-moment assessments and sensors, alerting us when significant changes need to be addressed. Chatbots can offer interactive psycho-education or intervention content whenever and wherever we want.

Introduction

currently many technologies can only interact with users in specific health-related tasks, such as chatbots and embodied conversational agents with mental health intervention functions. These technologies can detect users' mental health status and provide corresponding intervention content, but they are not designed for long-term companionship and engagement. Sustaining positive wellbeing requires continuously monitoring and adapting one's mental health condition, instead of only acting when one is diagnosed with a mental disorder. In addition, some smart speaker devices have broader skills and services, such as interactive games, daily news reports, and music-streaming services, but their mental health or wellbeing skills are usually developed as independent "apps," not necessarily part of the voice agent's persona.

Introduction

This thesis explores opportunities for interactive agents to be helpful compan- ions that not only provide mental health interventions but also offer socio-emotional support outside of health-related tasks. We present a social robot that provides positive psychology interventions and a variety of useful skills in addition to prosocial behaviors (e.g., proactive greetings, pleasantries and calling users by their names) to enhance the rapport with the users over long-term interactions. We further investigate how people's personality traits impact the efficacy of the robot-mediated interventions and whether different robot personas benefit people with certain personalities better. Hense, two long-term deployment studies were conducted, and this thesis makes the following contributions:

Introduction

- Developing of a robot system that can be deployed for long-term studies in people's homes.
- Collecting a multi-modal data corpus that includes demographic, video/audio, self-reported wellbeing levels, and fine-grained quantifiable interaction data.
- Evaluating positive-psychology based robot skills designed to improve people's psychological wellbeing and integrated with the assistant and companion-like features.
- Investigating the effect of the robot's coach-like and companion-like interaction styles on the wellbeing intervention outcomes.
- Studying the impact of users' traits (e.g., age and personality) on the efficacy of the robot intervention.
- Identifying behavioral cues during human-robot interactions that can inform the progress of the intervention and rapport-building process.
- Learning design guidelines for enhancing robot-mediated interventions through personalization and rapport and for making social robots "livable" in people's home contexts.

Related Work

2.1 Mental Health and Wellbeing

- Several factors can increase the risk of mental illness. Genetic and biological factors have been found to contribute to the risk of anxiety and depression disorder in early life. Chemical imbalances in the brain have also been found to be associated with mental health conditions. Traumatic/adverse life experiences can also increase the risk of adverse mental health conditions by altering the pathophysiology and treatment response to depression. In addition, **loneliness and social isolation can negatively impact mental health, especially for older adults**.
- **Major depressive disorder (MDD) and generalized anxiety disorder (GAD) are two of the most commonly found mental health conditions [218].**
- **MDD is characterized by a "persistently depressed mood or loss of interest in activities, causing significant impairment in daily life,"**
- **GAD is diagnosed in those who "have excessive or unrealistic anxiety about two or more aspects of life" and show symptoms, such as palpitations, shortness of breath, or dizziness [6].**

Related Work

2.1 Mental Health and Wellbeing

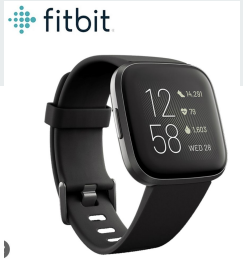
- **Antidepressants** can be prescribed to mitigate the imbalance in brain chemistry that contributes to depression [7, 182], and **psychotherapy** can also be used to reduce depressive symp- toms, resulting in therapeutic outcomes [299].
- Moreover, various types of psychotherapies exist, e.g., **psychodynamic therapy** [266], co**gnitive behavioral therapy (CBT)** [62], i**nterpersonal therapy** [183], and **dialectical behavioral therapy** [240].
- **CBT** has been shown to be effective in treating several mental illnesses, e.g., **depression** [63], **anxiety disorders** [146, 220], **alcohol and drug use problems [**192], **marital problems** [20], and e**ating disorders [**174].
- CBT focuses on helping patients learn how to identify and change cognitive patterns that negatively influence behavior and emotions [62].

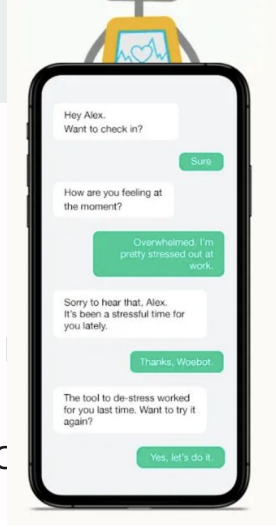
2.2 Positive Psychology

The use of **positive psychology interventions (PPIs)** as a treatment for major depressive disorder, which is comparable to the effectiveness of cognitive-behavioral therapy (CBT). PPIs focus on enhancing personal strengths and positive aspects of life to promote flourishing and well-being, making it a suitable intervention for both clinical and non-clinical populations. Numerous studies have shown the benefits of PPIs in **improving positive affect, happiness, and engagement, and meta-analyses have found that they effectively improve both hedonic and eudaimonic well-being.** PPIs have been used in various contexts for different populations, and randomized clinical studies have shown that they can improve subjective and psychological well-being while reducing depressive symptoms. The PPIs include topics such as gratitude, optimism, character strengths, resilience, savoring, and self-compassion. More details on the PPIs used in this thesis can be found in Section 4.1.

Related Work

.3 Technologies for Mental Health





- Fitbit1, use built-in sensors to collect information and detect user's behaviors to
  feedback.
- Woebot2, a mobile chatbot, provides text-based self-help content derived from C
  shown to reduce young adults' depressive symptoms over two weeks
- Mobile applications, such as Headspace3 and Calm4, offer meditation and breathing exercises designed to reduce stress and depressive moods.
- Embodied conversational agents (ECA) and social robots can also engage people in natural interactions by leveraging their embodiment and social behaviors.
- The eQuoo app, a gamified intervention for resilience, was shown to improve people's resilience, personal growth, and positive relationships with others
- MindMax combined video games and social networks with wellbeing modules and showed an increase in help-seeking intentions and a sense of connection [48].

2.4 Therapeutic Alliance and Health Outcomes

Interactive agents building relationships and rapport with people can have positive effects on health outcomes and patient satisfaction. **A strong human-agent alliance can improve continuity of care and prevent readmission rates, especially for patients with complex conditions.** Interactive technologies that support patients from hospitalization to post-discharge treatment can facilitate at-home care treatment and closely monitor health progress. Continuity of support through long-term human-agent interactions can positively impact patients' health outcomes, reduce re-admissions, and decrease healthcare costs.

Artificial agents, such as chatbots and social robots, can build rapport with people through verbal and non-verbal cues, creating a sense of familiarity and mutual understanding. This rapport can **increase people's willingness to self-disclose, which is critical in mental health interventions. Computer-based agents are perceived as non-judgmental, allowing for more openness in discussing sensitive or stigmatized information.** Overall, building a positive human-agent relationship can enhance the effectiveness of technology-mediated mental health support.

2.5 Patient-centered Healthcare

The **aptitude-treatment interaction (ATI)** research shows that individualized treatment plans matching each patient's specific characteristics result in better therapeutic outcomes . **Personalized interventions have been demonstrated to improve patients' adherence and health outcomes,** making predictors of patient outcomes valuable tools for clinicians to prescribe the most suitable treatment for each individual [18]. Patient and therapist factors have been studied as predictors of intervention or treatment outcomes, with patient-based predictor variables including demographics, diagnoses, personality traits, patient expectancies, and symptom severity . Additionally, care-provider characteristics such as experience, training, and skill have been studied as possible predictors of working alliance.

2.6 Personality Traits and Health Outcomes

Personality traits are predictive of adherence to medical regimens and mental health, with high conscientiousness being positively correlated with longevity and the ability to cope with stress. Low neuroticism and high extraversion have been found to be correlated with high psychological well-being. Personality traits also play a role in adhering to lifestyle changes, treatments, and psychotherapy, with conscientiousness having a positive correlation and neuroticism having a negative correlation with treatment adherence. Personality traits can also predict dropout risk for internet-based CBT, with low risk associated with extraversion and high risk with openness.

2.7 Behavioral Cues in Mental Health Interventions

Verbal and non-verbal cues are important in detecting people's mental states. **Acoustic signals** and **speech behaviors** are used to infer people's affect in conversations, while facial expressions are used to express and interpret affective and cognitive states. Understanding affect is crucial for successful therapeutic interactions. Recent advancements in computational vision have made automatic facial expression recognition more accurate and reliable. The FACS system has been developed to identify facial emotions and expressions through action units.

There are different types of movement that are used to express affect, including **communicative**, **functional**, **artistic**, and **abstract movement**. These movements can be used alone or in combination to convey emotions. For example, fear is expressed through bent elbows, while shame is characterized by slow movement and low energy. Self-soothing body movements like touching one's neck, face, or body, and holding or crossing one's arms, can indicate anxiety. Head movements and orientation can also convey emotions, affirmation, and affiliation during interactions.

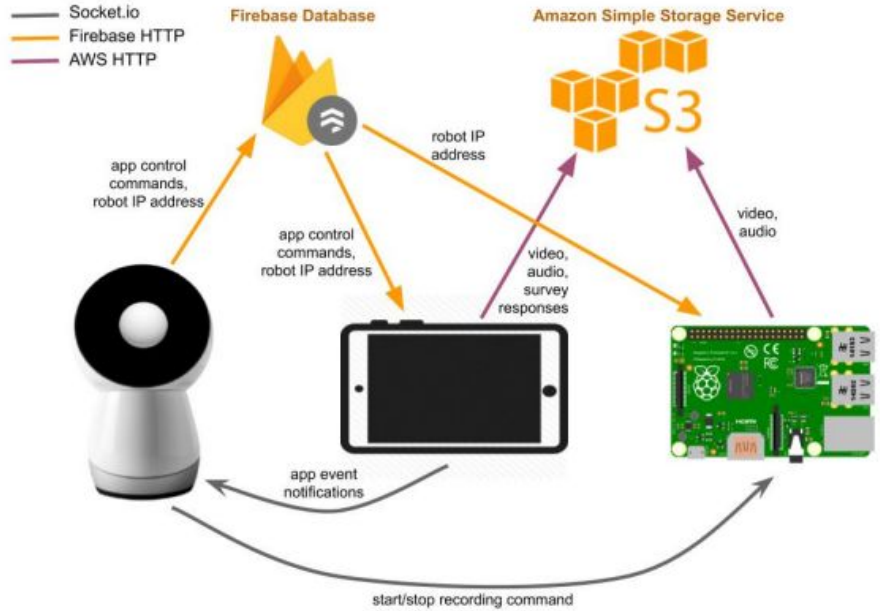
2.8 Summary

With mental health issues rising globally, interactive technologies have been explored as one of the solutions to make mental health interventions more easily accessible to those in need. Prior works have focused on creating these technologies as a useful tool and an expert system to deliver psycho-therapeutic interventions with increased accessibility only within a health- or wellbeing-related context. Existing findings on benefits of clinician-patient rapport and the computers-are-social-actor (CASA) paradigm suggest that there is an **opportunity to understand how enhancing the rapport and the human-agent relationship could positively contribute to the effectiveness of the mental health support social robots can provide**. Thus, **this thesis explores how social robots can be designed as a helpful and supportive companion that interacts with and engages with people as co-living partners in a home setting**. We further investigate the e**fficacy of robot-mediated PPIs in improving people's psychological wellbeing and the relationship between user's personality traits and the effectiveness of these interventions**. In addition, the relationship between observed behavioral cues and intervention outcomes is studied to learn valuable insights for interactive agents to adapt and tailor their behavior and interventions.

A Robotic Platform for Long-term Home Deployment Studies

We designed a robot station that integrates a Jibo robot, Android tablet and Raspberry Pi with a USB camera for our on-campus deployment study.

- It has a three-axis motor system that allows it to face any direction and use a variety of expressive movements.
- Jibo's two on-board
- cameras and microphone array allow it to locate and orient itself to users when interacting with them.
- Jibo can proactively greet and prompt
- users to engage in interactions to provide companionship for its users.
- Jibo robot1,Samsung Galaxy tablet, Raspberry Pi and USB camera.It is 20 × 9 × 14 inches and weighs about 16 lb.



The software architecture for the robot station. The Jibo robot, **Android tablet** and **Raspberry Pi** communicate with one another via **Socket.IO** and **Firebase Messaging**. The recorded interaction data is uploaded to the **S3** after each session is completed.

Designing Robot-mediated Positive Psychology Interventions

In our research, we programmed our robot to deliver evidence-based **positive psychology** interventions. We covered various topics in positive psychology over multiple sessions, including **gratitude**, **character strengths**, **self-compassion**, and **mindful listening**. These interventions were implemented in two different studies, with seven sessions in Study 1 and twelve sessions in Study 2. In this section, we provide a theoretical and empirical background of the interventions used in both the college-deployment study (Study 1) and the home-deployment study (Study 2).

Three Good Things exercise

In this exercise, participants are asked to “write down three things that went well each day and their causes every night for one week” and also write why it each good thing happened.

Study 1: Interactions for College Students

#	Session	Content Description
1	Positive psychology [262]	Introduce positive psychology and learn how to interact with the robot.
2	Character strengths [209]	Introduce what character strengths are and identify one's own signature strengths.
3	Signature strength [229]	Pick one signature strength and think of a new way to use it to improve well-being.
4	Three good things [228]	Define what gratitude is and write down three things that went well and why they were positive.
5	Gratitude letter [264]	Write a letter of gratitude to someone who has not been properly thanked.
6	Savoring [276]	Choose a small moment to fully feel and appreciate experiences that one normally hurries through.
7	Wrap-up	Review the previous sessions, evaluate each intervention and encourage continuation of practicing the interventions.

Study 2: Coach-like and Companion-like Robots for Adults

In Study 2, two different communication styles/personas were explored for the robot: **the coach-like robot**, which acted as an instructor with expertise in positive psychology interventions, and the **companion-like robot**, which presented itself as a peer learning the interventions alongside the participant. The coach-like robot provided **direct instructions and used a friendly tone and animations,** while **the companion-like robot introduced the intervention content as if it had learned it from a friend and asked if the participant wanted to try it together.** Both robots engaged in the intervention activity and shared their own thoughts and experiences, encouraging participants to do the same.

Coach-like Jibo: Very often, we pretend to listen to people who are talking to us, but in fact our mind is just wandering somewhere else. We sometimes even keep nodding, pretending we are interested in the conversation, but we are not fully present with the person. Can you remember and share the last time someone did that to you or you did that to someone?

Chapter 5 Data Collection

Several self-report questionnaires were administered to measure study participants' personality traits, psychological wellbeing , mood/affect, and readiness to change during the study.

In Study 1, the **Mini-IPIP** [77], the **Ryff's Psychological Wellbeing Scale** (RPWS) [147], **the Brief Mood Introspection Scale (BMIS)** [187], and **Readiness Ruler (RR)** [128] were administered before the study as a pre-test assessment.

After the study, the **RPWS, the BMIS, the RR, and the Working Alliance InventoryShort Revised (WAI-SR)** [203] were administered, and a semi-structured interview was conducted. For Study 2, we administered the Mini-IPIP and the PHQ-9 [163] as a pre-screening measure. During the study, we sent out the electronic weekly survey containing the RPWS, the Positive and Negative Affect Schedule Short Form(PANAS-SF) [289], and the RR on a weekly basis. The self-reported scales used in Study 1 and Study 2 are attached in Appendix A-I.

Table 5.1: List of self-reported scales administered in Study 1

Time	Measures
Pre-study	Mini-IPIP Ryff's Psychological Well-being (RPWS) Brief Mood Introspection Scale (BMIS) Readiness Ruler
Post-study	Ryff's Psychological Well-being 42 Items (RPWS) Brief Mood Introspection Scale (BMIS) Readiness Ruler Working Alliance Inventory-Short Revised (WAI-SR)

Table 5.2: List of self-reported scales administered in Study 2

Time	Measures
Pre-assessment	PHQ-9 Mini-IPIP
During study (weekly)	Ryff's Psychological Well-being 18 Items (RPWS) Positive and Negative Affect Schedule (PANAS) Readiness Ruler (RR)
Post-assessment	Working Alliance Inventory-Short Revised (WAI-SR)

Video and Audio Data

Whenever the system was recording, the Android application displayed a live video feed at the bottom right corner on the tablet screen to notify the recording status. Once the session with the robot was completed, the tablet application uploaded the recorded data with other relevant meta data to S3, and the local data was deleted from the table. After the study, the audio data were transcribed by a professional transcription vendor1 . The video data and the audio transcriptions were used to analyze participants' verbal and nonverbal behavior cues.

Post-study interview

We conducted a semi-structured interview with each participant at the end of the study to gain more qualitative feedback on the robot.

Table 5.3: List of Post-interview Questions

#	Question
1	What was it like having Jibo in your home/room?
2	Describe to me your interactions with Jibo.
3	What were three things you liked about your interactions with Jibo?
4	What were three things you disliked about your interactions with Jibo?
5	What other things did you do with Jibo other than the wellness skill? What did you like/dislike about them?
6	(if applicable) What did you think of the wellness activity content?
7	(if applicable) What did you think about the length of each session and the amount of content presented? Did you find them interesting or boring? Why?
8	What did you think of the robot's personality and talking style? Too formal or casual? Why?
9	(if applicable) Would you continue practicing the wellness activities you learned from Jibo even after the robot is no longer with you?
10	Let's imagine a world where everyone has a personal robot like we have smartphones now. If there's no restriction in technology or resources, what would you like the robot do for you? What would be your "dream" robot?

Chapter 6 Study 1: Improving College Students' Wellbeing with Social Robot

We asked the participants to complete the positive psychology session with the robot once a day any time during the day they found suitable.

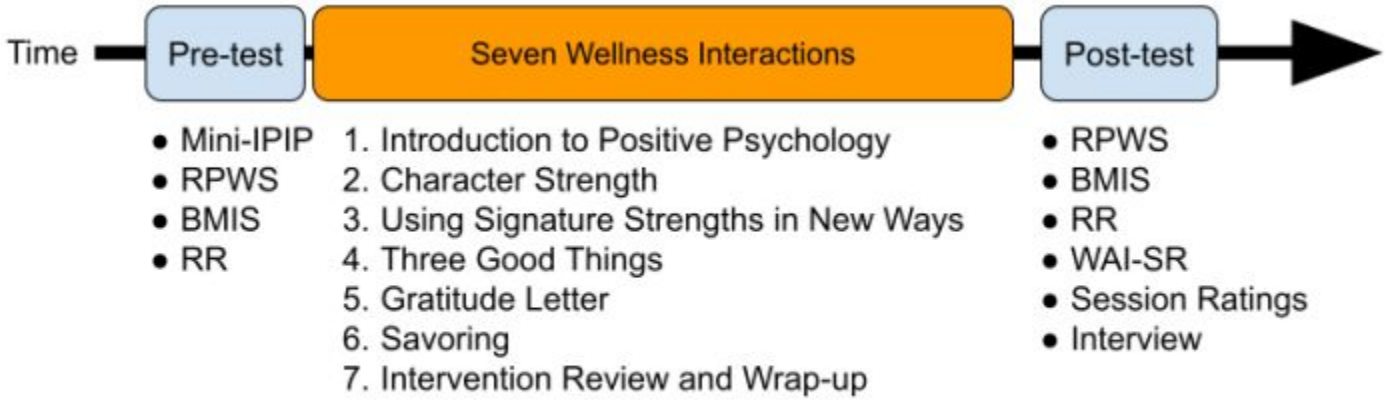


Figure 6-1: Experimental design of Study 1.

Chapter 6 Study 1: Improving College Students' Wellbeing with Social Robot

We hypothesized that positive psychology interventions (PPI) provided by a social robot that builds rapport with college students can improve their psychological wellbeing, mood, and readiness to change behavior.

RQ1. Can a robotic positive psychology coach improve college students' psychological well-being?

RQ2. How do students' personality traits affect the efficacy of the intervention?

RQ3. What effect does students' rapport with the robot have on the intervention outcomes?

RQ4. Can we predict the intervention outcomes by observing students' behaviors during their interaction with the robot?

Chapter 6 Study 1: Improving College Students' Wellbeing with Social Robot

Hypotheses

H1. Students' psychological well-being, mood and motivation for behavior change will significantly improve after completing the positive psychology interventions with the robotic coach.

H2. The outcomes of the interventions will differ based on students' personality traits.

H3. Students' rapport with the robot and the intervention outcomes will have significant associations.

H4. Students' engagement and behavioral cues are associated with the intervention outcomes.

Chapter 6 Data Analysis Methods

- **The changes in participants' psychological well-being (RPWS), mood (BMIS) and readiness to change health behavior (Readiness Ruler) were analyzed by conducting paired sample t-tests.**

- **We automatically extracted non-verbal features from audio/video data, and studied the correlations between these features and the change in self-reported wellbeing, mood, and readiness to change**

- **To analyze body movement and gestures, we extracted body joints from the video captured with the USB camera as it had a wide-angle view suitable for capturing the upper body.**

Chapter 6 Data Analysis Methods

List of non-verbal features extracted for analysis

Table 6.1: List of non-verbal features extracted for analysis

Behavior Type	Feature
Facial Expression (Affdex)	brow raise
	brow furrow
	inner brow raise
	eye widen
	eye closure
	cheek raise
	dimpler
	nose wrinkle
	lip press
	lip suck
	lip corner depressor
	lip stretch
	lip pucker
	lid tighten
	upper lip raise
	chin raise
	jaw drop
	mouth open
	smirk
	smile
	attention
	engagement
	valence
	contempt
	surprise
	disgust
	anger
	joy

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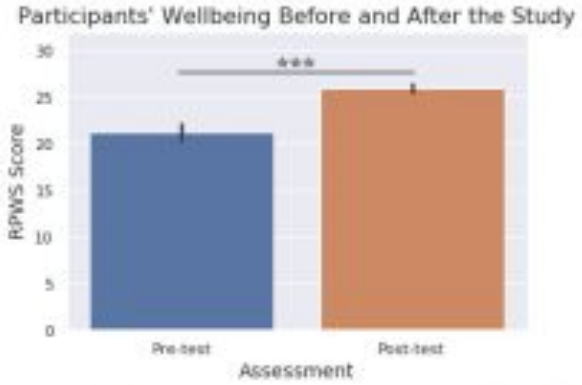
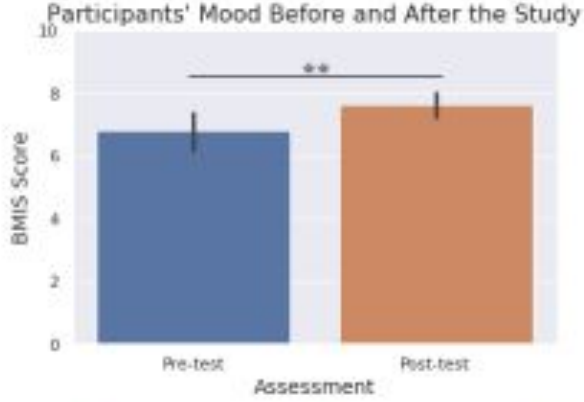
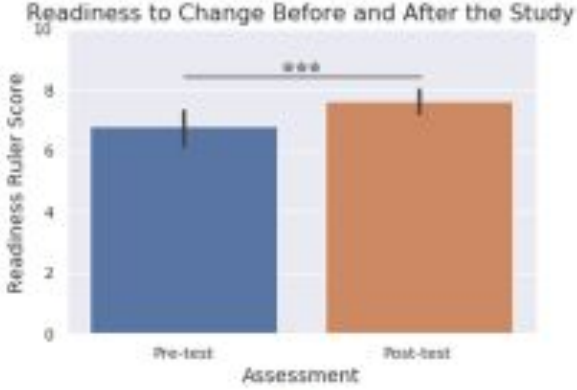
Chapter 7 Study 1: Experimental Results



(a) Ryff's Psychological Well-being Scale



(b) Brief Mood Introspection Scale



(c) Readiness Ruler

Chapter 7 Study 1: Experimental Results

The on-campus deployment study demonstrated that students who participated in our study showed statistically significant improvements in their psychological wellbeing, mood and readiness to change after interacting with the robot (H1). Results

from the WAI-SR suggest that students built positive working alliance and rapport with the robot but there was no statistically significant association between students' working alliance with the robot and their wellbeing outcomes (H3). We also found that students perceived the robot-mediated PPIs positively but there were differences in the level of satisfaction for each PPI.

Study 1: Design Insights from Post-Study Interview

Qualitative analysis on the post-study interview showed that our **robot was able to successfully interact with students** in their dormitory rooms and **delivered positive psychology-based wellness interventions**. **Participants generally had positive experience with the interventions provided by the robot** although there were mixed responses with the session on character strengths just as it was shown in Section 7.3. Participants appreciated the short length of the wellness session although some students mentioned longer sessions that provided more depth to the contents would have beneficial. Most students (91%) noted that the robot was friendly and pleasant to interact,noting the benefit of its physical and social presence that provided non-judgmental companionship. However, there were **concerns regarding the security and privacy with the robot as they had limited control over the robot's attentive behaviors in small dormitory rooms**. **The limited natural understanding capability of the robot also frustrated some participants and we found the desire for more humanistic and companion-like interactions.**

- Our study was exploratory in its nature and did not include a control group who did not receive any robot intervention. Thus, we cannot argue the students' improved self-report outcomes were caused by the interactions with our robotic coach. However, we would like to note that it is very unusual to observe significant improvement in college students' well-being during an academic term. The SNAPSHOT study [246] has shown that students' well-being generally declines over the course of a semester. Our participants started the study during the first half of a Fall semester, and completed it in the latter half of the semester. Thus, our participants' improvement in psychological well-being goes against the typical trajectory [246], and **this suggests that the robot coach's positive psychology interactions likely played a positive role in the improvement of students' well-being**.

- Lastly, our data suffer from common challenges of uncontrolled and noisy data collected in the real world. For example, sometimes the face of the participant was not completely visible, or the face was captured from a very low angle, causing image deformations and obstruction. At times, the room had very low illumination and the acquired videos were dark. These challenges can hinder the performance of the automatic models used to infer the behavior features.

Study 2: Designing a Companion-like Robot for Wellbeing

Based on these existing works, we propose a new way for social agents to deliver mental health interventions in a “companion-like” style, in which the agent uses gentler language to prompt users to engage in the intervention. In this new style, the robot does not instruct the human user but demonstrates the intervention activity first and invites him/her to join in, instead of using explicit directives for instructions. The robot also acts like a peer who also participants in the positive psychology activities for shared experience and uses self-disclosures to strengthen the human-robot rapport.

Study 2: Designing a Companion-like Robot for Wellbeing

We conducted an 8 week-long between-subjects study with two experimental conditions and a control condition in order to compare the impact of different intervention delivery styles. Participants in the two experimental groups (the **coach-like condition** and the **companion-like condition**) received a Jibo robot station that is equipped with twelve positive-psychology based interventions that are each 5-7 minutes-long.

• Control condition: The control group lived with Jibo with its basic skills without the positive psychology intervention.

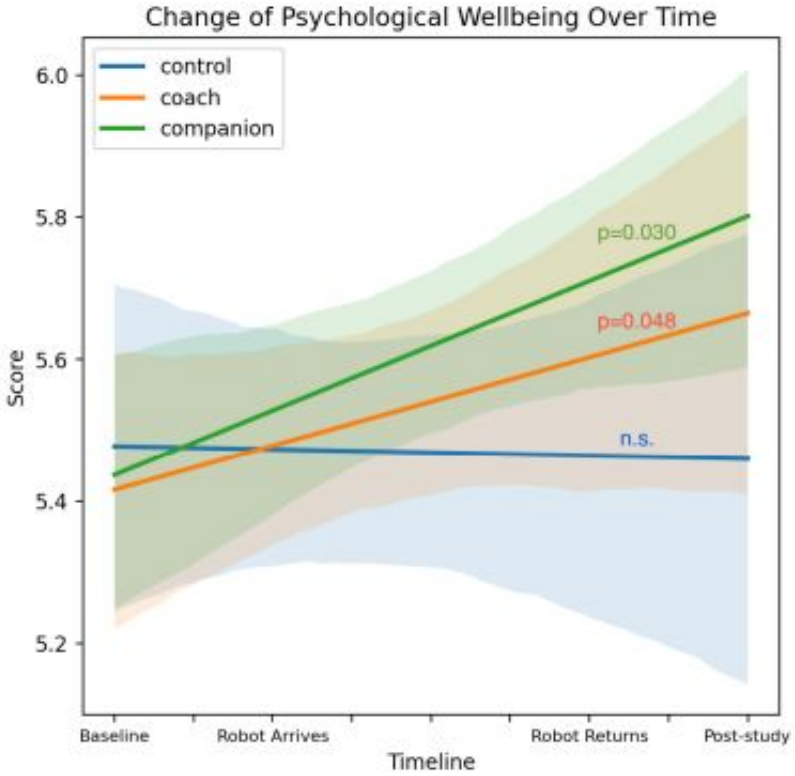
• Coach-like condition: Jibo presented itself as a positive psychology coach that guides users through twelv intervention sessions over the course of four weeks.

• Companion-like condition: The robot provided the same intervention content that the instructional Jibo provides, but delivered it in a more informal and casual way as if delivered by a friend. It offered examples a used selfdisclosures to make the interactions more personal.

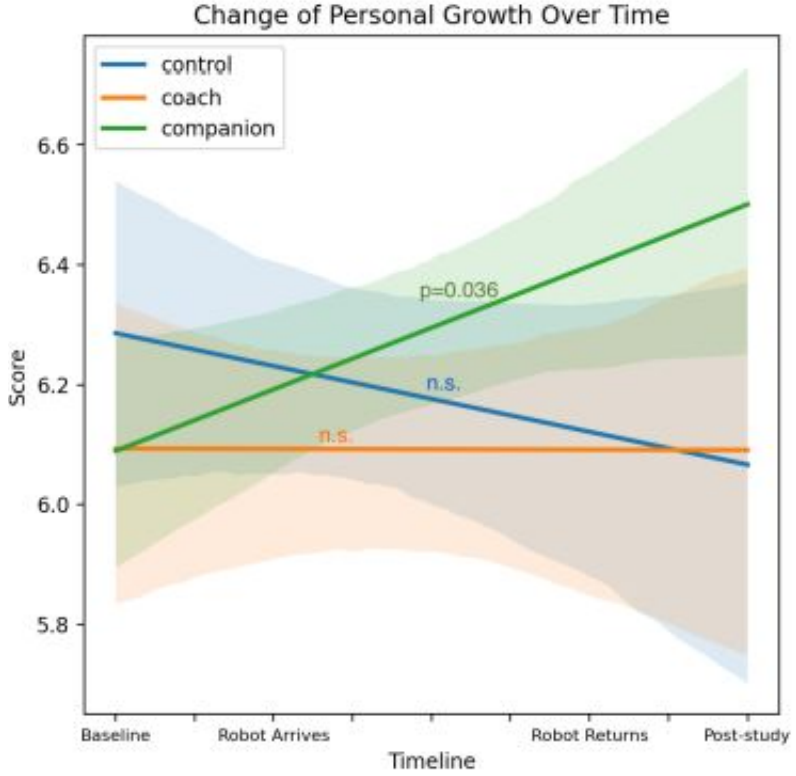
Study 2: Designing a Companion-like Robot for Wellbeing

Hypotheses

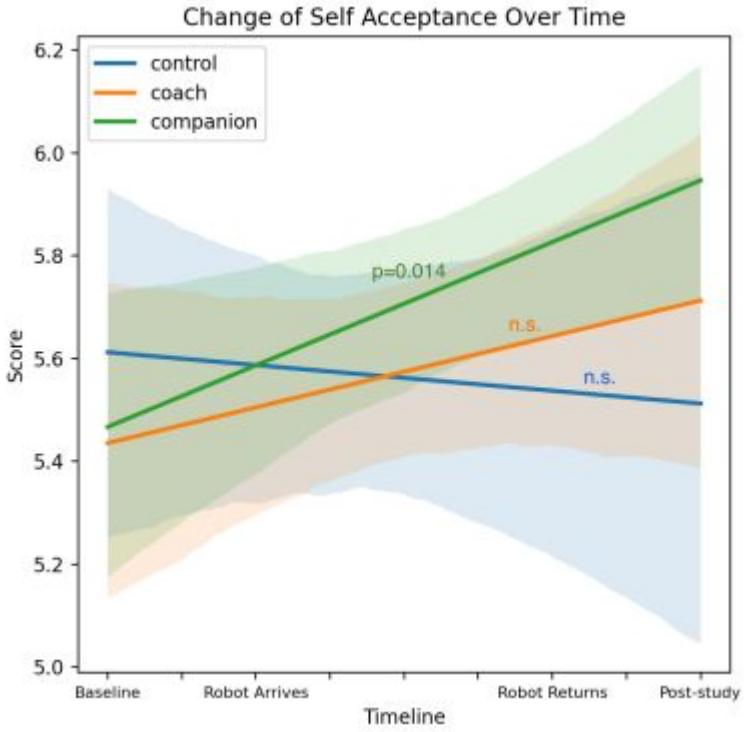
- H1. Participants in the coach-like and companion-like conditions will improve psychological wellbeing, affect and motivation for behavior change during the study but participants in the control condition will not show any significant change in study measures.
- H2. Participants who are clustered as the high neuroticism group based on the K-means clustering algorithm will show better intervention outcomes, adherence to the study protocol and rapport with the companion-like robot than with the coach-like robot.
- H3. Participants' working alliance with the robot will positively impact the intervention outcomes and adherence behavior.
- H4. Participants' engagement with the robot outside of the intervention measured by the number of skills used will be significantly correlated with their working alliance.



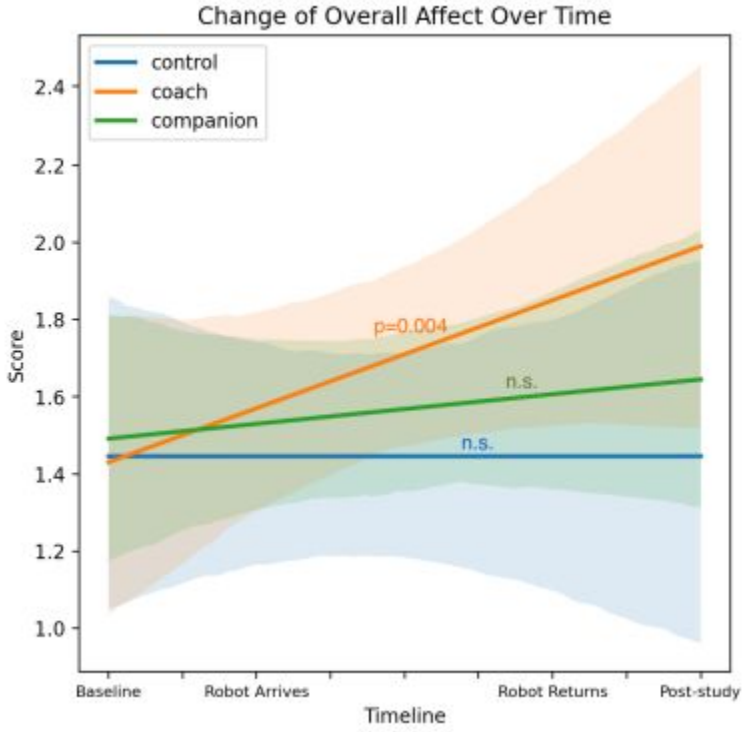
Participants in the coach-like (p=0.048) and the companion-like (p=0.030) conditions showed statistically significant improvements in their psychological wellbeing (RPWS_total).



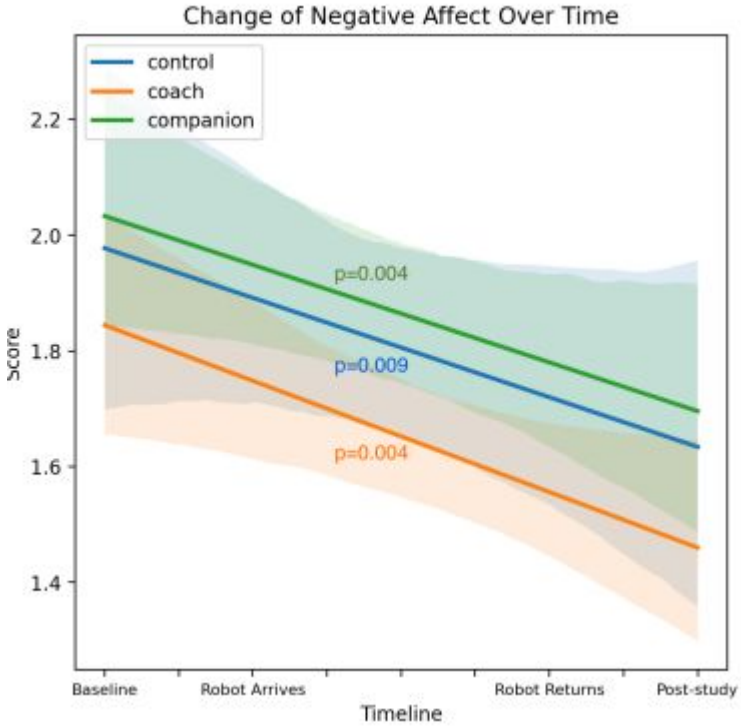
Participants in the companion-like condition (p=0.036) showed a statistically significant improvement in their personal growth (RPWS_PG)

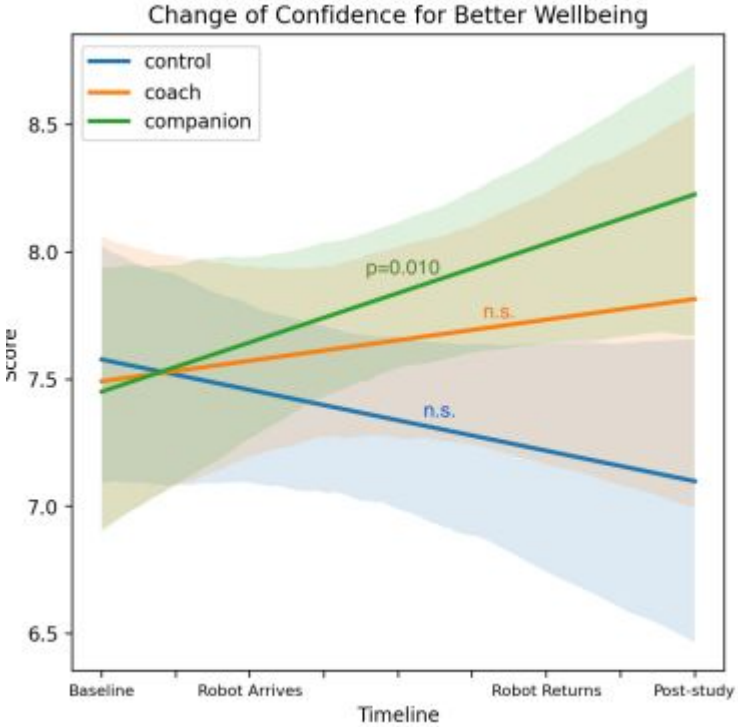


Participants in the companion-like condition (p=0.014) showed a statistically significant improvement in their self-acceptance (RPWS_SA).

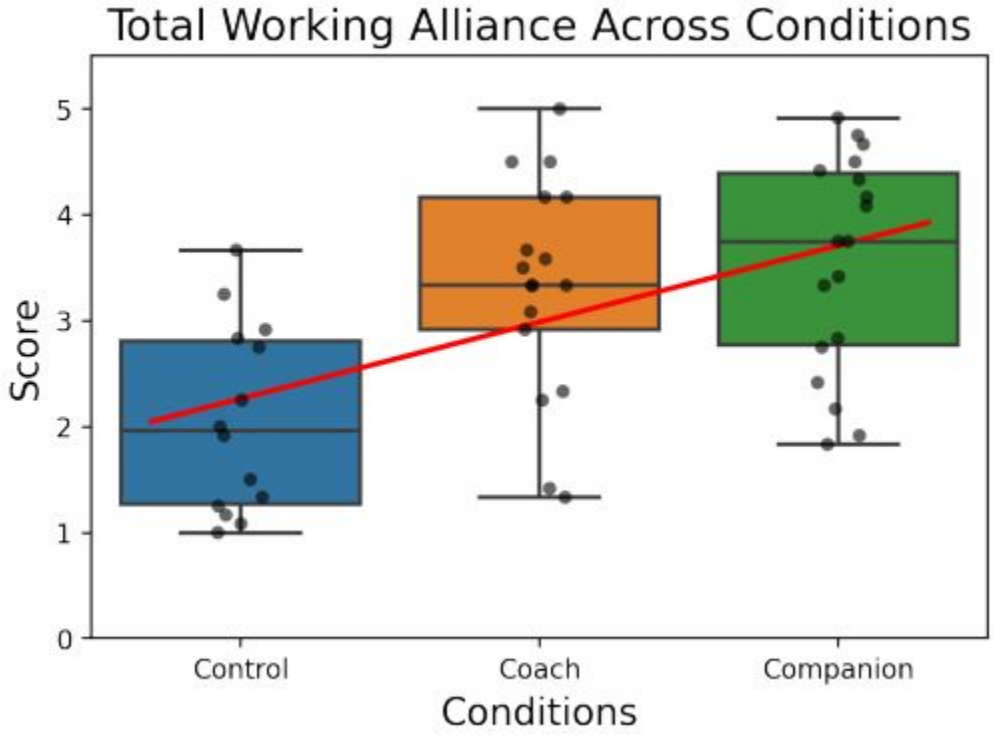


Participants in the coach-like condition (p=0.004) showed a statistically significant improvement in their overall affect (PANAS_total).





Participants in the control (p=0.004), the coach-like (p=0.009), and the companion-like (p=0.004) conditions showed statistically significant reduction in their negative affect (PANAS_NA)



Participants' working alliance with the robot showed an increasing trend of\
Control < **Coach** < **Companion**, p<0.0001.

Study 2: Designing a Companion-like Robot for Wellbeing

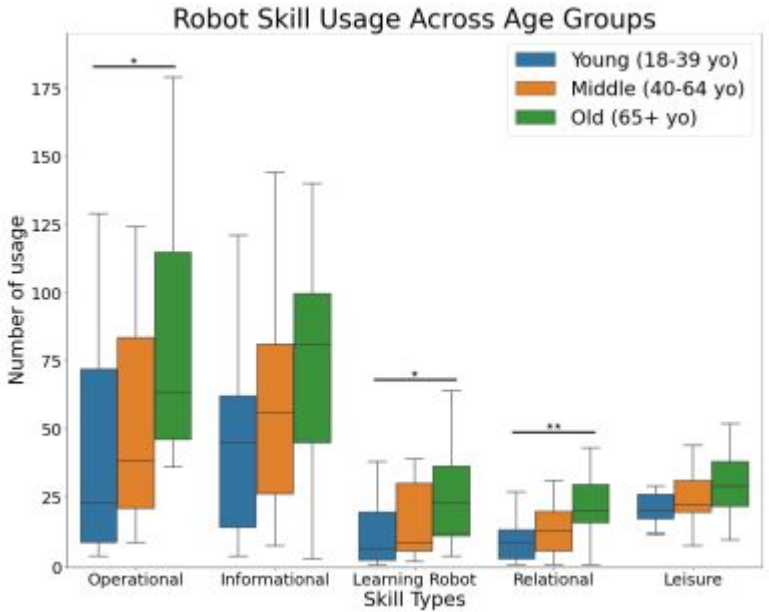
Our analyses showed that the **companion-like robot** **was the most effective in improving participants' psychological wellbeing** (RPWS_total), **personal growth**(RPWS_PG), **self-acceptance** (RPWS_SA), and confidence for **wellbeing change**(RR_conf) as well as **building therapeutic alliance with them** (WAI_SF). With the **coach-like robot,** participants showed improved overall psychological wellbeing(RPWS_total) and overall affect (PANAS_total). Interestingly, all three conditions(control, coach-like, and companion-like) were associated with reduced negative affect(PANAS_NA). Correlation analyses between the weekly study measures and **participants' working alliance with the robot suggest the human-robot rapport could either impact or indicate the effectiveness of the wellbeing interventions delivered through the robot, just as clinician-patient rapport are repeatedly shown to be a predictor for treatment outcomes.**

Study 2: Post-study Interview

The post-study interview data showed that participants **enjoyed interacting with the Jibo robot** in their homes and found the **positive psychology interventions helpful for reflecting on their own lives.** The robot's ability to provide not only wellbeing interventions but also other useful skills and prosocial behaviors was considered a strength compared to other devices such as smart speakers. The physical embodiment of the robot positively impacted how participants engaged with it and enhanced its social presence in the home context. However, some participants felt discomfort with the robot's proactive behaviors, and the dialogue management could be improved to better detect the end of responses, especially with open-ended questions. Participants with disabilities also faced some difficulties in using the robot, but they found different ways to engage with and enjoy it. **Future research will improve the robot's accessibility with more careful considerations and strategic design choices.** Finally, the COVID-19 pandemic and social distancing policy affected how participants perceived and practiced some of the wellbeing exercises provided by the robot. While some activities were challenging, the **robot's companionship and social presence mitigated loneliness for some participants, especially those isolated for an extended period of time.**

Study 2: Exploratory Analysis on Age and Robot Usage

Many Gen X and younger Boomers, who are now in their middle ages, witnessed the birth of personal computers and gradually adapted to using digital devices for work and personal use. In contrast, older adults are generally less likely to use technology than younger people, and there exists a "**digital divide**" **within older adults** [44, 67, 211]. However, **research shows that many older adults have positive attitudes towards the technology they use,** which contradicts stereotypes that they are not interested or unwilling to use technology [197]. **The potential benefits of social robots for older adults have been widely explored in the field of Human-Robot Interaction** [169, 29, 75, 272].



Design Insights and Future Work

Once robots are deeply integrated in our daily lives, their idle behavior may become the dominant behavior that consumers experience. Although not actively engaging people, interactive agents' idle behaviors can play a significant role in user's perception and acceptance of the agent. If a user is not comfortable with a robot's idle behavior, they will begin distancing the agent from the social centers of their living spaces and eventually cease all use of the agent. **All of a social robot's behaviors play a role in how they build a relationship with users.** In order to begin building that positive relationship it is vital to take measures to ensure that participants feel at ease when inviting new technology into their homes. **Agents should be able to provide clear information** to users on video and audio data usage to promote a sense of privacy. **Users should be given the ability to control how their video and audio data are used,what information they are being proactively told by an agent, and an agent's sleep and wake cycles.** To give users an overall sense of comfort, agents should notify users before proactively engaging to ensure that the user wants to interact and to warn users before creating unwanted noise. With these guidelines we can create more attractive and user-conscious pieces of technology that have the potential to enhance the home environment for consumers.

Chapter 19

In this thesis, we present social robots deployed in the real world to live and interact with people in their homes and act as a helpful companion, rather than a tool. The two long-term deployment studies in-the-wild with more than a hundred participants demonstrated that unlike other existing health technologies, a social robot can create unique opportunities to build rapport with its users through pro-social behaviors.

Our studies showed that the robot-mediated mental health interventions **can successfully improve people's psychological well-being, mood/affect and readiness to change behavior for better well-being.** The robot's prosocial and companion-like behaviors along with other useful skills further enhance the efficacy of the intervention. The robot's ability to engage with people outside of the health-related tasks enabled them to build rapport across various contexts over long-term interactions. The therapeutic alliance between the agent and people is associated with the efficacy of mental health interventions and could potentially improve their willingness to continue the treatment even after the removal of the robot.

Conclusion

In addition, our studies informed us that interactive technologies should be carefully designed to support people with special needs. Enabling multiple ways to interact with the device could increase accessibility of these technologies, e.g., using both speech and touch based inputs. Further considerations should be made to ensure social robot technologies can benefit those in dire need. For instance, one of the eligibility criteria for participation was having access to wireless internet at home. This alone could prevent many people with low socioeconomic status (SES) from participating in the study, even though they are more likely to experience more dire mental health conditions caused by the COVID-19 pandemic.

Our future work will include such endeavors to reach out to people with diverse socioeconomic status and racial/ethnic backgrounds, and collaborate with them in designing assistive interactive technologies.