Fostering Social Connection through Expressive Biosignals

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Abstract

We are living in a world where social technologies connect more people than ever before. However, barriers inherent to these platforms, such as minimal social cues and inauthentic interactions, can limit our ability to meaningfully connect. To address these issues, I introduce ***expressive biosignals*** as a novel intervention to foster social connection over technology. Expressive biosignals are sensed physiological data presented as a new type of social cue to help people gain a deeper understanding of each other's underlying psychological states. As sensing and sharing these data become increasingly possible in our everyday lives, we must address the following questions: how are biosignals shared and perceived, how do they influence communication, and how can they be designed most effectively to facilitate positive interactions?

In my thesis, I present a series of studies that address these questions through the design, development, and deployment of expressive biosignals systems. I investigate the social dynamics involved in sending and receiving heart rate and brain activity, including people's motivations for sharing these personal data with others, the effects of biosignal sharing on interpersonal judgments, and the everyday interaction patterns that they afford in dyadic communication. In the final stage of my thesis work, I illustrate the value of integrating biosignals into communication through a one-month field study that compared a biosignals sensing OFF and ON version of HedgeHugs, an Apple Watch and iPhone application that enabled romantic partners to share biosignals-based animations with each other. Taken together, these works show that expressive biosignals have the potential to facilitate various components of communication and consequently, foster mutual feelings of connection. Specifically, biosignals can support senders' emotional expressions and receivers' perceptions of and responses to those expressions. My thesis makes three main contributions: (1) an articulation of the design space for expressive biosignals, (2) theoretical models for their influences on communication and connection among interaction partners, and (3) novel interventions for improving social connection through clarifying and conveying our internal experiences.

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Chapter 1

Introduction

As social creatures, humans fundamentally need to feel connected with others. From socializing with friends and family to participating in professional collaborations, frequent and meaningful connection leads to happier, healthier, and kinder people [63, 149, 232, 255, 262]. However, we are living in an increasingly socially disconnected world, marked by epidemic levels of loneliness in adults recognized by the U.S. Department of Health [6], and polarization between people with different viewpoints and backgrounds as a top global risk declared by the World Economic Forum [94]. In 2020, with the global COVID-19 pandemic diminishing social contact due to social distancing and quarantining, the need for social connection is more prominent than ever before.

Today, we rely heavily on technology-mediated communication to connect us with others. In 2019, people sent over 41 million messages per minute on mobile messaging services like WhatsApp and Snapchat [62], and social media sites like Facebook and YouTube had over 3.5 billion active users [156]. In 2020 in the United States, social applications like Nextdoor and HouseParty experienced a major rise in usage, as people desired new ways to interact with each other when they could not physically meet during the pandemic [163]. However, while digital platforms can connect us with a broad set of people, they can also limit our ability to *meaningfully* connect with those people. In recent years, research has shown that popular forms of social technologies are actually associated with social isolation [222, 240, 263] and decreased empathy [55, 164]. With the widespread use of technology-mediated communication, it is crucial that we investigate new ways to design technologies that can help bring people closer together, rather than farther apart.

Despite vast improvements in communication technologies, mediated interactions have not achieved the same quality as face-to-face interactions. Social connection is noteably challenging, where prior work has shown the potential for text, audio, and video channels to negatively impact the development of understanding, trust, agreement, and impressions between people [40, 41, 42, 43, 52, 55, 87, 224]. To address these issues, many works have attempted to recreate the experience of face-to-face interactions over technology by eliciting feelings of "being there" with another person. Techniques include reintroducing nonverbal cues that are typically available face-to-face [219, 279] and displaying full body projections of communication partners [227, 236]. While these systems show promise in improving mediated communication, they are difficult to access in everyday situations because they require specialized equipment and extensive instrumentation.

New technology and tools present unique opportunities to enhance social connection by going "beyond being there" [82, 127, 140, 217, 299]. Rather than imitating face-to-face interactions, we can take advantage of the affordances of these technologies and enable new ways to communicate. For example, instead of reintroducing existing cues, we can augment interactions by exploring new types of cues only available through technology. Researchers have investigated this possibility through the use of different symbols, imagery, and viewpoints that can be used to express oneself, address others, and gain new perspectives online [37, 117, 130, 207]. In my work, I propose a novel cue that leverages wearable devices to facilitate social connection by revealing signals that are imperceptible to the human eye: *expressive biosignals*.

Expressive biosignals are physiological data such as heart rate and brain activity displayed as powerful new social cues. The growing ubiquity of unobtrusive consumer-grade wearable physiological sensors opens up the possibility to explore sharing these data in social contexts. We can already see a glimpse of this potential in social fitness competitions popularized on Fitbit and haptic heartbeat sharing introduced by Apple's Digital Touch app. Biosignals naturally change with our cognitive and emotional states as a result of the autonomic nervous system, the system in charge of our fight-or-flight responses [170, 183], and have been used extensively in the field of Affective Computing to predict and moderate moods such as stress and frustration [69, 121, 131, 199, 253]. Revealing these invisible changes in interpersonal settings could help convey our underlying thoughts and feelings in a deeper, more authentic way, and ultimately enable us to better understand and connect with each other.

My thesis explores expressive biosignals through the design, development, and deployment of novel communication systems that integrate wearable sensors. My research illuminates both the promise and challenges in using expressive biosignals in social contexts, addressing fundamental questions around people's desires to share or not share them with others (Chapter 3), their social meaning and influence on perceptions of others (Chapter 4), and new patterns of interaction they can afford (Chapter 5). In the final stages of my dissertation work, I highlight the role that expressive biosignals can play in communication, including their effects on specific components of communication, social connection, and social support (Chapter 6). I conclude by synthesizing these works and proposing both a theoretical model and design space for expressive biosignals, as well as future directions for expanding on this research (Chapter 7). Taken together, my thesis contributes novel intervention systems for social connection and an understanding for how sensed data about our states can affect communication.

Chapter 2

Background

2.1 Social Connection in Mediated Contexts

Social connection, or social connectedness, can be defined as "a person's subjective sense of having close and positively experienced relationships with others in the social world" [262]. Social connection is critical to both our individual well-being and health [63, 151], and our ability to understand, work with, and help others, including those who are different from us [262]. Given the importance of social connection in individual lives and society as a whole, academics, leaders, and major world organizations are now recognizing recent declines in social connection as a global crisis [24, 94, 129, 206].

Some researchers believe the current lack of connectedness may stem from the widespread use of technology [287]. In particular, social technologies, despite their ability to functionally connect people, have the potential to further distance them. For instance, sharing different views on social media can reduce empathy and deepen existing divisions in viewpoints [22]. Platforms for synchronous conversation, such as text chatrooms and video conferencing, can inhibit the development of trust and cooperation between distributed collaborators [41]. Recent years have seen the development of a variety of interventions to address these issues and foster social connection over technology. Below, I highlight four categories of interventions that focus on different social phenomena that contribute to connectedness: social cues, social presence, empathy, and social support.

2.1.1 Technological Interventions

Social Cues

Technology-mediated communication limits access to important nonverbal cues, such as our body posture and facial expressions, that are typically available face-to-face. These cues can convey important information about our affect, attention, needs, and attitudes [158, 282], which are essential to outcomes related to social connection, such as rapport, liking, and intimacy [13, 47, 107, 114, 286].

Prior work has produced a number of interventions to reintroduce these cues into mediated contexts. These interventions include systems that convey gaze awareness and eye contact, such as gaze correction over video [173], visual indicators like spotlights to represent where people are looking [296, 323], and multiple displays to simulate spatial perspective [219]. For body gestures and movements, researchers have built visualizations to enhance awareness of gestures over video [187], as well as avatars and remote controllable robots that embody a user's movements [174, 218, 294]. Other systems attempt to preserve original nonverbal cues, rather than using visual and physical proxies, through high quality presentations of remote people, including life-size portraits over video [137, 182] and full-body projections and holograms in mixed reality [227, 233, 236]. These interventions can positively impact social outcomes such as trust, cooperation, and quality and efficiency of collaboration. However, they are not yet widely accessible in everyday life, as they tend to require specialized hardware or are primarily applicable in certain social contexts, like collaboration.

My thesis work proposes expressive biosignals as a new type of social cue to augment communication and promote social connection. Expressive biosignals could go beyond existing nonverbal cues by revealing our underlying mental states and providing deeper insight into our thoughts and feelings. Moreover, by leveraging unobtrusive sensing technologies, we can capture and communicate these data in a variety of everyday social contexts. I highlight this potential in Chapters 3 and 4.1, which describe studies that investigate how people share and understand biosignals as a social cue.

Social Presence

Social presence has various definitions, but for the purpose of this thesis, I adopt Biocca and colleagues' succinct definition: "the sense of being with another" [38]. Factors such as a lack of *immediacy* and *intimacy* can reduce social presence when people communicate through mediated channels [114, 115]. Promoting social presence should promote feelings of connectedness [138].

Technological interventions that increase social presence have explored reintroducing social cues, as described in the previous section, as well as using new cues to enhance awareness and synchrony with one another. For the latter, researchers have designed ambient displays that integrate lights, sounds, and activity streams into household items to signal when people are thinking of each other and provide context on what they are up to (e.g., what they are watching on TV) [56, 74, 81, 195, 210]. Some systems focus solely on providing contextual information, including location, social interations, phone battery life, photos, music, and live video streams [23, 32, 70, 112, 116, 160]. Prior works have also enhanced social presence by enabling shared experiences over technology, including shared activities like watching movies [45] and dining together [304], and the feeling of physical touch in the form of pens [252], slippers [57], cubes [168], and textiles [84] that use haptics and heat.

Building on prior social presence interventions, expressive biosignals could enable feelings of intimacy and immediacy by providing new contextual information about our psychological states. Additionally, displaying these data on the wearable devices that sense them could not only help people stay connected throughout their daily lives, but enable them to feel physically in touch with each other. I demonstrate these affordances in Chapters 5 and 6 through the design and deployment of Animo and HedgeHugs, two smartwatch applications for communicating animated heart rate messages.

Empathy

While interventions for empathy have been widely explored in social psychology literature (e.g., compassion meditation, skills workshops, role-playing) [321], research on technological interventions in this space is still limited. A few works have studied the potential for features of existing communication platforms to affect aspects of empathy. For instance, researchers have found that framing in video conferencing and webcam elevation can affect self-reported cohesion with a remote partner [220] and decisions made in one's own self-interest [284], respectively. Emotional and intimate self-disclosure on social media can also foster closeness between users and influence empathetic responses [20, 48, 188]. However, these prior works have focused on different constructs related to empathy, rather than directly evaluating empathy.

Researchers have also developed empathy interventions that allow users to experience the world from the perspective of a distant other. Empathy glasses, for example, is a tool that allows you to view the world from the perspective of another person in real time [181]. In the same vein, virtual reality (VR), often described as the "ultimate empathy machine" [211], has immersive qualities that enable users to experience life from another person's perspective [36]. VR experiences have also shown potential to increase empathy for stigmatized groups, including refugees [167] and homeless people [125]. However, while VR is a promising platform on which to design empathy interventions, it has some limitations. For instance, building games and stories require experts to design experiences around very specific narratives. Moreover, the experiences may be difficult to integrate into everyday expression and consumption of stories, which occurs on platforms like social media on a daily basis.

Expressive biosignals could promote empathy in communication by providing a means for people to understand each other's subjective experiences. For instance, biosignals could vividly illustrate personal stories by expressing how a narrator felt at different moments. In Chapter 4.2, I describe a study that investigates this potential and addresses limitations in prior empathy interventions. Specifically, I focus on the ability for expressive biosignals to foster empathy, operationalized as emotional perspective-taking [85, 277], for a stigmatized group member through heart rate graphs displayed in a prototype of a storytelling platform.

Social Support

Like empathy, offline social support interventions have a long history of research and implementation in the real-world, taking a variety of forms such as organized peer support groups and individual professional support [126]. However, quality social support can be difficult to access offline due to barriers such as stigma around seeking help and burdening others [113, 118, 259], as well as the inability find experienced supporters [175].

More and more people are now seeking social support on online platforms [289]. Walther and Boyd suggest that these platforms have unique features that could reduce barriers to social support, such as ease of access and anonymity [301]. A breadth of research has investigated social support in blogs and social media [242]; however, these platforms have shown mixed results for improving health outcomes [110, 241, 289]. Following recent trends in mobile health applicatons, researchers have begun building mobile social support applications to provide more accessible, just-in-time social support. This line of work is still growing [205], and primarily uses chat applications and text messaging to enable supportive conversations between peers, including for people with diabetes [246], smokers who are in the process of quitting [108], and people making decisions around weight loss [8]. While these interventions facilitate the availability of social support by connecting peers through mobile chats, they primarily rely on people to initiate calls for help themselves. This is a major limitation, as people often experience difficulties in recognizing and expressing their need for help, due to factors such as viewing their situation as "normal" and stigma around help-seeking [113].

Expressive biosignals could reduce barriers to social support helping people recognize stressful situations and encouraging them to seek support from others. They could also facilitate the desire to support others through vivid validation of someone's need for help. In Chapter 6, I explore this potential by investigating how people understand and react to their own and others' expressive biosignals, in the context of romantic relationships.

2.2 Physiological Sensing

Wearable sensor devices have evolved to record a variety of biosignals unobtrusively in everyday life. In this section, I highlight biosignals frequently used by researchers, practictioners, and consumers: heart rate, skin conductance, and brain activity.

Heart rate

Heart rate can change for a number of reasons, such as due to emotions, physical activity, eating, intaking caffeine or other drugs, or smoking [1]. It is perhaps the most common consumer-tracked biosignal, given its popularity in smartwatches (e.g., Apple Watch) and fitness trackers (e.g., Fitbit), as well as smartphone apps that simply record it through the phone camera (e.g., Cardiio). These devices typically rely on photoplethysmography (PPG) sensors, which use light to detect changes in blood flow. Due to limitations such as optical noise and sensor location, PPG is primarily used to measure *average* heart rate. Devices with electrocardiography (ECG) sensors can produce more granular and accurate measures of heart rate, such as heart rate variability, or the variation in consecutive heartbeat intervals [7, 306]. Researchers have used both heart rate and heart rate variability for mental and physical stress detection [250, 275, 276] and emotion classification [44, 145, 291].

Skin conductance

Skin conductance, or electrodermal activity (EDA), refers to changes in the electrical conductance of the skin based on the state of sweat glands. Researchers have used skin conductance to detect physiological arousal related to emotions [59, 145], engagement [124], stress [18], empathy [202], and synchrony with other people [58, 183, 267]. Consumer-grade wearables that sense skin conductance are less available than those that sense heart rate, but include the empatica E4 wristband and the Shimmer3.

Brain activity

This biosignal is typically measured using electroecephalography (EEG) to record electrical brain activity. EEG signals fall under different frequency bands that map to different mental states (e.g., higher beta wave activity being associated with activte thinking [176]). Recent consumer-grade headsets such as the Muse, NeuroSky, and EMOTIV EPOC+ and Insight have introduced new applications for meditation and gameplay based on EEG. Like with heart rate and skin conductance, researchers have used EEG data to classify emotions [143, 184, 235], as well as engagement, cognitive load, and performance in driving [11, 186] and learning tasks [35, 214].

2.3 Biosignals in Communication

To date, biosignals have largely been used in the context of biofeedback, or the presentation of biosignals for individual monitoring, tracking, and ultimately, control [18, 260, 283, 309]. For instance, popular commercial wearable heart rate monitors, such as the Fitbit or Mio watches, and several research systems have used heart rate to support fitness and physical health [109, 230, 247, 274]. Affective Computing research has expanded biosignals to social applications (in addition to health), detecting emotional and psychological states for social skills training and virtual tutors [16, 86, 88, 165, 239]. However, these applications target individual understanding and monitoring of physiological data.

Only recently have researchers started extending biosignals to interpersonal contexts in which biosignals are shared with others as part of social interactions. These prior works include exploratory systems that are deployed to test the potential for integrating these technologies in different social contexts, and a few experiments that measure the impact of sharing biosignals in these contexts.

2.3.1 Exploratory Work

Most prior expressive biosignals work are exploratory in nature, and involve the design and deployment of a system with real-world users. Qualitative results from interviews and observations during deployment have shown the potential for expressive biosignals to facilitate positive social outcomes by revealing users' physiological states. For example, researchers have explored the design of biosignal systems to support self-awareness and communication between interaction partners [119, 270, 312], as well as to encourage intimacy and social connection [135, 215, 307]. In playful and entertainment settings, displaying the physiological states of players and performers has been shown to enrich interactions in both cooperative [298] and competitive [97] ways, as well as to increase and provide feedback about engagement among spectators [72, 120, 258]. Researchers displayed biosignals in diverse ways for the purposes of these studies, incorporating them into lamps, fashion items, benches, mobile applications, and more.

Findings from these prior works also have implications about the social meaning and functions of biosignals. For instance, Solvák and colleagues, who deployed a technology probe (a laptop that provided visual and aural feedback of heart rate) in the homes of five couples, proposed that heart rate sharing functions both as a means to provide information about emotional states, and a means to feel connected with other people [266]. At the same time, Howell and colleagues suggest that the information-focused function has limitations, where the meaning of certain biosignals can be ambiguous. Specifically, they observed that viewing data from a wearable display of skin conductance caused users to make diverse interpretations for the wearer's emotional state. The authors suggest that this interpretive uncertainty could both support and inhibit biosignals as a social cue, by encouraging open reflection but disrupting impression management [132]. In follow-up work, they further question the tendency for biosensing systems to prescribe discrete categories of emotions to people, highlighting the importance of subjective reflection on personal data [133, 134].

2.3.2 Experimental Work

A few researchers have sought to clarify the effects of integrating biosignals into social contexts using experimental methods. Their works involve laboratory setups or surveys to measure how the display of biosignals affects interpersonal perceptions and behaviors. For instance, Janssen and colleagues demonstrate that the sound of a heartbeat can increase feelings of intimacy and closeness, measured using distance that people placed between themselves and another person in a virtual reality setting [142]. Tan and colleagues developed a system that displays changes in heart rate, skin conductance, and respiration, which helped reduce stress and perceptions of workload in worker/instructor-based collaboration around building a K'Nex device [278]. Merrill and Cheshire conducted two separate experiments to investigate the effects of heart rate information on trust, including through a graph shown during a trust game, and text appended to a text message. They demonstrated that an individual's elevated heart rate is typically associated with negative mood, such as being upset or anxious, which can affect how people trust others, depending on the situation and relationship with that person [208, 209]. Finally, Curran and colleagues explored the influence of biosignals shown during a VR narrative on empathic accuracy (ratings of a target's feelings) and "state empathy" (feeling of being in a target's shoes). Participants watched the VR narrative from a target person's field of view with or without a graph of the target's skin conductance. Surprisingly, they found that biosignal information decreased empathic accuracy and did not affect state empathy [73]. Altogether, these works demonstrate that biosignals can indeed impact how people perceive each other, in terms of their understanding of each other's mental states.

2.3.3 Communication Framework

While research in the domain of expressive biosignals has produced important implications around the meaning of biosignals and their potential for affecting social perceptions, they tend to be highly open-ended or tied to specific contexts. There is a lack of formal understanding on the design and integration of biosignals in the broader process of communication, and how they might subsequently impact social connection. In my thesis work, I explore possibilities for the design of expressive biosignals, including the types of biosignals that can be shared, who they are shared with, how they are represented, and on what platforms they are communicated. I use a communication framework as a guide to understand how they are used in communication, the challenges they experience, and how they relate to social connection with others. I draw from the interactional model of communication [308], which treats communication as a two-way process in which a sender sends a message to a receiver, who can send feedback back to the sender. I investigate how different designs for expressive biosignals systems can affect components of this model, including sending expressive biosignals, and receiving and responding to expressive biosignals.

Sending Biosignals

First, what motivates someone to share (or not share) their biosignals? Most research on biosignals sharing have focused on very specific use cases and events (e.g., gaming, collaboration), are tested over short periods, or provide participants with limited control over sharing. However, there is evidence that people are not always comfortable with sharing biosignals, where it may feel "too personal," awkward, or not understandable [119, 266]. Moreover, the inherent ambiguity of biosignals [132] could affect the way they are shared. As shown in Merrill and Cheshire's experimental work on trust, the relationship between individuals and the context in which biosignals are accessible may play a key role in determining how they are interpreted and understood by others [208, 209], and subsequently how they can be meaningfully expressed through sharing. Given the ambiguity and sensitivity of these personal data, it is critical to understand the implications of revealing them to others. To this end, I investigated the following research question:

- **RQ1.** When are people willing or not willing to share their biosignals with others?
- **RQ2.** How can they meaningfully express their biosignals to others?

To answer these questions, I deployed an Android application that connects to a heart rate sensing wristband and prompts users to text their heart rate to their contacts. This application explores the design of an expressive biosignals system integrated into our existing means of communication, using a fitness device to enable heart rate sharing on mobile messaging applications. Through this application, I investigated the contexts in which people share their heart rate, how they make decisions around sharing (e.g., whether, when, with whom, and how to share), and how they manage or resolve the ambiguity of heart rate with the people they share with. I describe the details and results for this study in Chapter 3.

Receiving Biosignals

When someone receives a message with someone else's biosignals, how do they understand them and how does that affect their perception of the sender? Leahu and Sengers emphasize that in exploring the use of biosignals for human interpretations, we must understand the potential subjectivity of those interpretations [179]. Indeed, prior work shows that biosignals are fairly ambiguous [132] and can lead to different perceptions about other people, depending on the context [208]. At the same time, exploratory studies suggest that biosignals can enhance understanding of another person's emotional state and build social connection with them [215, 307], such as by fostering empathy and social awareness [119, 132]. This suggests the need to further understand the factors that affect people's interpretations of expressive biosignals, and how they might affect social connection. To address this gap, I investigated the following questions on how different forms of biosignals information affect interpersonal perceptions:

- **RQ3.** How do different biosignals representations affect impression formation?
- **RQ4.** How does the presence of biosignals information affect empathy?
- **RQ5.** How does the visualization of biosignals information affect empathy?

Chapter 4 describes two projects that research these questions. The first is a study I ran to examine the design of biosignals representations, as different representations could affect people's understanding of both the data and the person who shared the data (RQ3). To explore a new area for expressive biosignals design, I focused on a different type of data: brain activity, shared amongst strangers. In this study, participants rated their impressions of a target person from six visualizations of their brain activity data. The second study aimed to understand how expressive biosignals affect empathy and closeness (RQ4 and RQ5). I used a vignette experiment setup to imagine biosignals integrated into online storytelling platforms, focusing on sharing with someone with whom people may have more difficulting connecting – a member of a stigmatized group.

Dyadic Sending and Receiving

The first two stages of my thesis investigate expressive biosignals in one-way communication, focusing solely on the sender or on the receiver. In this third stage, I moved to *dyadic* communication of expressive biosignals. As results from Chapters 3 and 4 suggested a number of challenges in sharing and displaying biosignals (e.g., cognitive load, privacy concerns), I investigated ways to seamlessly integrate biosignals into communication. Specifically, I explored the affordances of dyadic sharing on a smartwatch. Smartwatches have built-in biosignals sensors, and thus could enable sharing directly on the device. However, their limited screenspace gives rise to issues in their ability to present the information necessary to meaningfully communicate ambiguous biosignals. To understand these potential opportunities and challenges, I explored the following:

- **RQ6.** How will people use expressive biosignals in dyadic communication on a smartwatch?

In collaboration with Snap Inc., I built Animo, a smartwatch application that enables the sharing of heart rate-based animations with a partner. In designing Animo, I explored the integration of biosignals into everyday communication, using short playful animations for engaging and emotional representations, and the smartwatch as both a sensor and an unobtrusive new communication platform. We deployed Animo for two weeks and analyzed how pairs of participants understood and used the application with each other. I describe this study in detail in Chapter 5.

Communication with and without Biosignals

In the final stages of my thesis work, I explored the value of integrating biosignals into communication by testing communication with and without biosignals. I distinguished how the unique characteristics of biosignals may support diffent aspects of communication and influence social connection, compared to when biosignals are not present. Additionally, I investigated different forms of feedback that receivers use to respond to their partner's biosignals. In particular, since results from Chapter 5 showed that people desire to respond to biosignals in supportive ways, I explored their potential to impact social support.

- **RQ7**: How does the integration of expressive biosignals in dyadic communication affect the stages of communication?
- **RQ8**: How does the integration of expressive biosignals in dyadic communication affect feelings of connection?
- **RQ9**: How does the integration of expressive biosignals in dyadic communication affect social support?

I collaborated again with Snap Inc., building directly on our Animo research to create HedgeHugs, an app for the Apple Watch and iPhone. We iterated on the design of HedgeHugs to explore hybrid automated/manually-selected biosignals-based states represented by playful avatar animations, as well as app-specific reactions to biosignals. I deployed two versions of HedgeHugs, with biosignals sensing OFF or ON, in a one-month field study to answer the above research questions. Details for this work can be found in Chapter 6.

Table 2.1: Research Questions

Chapter	Research Questions
3	**RQ1.** When are people willing or not willing to share their biosignals with others?
	RQ2. How can they meaningfully express their biosignals to others?
4.1	**RQ3.** How do different biosignals representations affect impression formation?
4.2	**RQ4.** How does the presence of biosignals information affect empathy?
	RQ5. How does the visualization of biosignals information affect empathy?
5	**RQ6.** How will people use expressive biosignals in dyadic communication on a smartwatch?
6	**RQ7.** How does the integration of expressive biosignals in dyadic communication affect the stages of communication?
	RQ8. How does the integration of expressive biosignals in dyadic communication affect feelings of connection?
	RQ9. How does the integration of expressive biosignals in dyadic communication affect social support?

Chapter 3

Sharing Biosignals with Others

This chapter has been adapted from [190]. In the first stage of my thesis work, I focused on the *sender's* side of expressive biosignals, exploring what it means to share one's own biosignals with other people. Though both research systems and commercial products like the Fitbit and Apple Watch have incorporated the ability to share our biosignals with others, it is unclear why and how people will share these personal and private data. I investigated people's motivations to share, including which situations are appropriate and what factors influence sharing in those situations, as well as the behaviors people engage in to express their biosignals to others. I addressed the following research questions:

- **RQ1.** When are people willing or not willing to share their biosignals with others?
- **RQ2.** How can they meaningfully express their biosignals to others?

3.1 Summary

We developed an Android application that linked to a wearable heart rate sensor and allowed for the direct sharing and real-time broadcasting of users' heart rate via text messaging. We deployed this application in a two-week field study to investigate the contextual triggers, perceptions, and consequences of users' sharing behaviors. The study (N=13) utilized a combination of Experience Sampling Methodology (ESM) and qualitative interviews to discover the situations in which users were more or less likely to share their heart rate with contacts, and the subsequent interactions that occurred after sharing. The results revealed that participants used heart rate sharing as a means to express emotions and provide daily updates, as well as simply a novel and playful form of communication. They reported a variety of communicative consequences of their sharing as well as specific logistical and psychological barriers to sharing. The implications of these results for the design of expressive biosignal sharing systems for supporting positive social interactions are discussed.

3.2 Introduction

While major inroads have been taken to investigate the implications of physiological sensors for intrapersonal outcomes, such as health management, we are only beginning to see a glimpse of the potential for the *sharing* of physiological data in interpersonal, social contexts. For instance, step tracking devices such as the FitBit have enabled users to engage in social fitness competitions, while heart rate-sensing smartwatches like the Apple Watch have introduced haptic heartbeat sharing. As new modes and means for sharing and understanding our data emerge, it becomes increasingly critical to understand the implications of revealing our biosignals to others. What are the social and psychological consequences of the ability to share our physiological data? How can we inform system design and policy that account for people's preferences and help them become informed participants in the use of physiological sensing systems?

In this work, we take a broad, exploratory approach to better understand how individuals would utilize and respond to a system that allows for the real-time sharing of their physiological responses. Using a combination of Experience Sampling Methodology (ESM) and semi-structured interviews, we investigate users' sharing patterns, including the contexts most likely to trigger or inhibit sharing, motivations underlying sharing decisions, and the communicative and interpersonal consequences of those decisions. We contribute a study that reveals how people share their heart rate through their natural communication channels, finding that heart rate can be used for interpersonal expression of emotion, daily activities, and playfulness, depending on contexts and relationships between users. We present a set of design implications based on our findings that suggest new directions for the development and integration of expressive biosignal systems into social interactions.

3.3 Background

Sharing and Ubiquitous Computing

Though research around biosignals in ubiquitous computing tends to focus on individual monitoring, several works in this field have explored the sensing and sharing of other types of user data. For instance, a number of researchers have investigated preferences and practices around location sharing [203, 268, 280], including sharing behaviors based on hypothetical ESM requests from contacts to share location [67], and willingness to share with different types of contacts [311]. Other ubiquitous systems have been built to record and share streams of user activity. Ubiquitous healthcare, for instance, is a growing field with multiple areas of application, including activity tracking of elderly people to inform physicians and family of their daily life activities and physiological states [90, 100]. Systems that track and share personal data, particularly physical activity, through social awareness streams like Twitter are also commonly used to connect with friends and family [89, 245]. Some systems have also monitored and publicly displayed user activity levels for the support of collaborative tasks and work environments [162, 297]. However, many of these systems focus on individual sharing behaviors and preferences, and have generally not explored the interpersonal consequences and interactions that might result from sharing. Our work expands on past work on sharing user data ubiquitously by investigating the sharing of physiological data—specifically heart rate sharing on mobile phones in everyday contexts.

3.4 Methodology

To explore our research questions and understand heart rate sharing *in situ*, we built an Android application that prompts participants to share their heart rate. We conducted a study that used the Experience Sampling Method (ESM) [66, 177] to determine when, with whom, and why participants were more or less inclined to share their data using this system, as well as follow-up interviews to probe more deeply to understand users' experience, sharing decisions, and the social and communicative impact of those decisions.

Overview

The study took place over two weeks at a northeastern city in the United States. During those two weeks, participants wore a commercial heart rate sensing wristband daily during a self-defined 12-hour waking period and used our Android application. The application connected with the wristband via Bluetooth LE and prompted users to decide whether or not to share their heart rate (via the messaging application of their choice) up to ten times per day. After participants made their decisions about sharing their heart rate, they were prompted to answer brief ESM questionnaires to clarify the contexts and reasons behind those sharing decisions. The application saved participants' heart

Table 3.1: Participant Table (1st wave above the divider, 2nd wave below)

ID	Gender	Age	Ethnicity	Occupational Status	# Share Prompts	# Shared	# Did Not Share	# ESMs	# ESMs Answered	% ESMs Answered
71	F	20	White/Caucasian	Undergraduate Student	60	9	51	103	82	80%
67	M	25	Asian	Graduate Student	45	33	12	129	69	53%
22	F	26	White/Caucasian	Part-time Employment	48	2	46	59	51	86%
39	F	21	African-American	Undergraduate Student	15	4	11	42	11	26%
28	M	24	Asian	Graduate Student	19	19	0	72	66	92%
57	M	44	African-American	Full-time Employment	91	36	55	234	176	75%
74	M	38	White/Caucasian	Full-time Employment	32	17	15	88	24	27%
94	M	33	African-American	Part-time Employment	45	23	22	125	96	77%
36	F	23	Asian	Graduate Student	64	18	46	154	92	60%
87	F	39	African-American	Part-time Employment	63	40	23	171	119	70%
21	F	54	White/Caucasian	Full-time Employment	51	10	41	130	73	56%
60	M	24	Asian	Graduate Student	55	12	43	137	91	66%
44	F	23	Asian	Graduate Student	37	13	24	100	84	84%

rate data, sharing decisions, and ESM responses on the participants' phones, and these data were uploaded periodically to a secure server. Participants were also required to come into the laboratory three times during the study (30-60 minutes each time) for instructions, equipment, and interviews.

Participants

Sixteen participants took part in this study; however, we removed data from three participants from all analyses. These participants either did not understand the instructions (e.g., one participant who instructed his contacts to ignore all of his share messages), had issues using the application on their phone and needed to drop out of the study, or had deleted their data from their phone before the exit interview. The remaining 13 participants included seven female and six male participants. Participant ages ranged from 20 to 54 years old (M=30.3, SD=10.5). Four participants identified as White/Caucasian, five as Asian, and four as African-American. Participants also had diverse occupations: seven were full-time students (two undergraduate, five graduate), three worked full-time, and three worked part-time. Two participants noted that they owned a heart rate sensor, including the Moto 360 and a Garmin sensor, but both stated that they rarely used it. Participants were recruited from a university participation pool, and were compensated with $50 upon completion of the study.

Procedure

Introduction Phase At the start of the study, participants came to our laboratory to be introduced and instructed on participation in the study. During this introduction, participants first completed a questionnaire to specify their demographics (gender, age, and ethnicity) and describe their prior use of heart rate sensors. The questionnaire also asked participants to list their most commonly used messaging applications (e.g., default phone messaging system, Facebook Messenger, etc.) and to identify the six people they most frequently contacted through those applications within the previous week. The former was used to track which applications they would likely use during the study and ensure that they would be made available through our study application. The latter was used to track whom the participants would most likely select as recipients for heart rate sharing messages. Given the novelty of heart rate sharing and the intimate nature of the heart [142], we expected that participants would primarily share their heart rate with their most frequent and closest contacts (most of the contacts listed were significant others and close friends and family). To track this information, whenever participants shared their heart rate, the application would ask them with whom among these six they

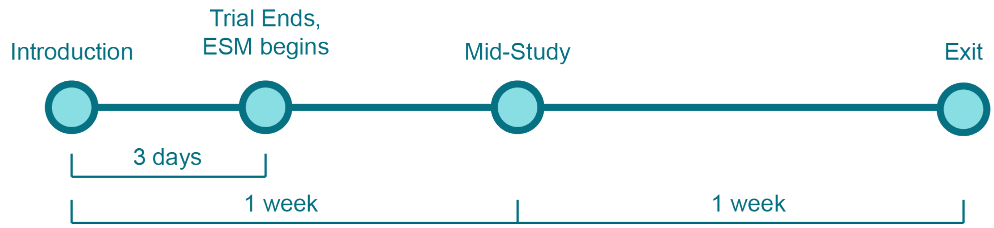


Figure 3.1: Timeline of the study phases.

shared, or if they shared with someone else (in which case, they were asked to provide that person's initials).

While participants answered the questionnaire, an experimenter installed the study application on their phones to ensure compatibility for the study (we required phones with Android versions 5.0+). Participants were then briefed about the purpose of the study and given instructions on using the application and watch. We gave detailed instructions for sharing heart rate through the application, which included two methods: direct sharing (messaging their heart rate value in beats per minute to others), or broadcasting (messaging a URL for their heart rate live-stream to others), which we describe in detail in the following section. We also explained (verbally and in the consent form) which data would be sensed and collected during the study (e.g., heart rate data, activity, messages they sent related to the study), and the requisite permissions participants had to grant on their phones.

After the experimenter explained the study to the participants, they stepped through the application setup. As part of the setup, participants entered their demographic information (age, gender, height, and weight, which were used to warn participants about potentially dangerous abnormal heart rates), calendar events in which they would be interested in broadcasting their heart rate, the six contacts they most frequently communicate with, and the daily 12-hour waking period during which they agreed to wear the watch and use the application. Then, participants were asked to wear the watch for two minutes while sitting and for two minutes while walking in order to determine an average heart rate baseline for each activity. These baselines were used by the application as part of the logic for prompting participants to share their heart rate (described in the following section). Participants were then free to leave and use the wristband and study application for the next two weeks.

Trial Phase The first three days that participants used the study application were treated as a "trial phase." This was included to help participants get acquainted with the application and acclimated to what heart rate sharing would look like during the two weeks, as heart rate sharing is not a common type of interaction that participants were expected to readily understand. During these three days, the application was in "Trial Mode," and it simulated heart rate sharing by displaying share notifications, but not giving participants the option to share. Instead, the notification would state that their heart rate was shared with or broadcast to a random person from the six contacts they listed during the Introduction Phase, but would not actually share any information with anyone else. The study was scheduled such that this phase would include weekdays and weekends (Thursday to Saturday or Saturday to Monday) in order to account for heart rate changes for different types of schedules.

ESM Phase After the trial phase ended, the study application would end the "Trial Mode" and display normal prompts to share heart rate. That is, participants would have the option to say "Yes" or "No" to share their heart rate or broadcast link when the notifications arrived. If participants selected "Yes" to share, they could choose a messaging application through which to share, identify whom they wanted to share with, and decide how they wanted to construct their message. After making decisions to share or broadcast their heart rate, they would be prompted to answer brief ESM questionnaires on their phone, asking them what they were doing at the time they were notified, with whom they shared their heart rate or broadcast link (if they answered "Yes" to sharing), and why they decided to share or not share their heart rate. Participants were reminded at the end of the Introduction Phase that sharing was optional, and that they were not required to always answer "Yes" to sharing. This phase lasted for the rest of the study.

Mid-study Phase After one week of applicaton usage, participants returned to the laboratory for an interview in which they were asked to report their initial thoughts about their sharing experiences. We also used this interview to identify and correct any technical problems that arose in the application, and to ensure that participants had fully understood the instructions we had given them during the Introduction Phase.

During the interview, we asked participants whether they were surprised by the heart rate values that appeared in the notifications, whether there were times they thought they should have been notified (e.g., when they perceived that noteworthy changes in heart rate had occurred), and what they thought about their own heart rate. To gauge participants' heart rate sharing activity during the first week of the study, we asked if they shared their heart rate, and, if so, when, with whom, and why, as well as how they felt about sharing, how they made the decision to share, and what reactions they received. We also asked participants when and why they did not share their heart rate. We asked the same set of questions regarding heart rate broadcasts and, in addition, inquired whether participants viewed their own broadcasts. Finally, we asked if there were times they wanted to share or broadcast their heart rate but were not able to, or if they shared their heart rate at all outside of the notifications.

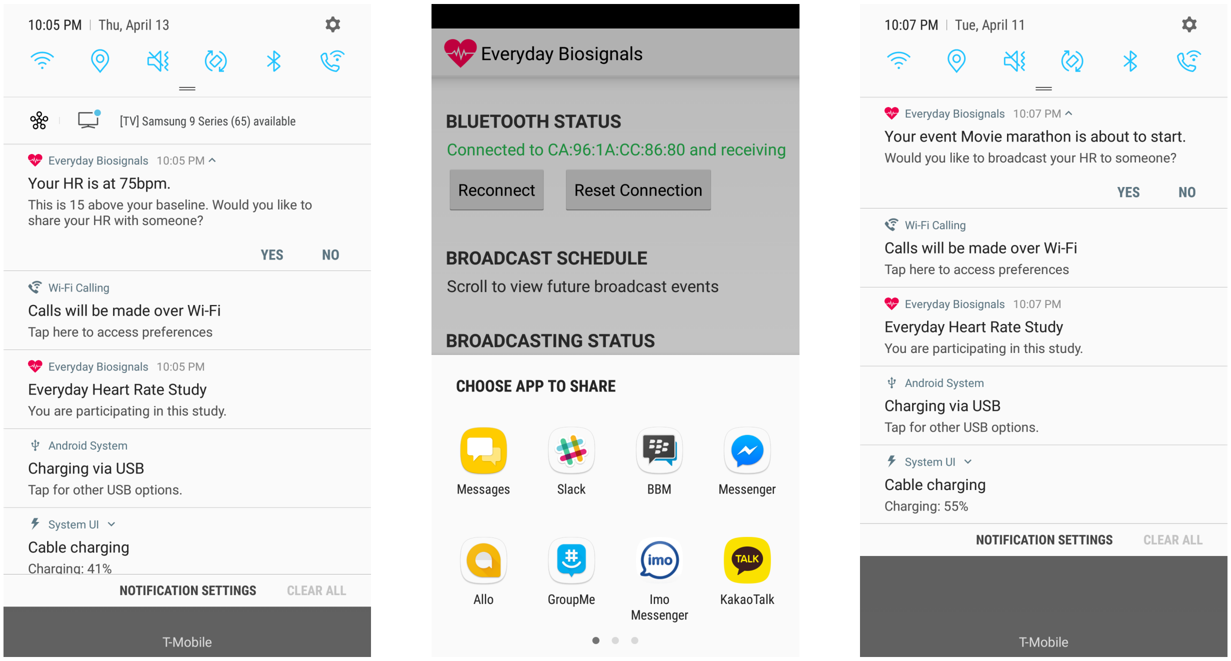
Exit Phase At the end of the study, participants returned to the laboratory to complete an exit interview and to return their equipment. Data from their phones, including recorded heart rates, shared heart rates, ESM responses, and screenshots of heart rate messages they shared were also downloaded at this time. The interview contained similar questions as the mid-study interview, with additional questions to gauge whether communication quantity or quality changed between participants and their contacts. We also asked participants for their feedback about the heart rate sharing application—specifically, their perceptions of its limitations, what information might have been lacking, and what they would have changed generally or about sharing.

Heart Rate Sharing System

For the purposes of the study, we developed an Android application that prompted participants to share their heart rate with their contacts using text messaging applications.

Heart rate monitor Our Android application connects with the Mio Alpha 2 watch [4], a consumer-grade fitness watch with a built-in optical heart rate sensor, via Bluetooth LE. We chose the Mio Alpha 2 for a number of reasons: **accuracy**, which we based on consumer reviews that compared different wristbands to chestbands, as well as prior research that used Mio technology [295]; **Bluetooth capability**: we required real-time heart rate streaming to our application in order to inform heart rate sharing; **battery life**: with the heart rate monitor continuously on, it was important to ensure that participants in the present study would only have to charge their watch at most once a day; and **user interface**: the participants would be using the watch during most of their waking hours for two weeks, thus, we aimed to reduce their discomfort wearing the technology and minimize any difficulties using it (in contrast, chestbands are known to be more accurate but would be less comfortable).

We note that the Apple Watch is an existing product that measures heart rate and allows for heartbeat sharing between Apple users. Heartbeat is shared through the Digital Touch feature, where a user can hold their fingers to the watch face to send a heart visualization and haptic feedback matching the user's heartbeat. Had we used the watch for the study, participants could have shared through this heartbeat feature, and their contacts would have been able to respond with their own heartbeat. While two-way sharing would have informed the study by helping us understand when people reciprocate sharing behaviors, we ultimately decided not to use the Apple Watch in order to have a



(a) Notification prompting user to directly share their current heart rate to someone.

(b) Choosing to directly share opens options to share through existing messaging apps.

(c) Notification prompting user to broadcast their heart rate during a scheduled event.

Figure 3.2: Screenshots of application sharing notifications.

higher level of control over the sharing interface and how the participants would interact with the application. Additionally, we wanted to avoid using existing visualizations in order to explore how users would describe their own heart rate as part of sharing.

Direct sharing The application allows users to communicate their heart rate in two ways: direct sharing and broadcasting. With direct sharing, users could send a pre-scripted but partially editable text message reporting their current heart rate value in beats per minute (bpm) to their chosen contacts. In the present study, in order to maintain the integrity of the ESM methodology, participants could make direct shares only when they received a notification to do so from the application (Figure 3.2a). These notifications would state participants' current heart rate and indicate how it compared to their baseline heart rate (derived from measurements taken both during the Introduction and Trial Phases), and asked participants if they wanted to share that heart rate with someone else.

If participants chose to share, they would be prompted to choose a message type (text with or without media) and a messaging application (Figure 3.2b). We allowed sharing through any application participants had installed that allowed text and media sharing, such as the phone's default messaging system, Google Hangouts, and WhatsApp. We opted to allow sharing through a variety of messaging applications, rather than strictly through our own application, in order to allow for participants to share with their contacts in a naturalistic fashion using their typical communication channels. The selected application would open up with a default, pre-scripted text message describing the participant's heart rate. Participants were informed at the beginning of the study that they were permitted to edit this message as long as they left the heart rate value intact and unaltered.

The application sent notifications to participants' phones up to ten times per day, with each notification spread out at least 45 minutes apart within participants' pre-defined 12-hour waking period in order to limit intrusion on their everyday lives. Notifications were displayed either at random or based on major changes in participants' heart rates (up to five notifications daily each). We included both types of notification logic in order to ensure that participants would be notified during a variety of contexts (as per traditional ESM studies), as well as during moments of fluctuating heart rate. We expected participants might be especially likely to share during the latter because of their anticipated interest in considering current activities or experiences that might have caused those changes. We determined major heart rate changes from a random sample of heart rate values taken during the Trial Phase (during the Trial Phase, we based changes on a difference of at least 15 bpm from the Introduction Phase baselines). Major changes were considered to be any heart rate value less than the 16th percentile or greater than the 83rd percentile of the sample collected from the participant. These thresholds were chosen to ensure that participants would receive a sufficient but not onerous number of notifications during the day, which we tested using a subset of data recorded from a pilot study conducted prior to the start of the main study. In addition, we used Google's Activity Recognition API and Android's built-in step sensor to determine walking activity, during which we would instead use the walking baseline, recorded during the Introduction Phase, to determine the threshold. This helped ensure that the application would not notify participants only when they started walking, as heart rate will naturally increase during physical activity.

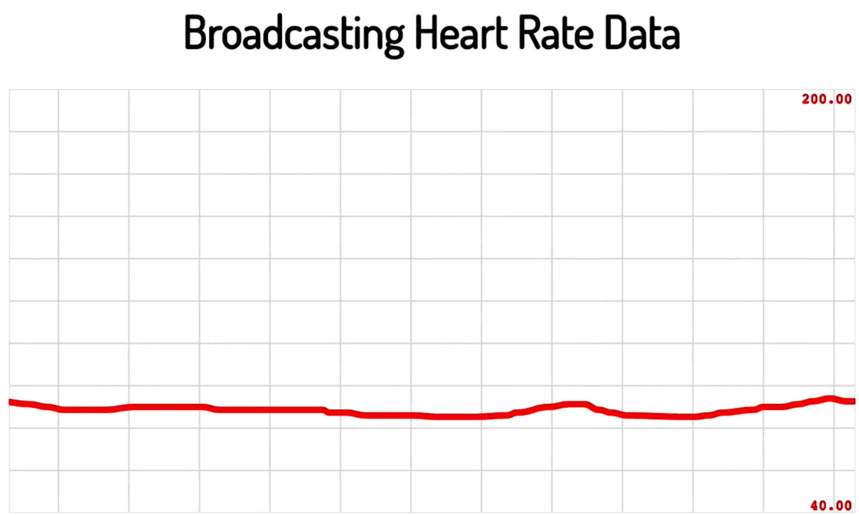


Figure 3.3: Broadcast Graph

Broadcasts The second type of heart rate sharing opportunity was broadcasting. Heart rate broadcasts were live-streams of participants' heart rate during designated events. Live-streams were displayed as a continuous line graph accessible to participants and selected contacts on a website that we had developed (Figure 3.3). The website was developed using JavaScript, HTML, and MySQL, and was hosted on an HTTPS server at our university. We decided to include broadcasts as an additional type of sharing that would offer a continuously updated, real-time display of heart rate during specific events. Past research has shown that audience members at different events, such as marathons or amusement park rides, can become more engaged with the event and its participants when they were allowed to view the participants' physiological activity [72, 258]. In this study, we aimed to clarify the range and types of events our participants would select for broadcasting their own physiological activity.

Broadcast events were created at the start of the study. During the Introduction Phase, participants each chose several events that they identified as being potentially meaningful to broadcast (e.g., watching Netflix, eating dinner with friends, dancing, etc.), and entered the details of these events (a descriptive label and the start/end time for the event) into the study application. During the study, before their specified events started, participants would receive a notification asking if they would like to broadcast their heart rate to someone else (Figure 3.2c). If they chose "Yes," they would be prompted to choose a messaging application for sending the website URL to their contacts. As with direct sharing, default text was pre-populated when participants opened the messaging application; participants were permitted to edit the default text provided that they did not remove the URL.

ESM questionnaires To display ESM questionnaires, our application was integrated with AWARE [91]. AWARE is an Android framework that can capture data sensed on Android phones. We used the AWARE ESM sensor to trigger questionnaires when participants chose to share or not share their heart rate or broadcast link.

Adjustments Throughout the Study

Updates to the study application were made frequently at the start of the study to address a number of technical issues (e.g., Bluetooth disconnects, scheduling errors) that emerged as participants used the application. These updates were emailed to the participants along with installation instructions and information about how to diagnose and fix these known bugs.

The study was also conducted in two waves (one week apart), with slight differences arising between the two waves as a result of our attempts to address issues that occurred in the first wave. Specifically, during the first wave, a small number of participants did not fully understand the purpose of the study and heart rate sharing after they were given the initial instructions. We clarified the instructions during the mid-study interview for these cases; however, for the second wave of participants, we updated the instructions during the Introduction Phase to include these clarifications. We also adjusted the default message in the second wave to include the heart rate difference with participants' baselines, according to feedback from participants in the first wave. Aside from these differences, the procedure was identical in all other respects for the two waves of data collection.

Analysis

We analyzed the open-ended responses from the ESM questionnaires and from the audio-recorded interviews. We took a bottom-up approach to our analysis. We performed open-coding for both the open-ended ESM responses and interviews, focusing on sharing opportunities (including hypothetical moments where participants expressed interest or intention to share) as the main unit of analysis. Codes for open-coding were first created using a random sample of responses, and then applied to the rest of the responses [251]. A similar approach was taken for the analysis of the interviews. Codes were grouped in terms of characteristics, according to what triggered or inhibited sharing, how participants shared, and participants' reflections on their sharing experiences. Themes were formed across these groups, and discussed and refined during the writing process.

3.5 Results

Our results captured a variety of heart rate sharing instances, as expected with the use of ESM methodology. The combination of prompts triggered randomly and by changes in heart rate resulted in a range of contexts and activities for which participants made decisions around sharing their heart rate. These included more mundane day-to-day settings, engaging and entertaining activities, as well as social situations (see Table 3.2). Participants' moods and activities changed with each context, ultimately affecting their sharing behaviors. In our analysis, we gleaned distinct patterns of sharing motivations and behaviors, interpersonal consequences, and barriers to sharing. We discuss major themes that emerged from these patterns in this section.

Table 3.2: Contexts from ESM prompts

Context type	**What they were doing**
Daily routine	Eating, cooking, cleaning, napping, lying around, driving, riding the bus, getting ready for the day, finishing the work day
Physical activity	Walking, running, biking, working out, dancing
Work	Working, studying, attending class, holding office hours, grading, volunteer work, interview prep, giving a presentation
Entertainment	Playing video games, playing in an online poker tournament, surfing the web, watching Netflix, watching TV, watching YouTube, reading, playing ukelele
Social	Talking to someone on the phone/video, meeting friends for dinner, celebrating friend's birthday, reuinion, hanging out with family, attending or waiting for meetings

3.5.1 Sharing Behaviors

On average, participants chose to share their heart rate 41% of the time (Table 3.1) over the two weeks (not including broadcasts, with the mean number of shares being 18, SD=12). Participants demonstrated different patterns of sharing according to what triggered sharing, why they shared, and how they shared their heart rate.

Expressions of Emotional or Psychological States

In accordance with past research [119, 266], several participants focused on the association of heart rate with emotional and psychological states, and viewed heart rate sharing as an opportunity to convey or express those states to someone else (P71, P39, P36, P57, P22, P74, P60). Their reported sharing behaviors, as well as their desire to share in moments when they did not receive sharing prompts, illustrate this theme.

For example, several participants perceived a link between their heart rate and their experience of stress:

> "*I guess I sort of thought about [heart rate] as an indicator of stress*." - P22

> "*We look at a variety of things [on YouTube] and there are some political things that get me a little bit fired up. People talking very foolishly sometimes, and you sit down and want to throw something at the computer screen.... Sometimes I did, sometimes I didn't [want to share]. Sometimes I just want to express what I feel at the time*." - P57

One participant was primarily interested in sharing her heart rate during moments when she felt unable to visibly express her stress to people who were physically present or when she wanted to share her feelings of stress with remote friends or family members. This participant described two distinct situations where this was the case: facing perceived discrimination at a bar and going on a date.

> "*[The bouncer] like, wouldn't let me in because he said I had an attitude. Which was like, I think that was really like stressful for me because as a black woman you're always labeled as being sassy.... I talk with my dad a lot about this...I think that's a situation I would have shared with my dad.... I think it's just, thinking about when you face issues of discrimination, how your body reacts, I think that's interesting. It's interesting because you're there and especially after you've been told you have an attitude you have*

to remain calm but like, you're just so worked up as well, but there's that contrast between how you feel versus what you're giving off to other people." - P39

"*I'm one of those annoying girls where it's like I text my friends everything when I'm on a date. I feel like that would have given them information.... Like sometimes I just get super stressed on dates, and think again it's where you seem calm but you feel your heartbeat going fast. I feel like that can either be a good thing or bad thing.*" - P39

Another participant desired to share her heart rate to express her emotions during moments of conflict with others. She mentioned two specific cases where she had hoped the sharing notification would come up. In both instances she wanted to let her boyfriend, as the person who cared most about her life, know how she was feeling.

"*My dad and I have sort of a rocky relationship, and we were talking and I noticed that my heart rate was elevated on the watch, and I would have sent it to my boyfriend.... Another time would be, my boyfriend and I were fighting and I noticed it was elevated, and I would have sent him that.*" - P22

Participants tended to associate moments of stress with elevated heart rate and often shared when their heart rate was higher than their baseline. However, some participants were also interested in sharing when their heart rate was lower. One participant, for instance, felt that his heart rate lowered as a result of watching an emotional video, and wanted to share that with his girlfriend whom he missed. Two other participants associated lower heart rates with calmness. One shared a lower heart rate to express that she was calm to a contact who tends to worry about her. Another shared to show that she was capable of being calm in a negative situation:

"*In class, where the professor wants to make us miserable, I would like share it, 'oh yeah, he wasn't successful'…I was like calm…so I sent my heart rate.*" - P71

Though some participants simply wanted to express themselves, one participant was motivated to share in order to gain support from her contacts (Figure 3.4b). She appended text about her feelings to the default message, and sent it to friends she believed would be sympathetic towards her:

"*I think I shared two indicating that I'm feeling blue…. I'm interested in how people would react to it if I'm sharing my negative emotions. Do people actually care about me…. I was seeking comfort in a way but in a very indirect way. By sharing heart rate I'm implying that I might need help…so this is a very indirect way of sharing my emotions. So I'm interested if they can sense it.*" - P36

Participants who associated heart rate with emotional changes also chose to broadcast events during which they expected to experience stress, excitement, or calmness. These included events such as participating in festivities during Holi (the Hindu "festival of colors"), taking one's children to the dentist, taking an exam, attending church, and participating in project and advisor meetings.

"*[Holi is] going to be something exciting, and my heart rate is surely going to shoot up that day.*" - P60

"*It's just an event that involves the kids and it can potentially be frustrating. It's always an adventure, so you never know what's going to happen.*" - P74

"*Japanese class…because it's usually a very soothing class for me.*" - P36

As these cases illustrate, a number of participants deemed their heart rate to be an indicator of their current emotional or psychological state—and the sharing of their heart rate to be a means of expressing those states to close others to increase their understanding of those subjective experiences.

Daily Updates

Some participants integrated heart rate into their everyday conversations with their close friends and family (P71, P60, P39). These participants wanted to update these close contacts whenever there was something going on in their lives, such as a change in their current activity.

> "*[I shared j]ust to let them know that I'm changing my activity, or maybe to let them know that I've woken up…or if it's too high then maybe I'm out and doing something or maybe running…. So they have a sense that I'm not at home, or if I'm at home, I'm eating and stuff.*" - P60

These participants used heart rate sharing as a way to give an update that represented "small instances" of their daily lives that they were simply making "commentary" about. In these cases, participants chose to share primarily with people who typically knew and cared about their day-to-day activities, such as family members and significant others.

> "*[My boyfriend] asked me to [share]… I think he asked me to because he's interested in my life in general. I thought it was fun sometimes because we pretty much know what each other's up to…so it was usually a commentary on what I was doing.*" - P71

> "*I think it was mostly just people who I talk to about, like, my day-to-day activities with…for example I don't drink coffee often, so people who I would tell I had coffee that day, like you know those really small things.*" - P39

In one case, a participant's contact was even able to start predicting what he was doing based on his heart rate:

"*It actually served a good purpose. My mother actually knew if I was eating, because she could guess the time and the heart rate and she could sense that I was maybe eating or cooking food, so she already knew that.*" - P60

For these participants, heart rate sharing became a means of providing daily updates to people they cared about. The messages they sent could replace or supplement typical updates, both when they were asked about what was going on in their lives and when they simply felt like sharing these updates. Their motivation was primarily to allow those who care about them to have insight about their daily routines, activities, and experiences.

Novelty

While the previous sections demonstrate that many participants shared at specific instances according to their feelings or activities, a number of participants decided to share due to the sheer novelty of heart rate sharing itself (P67, P28, P74, P21, P94, P87, P44). These participants felt compelled to share simply because they were prompted to do so and wanted to experiment with sharing as a new form of communication; thus, their shares were largely indiscriminate, triggered whenever they received a notification.

"*[I shared] just whenever I wasn't too busy doing something else.... If it was a situation where I could focus on it for a second.* (*Interviewer*: '*Why did you share whenever*?') *The novelty's still there.*" - P74

Participants who were intrigued by the novelty decided to share to see how others would react. To them, heart rate sharing seemed "weird" and "odd" and, consequently, they were curious about how their contacts would respond to it. One participant noted that the more reactions she saw, the more comfortable she felt about sharing:

"*Especially when I first started [sharing] I was like...who would think this is least weird.... And once I did that, it built my confidence up a little.... I think the next one was [A], and I was just curious about how he would* *react...because he does live in another culture.... [H]e didn't have a question about what I was doing, so that kind of satisfied that.*" - P21

Participants also occasionally tried to "mix it up" by sending to different contacts to see more initial reactions, especially when their previous contacts began responding to their messages less frequently:

"*Usually for the first one their reaction would be more intense or stuff like that, so I kinda wanted to switch to another person to see what people say.*" - P36

"*Because other people weren't responding anymore, so I was like maybe if I send it to her she'll respond, and you know if I ask her to.*" - P87

However, the novelty effect tended to wear off in the second week. During the latter half of the study, some participants reported that they habituated to sharing and, as a result, shared less often.

"*Initially it was good, but later on it just felt like a redundant thing, sharing the same kind of information over and over again. So later on, I stopped sharing.*" - P44

Playfulness

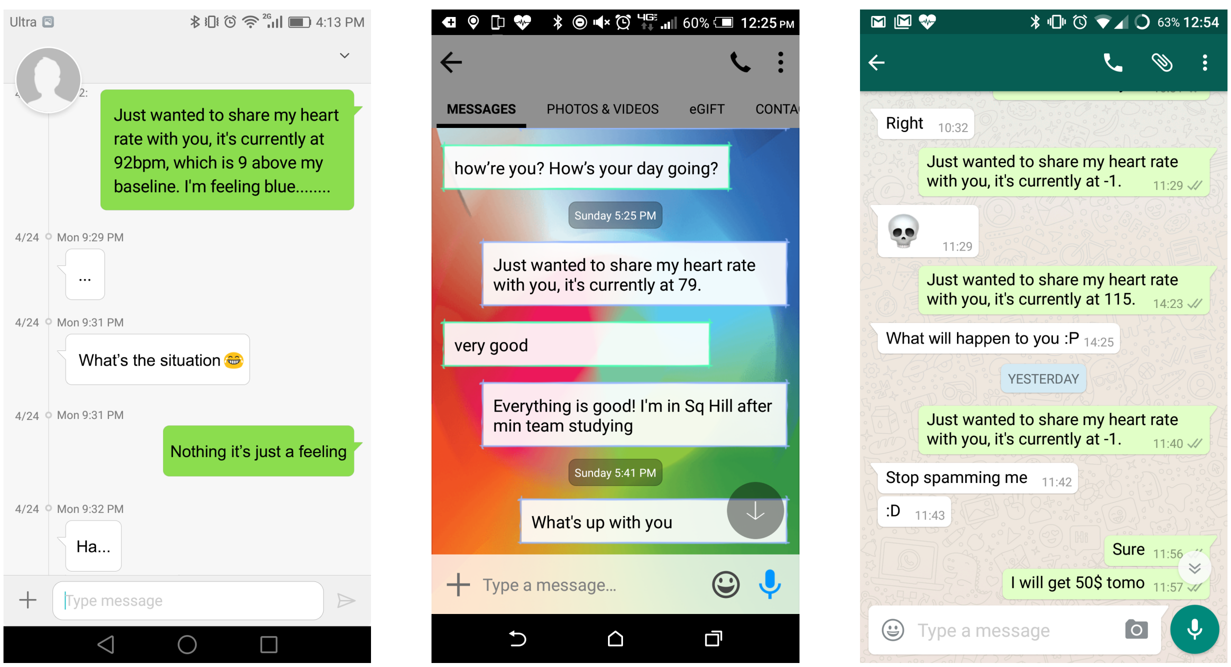
While many participants shared simply to try out heart rate sharing, some participants viewed the novelty of heart rate sharing as a fun way to interact with their contacts (P67, P28, P74, P36, P71). They shared their heart rate whenever they were in a playful mood or found the heart rate value amusing. For instance, in one ESM response, a participant mentioned that she and her contacts "laugh about high heart rates" (P71). Another participant constructed his heart rate messages to be funny by adding images and media to it, sharing with his wife because he "knew it would make her laugh" (P74).

One participant shared often because it became an inside joke with his friend (Figure 3.4d). Though the app occasionally showed inaccurate data when it lost connection to the watch (e.g., a -1 bpm, which most participants ignored), this participant would share anyway for fun.

> *"After a while it became a humor thing of sharing it with [him]...he was the guy who would always comment, 'it's very high, you're going to die.'"* - P28

Type	**Emotional Expression**	**Daily Update**	**Novelty**	**Playfulness**
Trigger	Feelings	Changes in activity	Share notifications	Share notifications and amusing heart rate values
Motivation	Express feelings to contacts, seek support	Let contacts know about their daily activities	Try it out and see people's reactions	To make people laugh or freak them out for fun
Use of Data	Relating changes in heart rate to their emotions	Relating changes in their heart rate to what they are doing at the time	Leaving the default message	Leaving the default message for mystery or adding media for fun

(a) Description of sharing behaviors.



(b) Emotional Expression, translated from Chinese.

(c) Daily Update.

(d) Playfulness, translated from Hindi.

Figure 3.4: Screenshots and descriptions of sharing behaviors.

Another participant chose from his list of six at random to see what kinds of funny reactions he would receive. He occasionally chose to keep an "air of mystery" during his conversations by purposely *not* explaining the data:

> "*Sharing, I just did it because it was asked for me to share, or I just wanted to freak out someone by sending it*." - P67

3.5.2 Consequences of Sharing

Heart rate sharing elicited a number of responses from participants' contacts. Participants described the different conversations they had with their contacts about the heart rate, which were affected by factors such as their relationship with their contacts and the ways their contacts interpreted or responded to their heart rate data.

Meaning-making from the Data

Most of the participants' contacts reacted to heart rate sharing with questions such as, "What is this," "Why are you sharing this," and "What are you doing?" Participants' contacts, who were not given any prior explanation about the study as context for participants' sharing behavior, were initially confused and surprised to receive unexpected notifications about the participants' heart rates. Participants realized that the heart rate value by itself may have been difficult to interpret.

> "*I don't think that anyone on that list has a good concept of what their heart rate is or what that number means in context to me, like if that's my resting heart rate or whatever. So I don't mind sharing it, but I don't think they would understand it or have enough information to understand it*." - P22

As one means of countering any potential issues concerning the receipt of unexpected heart rate notifications, many participants specifically chose to share with people they believed would not need any additional explanation about what their heart rate meant or why they were sharing it. They thought that these contacts would not respond negatively to a message that appeared out of the blue or that, to others, may have seemed "weird."

> "*It just never really felt comfortable with that kind of non-sequitur with anybody else...It's just different [with my wife], you don't necessarily have to explain or give any context necessarily.*" - P74

> "*They would understand—not understand, but know what's going on. Like everybody else might freak out, like, 'what the heck is this.*"' - P57

However, despite these expectations, participants' messages were often met with confusion, questions for clarification, or, in some cases, very little reaction at all. One participant speculated that this was perhaps due to the fact that she did not provide enough information to explain the meaning behind her shared heart rate:

> "*Maybe that's why nobody responded, because they didn't know what was happening.... I think maybe I just expected people to know what was happening around me more. I made assumptions...I thought it would give them some insight without changing the default text....*" - P39

Upon realizing their contacts' initial confusion, many participants followed up on the original sharing message to provide elaborating contextual information. They would generally explain what they were doing at the time, to help their contacts understand why their heart rate was at a particular level in that moment (Figure 3.5a). If participants were asked why they shared, they explained that they were testing a heart rate sharing application, as per the instructions given to them for the study. Some participants also included additional media or altered the default text in order to provide more context to their contacts:

> "*Most people probably never had anyone send them their pulse rate, so it's kind of just an odd thing to do. But if you do it in conjunction with*

something with a little more content, it kind of makes it relevant. Here's a picture of what I'm talking about versus here's a random number…just to give something to come with that dry statement of 'hey, here's my pulse rate, it's high or low,' so you have a picture…just something to correspond with that number or sort of illustrate it." - P74

Health Concerns

Though many of the participants' contacts required more context to understand their heart rate, almost all contacts expressed concern for the participants in their initial reactions. They inferred that notifications about high or low heart rates were an indicator of potential physical health issues, and addressed these concerns to participants. A few contacts even called participants soon after they received the message to confirm their health:

> "*She texted me 'what's going on,' but I didn't see the 'what's going on.' Like I said, she's like a mother figure, so when she didn't hear from me, and she sees that I'm monitoring my heart rate, like she jumped on the phone like 20 minutes later like, 'I said, what's going on'…. Basically I told her, 'don't worry I'm not dying. It's not like I'm wearing this for a hospital or something, I'm just wearing it to wear it and I'm sending this to you.*"' - P94

Given that heart rate is often associated with health, some participants made sure not to share with others when their heart rate seemed too high or too low. These participants usually avoided sending their heart rate to their parents so as not to worry them.

> "*When it's high I really don't want to share it with them, because they would get worried about it, so I didn't send it to my mom or dad.*" - P44

In one case, a participant lied about what he was doing so that he would not worry his parents. At the time, he believed his heart rate reflected his own worries about finishing an assignment. However, having accidentally shared his heart rate with his parents at that time, he decided to instead tell them that he was running:

> "*Once maybe I did share it with them and they asked me what I was doing. So I had to lie to them and tell them that I was running because I didn't want to tell them I was worried or something…Indian parents they get really worried if they feel that you are not feeling well…. So I just wanted to tell them it was nothing to worry about*." - P60

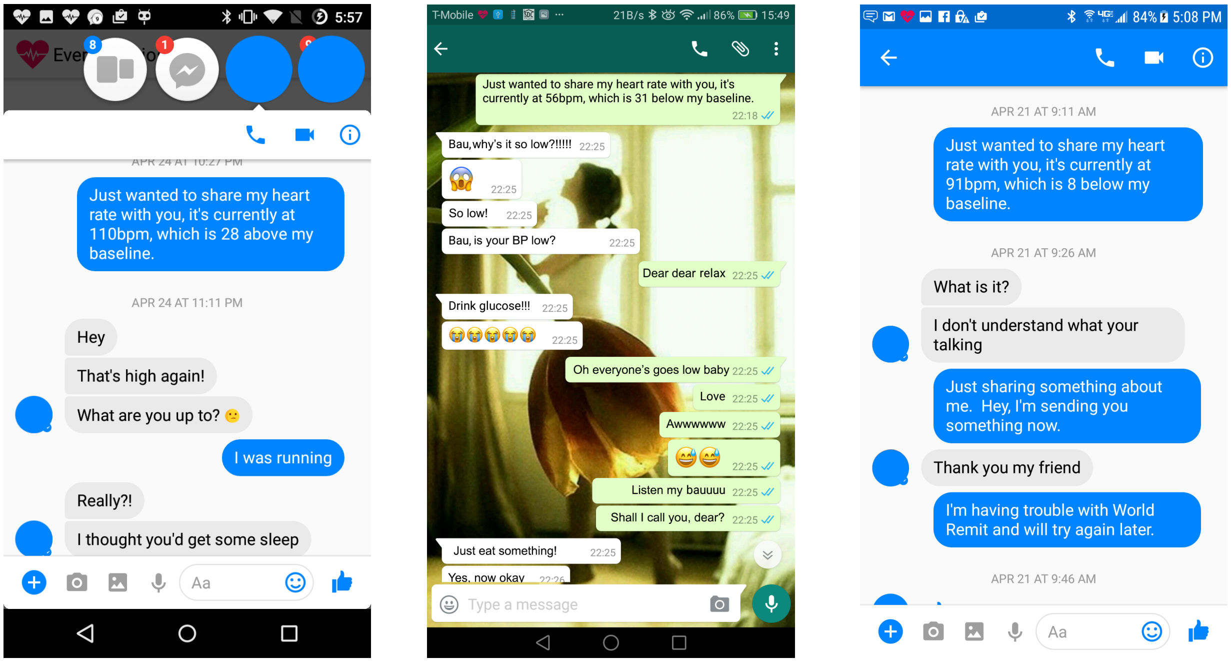
One participant, however, made the decision to share in relation to her health. During the study, she discovered that she had a heart problem (she had visited her doctor after the application notified her that her heart rate was abnormally low). This participant shared her heart rate several times with her husband, who would respond with concern and suggestions to support her health:

> "*Because he was with me when it went up, and it went up really high and really low, and he was with me in the hospital…and he's with me when…stuff goes up, and is like, 'why is it going up so high, you need to calm down,' or, you know, 'go walk away, or go talk or whatever*.'" - P87

Opened Communication

Though most participants felt that there was no change in the quantity or quality of their communication with their contacts, two participants mentioned that sharing their heart rate helped them open up communication with specific contacts. They felt that sharing had helped them overcome some difficulties they had previously experienced when conversing with these contacts.

One participant felt that heart rate sharing was akin to revealing a part of herself with another person (Figure 3.5c). Thus, sharing her heart rate helped pave the way for her to have a more difficult conversation with that person.



(a) Meaning-making. (b) Health concerns, translated from Hindi. (c) Opened communication.

Figure 3.5: Screenshots of sharing consequences.

> "*Afterward, I felt I was able to talk to him about something that was kind of difficult...I kind of felt like sending the heart rate thing had opened that door a little bit.... I felt like I could talk to him about things more...like, it wasn't just a one-sided communication.*" - P21

In another case, a participant felt that his communication with his grandmother had improved as a result of sharing. He believed that his prior interactions with her were very formal, but sharing his heart rate with her helped him achieve a more casual and interpersonal relationship with her:

> "*I don't generally share too much with her how I'm feeling and stuff like that. It's generally a formal kind of talk that we have. But I felt that this was something really interpersonal, so I felt good. She was worried about me,*

she was asking me, so I told her, so we had this rapport going on. So I liked that, it was good." - P60

3.5.3 Barriers to Sharing

Though participants exhibited different types of sharing behaviors, they also encountered moments where they did not want to share their heart rate. They reported certain barriers to sharing that they attributed to limitations of the system and the timing or frequency of the prompts, as well as to limitations of the heart rate data itself.

Logistical Feasibility

Almost all of the participants stated that a major reason behind not sharing their heart rate was that they were too busy to engage with the application and answer the share prompt. These busy moments usually occurred when participants needed to work or were involved in something that required their full attention, such as driving, playing games, or bathing their baby. Participants also missed several notifications throughout the day due to the notifications only appearing on their phone. For example, they did not always pay close attention to their phone, or they had their phone on silent when they were busy. One participant noted several periods where she could not look at her phone at all, as she worked irregular shifts at a store that required her to leave her phone in her locker during work hours.

A few participants were also limited by the schedules enforced by the application. These participants had to consider which of their contacts would be available during the waking period they had previously defined. For example, one participant, who primarily shared with his family and girlfriend in India, noted that there was a fixed period during the day when he did not share because they would not be awake. Another participant stated that he was a "night owl," and his waking period, defined as 9PM to 9AM, limited whom he could share with:

> "*The way I see it—a lot of people don't put their phone on vibrate. Let it be three o'clock in the morning and I'm hitting you up, telling you that my heart rate is 97 beats per minute as you've been asleep. It's not pretty.*" - P94

Many participants also missed several or all of their scheduled broadcasts. They had either failed to notice the prompt to start the broadcast before their event started, or experienced a change in their schedule and decided that the broadcast was no longer relevant.

Finding Interesting Moments

Another barrier to heart rate sharing was participants' desire to exclusively share interesting or noteworthy moments or events with their contacts. Though what counted as "interesting" varied per person, participants frequently evaluated whether their heart rate would be worth sharing to their contacts (e.g., whether it would open up a dialogue or elicit a response).

> "*I guess it was sort of anticipation of whether this was going to elicit a chuckle, or is this going to be met with silence.... Is this funny or not, is this interesting or not*?" - P74

Some participants determined what was interesting based on the perceived relevance of the heart rate and/or the context in which it had been triggered. For example, P22 shared her heart rate with a friend because it had shot up when that friend sent her a text message about wedding plans (Figure 3.6a). P74 shared his heart rate with his cousin-in-law after he had just parted ways with their family after a day at the park. Both participants had adjusted the way they shared by adding media or changing the text of the default sharing message.

> "*The number in and of itself, I don't know how relevant it is… I have to explain what that number means to me, like my friend…I explained to her, like I didn't give her the number. I said that it was increased, because I felt like that was the important part, not so much the number.*" - P22

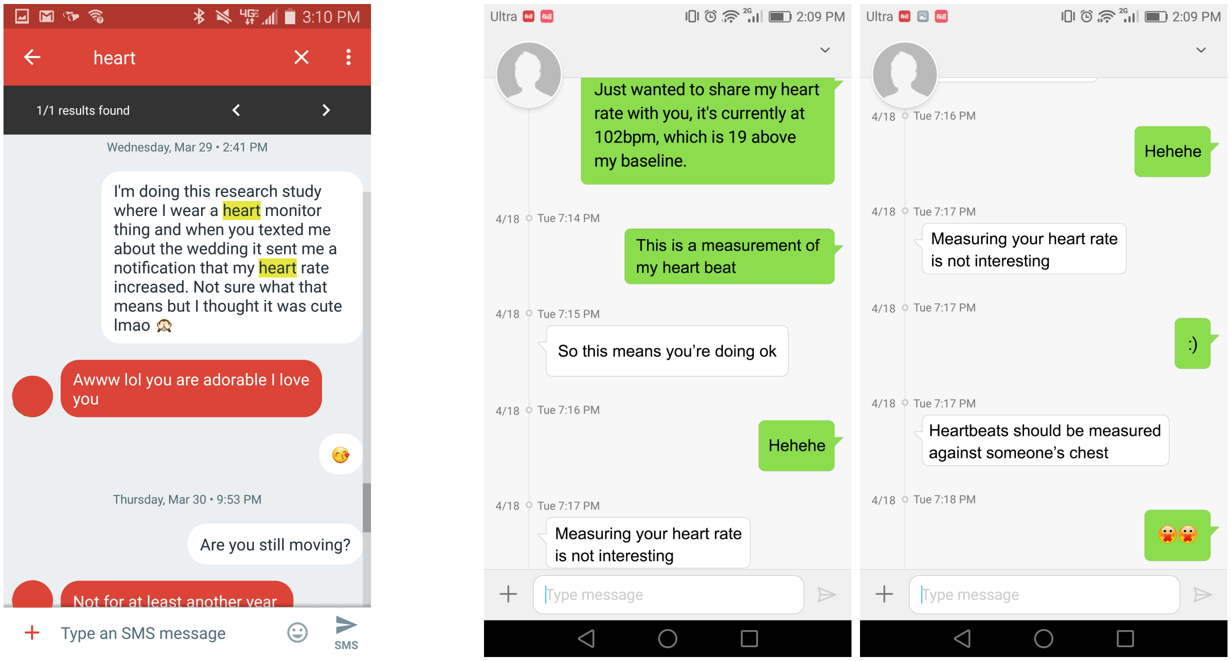
For other participants, what was interesting depended on how they felt or what they were doing at the time. For instance, if they "felt normal" even when their heart rate was above or below their baseline, or if they didn't seem to be doing anything significant, they typically did not share their heart rate.

> "*Pretty much [I shared] when I felt like there was something significant happening. Like I don't remember exactly when but a lot of times it would ask me if I wanted to share it and I was like sitting at home chilling, and I was like, there's nothing significant about this.*" - P39

Participants similarly chose to broadcast events (or reported wanting to broadcast) when they believed their heart rate graph would show interesting fluctuations. Many participants expected this would occur during events involving high levels of physical activity, such as biking and belly dancing, or high levels of emotional intensity (as described above). One participant stated that she ended up not broadcasting because she thought it would be "boring," since there would be no interesting changes in the graph to watch:

> "*It was just a flat line, really, and it wasn't doing much, and I couldn't foresee it doing much in the future, and it seemed like anyone who would watch it would watch it for five seconds and then go away.*" - P22

Two participants felt that their heart rate would generally not be interesting to anyone but themselves. They believed that they would not have shared outside of the study because "nobody cares" about their heart rate, and no one else would have any use for it.



(a) Making heart rate relevant

(b) The conversation P36 had with her contact, implying the intimacy of heart rate (translated from Chinese).

Figure 3.6: Screenshots demonstrating sharing barriers.

> *"I don't want to know the data of someone else's heartbeat.... I don't have any use for it...what is the value if it doesn't mean anything to me."* - P67

However, one of these participants noted that while most people would not have use for his heart rate, there was a possibility that his parents would be an exception because they tend to care about *all* aspects of his life. This is similar to participants who primarily shared with their significant others because they believed that they are the ones who care the most about their lives. Thus, for some, heart rate sharing may be most interesting to intimate others.

Vulnerability and Intimacy

In line with previous research about heartbeats [142], some participants expressed their belief that heart rate is very intimate. Because of its deeply personal nature, they did not always feel comfortable sharing their data with others. For instance, one participant received a response from a male friend that referenced the intimacy of heart rate sharing (Figure 3.6b). She later hesitated whenever she shared because she did not want the recipient to interpret it incorrectly:

> "*Even with my close friends, I was concerned a lot about whether I should share my heart rate with people. It's just something too intimate.... My best two friends it's fine, but yeah. Sharing with a guy, like, a male friend, I will hesitate more because heart rate is...it just indicates intimacy and I'm not sure if it's proper.... It's like flirting with a guy.... So that's why I'm concerned if I'm conveying the wrong message to him by sharing heart rate*."
> - P36

Some participants also felt vulnerable about heart rate sharing due to the potential to be judged by others based on their heart rate value. They felt that by sharing their heart rate, they would be giving other people too much information about their physical state or fitness level:

> "*It makes you feel kind of vulnerable. Because you're basically, quite literally, sharing your heartbeat.... It's like at first when your heart beats fast people are judging me because they're like, oh you're not taking care of your heart, you're sitting down*?" - P94

However, while some participants felt hesitant about sharing due to the intimate nature of the heart rate, one participant enjoyed the idea of sharing something so personal. In particular, she felt that by sharing her heart rate, she was sharing something unique to her but at the same time universal to everyone:

> "*I was showing something about myself, so I kind of like that. ...Everyone's connected by having a heart and a heart rate, but whatever your heart rate is at a particular time is unique to you in that time. And it changes all*

the time, as you can see clearly from the watch. So it's kind of unique in that moment.... It's something personal to you but it's also something that everyone has. So it's sort of both universal and personal." - P21

3.6 Discussion

Supporting Interactions with Heart Rate Sharing

Participants shared their heart rates with their contacts in a variety of personally meaningful and expressive ways, demonstrating the potential for this new type of interaction to support interpersonal communication. In line with past research [266], heart rate sharing was viewed as a form of emotional self-disclosure, where participants shared as a means to express their affective states to their closest contacts and even signal to them when they were in need of support. Emotional expressions are known to be crucial to conveying information about our needs and intentions to other people, and can improve the quality of our interactions and closeness of our interpersonal relationships by increasing empathy and trust between individuals [157]. While we typically express our feelings through verbal or visible behaviors, our findings suggest that heart rate sharing can provide a new and more concrete means to detect and express our feelings based on our bodily changes. In particular, during difficult situations or moments when our subjective experiences do not match what others observe or expect from us, revealing a change in heart rate can validate the way we feel, both to ourselves and others. This is likely due to assumptions that our biosignals represent objective information about our states [266].

"*I guess I have a concept of how emotionally taxing it was for me, but to see it in numbers...that would...make it more real that that's what I experienced.*" - P22

In addition to these emotional expressions, participants used heart rate to inform people about their activities in more mundane everyday occurrences. Past work suggests that heart rate can act as a implicit contextual cue [119]; our findings extend this by showing that participants will also use heart rate to explicitly signal to others how their bodies change as they go about their day. Sharing in this manner appeared to support social connectedness, helping participants keep their contacts constantly aware and in touch with their lives. One participant, whose primary contacts were in India, felt that this made heart rate sharing especially beneficial for remote communication. Research on remote communication supports this, where those in long-distance relationships tend to want to know about each other's more mundane daily moments to feel more connected [195].

Participants' sharing behaviors also led to social interactions with their contacts that encompassed a variety of topics, from meaning-making discussions to conversations about health and well-being, as well as a variety of tones, from deep and intimate to light and playful. Furthermore, while some participants who perceived their heart rate to be deeply intimate reported some level of hesitation about sharing their data, others leveraged that intimacy to initiate more open verbal communication with contacts. These findings show that heart rate sharing can open new types of meaningful interactions and conversations with others.

Taken together, our findings demonstrate that heart rate is capable of acting as a powerful new computer-mediated cue. Prior work has established that we lack access to essential nonverbal cues in computer-mediated communication (CMC), including body language and facial expressions, which can lead to depersonalization, misunderstandings, and distance between interaction partners [40, 158]. Emojis and emoticons are perhaps the most common CMC solution used to compensate for these missing nonverbal cues, particularly for expressing emotions [79]; however, these communication tools are known to elicit multiple interpretations from different audiences [197, 213] and potentially reduce the intensity of users' emotional experience [79]. We suggest that heart rate could supplement CMC interactions as a new cue by providing information about our underlying responses to different situations, which we would otherwise be unable to visibly express. Heart rate can be used to signal our emotions, our activities and context, playfulness, and our need for support or connection with others at particular moments—features that have all been identified as significant benefits for communication technologies [320]. Additionally, unlike emojis, heart rate stems from our bodily reactions. As noted by P21, people may subsequently feel personally connected to their heart rate, while recognizing that everyone has one. Thus, heart rate may be able to provide a more "universal" (P21) cue for representing our subjective experiences, and convey an emotional intensity that may be lacking in current CMC.

Other biosignals can also reflect our bodily reactions to our subjective experiences, and thus may similarly serve as effective computer-mediated cues when shared with others. Skin conductance and brain activity, for instance, are known to change with our engagement levels, emotions, and cognitive processing [34, 99, 124, 183], and thus could also enable users to express themselves, explain their contexts, and connect with other people. With recent developments in consumer-grade wearable biosignal-sensing technology, such as the empatica Embrace [3] or the Muse brain-sensing headband [2], future work should consider investigating the sharing of these different types of biosignals and their ability to support social interactions.

Heart Rate as Ubiquitous Data

Our research demonstrates the potential for leveraging sensing technologies to introduce expressive biosignals like heart rate as a new form of ubiquitous data, which can support communication by fostering self-expression and interpersonal connection. At the same time, we find that the sharing of physiological data elicits reactions and raises issues similar to those that are evoked by the sharing of other types of ubiquitous data, such as location and physical activity. Having control over when and with whom to share heart rate was important to participants. Paralleling findings from research on location sharing, participants in the present study preferred to share their heart rate data with their closest contacts, particularly when the information was relevant to those contacts or would be interpretable by them based on shared context or information [67, 311]. Additionally, like in the case of location sharing, we found that heart rate could be interpreted differently than intended if not explained by the sender [268]. Failure of participants to explain or provide context for their heart rate inhibited their contacts' ability to understand their motivation for sharing. As in the case of activity sharing [89], heart rate receivers would subsequently respond with confusion or apathy. While these motivations may not have been clear to participants' contacts, our results suggest that participants shared for both purpose-driven (e.g., support-seeking) and social-driven (e.g., expressing interesting moments or aiming to evoke particular impressions) reasons [280]. Clarifying and supporting these different motivations, in addition to considering the other aforementioned issues surrounding heart rate as a form of ubiquitous data, will be critical for improving the design of heart rate sharing technologies. In the following section, we discuss design implications for improving these technologies for expressive heart rate sharing.

Design Implications for Expressive Heart Rate Sharing

While our findings demonstrate the social implications and opportunities for heart rate sharing, challenges and feedback described by our participants suggest important design implications for systems that enable expressive heart rate sharing.

Disambiguation with Context-Awareness As the experience of many participants in the present study indicated, the sharing of heart rate data without the addition of elaborative contextual information often resulted either in initial confusion from recipients or interpretations that did not align with sharers' actual subjective experience (e.g., a concern about their health or well-being). Participants either falsely assumed that their contacts would know or be able to infer their context or current states from the heart rate, or lacked the motivation to alter the default text to provide this clarification. Thus, it is important that sharing systems encourage and facilitate sharers' clarification of context to reduce the occurrence of crossed signals. This may take the form of visualization schemes that provide clearer connotations of a particular psychological state (and the ability to choose between alternative schemes), the provision of tools that link physiological responses to disambiguating context clues (e.g., kinetic typography tools that display text in a style indicative of one's current state), or the automatic integration of media or sensed activity data within the text of sharing messages.

In-the-moment vs Reflective Feedback Participants' sharing behaviors in the present study suggest that an expressive biosignal system that only accommodates in-the-moment sharing of physiological data may be inherently limited. Most participants were simply not able or not inclined to respond to all sharing notifications, either for logistical reasons (e.g., not having access to one's phone or the ability to use it in moments when noteworthy changes to heart rate have occurred) or motivational ones (e.g., habituating to the repeated prompts to share or feeling disinclined to continuously make decisions to share). One solution, as discussed in the previous section, is to enhance the system's awareness of a user's context in order to achieve a finer-grained accuracy for delivering sharing prompts. Another solution is to equip the user with the ability to receive post-hoc, retrospective access to their data from a previous time period (e.g., the last 24-48 hours) to allow them to reflect on their physiological responses and their meaning before making decisions to share. Such reflective feedback features would also give users the opportunity to ponder the longer-term patterns in their own biosignals. This could encourage users to make meaning of their responses, their likely contextual or situational triggers or antecedents, and the most personally beneficial or appropriate ways of sharing their data.

Increasing Appeal Participants offered a number of observations and recommendations for ways to increase the usability and expand the functionality of the system in order to make it a more pleasurable experience. For example, several participants noted the constraint of being able to share only a single numeric indicator of their heart rate, and expressed a desire for a wider array of options for both the data available to share (e.g., trends in their heart rate, blood pressure, steps taken) and the means of depicting or presenting the data (e.g., the use of graphical representations of heart rate).

> *People wouldn't be interested in seeing just a number...it would have been much better if it was shared as a GIF to people.... So the time wouldn't matter...since they don't have to do an extra work of opening a link...people would be more willing to see it.* - P28

In addition to GIF replays of heart rate, participants suggestions for visualizations included heart beat graphs (as opposed to heart rate, which has slower and less engaging visual changes), and heart images to make the expression of heart rate more vivid. In the following chapters, I explore different visual designs to present heart rate (and other biosignals) in a more engaging and expressive manner.

Product Improvements In sum, heart rate sharing technologies should consider implementing new designs or features to support sharers' intentions and desires to share, as well as receivers' understanding of the shared heart rate. In particular, existing heart rate sharing technologies do not support contexts for sharing that could facilitate users' self-expression and interactions with their contacts. The Apple Watch, for instance, allows users to share their heartbeat with their contacts through graphic and haptic feedback, yet does not provide a clear incentive for users to do so. While the feedback provides a visually appealing format for sharing heart rate, the application would benefit by signaling to users the right moment to share. Considering Affective Computing solutions for detecting emotional states, or working in combination with other existing sensed data, such as location or activity, to provide context, could help users identify these interesting moments for both in-the-moment sharing and post-hoc reflection. For instance, one participant suggested adding an accelerometer to the application in order to identify these moments:

> *Maybe it could have an accelerometer or something, so it could actually detect what I'm doing.... If my heart rate shoots up it should understand why it shot up... I believe the ultimate goal...is to send out of the ordinary readings, I would want it to send me something unexpected.* - P60

Customizable settings could also reduce the need to attend to application notications by allowing for personalized automated share messages or limiting acceptable times for sharing. Additionally, given the intimacy and personal nature of heart rate sharing, current and future products should incorporate privacy settings that give users control over when, with whom, and how they want to share. Exploring these potential design solutions is a focus of the next stages of my research.

Limitations

We sought to investigate heart rate sharing in users' everyday contexts, employing a combination of ESM and semi-structured interviews. In order to encourage more natural sharing behaviors, we had participants use their own phones and messaging applications to communicate with their contacts during the study. This allowed for a higher level of ecological validity in studying how participants would use the application in the wild; however, the diversity of lifestyles as well as the lack of uniformity in the models of phones used by participants inevitably resulted in irregularities and difficulties in data collection. For instance, participants would not always receive or see ten notifications each day and different participants could receive different numbers of notifications based on their activities, availability, and the accessibility of their phones, subsequently affecting the number of sharing opportunities. Similarly, participants answered varying numbers of ESM questionnaires. Both cases usually resulted from the fact that participants could not always attend to to their phone or even have it on their person.

Irregularities in notification prompts were exacerbated by the two-device system setup, where heart rate was streamed from the Mio Alpha 2 watch to users' mobile phones. All participants experienced Bluetooth connectivity issues at some point during the study, interrupting the stream of their heart rate to the phone. The frequency of these connection issues also varied across different phones, as participants had a range of devices, including those from the Samsung Galaxy series, OnePlus, Huawei, HTC, and Motorola. Participants also occasionally forgot to wear their watches or to charge them overnight, despite reminders on their phones and daily check-ins from the experimenters; thus, they may have experienced a few hours of lost sharing opportunities. However, despite these irregularities, we were able to glean an ample amount of data from all participants to inform our analysis around their sharing behaviors. In Chapters 5 and 6, I explore biosignals sharing on smartwatches, which enabled delivering prompts on the watch itself rather than via a connected phone application.

The study was also limited in its heart rate sharing capabilities. Specifically, the setup of the study only allowed for one-way heart rate sharing, as participants' contacts were not equipped with the study application or heart rate monitors. One participant actively wondered whether any of her contacts would send their heart rate back to her whenever she shared, but was unsure if they had a heart rate monitor that could support this. For the purposes of this study, we focused on heart rate sharing at the individual level, focusing on individuals' decisions to share their heart rate and how they felt afterwards. We were also interested in understanding how individuals would explain their shared heart rate and decisions to share with their contacts, who would have no prior knowledge of the study, and gauge the initial reactions they would receive, given that heart rate sharing is a novel type of interaction. However, social interactions and feelings about heart rate could change when both parties have the ability to share their heart rate with each other. In the next stages of my thesis, I address these limitations by investigating biosignals sharing on the receiver's end, as well as dyadic level sharing.

Chapter 4

Understanding Others' Biosignals

In the next stage of my thesis work, I explored the *receiver's* side of expressive biosignals, or what it means to view someone else's biosignals. Though my prior work on sharing biosignals demonstrates how people express their heart rate to others, it is unclear how receivers of those biosignals understand those expressions and ultimately perceive the sender. In order to transform biosignals into a new social cue, we need to better understand how people interpret and react to them to convey them in a socially meaningful way.

4.1 Exploring the Visualization of Biosignals

This chapter has been adapted from [189]. In a first step to understanding a receiver's perceptions of biosignals, I investigated how the representation of biosignals affects people's interpretations of those biosignals and impressions of the sender. In the previous chapter, I deployed an expressive biosignals system that simply displayed heart rate as a number in text, but study participants desired more appealing and expressive representations, such that they would appear more interesting and engaging to receivers. Moreover, researchers who have built systems that display biosignals have employed a breadth of representations, such as colored lights [270], graphs [209], and icons [278]. Given the diversity in these designs, receivers may form different perceptions for different representations. Thus, in this stage of my thesis work, I explored how different representations affect interpersonal judgement, specifically, impression formation.

- **RQ3.** How do different biosignals representations affect impression formation?

4.1.1 Summary

We conducted a study to explore the design of representations for biosignals. We compared the influence of a variety of brain activity visualizations on impression formation. Results revealed that while participants readily infer emotional and cognitive states from visualized brain activity, the ambiguity of the data can lead to diverse perceptions and interpretations. Participants also expressed concerns that the observation of another individual's data during interaction might be invasive or distracting. We present a set of design considerations addressing issues of interpretability, integration, and privacy of biosignals in interpersonal contexts.

4.1.2 Introduction

We typically form impressions of other people based on the visible behavioral cues that they give off—body language, facial expressions, and voice tone and pitch [12, 103, 243]. However, expressive biosignals could reveal previously *invisible* data about others that can inform our impressions, where data like heart rate and brain activity could signal changes in people's emotions and cognitive processing [34, 99, 170]. Supplementing our observation of behavioral changes with access to these physiological changes could enhance our inferences of other people by better sensing and understanding their emotional and cognitive states.

In this research, we examine how people form impressions of each other based on visualized biosignal data. The impressions that we form are traditionally affected by visible nonverbal behaviors both consciously and unconsciously controlled [103, 243]. Research shows we readily form initial impressions from even brief observations, or "thin slices," of expressive nonverbal behaviors very quickly, in less than two minutes in some cases [12]. Moreover, research stemming from attribution theory has revealed that individuals tend to draw automatic judgments about others' personal dispositions (i.e., characterizing their internal states or traits) from observed verbal and nonverbal behaviors [102]. In our work, we investigate whether short clips of visualized EEG data might similarly provide perceivers with expressive social information with which to form impressions, and how variations in representations of the data affect the impressions that we form of others.

We contribute key design considerations, challenges, and opportunities that arise in developing an expressive biosignal system that displays a user's brain activity. We created six visualizations of brain activity and assessed participants' impressions and reactions to each in a controlled laboratory setting. Results revealed that participants associated sensed brain activity with particular emotional and cognitive states, but their interpretations of those states were strongly skewed by design features of expressive biosignal visualizations. Additionally, we gleaned concerns of privacy and cognitive load when considering the use of the visualizations for communication, depending on the level of interpretable information present. Our research reveals important insights and unresolved issues concerning the integration of displayed brain activity in social contexts, and lays the groundwork for crucial next steps in the design and deployment of expressive biosignal systems.

4.1.3 Background

Impression formation and expressive behaviors

While past research has begun to reveal the impact of shared biosignals on interaction quality and outcomes, it has not directly investigated whether individuals will use biosignals as cues to form impressions about a person's traits or states. Moreover, existing systems have visualized biosignals as graphs [72, 209, 258], numbers [266, 298], icons [278], ambient lighting [270], and clothing [132, 307], providing different types of information (e.g., levels of biosignals data, changes over time) and levels of abstraction from the data (e.g., raw graphed data vs. iconic representations), but studies involving these systems have not tested how varying presentations of biosignals might differentially influence impression formation. To our knowledge, only a recent study by Hassib and colleagues has directly compared different biosignal designs [119]; however, the authors focused on supporting communication between close friends and partners, rather than discerning the first impressions made when given different biosignal visualizations.

There is strong reason to believe that individuals *will* be likely to use biosignals as cues for impression formation. Prior work has shown that observing other nonverbal expressive behaviors in someone else, such as body gestures and facial expressions, can guide inferences about their emotions, opinions, and physical and cognitive states. Research on "thin slices" of behaviors suggests that we use this information to form judgments and forecasts of others' traits when behaviors are visible for as little as 30 seconds in video clips. These behaviors can be telling of individuals' unique personal styles [10], and thus have an important influence on how we present ourselves [78, 103] as well as form impressions of one another. Riggio and Friedman, for instance, found that people's impressions of subjects who gave spontaneous explanations were affected by frequency of certain expressive behaviors (e.g., facial expressions) and fluidity of those behaviors [243]. Similarly, Gifford and colleagues have shown that observers readily encode expressive nonverbal displays and rely on them to make inferences about personality traits [101].

Biosignals may similarly have expressive capabilities by conveying information about a user's mental states during subjective experiences. Heart rate and skin conductance, for instance, are known to be associated with changes in emotion [170, 183], and have been used by people to interpret emotional states such as stress and excitement in others and themselves, albeit with some ambiguity [132, 209, 266]. Merrill and Cheshire's recent study demonstrate that these interpretations can be drawn even from fake biosignals [209]. Further, in some cases, these interpretations can affect beliefs about traits such as trustworthiness or reliability [208]. Thus, like other expressive nonverbal cues we typically rely on, displays and representations of biosignals might be able to provide useful social information that can become a basis for forming impressions of others.

Our research aims to further our understanding of biosignals as a social cue by investigating the impressions evoked by visualizations of brain activity. Unlike heart rate and skin conductance, interpretations of brain activity in social contexts have not yet been explored. Brain activity may be capable of conveying social information as it can vary with our emotional and cognitive states [34, 99], and has shown potential for detecting the underlying processes in social interactions [19]. Additionally, per the research direction introduced by Leahu and Sengers' work [179], as detection of social experiences through brain activity advances, it is important that we understand people's subjective interpretations of brain activity. At the same time, the ambiguity of biosignal data suggested by past studies points to an important need to explore how to represent brain activity in a way that can support meaningful interpretation. To address these gaps, we ran an exploratory study to advance our understanding of the impressions evoked by sensed and shared brain activity, and to explore the effects of different visual representations of brain activity on those interpretations.

4.1.4 System Design

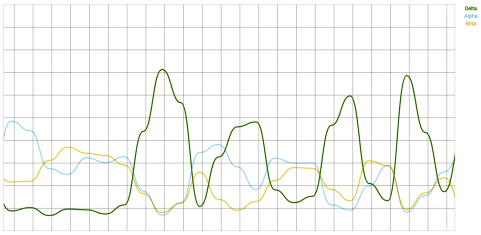
For this study, we built a simple expressive biosignal system using the Muse brain-sensing headset, a consumer-grade unobtrusive wearable technology with seven sensors that can measure a user's EEG waves. We developed a web application that visualized brain waves using the "relative band power" path in recorded Muse data. Brain waves differ according to frequency ranges, and have been associated with different cognitive and emotional states [34, 99, 176]. In this study, we showed three brain waves in the visualizations (delta, alpha and gamma) to cover a range of mental states.

Table 4.1: Visualized brain wave types and their associated states [139, 176]

Brain Wave	Frequency	Color	Associated State
Delta	1-4Hz	Green	Deep sleep
Alpha	7.5-13Hz	Blue	Relaxation and disengagement
Beta	13-30Hz	Yellow	Focused concentration and active thinking

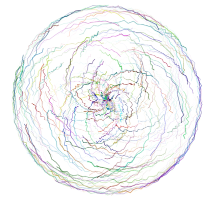
We created six visualizations of brain activity as part of the expressive biosignal system. We designed these visualizations to explore how different presentation types would influence impression formation. Specifically, we explored visualizations that varied in the the level of interpretation from the data, as per the data representation dimension described by Hassib and colleagues' work on biosignal designs [119]. Visualizations that were more *interpreted* manipulated or added additional meaning to the display of the data, while visualizations that were more *raw* presented the data closer to its raw numerical form. We also included visualizations with different information levels, based on number of brain waves present in a moment. Each of the six visualizations are described below (and can be seen in Figure 4.1).

Graph Graphs are the most common form of visualization used to display biosignals (e.g., in biofeedback); thus, we included it to provide a familiar and basic representation



(a) Graph.

(b) Sliders.



(c) Swirl.

(d) Colors.

(e) Light.

(f) Emoji.

Visualization	**Representation**	**Info Level**	**Display**
Graph	More raw	All 3 brain waves over time	Stream of brain waves across graph, highlighting the most active brain wave/second
Sliders	More raw	All 3 brain waves at given moment	Circles representing brain waves sliding left or right depending on values of the waves
Swirl	More interpreted	All 3 brain waves at given moment	Animated swirling lines: delta for line speed, alpha for line smoothness, beta for number of lines
Colors	More interpreted	All 3 brain waves at given moment	Overlaid color gradients with changing opacity based on brain wave values
Light	More interpreted	1 brain wave at a time	Changing colors of an LED light according to most active brain wave
Emoji	More interpreted	All 3 brain waves at given moment	Changing opacity of emojis based on brain wave values: delta represented by sleeping emoji, alpha by relaxed emoji, beta by thinking emoji

(g) Description.

Figure 4.1: Overview of the 6 visualizations.

of physiological data. The graph streamed the different brain waves, highlighting the line with the maximum value at every second to represent the most active brain waves. We considered this visualization to be more raw because it presented the data by plotting the raw values on a graph. This visualization also showed the highest amount of information because it graphed and streamed changes in the brain activity over time.

Sliders This visualization displayed the brain waves as a set of sliding circles. The circles represented the delta, alpha, and beta waves, and would slide left for lower activity and right for higher. This visualization was considered to be more raw because raw values were plotted on a horizontal line. However, less information was available in this visualization than in the Graph, because one could only view the values of the brain waves at a given moment and not over time.

Swirl This interpreted visualization mapped the brain waves to the characteristics of animated swirling lines. To reflect the fact that delta waves are associated with sleepiness, when mental activity is typically slower, the speed of the lines was inversely related to the level of delta activity. Because the alpha is associated with a relaxed state, greater alpha activity resulted in smoother lines, while less activity resulted in lines that were more jagged (to suggest stress). Finally, beta was mapped to the number of lines in the visualization, with greater activity resulting in more lines to suggest the greater amount of thinking associated with high beta activity. The lines changed every second, thus one can view the activity of all three brain waves only at a given moment.

Colors This interpreted visualization mapped the brain activity to different colors. Green and blue, which are associated with peace and calmness, were chosen for delta and alpha waves, respectively. We mapped beta waves to yellow, since yellow is a more dynamic color [200]. We displayed the colors as a radial gradient on the screen, with each gradient's opacity controlled by the value of the associated brain wave. The gradients were overlaid on top of each other; therefore, all three colors would be available at a given time, though colors with higher activity would be more visible than others. For example, if there were higher levels of delta and beta activity present, but lower alpha, the visualization would appear yellow-green due to the overlay of the green and yellow gradients.

Light The Light was the only physical visualization we created. The Light consists of an Arduino, 2 LED lights, and a light bulb covering the system. The color of the Light would change according to the brain wave that had the highest activity at a given moment. To maintain consistency across visualizations, the color mappings were the same as those used by the Colors. This visualization shows the least amount of information, because users can only view one brain wave at a time (as only one color is shown at a time). Because the Light mapped the brain activity to different colors, like the Colors, we considered it to be a more interpreted visualization.

Emoji The Emoji visualization used emojis, or cartoon faces with different facial expressions, to represent the three brain waves. These emojis were created according to the definition of each brain wave, with delta represented by a sleeping emoji, alpha by a relaxed emoji, and beta by a thinking emoji. The opacity of each would decrease and increase, respectively, with lower and higher levels of brain wave activity. The Emoji mapped brain values to images, thus we considered the visualization to be more interpreted.

4.1.5 Methodology

In a within-subjects study, participants watched recordings of the six different visualizations that used the same source brain activity as input. Participants' self-reported ratings of the visualizations and their expressed opinions about the individual whose brain activity they viewed were used to ascertain users' evaluations, preferences, and concerns regarding the display of brain activity, as well as to investigate the impact of the visualizations' designs on impression formation.

Participants

Thirty-six participants took part in the study, which was conducted at a private university in the northeastern United States. Four participants were only able to partially complete the study; thus, we removed their data from all analyses. The remaining 32 participants included 18 females and 14 males, with ages ranging from 18 to 43 years old (M=25.94, SD=6.4). We recruited participants from the university participation pool, and compensated them with ten dollars in exchange for participating in the study. Most participants had no prior experience with brain-sensing headsets, but seven participants had worn a headset for either another research study (n=5), gaming (n=1), or for seizures (n=1).

Visualization Recordings

Prior to the study, we had recorded a user's brain activity as they wore the Muse and listened to an instrumental audio track. We chose this setup in order to provide a sufficient context for participants to simulate the subjective experience of the user. Impression formation literature has typically achieved this goal through vignettes or video clips [12]; however, we used an instrumental audio cue to ensure that the participants' judgments would not be influenced by other nonverbal cues given by the user (e.g., their voice or facial expressions). We also chose this cue in order to produce meaningful data to visualize, as past research has used music to elicit complex brain activity [234, 257]. The audio track ("Dream" by Rabpit, Deemo-version) was two minutes long, and was chosen for its evocative nature and its inclusion of a section with ambient crowd noise (to provide a minimal social prompt for impression formation). Given the research on "thin slices" of behaviors [12], we believed that two minutes would be sufficient for participants to form their impressions. All six visualizations used the same originally recorded brain activity as input.

Measures

In order to explore general reactions to the expressive biosignal system and initial impressions of the person whose brain activity they were watching (the target), we included a number of open-ended questions for participants to answer for each visualization recording. These included questions about what participants noticed in the visualization, their impression of the target, and their feelings about potentially using the visualization in a social interaction. We also included open-ended questions about their general reactions to the visualizations, including which they would prefer to use for different purposes (e.g., to provide impressions of themselves to others, form impressions of others, and predict how well they would get along with or work with someone).

In addition to the open-ended responses, we included several validated scales to assess participants' impressions of the target in each recording along specific dimensions:

Ten Item Personality Inventory/TIPI The TIPI is a ten-item scale used to assess the "Big Five" dimensions of personality (extraversion, agreeableness, conscientiousness, emotional stability, openness to experiences) [106]. Because participants would need to answer questions for individual visualizations six times, we chose to use this validated, short-form scale to reduce the time, redundancy, and fatigue that would otherwise be experienced with a longer personality scale.

Mind Attribution Mind attribution refers to the inferences people draw about the mental states of others, including their emotions, intentions, and thoughts [169]. Participants completed a ten-question scale assessing the extent to which they attributed different degrees of emotion (e.g., "This person has complex feelings"), intention (e.g., "This person has goals"), and cognition (e.g., "This person can engage in a great deal of thought") to the target.

Ambiguous and Positive Impressions We used Tanis and colleagues' six-question scale to assess the ambiguity and positivity of the impression participants formed of the target [282]. We modified the original scale by removing questions about the content of discussion, since participants did not interact with the target. We added two questions about how clearly participants could predict getting along or working well with the target. These items were included to assess whether participants felt they could use the visualizations to predict the quality of interactions in different contexts.

Finally, we include a visualization scale to assess the quality and effectiveness of each visualization. These included the amount of information the visualization presented, the clarity of the visualization and its changes in states, its intuitiveness, and its aesthetic qualities [201].

Procedure

Participants completed this study individually in a controlled laboratory setting. They took about one hour to complete the study, which involved completing experimental tasks on a computer screen. They were told that the research team had collected brain activity from people who had listened to a music clip while wearing an EEG headset, and that they would be viewing six visualization recordings of brain activity data and completing questionnaires about what they observed.

To ensure that participants understood the meaning of the brain activity, definitions of the three brain waves were accessible on-screen while they watched the visualizations. These definitions were also provided to support the impressions that participants would form. Participants completed a pretest assessing their understanding of these definitions.

Next, participants viewed six visualization recordings, one after another, presented to them individually in a random order. While participants viewed the recordings, they were able to hear the original audio that the target had listened to, without seeing the target person. With the exception of the Light, participants viewed screen recordings of the visualizations. Because the Light was physical rather than screen-based, participants were instructed to inform the experimenter when they were to view that visualization, at which point the experimenter set up the Light system next to the participant. After each recording, participants answered questions about the visualization. Once participants finished watching all of the recordings, they answered questions about their overall reactions to the visualizations. These questions are described in the previous section.

Though each visualization displayed the same recorded brain activity, we wanted to test whether participants would notice that the activity was the same. After participants watched all of the recordings and answered all of the above questions, we asked participants to answer whether they perceived that the data behind each visualization came from the same person.

Finally, at the end of the survey, participants completed demographic information, including questions about their gender, race, and age. We also asked participants whether they had any prior experience with EEG or brain-sensing headsets, and if so, to describe the nature of that experience.

Analysis

We performed analysis of the open-ended responses and survey scales using qualitative and quantitative methods.

We analyzed the open-ended responses using a grounded theory approach [273]. First, we reviewed a subset of the responses from each category of questions (e.g., impressions of the target, feelings about using visualization in an interaction) developing codes according to similarities in participants' observations and opinions. For example, for impressions, we developed codes for similarities in mentioned traits (e.g., "intellectual") versus states (e.g., "thinking"). Two raters used these codes to perform open coding independently on the same subset of responses to clarify their definitions. Then, the two raters independently coded the rest of the responses, meeting frequently to resolve differences and ensure high inter-rater reliability (overall Cohen's $\kappa = 0.74$). Finally, we performed axial coding, counting and grouping similar codes, and comparing them across visualizations to form higher-level themes.

We analyzed effects of the visualization type on the TIPI, Mind Attribution, Ambiguous/Positive Impressions, and Visualization scales using a repeated measures ANOVA, looking for distinct differences between the mean ratings of impressions and design quality. Since the brain activity was the same across all visualizations, we initially included participants' answers to whether they perceived it was the same as a between-subjects factor. However, we found no significant effects of this factor; therefore, we report the results for the full sample.

The results from both analyses were examined together during the writing process in order to refine overarching themes around participants' impressions from the different visualizations, and reactions to the expressive biosignal system. These results are discussed in the following section.

4.1.6 Results

Our results showed that participants were interested in visualizing brain activity and using visualizations for social perception and communication purposes; however, a number of concerns and challenges emerged regarding integration of these visualizations into social contexts. In this section, we discuss major themes formed in our analysis around the issues and needs to be addressed in developing expressive biosignal systems.

Perceptions of mental states and traits

Participants were generally willing to form impressions of the target when asked–only 19 of the 192 responses explicitly mentioned having difficulty or being unable to form any impression from the data. Participants usually described their impressions in terms of psychological states (112 responses) as opposed to traits (25 responses). As expected, mentioned states were typically tied to the presence of the different wave types and related to the associated states that we provided:

> "*Considering the amount of delta waves, I suggest the person was sleeping or feeling tired.*" - BV-7

> "*They were somewhat scattered, moving between very relaxed* (*deep sleep, green*) *and focused thinking* (*yellow*). *They were not focused on the music or enjoying it very much.*" - BV-41

Generally, users were less open to inferring stable traits than states from the visualizations. Most trait-related responses pointed out that the target is likely "an average individual." However, a few responses described him in terms of emotional stability (14), complexity of thought (12), or sociability (6):

> "*...seems to be a planner and a worrier.*" - BV-75

> "*Scientific, calculating.*" - BV-52

> "*They are very aloof, but when they meet others, they start to worry what the other people think of them.*" - BV-65

These traits appear to have been inferred from perceptions of the target's states throughout the audio. For instance, one participant who felt that the target is "very reserved and shy and doesn't like to go out much," also noted that "when there were others talking, the person was usually in deep sleep."

Influence of design features on impressions

Despite each visualization displaying the same brain activity, participants formed diverse impressions of the target across the different visualizations (Table 4.2). For instance, impressions that the target was relaxed were more present in responses to the Sliders (8) than to the Swirl (2). On the other hand, participants more commonly believed the target was in thought when watching the Swirl (8) as opposed to the Sliders (0). Trait-related responses similarly differed across visualizations:

> Colors: "*[S]omeone who is relaxed and stable.*" - BV-12
>
> Graph: "*A nervus [sic] wreck.*" - BV-84

Table 4.2: Prominent states mentioned in impressions, with associated brain waves in parentheses.

Visualization	States Mentioned
Graph	Sleep (delta), relaxation (alpha)
Sliders	Sleep (delta), relaxation (alpha), focus (beta)
Swirl	Thinking, focus (beta)
Colors	Either sleep (delta), relaxation (alpha), thinking, or focus (beta)
Light	Moving between sleep (delta), relaxation (alpha), thinking (beta)
Emoji	Sleep (delta), relaxation (alpha)

Salience of changes in activity These differences in impressions stemmed in part from the degree to which the different visualizations depicted changes in the different wave activity.

In particular, interpreted visualizations, which manipulated the display of the data, affected the prominence of certain waves. For instance, though beta was actually the least active wave in the data, participants primarily noticed high beta waves in the Swirl recording. This appeared to result from the mapping of beta to the number of lines present, which was more salient than the speed of the lines (delta) or smoothness of the lines (alpha). Subsequently, participants believed that the target was concentrating and thinking heavily while listening to the audio.

> "*It was much easier to tell when the person was concentrating vs. when they were not. Other than that, it was difficult to tell when the waves were changing*." - BV-37

> "*Not much - the number of lines representing beta waves seemed consistently high*." - BV-43

Salience of activity in all brain waves affected impressions formed from the Light recording. Since the Light constantly changed colors based on the brain wave with the highest relative value at the time, all three waves appeared to be prominent throughout the recording. Thus, participants noted that the target experienced multiple states:

> "*Very confused person who's going in and out of deep sleep, relaxation and concentration at the same time. Maybe the person is trying to relax and almost falling asleep, but is disturbed by the noise*." - BV-69

Visualizations that mapped data to the opacity of displayed images (Colors, Emoji) made changes in brain activity less conspicuous. For the Colors, all colors mapped to different waves were technically present at different opacities, but discerning the most prominent color might have been too difficult or too subtle (e.g., "more green" versus "more yellow"). Impressions made from Colors were generally in disagreement:

> "*Person is just relaxing on a nice day and watching the world go by*." - BV-69

> "*Not very relaxed, always engaged and active*." - BV-60

Similarly, for the Emoji, participants had difficulty determining which emoji was more opaque:

> "*...sometimes it was hard to differentiate between which one was lit up*" - BV-75

On the other hand, more raw visualizations that allowed for side-by-side comparisons of waves (Graph, Sliders) highlighted the high activity of delta waves, leading to expected descriptions of sleepy states. However, in addition to sleepy states, participants mentioned that the target might be relaxed or focused. Given that participants did not notice meaningful alpha or beta activity, it's possible that they projected their own feelings in their impressions in these cases, such as due to the relaxing nature of the provided audio:

> "*I think they would have felt relaxed, I know I did. Even the voices acted as a sort of white noise to mellow things out even futher [sic].*" – BV-91

Results from the repeated measures ANOVA for the Mind Attribution scale support findings around salient changes in each visualization (Table 4.3). Visualization type had significant effects on the Emotion ($F(5,155) = 2.50, p = 0.03$) and Cognition (with Huynh-Feldt correction, $\epsilon = 0.88; F(4.42, 135.58) = 3.20, p = 0.01$) components, as well as the overall Mind Attribution Score (with Huynh-Feldt correction, $\epsilon = 0.88; F(4.42, 136.99) = 3.00, p = 0.02$), which is the sum of the Emotion, Intention, and Cognition scores (Cronbach's α ranging from 0.68 to 0.93). More interpreted visualizations (e.g., the Light and Swirl) tended to lead to higher scores. The Swirl, which made beta waves more salient, was scored higher for cognition than other visualizations. The Light scored higher for emotion, potentially due to exposure to frequent color changes signaling changes in emotional state.

Visualization style and personality Different visualization styles may have also affected participants' impressions, particularly along the personality dimension. Though participants tended not to infer stable traits in their open-ended responses, results from the repeated measures ANOVA showed significant differences across visualizations for the TIPI scale (Table 4.3). Participants perceived differences in the target's Extraversion (with Huynh-Feldt correction, $\epsilon = 0.82; F(4.09, 126.8) = 2.48, p = 0.05$) and Emotional Stability (with Huynh-Feldt correction, $\epsilon = 0.91; F(4.53, 140.55) = 3.88, p = 0.003$) across

Table 4.3: Means of measures with significant differences across visualizations, with standard deviations in parentheses. Means that do not share a superscript significantly differed at $p \leq 0.05$. Visualizations with the highest and lowest means are listed in the last two columns.

Measure	Graph	Sliders	Swirl	Colors	Light	Emoji	Highest	Lowest
TIPI (/7)								
Extraversion	3.50^{c} (0.84)	$3.95^{a,b}$ (0.72)	4.30^{a} (1.23)	$3.75^{a,b,c}$ (1.13)	$3.95^{a,b,c}$ (1.28)	$3.53^{b,c}$ (1.32)	Swirl	Graph
Emotional Stability	4.14^{b} (1.19)	4.09^{b} (0.95)	4.06^{b} (0.97)	$4.55^{a,b}$ (1.25)	4.47^{b} (1.24)	5.09^{a} (1.09)	Emoji	Swirl
MIND ATTRIBUTION								
Emotion (/28)	19.13^{b} (4.10)	19.41^{b} (3.17)	$20.06^{a,b}$ (3.45)	$19.81^{a,b}$ (3.44)	20.50^{a} (3.11)	18.66^{b} (3.91)	Light	Emoji
Cognition (/21)	$13.16^{b,c}$ (3.30)	12.84^{c} (2.69)	14.59^{a} (2.86)	$14.31^{a,b}$ (2.65)	$14.41^{a,b}$ (2.89)	$13.09^{b,c}$ (3.46)	Swirl	Sliders
Mind Attribution (/70)	45.25^{b} (9.73)	46.03^{b} (7.50)	48.88^{a} (7.63)	$48.44^{a,b}$ (7.93)	48.91^{a} (8.17)	45.06^{b} (9.09)	Light	Emoji
AMBIGUOUS/POSITIVE IMPRESSIONS (/7)								
Feelings of Connection	3.00^{c} (1.41)	$3.50^{a,b}$ (1.61)	$3.59^{a,b}$ (1.24)	3.38^{c} (1.68)	4.06^{a} (1.63)	$3.69^{a,b,c}$ (1.73)	Light	Graph
VISUALIZATION (/5)								
Clear Changes	3.72^{a} (0.96)	4.03^{a} (1.00)	$2.81^{b,c}$ (1.18)	2.31^{c} (1.23)	4.13^{a} (0.79)	2.97^{b} (1.36)	Light	Colors
Easily Understand Current State	$3.44^{b,c}$ (0.98)	$3.81^{a,b}$ (1.12)	$2.72^{d,e}$ (1.17)	2.41^{e} (1.19)	3.94^{a} (0.80)	$3.16^{c,d}$ (1.14)	Light	Colors
Aesthetically Pleasing	3.22^{b} (1.10)	3.63^{b} (0.91)	3.41^{b} (1.04)	3.47^{b} (1.08)	4.25^{a} (0.80)	3.22^{a} (1.21)	Light	Emoji/Graph
Intuitive	3.13^{b} (1.13)	3.59^{a} (1.16)	2.66^{c} (1.18)	$2.81^{b,c}$ (1.40)	$3.31^{a,b}$ (1.15)	3.69^{a} (1.09)	Emoji	Swirl

visualizations. An LSD post-hoc test for these traits showed that the Swirl and Sliders had the highest mean ratings for Extraversion, while the Emoji had the highest for Emotional Stability (p-values below 0.03).

Characteristics of the visualizations likely influenced participants' judgments of the target's personality. For instance, the Swirl, Sliders, and Light may have produced the highest extraversion ratings as a result of their more animated, rapidly changing visuals, as high extraversion tends to be associated with high motion activity [166]. Lines were constantly swirling, circles were moving back and forth, or distinct colors kept changing, as compared to the slow right-to-left stream of the Graph or subtle opacity changes in the Emoji or Colors:

> Sliders: *The circles were changing quickly, and one circle would go from the farthest to the right to all the way on the left within a split second*. - BV-37

The high emotional stability rating for the Emoji was also likely to be influenced by the emojis provided in the visualizations. Emojis are a common representation of emotions; thus, participants may have inferred a limited range of emotions since we only showed three emojis. This may have also led to its low emotion score rating in the Mind Attribution scale.

> "*People already have preconceived ideas of what an emoji ought to represent, it would be very misleading to use only three symbols for the wide range of brain activity*." - BV-7

Visualization Preferences

Clarity and visual appeal We found that participants preferred visualizations that they believed to be "clear" in terms of their comprehensibility and representation of the brain activity, as well as visually appealing. The visualization most preferred by participants was the Light, for providing impressions of themselves, forming impressions of other people, and predicting how well they would work with someone else. People believed that the color changes were easy to notice, pleasant, and soothing to view:

> "*It was really easy to know what my brain was doing and the most interesting*." - BV-98
>
> "*The LED is soft and relaxing it has a calming affect [sic] to it, I just like it a lot*." - BV-87

Participants also preferred the more raw Sliders and Graph. Seven participants chose the Sliders to provide an impression of oneself to another person, primarily for being very easy to understand. Six to eight participants chose the Graph for forming impressions of other people and predicting interaction quality (getting along or working well with someone). Those who chose the Graph believed it was the most straightforward, familiar, and "clinical," trusting it for showing data as is:

"*It's self-explanatory and easy to interpret.*" - BV-70

"*I always believe in graphs, they provide the data correctly.*" - BV-92

Participants' preferences for visualizations were also reflected in the repeated measures ANOVA for the Visualization scale. Visualizations differed significantly in clarity of changes ($F(5, 155) = 14.64, p < 0.0005$), ease of understanding the current state ($F(5, 155) = 11.00, p < 0.0005$), and aesthetics (with Huynh-Feldt correction, $\epsilon = 0.90$; $F(5, 139.25) = 4.55, p = 0.001$), with an LSD post-hoc analysis showing that the Sliders, Light, and Graph were the most highly rated for clarity and understanding, and Light for aesthetics.

In addition, a third of the participants preferred the Emoji to predict positive interactions with another person. Like the Graph, participants felt familiar with the Emoji. The Emoji made emotions easily recognizable and "straightforward," which participants felt is important for predicting the quality of an interaction. The Emoji was also rated as the most intuitive from the visualization scale, where intuitiveness was significantly different between visualizations ($F(5, 155) = 4.57, p = 0.001$).

Perceptions of information levels on accurate understanding Participants also desired to present and glean accurate information from the brain activity shown in the visualizations. Participants expressed varied opinions about how that information should be conveyed. Eight participants believed that it was more important for the visualization to leave room for subjective inferences or show less information, such as in the more interpreted Light or Colors:

"*I thought that the LED light provides again a non-deterministic way of 'judging' someone without being too absolute*." - BV-69

"*The color gradient is the most vague of all the visualizations. This would be most beneficial to me because I would not need to act a certain way, the vagueness of the colors leaves that up to interpretation*." - BV-7

On the other hand, twelve participants preferred visualizations that they perceived to have more information, such as in the more raw Graph or Slider, primarily for forming an impression of or predicting the quality of interaction with another person. These participants believed that more information would help them better understand the other person:

Graph: "*It could show the change on how well we get together as a function of time, and you could see growth and decay of the relationship clearly*." - BV-65

Sliders: "*This visualization seemed to give me the most information, so I feel like I would be best able to judge more information about that person's state of mind to complete a task together*." - BV-41

Concerns about Privacy

Though participants felt that the visualizations would be informative, a third of their responses mentioned concerns that they would be too revealing and intrude on privacy. Many concerned participants mentioned they would be more interested in viewing their own, rather than others' brain activity:

"*I think it would be personally violating to see someone else's brain activity when speaking to them. I would be interested in seeing my own information because it might allow me to figure out when I'm thinking too hard and I need to relax*." - BV-91

The visualization that brought up the most concerns about privacy was the Sliders. Potentially, participants perceived that it revealed more information than they felt comfortable with. The Sliders made it easy to compare the different waves to each other and thus make assumptions about states.

> "*It might feel intrusive because it clearly provides a lot of information rather than general trends in brain activity*." - BV-41

Visualizations that provided less information appeared to garner fewer concerns about privacy. Regarding communicating with others with the Colors, one participant mentioned:

> "*I would feel comfortable; there doesn't seem to be very much information associated with each color so it's not too intrusive. It's also not super clear when one color fades into another*." - BV-60

However, less information may not always be positive. For instance, participants had the least privacy concerns for the Swirl. This may have been due to the fact that the Swirl was the hardest visualization to understand, and participants mentioned it was "confusing" and "difficult" using it to gain meaningful insight about the target's mental state. The complexity of the visualization could help ensure that the brain activity is not too revealing; however, a visualization that is difficult to decipher is less likely to provide any useful information at all.

Cognitive Load

Many participants were also concerned that the visualizations would be distracting if used during social interactions. They felt that a visualization would detract from a conversation because they would focus too much on understanding it and not attending to the other person. This concern was primarily expressed for the Swirl, which people believed would take more effort to interpret because of its complexity:

> "*I feel distracted because it takes quite a lot effort to analyze and interpret the visual information of the person's brain activity*." - BV-23

The Graph and Sliders were also considered distracting. Potentially, this may be because they show a lot of information at once. Viewers would have to process changes in all three brain waves over time and compare them to each other, thus taking away from conversation. However, participants were less concerned about distraction when they imagined using the visualizations for computer-mediated communication (9 responses, as compared to 26 for face-to-face). They felt that in mediated settings, they would be able to focus on the visualization more because there is less expectation to look at the other person than in face-to-face settings, and there would be more time to consider the visualization and manage self-presentation. The Emoji, in particular, was viewed positively since emojis are often used in mediated settings.

> Graph: "*When we're online we are usually multitasking, so it would almost make sense in this case*." - BV-37

> Swirl: "*I think I feel better than face-to-face, because now I have time to consider the other person's reaction and adjust my reactions*." - BV-92

> Emoji: "*It would fit in well in online communication, because emojis are already used there*" - BV-41

Feelings of Connection

Despite concerns around privacy and cognitive load, the open-ended responses also indicated interest in expressive biosignal systems from participants. 16 of the responses noted that the visualizations would be useful for providing an "additional layer of communication" that could people understand the mental states of other users and, subsequently, better consider their own reactions and behaviors. Generally, positivity around the system emerged while considering computer-mediated contexts, rather than face-to-face, given the limitations in existing cues that might cause communication issues:

> "*I think viewing brain activity during online chat is effective in helping me understanding the other person's reactions. It would cause less confusion or misunderstanding*." - BV-23

Certain representations of brain activity may also be more useful than others in promoting feelings of connection with others. Results from the repeated measures ANOVA ($F(5, 155) = 2.48, p = 0.03$) and LSD post-hoc analysis showed that these feelings were significantly higher for the Light visualization than others. Comments for the Light visualization in the open-ended responses similarly suggested its potential for connecting people through brain activity:

> "*Also, it may be easier to trust someone else by watching his actual brain activity. You feel like you know this person from deep heart*." - BV-77
>
> "*[I]t would be cool for an app that could allow couples to see what their partner is feeling over long distances*." - BV-26

This suggested connectedness may have been due to the physical and ambient presentation of the Light, as previous research has shown that ambient light can promote connectedness between remote individuals [210]. These feelings were also significantly higher than for the raw Graph, potentially due to the Graph's "clinical" appearance distancing participants from the target.

4.1.7 General Discussion

On the whole, our results reveal the potential for the sensing and sharing of physiological response data to influence interpersonal judgments and perceptions. At the same time, they elucidate key challenges that must be addressed in the design and implementation of expressive biosignal systems in order for them to effectively augment or improve self-expression and communication.

Brain activity as a social cue

We had participants rate their impressions of an individual while viewing that individual's brain activity, which was recorded while they listened to music. Our results show that, to some degree, individuals *are* willing to rely on expressive biosignals to form impressions about others. Participants drew the strongest conclusions about another individual's cognitive or emotional states based on their displayed data, as evidenced by the results on their open-ended responses and the Mind Attribution measure. Moreover, they reserved their most significant inferences about personality to the two traits of the "Big Five" that relate most strongly to emotional states (neuroticism/emotional stability) and cognitive states (extraversion/introversion, which has been shown to be linked with levels of cognitive arousal [204]). These findings show that participants were more willing to use expressive biosignals to draw conclusions about psychological states (i.e., a person's currently experienced emotions or level of cognitive activity) than they were to infer a person's stable dispositional traits. However, at the same time, we found that the impressions that participants formed varied widely depending on the visualization. Like other biosignals [132], the meaning of brain activity was indeed ambiguous and led to multiple interpretations, particularly as a result of different visualization design features.

Effect of different representations on impression formation

We compared various visualizations that were either more raw or interpreted in nature [119], yet displayed the same data. The different visualization formats significantly influenced participants' inferences. For interpreted representations, the manner in which the different brain waves were translated made certain changes more salient (e.g., noticeable beta waves-only for the Swirl, all waves for the Light). Raw representations, which allowed for more straightforward numerical comparison between waves, had more consensus in responses, suggesting that translating too far from the raw data could confuse viewers' observations of changes in the data. Additionally, independent of representation type, stylistic aspects of visualizations appeared to affect impressions based on participants' preconceptions (e.g., high motion with extraversion [166], emojis with emotions). Our work demonstrates that certain features of biosignals visualizations, such as imagery, animation, and amount of information, can produce diverse impressions even on the same data.

Considerations for communication contexts

We asked participants to describe their feelings about using each visualization in face-to-face and computer-mediated communication. In their responses, participants exhibited reservations about having access to another individual's biosignals, expressing concerns about violation of privacy or distraction from an interaction. At the same time, they desired to learn and provide enough useful social information through the visualization to support an interaction. Participants' preferences for visualizations thus varied based on how clear and informative the visualizations appeared. The Swirl sparked the least amount of concern for privacy, but was also the least preferred for being too complicated and unintuitive. The more raw Sliders was highly rated for its clarity, but also elicited privacy concerns because comparisons between brain waves were so easy to make. These visualization preferences and concerns point to the need to explore the right balance and comfort levels for addressing issues related to ambiguity, privacy, and cognitive load in expressive biosignal systems used for communication.

4.1.8 Design Implications

We present three major design considerations for the development of expressive biosignal systems, drawn from the results of our study and our plan for future work.

Designing for disambiguation

As the results of the present work demonstrate, an expressive biosignal system must account for individuals' subjective impressions from sensed data and, moreover, address the possibility that their interpretations may fail to align with the actual meaning of the data (i.e., the subjective experience or the true cognitive or emotional state of the individual whose data are being shared). Going forward, one critical question to be addressed is whether biosignals are equally ambiguous for those whose data are being sensed and those with whom the data is being shared: that is, are individuals uncertain about the meaning of both their own and others' data? If individuals indeed have some degree of insight about the connection between their current state of mental activity or emotional response and the corresponding changes in biosignal, perhaps systems that provide them with the agency to disambiguate their own biosignals will be key. The means of clarification might lie in visualization schemes that provide clearer connotations of a particular cognitive or emotional state (and the ability to choose between alternative schemes in sharing data) or the provision of tools that link physiological responses to disambiguating contextual cues. In the following chapters, I investigate these possibilities in new visualization schemes that represent discrete states, as well as the use of narrative text as a contextual cue.

Designing for privacy preservation

Because expressive biosignals by their very nature involve displaying personal information that is not typically public, designing systems that preserve users' preferred level of privacy–in regard to who should have access to the data and how it should be shared–is critical. Expressive biosignal systems may require flexibility in allowing users to opt for publicly visible versus privately displayed settings depending on interaction contexts or relationships. In some contexts, the value of expressive biosignals may lie more in the self-reflection it promotes [132]–for instance, when we desire to be mindful of our own physiological responses and their impact on our behaviors. In other situations, publicly displaying data may allow for individuals to better synchronize with and understand each other. For the rest of my thesis work, I focus on systems that enable private sharing as part of dyadic interpersonal communication, in order to explore how people communicate with each other when they have control over the biosignals they share with another person. However, future work outside of the scope of this thesis should investigate the impact and implications of personal and public biosignal displays and identify the contexts in which each is likely to be more desirable for preserving users' privacy while providing information that can help improve communication. For example, public sharing related to stress may be useful in tasks like advice giving, in order to consider the state of someone being counseled or providing advice. Indicators of cognitive processing may be useful in interviews or cooperative work, but may only be appropriate in anonymized displays to counter the potential discomfort of being exposed in a professional setting.

Designing for seamless integration

We also need to consider the cognitive load that is inherent in increasing the number of expressive nonverbal cues to which one must attend during impression formation or interpersonal interactions. Brain activity, in particular, can be difficult to follow due to its inherent complexity. EEG data is already a novel and unfamiliar element in typical social situations, and having to understand the meaning of different brain waves and interpret them from visualizations may end up being more distracting than supportive. These issues may be heightened in collocated interaction, when interaction partners' attentiveness to each other is more apparent and consequential. As alluded to by a number of our study's participants, in order to reduce the cognitive processing required for interpreting physiological data, expressive biosignal systems need to present the data in a clear yet unobtrusive manner. In addition to pre-interaction training for biosignals and orientation to how they are presented, systems may need to deliver feedback at only critical moments in an interaction. For instance, biosignals could be shared early on in an interaction, when impression formation is most key, or during high levels of excitement or engagement to enhance positive feelings or interest shown at that moment. Additionally, the platform on which biosignals are communicated may have important effects on people's ability to attend to the biosignals. Ambient lightbulbs that blend into one's environment or wearable displays that can be easily accessed may be less disruptive than viewing a constantly changing graph on a computer screen. In Chapters 5 and 6, I explore the seamless integration of biosignals by displaying them as short animations on smartwatches, which can be quickly glanced at on the wrist throughout the day.

4.1.9 Limitations

We conducted a study to explore how people form impressions of another person from different visualizations of that person's brain activity. While our findings contribute important design considerations for expressive biosignals systems, our work has some limitations. First, our study was designed such that participants did not interact with the target, and could only form their impressions based on how the target's brain activity changed with the progression of a piece of music. This was done in order to isolate the available cues, as interacting with the target would introduce additional cues that are known to influence impressions (e.g., visible nonverbal behaviors, manner of speaking, etc. [103, 243]). In Chapter 5, I aim to understand how to integrate expressive biosignals into dyadic communication, taking into account participants' feedback about the opportunities and issues in using these systems in actual interactions.

Second, participants did not have prior knowledge about brain activity, and were only given brief definitions of different EEG waves with which to base their interpretations. While we based our study design on the methodology employed in the "thin slices" body of research, we note that the nonverbal behavioral cues we typically depend on are those we have developed familiarity with over a long term. Participants were willing to form impressions based on their understanding of how mental states might change with changes in the brain waves; however, it is possible that they would be more equipped to form impressions given a longer period to become familiar with brain activity as a potential cue. Our work supports that the data is indeed ambiguous, thus, training programs should consider providing different contexts in which brain activity can be interpreted. Future studies should investigate how much training and experience users might need to develop an appropriate understanding of the data in social settings. In the following chapters, I focus on heart rate as an expressive biosignal, given the greater accessibility and familiarity people that have with heart rate data.

Finally, the EEG data used in the present study was recorded from a user who wore the Muse headset while listening to music. We chose the Muse due to its unobtrusiveness and ease-of-use. However, as a consumer-grade headset with only seven sensors, the Muse is less accurate than research-grade headsets that have many more sensors. For the purposes of this study, we focused on how the data *visualizations* would affect impressions; thus, we felt that having great accuracy in the data was not necessary. Of course, future integration of brain activity as cues in real-world settings will require accurate and reliable data. As brain-sensing technology advances, future work should consider using consumer-grade headsets that improve in accuracy. Given the current limitations in consumer-grade brain-sensing headsets, I focus on heart rate for the rest of my dissertation work.

4.2 The Effects of Displaying Others' Biosignals

This chapter has been adapted from [192]. Next, I sought to measure the impact of viewing biosignals on a receiver's perceptions. I focused on empathy, or our ability to understand another person's feelings, since the previous chapter indicated that people can interpret emotional states and even feel connected with others when viewing their biosignals. Moreover, several prior exploratory studies suggest that they can raise our awareness of others' feelings [119, 132]. However, since these prior works tend to conflate the availability of biosignals with their visual presentation, I separated the two to answer the following questions:

- **RQ4.** How does the presence of biosignals information affect empathy?
- **RQ5.** How does the visualization of biosignals information affect empathy?

4.2.1 Summary

We explore the potential for expressive biosignals to influence perceptions of a member of a stigmatized group. In a between-subjects experiment (N=62) participants read a fictional interview with a drug addict in prison, and rated their empathy and closeness with the interviewee. Participants were randomly assigned to read either 1) the transcript of the interview by itself, 2) the transcript with a text description of the interviewee's heart rate, or 3) the transcript with a graph of the interviewee's heart rate. Results demonstrate that providing information about heart rate can increase empathy in terms of emotional perspective-taking. Additionally, visualizing the heart rate as a graph, as opposed to

text, can increase closeness. We discuss the implications of these results and present suggestions for future directions.

4.2.2 Introduction

Prior work that has explored expressive biosignals has begun to show that information about another person's biosignals can help facilitate empathy and social awareness [119, 132, 191] and, in some contexts, a greater sense of intimacy and connection [142, 190]. These results point to potential opportunities for expressive biosignals to support interventions for bridging understanding with others, such as contexts in which feeling empathy or closeness with others is challenging (e.g., with members of socially distant groups, or physically remote others). However, the relationship between expressive biosignals and social connection with others is not well-understood. In particular, prior work often conflates the presence of biosignal information with their visual presentation [119, 132, 142, 190], where it is unclear what forms of biosignal information can affect empathy and closeness.

Building on the foundation provided by expressive biosignals research, the present study aimed to investigate how both the *presence* of another individual's heart rate information and *visualization* of the heart rate data might affect empathy towards others and feelings of closeness between the self and other. Moreover, to provide a strong test of the impact of expressive biosignals on these outcomes, we explored their impact with a target other who belonged to a stigmatized group, for whom there are likely higher barriers to empathy and closeness to overcome. This work contributes an experiment that helps clarify the relationship between biosignals and social connection, specifically with a stigmatized group member, as well as the implications for these data to augment how people share experiences with each other online.

4.2.3 Research Context

Stigma and Drug Addiction

To understand the effects of expressive biosignals on empathy and closeness, we explore this relationship in the context of perceptions of stigmatized group members. Though research has defined stigma in various ways, in our work we refer to a stigmatized person as one who is "socially discredited" [104] or has "undesirable characteristics" that "set [them] apart from others" [147]. According to Goffman, stigmatized people can include those with "a known record of mental disorder, imprisonment, addiction, alcoholism, homosexuality, unemployment, suicidal attempts, and radical political behavior" [104].

For the purposes of our study, we focus on empathy and closeness towards a convicted drug addict. In line with Goffman's claim, research has shown evidence for the stigmatization of drug addicts by the general public, where people with addiction are more likely to be viewed as dangerous and be blamed for their condition [68, 193, 318]. A United States national survey with 709 participants found that the public had significantly more negative views on drug addiction as compared to mental illness, where respondants were significantly less willing to work with a drug addict, more likely to accept discrimination against drug addicts (e.g., denial of employment and housing), and more likely to oppose public policies supporting drug addicts (e.g., government spending for treatment), as compared to people with mental illness [25]. Stigma towards drug addicts is a major issue that can affect their ability to access treatment, discouraging addicts to seek treatment and affecting health professionals' willingness to provide treatment [71, 292].

Reduced Empathy towards Stigmatized Groups

The challenge of building empathy toward members of stigmatized groups is a firmly established area of inquiry within social psychology. Despite its benefits for facilitating interpersonal and intergroup harmony and mutual understanding, empathy is neither a universal nor an automatic response. Social boundaries created by in-group/out-group distinctions on social identity dimensions (such as race, religion, or political affiliation) as well as differences in background or experience have been shown to diminish behavioral, neural, and physiological expressions of empathy for the other [60, 61, 95, 321]. These failures of empathy, when an individual could potentially experience empathy toward the other but does not because of salient social and psychological factors, are particularly difficult to bridge when the target other is a member of a stigmatized population. For example, Decety and colleagues found that participants who watched brief video clips of individuals experiencing physical pain attributed lower levels of pain to them if they had been told beforehand that they were AIDS patients than if they were not given this information [76]. Of particular relevance to the present research is that research on empathy and stigma has often positioned particular stigmatized populations, including drug addicts, as "extreme out-groups" [92] that typically elicit patterns of dehumanization, including reduced levels of compassion and recognition of group members' mental states [53, 93].

Research Inspiration

The present study is a conceptual replication of one initially conduced by psychologist Daniel Batson and colleagues [29]. In their work, participants were asked to listen to an interview conducted with a drug addict and were provided with explicit instructions either to try to remain objective or to imagine the interviewee's feelings while listening to the account. This study found that those participants who had been instructed to imagine the interviewee's feelings showed higher rates of empathy and prosocial behavior (donating to a counseling service for drug addicts) as well as more positive attitudes toward drug addicts as a whole.

We chose Batson and colleagues' work as a basis for our research for several reasons. First, experimental control is necessary to isolate the effects of biosignals on empathy and closeness. External factors in-the-wild or aspects of synchronous communication channels (e.g., immediacy or appearance in face-to-face, text, and video) are more likely to confound results. Moreover, we wanted to draw from existing experimental research known to observe a clear increase in empathy, such that we could investigate whether biosignals could have the same effect. At the same time, using a vignette setup increases the ecological validity of the study. Textual vignettes are a common form in which people share and consume stories today, including on social media, blogs, discussion forums, and other online platforms. For example, similar to how Batson and colleagues used an interview with a drug addict, Humans of New York [271], a highly popular photo blog, shares stories (often about personal struggles) through text excerpts of street interviews conducted by the blogger, Brandon Stanton. Prior HCI research has also used vignettes in a similar way: Andalibi and Forte, for instance, used vignettes in the form of social media posts as a prompt to understand how people respond to sensitive disclosures online [15].

Representative of the typical approach to inducing empathy or perspective-taking, Batson and colleagues' study provides an explicit instruction to attempt to empathize with a target other. Similarly, research on perspective-taking, or achieving an understanding of another's mindset or experiences, has utilized explicit instructions to achieve similar outcomes for out-groups (e.g., imagining a day in the life of members of other races or nationalities) [75, 98, 310]. Finally, a third line of work has focused on strategically crafting personal narratives describing the experiences of stigmatized others in ways that induce greater connections and empathy, including adding cues to similarity between self and other early in the narrative or delaying the disclosure of the other's stigmatized identity to allow a connection to form prior to the revelation [150]. In the present work, we investigate whether simply providing access to a stigmatized other's heart rate data could serve a similar function to these experimental inductions: to provide a cue to attempt to connect with and to understand the perspective and emotional experience of the other.

Hypotheses

Presence of Biosignals and Empathy We expect biosignals to positively influence empathy towards stigmatized others. In light of prior work on biosignals, we hypothesize that biosignals increase empathy, as defined by emotional perspective-taking and empathic concern.

- **H1.** The presence of biosignal information will increase empathy.

Our work also explores how expressive biosignals affect behaviors and perceptions known to be related to increased empathy. Drawing from Batson and colleagues' original study [29], we predict that the presence of biosignal information will promote prosocial behavior and improved attitudes towards stigmatized groups.

- **H2.** The presence of biosignal information will increase prosocial behavior.
- **H3.** The presence of biosignal information will improve attitudes towards stigmatized groups.

Visualizing Biosignals and Closeness Prior work suggests that text depictions of biosignals may not be as vivid as an animated visualization or audio representation [190]. Thus, we expect that visualizing biosignals as a graph, as opposed to describing the biosignals in text, will increase closeness with and salience of a member of a stigmatized group. We choose a graph to visualize biosignals for two reasons. First, graphs are commonly used to visualize biosignals in both research [72, 209, 258] and consumer applications that track biosignals, such as Fitbit and Muse. Therefore, the graph provides a suitable baseline case that would be familiar to participants as well as ecologically valid with respect to how biosignals are typically visualized in the real-world today. Second, a graph would help control the information conveyed to participants. Prior work shows that design characteristics of different biosignals visualizations can have a significant effect on interpersonal perceptions [189]. For instance, perceptions could be confounded by prior associations people have with representations like an emoji or audio or vibrations of a heartbeat, which are all culturally embedded. In our work, using a graph to visualize biosignal information, we hypothesize:

- **H4.** Visualizing biosignal information will increase interpersonal closeness more than presenting biosignals information as text.
- **H5.** Visualizing biosignal information will increase the salience of a target more than presenting biosignal information as text.

4.2.4 Methodology

We ran a between-subjects experiment where participants read a series of interview excerpts. Participants were randomly assigned to one of three conditions corresponding to the type of heart rate data that accompanied the excerpts: 1) *No HR*, meaning no biosignal information was provided at all, 2) *HR Caption*, meaning a caption about the interviewee's heart rate was provided, and 3) *HR Graph*, meaning a caption about the interviewee's heart rate and a heart rate graph were provided.

Participants

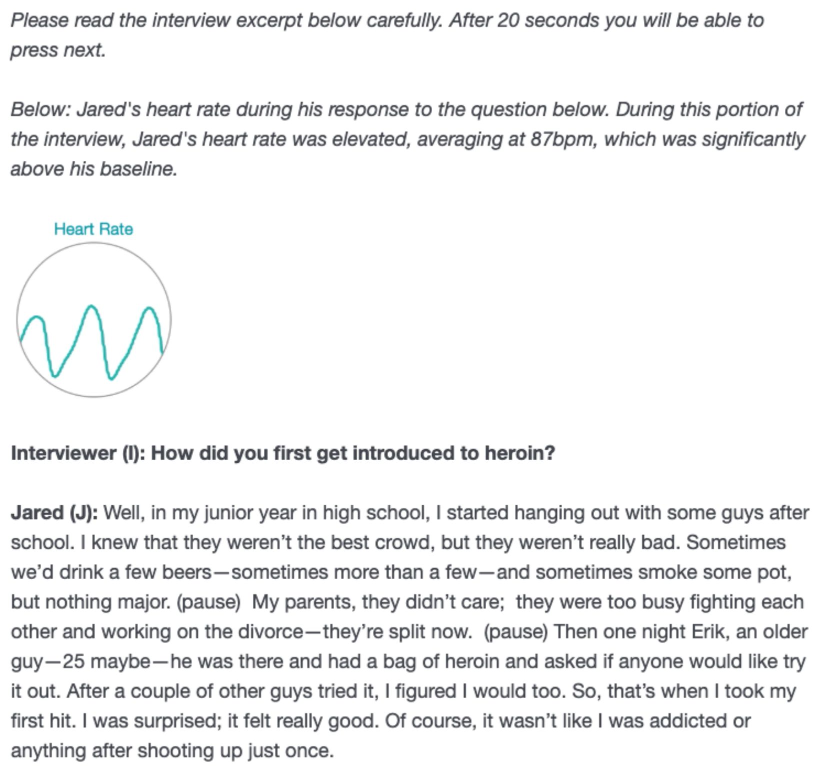
We recruited 72 participants from Amazon Mechanical Turk. We removed 10 participants who did not read or understand the materials in the online survey, based on their responses to the attention check questions we included. The remaining 62 participants included 24 females and 38 males, with an age range of 22 to 69 years old ($M_{\text{age}} = 37.47$, $SD_{\text{age}} = 10.16$). All participants were US Citizens. There were 23 participants in the *No HR* condition, 18 in the *HR Caption* condition, and 21 in the *HR Graph* condition. Participants were compensated $3.00 for participating in the study.

Procedure

We adapted our procedure from Batson and colleagues' prior work on empathy towards stigmatized groups, specifically drug addicts [29]. To increase ecological validity and believability, we modernized their materials with the cover story that we are creating an online platform for people to share personal experience with new forms of data (in this case, physiological data). The platform would be similar to existing online story-sharing websites such as forums and social media. Participants were told that we previously interviewed and recorded data from people from a variety of backgrounds, and that the purpose for the study was to collect reactions to the stories of our prior interviewees.

Participants completed the study by taking a 15-minute online survey. In the first part of the survey, participants read a transcript of a fictional interview. The fictional interview was conducted with a 22-year old man named Jared who was serving a 7-year sentence for possession and sale of heroin. In the transcript, Jared describes how he was introduced to heroin and became addicted, and his desire to start a better life after finishing his prison sentence. Though Batson and colleagues' original study used audio for Jared's interview, we decided to use text instead of richer channels, like audio or video, in order to reduce extra information and signals available to participants that could confound the results (e.g., Jared's voice or appearance).

In order to manipulate the presence of biosignal information we included two biosignal information conditions, one with (*HR Graph*) and one without a visual (*HR Caption*). Heart rate information is known to be ambiguous and can be interpreted in various ways [208]. In fact, in our preliminary pilots, many participants cited withdrawal as a cause for the changes in Jared's heart rate. To guide participants' interpretations around



Please read the interview excerpt below carefully. After 20 seconds you will be able to press next.

Below: Jared's heart rate during his response to the question below. During this portion of the interview, Jared's heart rate was elevated, averaging at 87bpm, which was significantly above his baseline.

Heart Rate

Interviewer (I): How did you first get introduced to heroin?

Jared (J): Well, in my junior year in high school, I started hanging out with some guys after school. I knew that they weren't the best crowd, but they weren't really bad. Sometimes we'd drink a few beers—sometimes more than a few—and sometimes smoke some pot, but nothing major. (pause) My parents, they didn't care; they were too busy fighting each other and working on the divorce—they're split now. (pause) Then one night Erik, an older guy—25 maybe—he was there and had a bag of heroin and asked if anyone would like try it out. After a couple of other guys tried it, I figured I would too. So, that's when I took my first hit. I was surprised; it felt really good. Of course, it wasn't like I was addicted or anything after shooting up just once.

Figure 4.2: Example screenshot of the interview excerpt in the *HR Graph* condition.

Jared's feelings rather than drugs, participants were told that Jared shared about his experience and feelings as part of the interview. This was done in all three conditions to ensure that participants in each condition had the same background information for the interviews.

In the *HR Graph* condition, participants viewed an animated graph of Jared's heart rate (represented by a per-beat graph). To ensure that participants in both conditions received the same amount of heart rate information, the provided caption was the same (that Jared's heart rate was elevated at an average beats per minute significantly above his baseline) and the graph was kept as neutral as possible (e.g., it kept a static rate of change and did not contain drastic peaks). To reduce potential differences in how participants related the graph to different sections of the interview, we split the transcript into four excerpts, where each excerpt included a question asked by the interviewer and Jared's response to that question. Each excerpt was shown with a section of the graph. To reduce variation between the graph information seen with each excerpt, graph sections changed at a similar rate and had a similar number of peaks. This was done in order to control the information we presented, such that Jared's heart rate would appear consistently high throughout the interview. An example screenshot of an excerpt in the *HR Graph* condition can be seen in Figure 4.2. Additionally, to control for the time spent reading Jared's responses and viewing the graph, participants were given 20 seconds for each excerpt. The *HR Caption* and *No HR* conditions followed a similar structure as the *HR Graph* condition, except without the graph and without the graph and caption, respectively.

After reading the transcript, participants answered several questions about the excerpts and their demographic information. The end of the survey included a debrief, explaining the purpose of the study and that Jared is a fictional person.

Measures

Participants answered questions related to their experience reading the excerpts and, if they were in either the *HR Caption* or *HR Graph conditions*, viewing Jared's heart rate information. They were also asked to answer questions about their perceptions of Jared and more generally, drug addicts. We included the following measures:

Empathy For our purposes, we operationalized empathy in two ways: empathic concern and emotional perspective-taking. Empathic concern refers to feeling *for* another person in need, and consists of emotions such as sympathy, compassion, warmth, tenderness, softheartedness, and being moved [26]. We included the six empathic concern items as part of a 15-item question asking participants to rate their feelings towards Jared. Emotional perspective-taking refers to inferring another person's emotional state based on their context [277]. To measure emotional perspective-taking, we used a shortened version of the PANAS scale, a widely used measure for perceptions of emotions, with items for positive and negative emotions [303]. We included five positive (excited, strong, enthusiastic, proud, determined) and five negative emotions (distressed, scared, hostile, ashamed, nervous) to cover a diverse and relevant set of emotions to Jared's story.

Prosocial Behavior Batson and colleague's prior work using the Jared interview suggests a positive relationship between empathy towards a stigmatized group member and prosocial behavior towards the whole group [29]. We included two measures of prosocial behavior: one that aligned with Batson and colleagues' use of donations as a measure of prosocial behavior, where MTurk participants could donate a portion of their HIT reward (ranging from $0 to $2.50 in increments of $0.50) to a local Addiction Counseling Service (with no connections to Jared), and another where they could leave a message of support for Jared.

Attitudes towards Stigmatized Groups Batson and colleagues' prior work also suggests a positive relationship between empathy towards a stigmatized group member and attitudes towards the whole group [28, 29]. Thus, we included a scale to measure attitudes towards people addicted to hard drugs (e.g., "People addicted to hard drugs lack self-control and inner strength.", "People who end up addicted to hard drugs only have themselves to blame" [29, 46]).

Closeness To measure interpersonal closeness, we used the Inclusion of the Other in the Self (IOS) scale [17], asking participants to use the scale to rate how they saw themselves in relation to Jared, and how similar to Jared they felt.

Salience of Jared To measure the salience of Jared, we included scales for social presence and experience taking. Social presence is the "degree of salience" of another person [265]. We included scales that highlight several aspects of social presence, including how "real" (as opposed to abstract) Jared seemed [171], the participants' ability to assess the Jared's reactions and get to know Jared [221], and the immediacy and intimacy of the excerpts [114]. Experience taking refers to the extent to which someone simulates a character in a narrative. This seven question scale includes items such as "I found myself feeling what Jared was feeling." [150].

Experience with Hard Drugs Participants' perceptions of Jared could be affected by their knowledge of and experience with hard drugs or users of hard drugs. Therefore, we included one question to measure participants' experience with hard drugs, asking participants to optionally respond to whether they or their loved ones (e.g., friends or family) had any experience with hard drugs.

Attention Check Finally, we included several questions to ensure that participants were reading and understanding the interview and graph. These included questions about details that Jared described in the interview itself (e.g., "What is Jared planning to do after his prison sentence?"), and details about the graph (e.g., "What was the graph plotting?").

4.2.5 Results

For each of the outcome measures reported we employed a one-way analysis of covariance (ANCOVA) and two planned contrasts to evaluate our hypotheses related to the presence and visualization of heart rate data: 1) a *presence* contrast that compared the *No HR* condition to the average of the *HR Caption* and *HR Graph* conditions (reflected in contrast coefficients of -1, .5, and .5, respectively), and 2) a *visualization* contrast that compared the *HR Caption* and *HR Graph* conditions (with contrast coefficients of -1 and 1). We also applied Bonferonni correction for ANOVAs on individual items within scales (i.e., dividing the critical p-value by the number of comparisons made). To control for effects of experience with hard drugs, we included responses to the experience with hard drugs measure as a covariate.

Table 4.4: Means of measures with significant differences across conditions at $p \leq 0.05$ (with Bonferonni correction for individual scale items). Empathy (PANAS) measures compared *No HR* vs *HR Caption* and *HR Graph*, while Closeness measures compared *HR Caption* vs *HR Graph*.

Measure	**No HR**	**HR Caption**	**HR Graph**
PANAS - Jared's feelings (/5)			
Nervous	2.30 (1.02)	3.39 (1.04)	3.29 (1.06)
Strong	2.57 (1.08)	1.83 (0.92)	1.62 (0.74)
IOS - Closeness to Jared (/7)			
Closeness in Relation	2.17 (1.07)	2.00 (1.03)	3.19 (1.72)
Similarity	2.09 (1.28)	1.67 (1.03)	2.71 (1.52)

Empathy

We conducted a one-way ANCOVA on the empathic concern and PANAS scales. We analyzed the PANAS scale by separating the sets of positive and negative emotions. Additionally, since Jared's story dealt with specific emotions, we analyzed individual items in the PANAS scale to investigate the most relevant emotions to the narrative. Results from the ANCOVA test on the empathic concern scale and PANAS positive or negative affect scales did not indicate significant differences between the conditions at $p \leq 0.05$. However, results from the ANCOVA test on the individual items of the PANAS indicated significant differences between conditions on two emotions (at $p \leq 0.01$): nervousness ($F(2, 58) = 7.17, p = 0.002$) and strength ($F(2, 58) = 6.12, p = 0.004$). Results from the planned *presence* contrast indicated significant increase in participants' perceptions of Jared's nervousness ($F(1, 58) = 14.34, p < 0.001$) and a significant decrease in perceptions of strength ($F(1, 58) = 11.57, p = 0.001$) in the two *HR* conditions compared to the *No HR* condition. These results partially support H1, where providing information on biosignals affected empathy in terms of emotional perspective-taking, but not empathic concern.

Prosocial Behavior and Attitudes

We conducted a one-way ANCOVA on donation amount and attitudes towards people addicted to hard drugs, and chi-square tests on whether participants donated at all or left a message of support. Results from these tests did not indicate a significant difference in participants' prosocial behavior (both for leaving donations and support messages) or attitudes towards people addicted to hard drugs between conditions. We reject H2 and H3, which predicted that the presence of biosignals information will increase prosocial behavior and improve attitudes towards stigmatized groups.

Interpersonal Closeness

We conducted a one-way ANOVA on the IOS closeness scale[1]. We also ran the *visualization* contrast on both scales. Results from the ANOVA test indicated a significant difference between conditions for how close participants felt in relation to Jared ($F(2, 59) = 4.86, p = 0.01$). Similarly, results from the ANCOVA test indicated a significant difference between conditions for how similar participants felt to Jared ($F(2, 58) = 3.26, p = 0.05$). Results from the planned contrast indicated that participants felt significantly closer in relation to Jared ($t(33.34^2) = 2.66, p = 0.01$) and more similar to Jared ($F(1, 58) = 6.35, p = 0.01$) in the *HR Graph* condition compared to the *HR Caption* condition. These results support H4, which predicted that visualizing biosignals, as opposed to presenting biosignals as text, will increase interpersonal closeness.

Salience of Jared

We conducted a one-way ANCOVA for each of the three social presence scales and the experience taking scales, including on both individual items from the scales. None of

[1]Since this measure did not meet the assumption of equal variances at $p = 0.007$, we ran an ANOVA instead of an ANCOVA, and a one-way ANCOVA on the IOS similarity scale

[2]We note that this result has a different degree of freedom because it does not assume equal variances.

these measures indicated significant differences between the conditions at $p \leq 0.05$. Thus, we reject H5, where visualizing biosignals information did not increase the salience of Jared more than simply presenting the information as text.

4.2.6 Discussion

Altogether, our results support and extend prior work by demonstrating the potential for expressive biosignals to function as a novel intervention for empathy and closeness. In particular, we show that providing information about heart rate can increase emotional perspective-taking for a stigmatized group member. Additionally, visualizing heart rate, as opposed to just describing it in text, can promote interpersonal closeness with a stigmatized group member.

Effects of Heart Rate Information on Empathy

Our results partially supported H1, which predicted that heart rate information, presented as a caption or in a graph, will increase empathy. We measured empathy in two ways: emotional perspective-taking and empathic concern. Participants reported significantly higher emotional perspective-taking when they saw information about Jared's heart rate alongside the interview, where Jared's nervousness and lack of strength was more salient. This supports and provides quantitative evidence for prior work [119, 132, 190, 191], showing that the presence of biosignal information provides cues that people use to infer someone's emotional state based on context. We also extend prior work by highlighting the potential for biosignals to affect empathy for a stigmatized group member.

However, our results did not show significant effects on empathic concern. One possible explanation is the limited modality of the interview, which was shown in text. Unlike Batson and colleagues' original study [29], we purposefully did not use an audio recording of Jared's whole interview. We included only text excerpts from the interview.

Given that audio is more contextually rich than text [77], potentially an audio recording combined with heart rate data is necessary to observe greater effects. Future work should explore comparing different modalities of communication (e.g., text, audio, video) with the presence or absence of heart rate data. Additionally, our results on emotional perspective-taking showed significant effects only for perceptions of Jared's nervousness and strength. Potentially, the salience of these emotions may not be as relevant to empathic concern as others, such as regret or worry (which are emotions present in narratives used in prior empathy work [28]). Another alternative explanation is the cultural context of the participants. Though we had asked participants about their experience with hard drugs or users of hard drugs, participants' attitudes towards drug addicts could have been indirectly affected by their cultural understanding of drug addiction (e.g., varying knowledge of drug addiction per US region, the recent declaration of the opioid crisis as a national emergency). Future work should explore the effect of biosignals information on perceptions of drug addicts in different cultures and regions, as well as perceptions of other stigmatized groups.

We did not observe an influence of biosignal presence on prosocial behavior or attitudes towards stigmatized groups. Given that we did not observe significant effects on empathic concern, this aligns with prior work about empathic concern and its related effects [28, 29]. Additionally, our analysis yielded a mean of $0.22 in donations, 7% of the amount they could donate (their payment for the task), as compared to 13% in the low empathy condition in Batson's original study [29], or roughly 10% in some studies on charitable giving [249, 256]. This is potentially due to limitations in our donation measure. The original study asked student participants if they were interested in allocating some of a (fictional) university committee's budget to an Addiction Counseling Service. In contrast, we asked MTurk participants to donate some of their personal funds from completing the task. Since participants were incentivized to participate based on money compensation, they were likely more attuned to their own funds than students were to their school committee's funds.

Effects of Heart Rate Visualization on Closeness

We show that a heart rate visualization, as opposed to just text describing a heart rate, can promote interpersonal closeness with a stigmatized group member: IOS ratings for participants' relation to Jared and similarity to Jared were significantly higher for the *HR Graph* condition than the *HR Caption* condition. This suggests that while simply providing heart rate information in different forms can help increase awareness of someone else's state, *visualizing* the heart rate changes is important for improving the relationship with that person. Moreover, our results extend past work showing the effects of audio heart rate cues on closeness [142]; we demonstrate that visual heart rate cues can similarly affect closeness, including for socially distant others.

At the same time, the heart rate visualization did not have significant effects on participants' ratings for social presence or experience taking. Potentially, the visualization we chose for heart rate, a graph, did not provide a vivid representation of Jared's feelings. Indeed, the form of a screen-based graph of raw data may be too "clinical," as compared to more physical or abstract forms such as a colored light bulb [189] or worn watch with haptic feedback [191]. In the following chapters, I explore the potential for both abstract and anthropomorphic visualizations displayed on a smartwatch, a device physically worn on the body, to affect the overall salience of the other person.

Implications for Technology

Our results support that expressive biosignals can influence perceptions of stigmatized others whose stories they read online. Online platforms are increasingly used to share and consume personal stories. These include popular social media sites like Twitter that encourage broad discourse using hashtags, blogs that collect and disseminate stories like Humans of New York or Hollaback!, anonymous forums like microaggressions.com, or Facebook groups that function as online support for health-related issues. While these platforms provide opportunities and outlets for people to share their experiences, the audience who will read or respond to those stories may not necessarily be able to connect with or understand them–as evidenced by known challenges in polarization, harassment, implicit biases online [21, 96, 146]. This can be exacerbated with the growing possibility to encounter diverse others online who may perceive them as stigmatized or part of an out-group.

The present research on expressive biosignals introduces a promising new direction for the use of physiological data to mitigate this divide on online platforms. Our results show that biosignals like heart rate can help people understand others' emotional state, which otherwise can be difficult to recognize when communicating at a distance. The presence of biosignals could augment stories shared online by increasing their emotional quality and helping people better express themselves. This could be especially helpful for highly emotional experiences that may be unfamiliar to others or difficult for someone to convey through just words. For instance, one might share an experience of stereotype threat alongside their heart rate information during the experience. The heart rate information could help others who are not familiar with stereotype threat to better recognize and understand its emotional effects. Additionally, our results suggest that incorporating vivid visualization schemes for biosignals would heighten feelings of closeness that may be difficult to experience with someone in a different social group. Platforms that incorporate biosignal data into story-sharing should consider representations beyond raw numbers, such as dynamic graphs, which could help readers of stories better connect with the storyteller. Designers of existing and future online platforms for story-sharing should explore the potential for integrating biosignals as a novel cue to enhance the creation and consumption of personal stories, as well as connection with storytellers.

With this call to action, however, we offer two crucial caveats. First, any application that entails the collection and display of personal data should prioritize the agency of users to preserve their own privacy and to choose how and with whom their biosignals are shared. People may have concerns about the intrusiveness of this intimate and sensitive data [189, 190]; thus, we need to understand the privacy controls that are necessary for this type of data [315]. In the present work, for example, we explicitly state that Jared agreed to share his heart rate data with participants. Second, because of the inherent ambiguity of biosignals and the potential authority imbued to systems that collect and display them, designers should provide users with the guidance for critical reflection and discussion of biosignals as part of users' interpretive process [133, 134].

4.2.7 Limitations

The present work revealed that accompanying a personal narrative from a member of a stigmatized group (individuals battling drug addiction) with access to that person's heart rate data and visualizations of that data facilitated greater emotional perspective-taking and perceived closeness, respectively. At the same time, the results did not show an impact of heart rate data on several key outcomes, most notably empathic concern and prosocial behavior. In future work, outside of the scope of this thesis, I aim to replicate the findings from the present study to other stigmatized groups (e.g., racial out-groups or members of different political parties) and, moreover, compare the relative impact of heart rate information and visualizations on perceptions and responses to non-stigmatized groups, as compared to stigmatized groups (or more broadly, between in-group and out-group members).

Additionally, outside of the scope of this thesis, I aim to extend the present findings on emotional perspective-taking and closeness through iterations on our study setup. This includes investigating other emotional states (beyond those studied in the present work), such as personal narratives about the uncertainty and anxiety faced by particular stigmatized out-groups (e.g., racial minorities) who experience prejudice and discrimination. In the next stages of my thesis, I also explore the design of different visualization schemes that might be more conducive to increasing connection with and salience of another person, including embodied and physical representations [189] that have shown promise in my previous work.

Finally, I reiterate that in the present research we prioritized high experimental control and internal validity, by relying on a previously established study protocol as a foundation and attempting to isolate the impact of biosignals displays on empathy and closeness. In Chapter 6, I aim to establish the external validity of these findings via a one-month field study conducted in a more naturalistic setting.

Chapter 5

Animo: Dyadic Biosignals Sharing on Smartwatches

This chapter has been adapted from [191]. The previous chapters have focused on only one-way biosignals sharing, isolating the sending and receiving components of communication to understand how people express and perceive biosignals, respectively. In this chapter, I investigate how these expressions and perceptions will develop in two-way sharing, including the interactions that interactants engage in when they can view each other's data, and how they build understanding around their biosignals together. I examine two-way communication to understand potential interaction patterns that arise when both people can share their biosignals, and explore smartwatches as a new platform to seamlessly integrate expressive biosignals. I focus on the following question:

- **RQ6.** How will people use expressive biosignals in dyadic communication on a smartwatch?

5.1 Summary

We present Animo, a smartwatch app that enables people to share and view each other's biosignals. We designed and engineered Animo to explore new ground for smartwatch-based biosignals social computing systems: identifying opportunities where these systems can support lightweight and mood-centric interactions. In our work we develop, explore, and evaluate several innovative features designed for dyadic communication of heart rate. We discuss the results of a two-week study (N=34), including new communication patterns participants engaged in, and outline the design landscape for communicating with biosignals on smartwatches.

5.2 Introduction

While research suggests that expressive biosignals can facilitate interpersonal communication, integrating biosignals seamlessly into communication remains a challenge. Given their novelty as a cue, expressive biosignals face issues in interpretation, cognitive load, and privacy [189, 190]. To address these issues and further explore the design space of expressive biosignals, we propose a new way to share biosignals: sharing them directly on smartwatches themselves.

Smartwatches could provide an unobtrusive and unique platform for sharing biosignals directly to another person. Many smartwatches already have built-in sensors that enable continuous monitoring of biosignals like heart rate (e.g., Apple Watch, Fitbit Versa, Mio SLICE, etc.), and thus do not require additional equipment to record the data. The form factor of a smartwatch could also afford intimate and vivid interpersonal communication. Being physically on the body, the device would be noticeable, easily accessible, and tangible–factors that can promote social presence and connectedness [138, 293].

Moreover, exploring expressive biosignals on smartwatches would advance research on smartwatch communication, which suggests that beyond simply extending text or call notifications [144], the smartwatch itself could offer a lightweight yet rich communication channel [159].

Our research is motivated by two questions. First, how does sharing biosignals on a smartwatch impact communication? Specifically, what kinds of communication does this afford and what patterns emerge? Second, how do people make sense of their own biosignals and develop that understanding with each other? Given that biosignals are often ambiguous [132, 189] and the smartwatch screen has limited space, we aim to pinpoint the information necessary for meaningful communication. We examine these questions through the design and deployment of a smartwatch app, and reflect on the design landscape that this work uncovers.

5.3 Background

Communication on Smartwatches

With the rising popularity of smartwatches, more researchers are exploring their capabilities. Given their ubiquitous nature and built-in sensors (e.g., biosensors, accelerometer, GPS, etc.), many works use smartwatches to understand and learn human behaviors, especially for health monitoring [14, 54, 290]. In a similar vein, research regarding the smartwatch user experience shows that personal monitoring activities, such as fitness and activity tracking, are some of the most popular features of the watch [144, 237, 272].

Fewer studies have explored the social applications of smartwatches. Mobile communication typically occurs via phone calls and text messaging, which are difficult on a small screen on the wrist. Subsequently, many researchers are exploring better text entry for small-screen devices [83, 105, 226, 314, 317]. However, we argue that smartwatches enable opportunities for communication less focused on text. In fact, much of communication online contains non-textual cues. Emojis are the most common, and are used for emotional information or for expressive and playful interactions [79, 313, 324]. People also share non-textual cues for their context, such as their location [203, 268, 280] or activity [89, 245]. Even "one-click communication," such as "liking" online social media posts, can provide diverse cues (e.g., support, agreement) [261].

Smartwatches have the capability of communicating in a non-textual way. Kim and colleagues provide one example: using the Yo app as inspiration, they suggest conveying affect or location through the smartwatch. Using simple yet expressive imagery (e.g., kinetic typography) or built-in sensors (e.g., GPS), they describe the potential for rich single touch messaging on the smartwatch [159]. In the present work, we build on this research by exploring the non-textual communicative abilities of the smartwatch, using biosignals.

Biosignals present an opportunity to explore novel and expressive communication cues afforded by the smartwatch. Most existing non-textual cues are easily accessible on platforms other than the smartwatch, such as smartphones or desktop computers. Biosignals, on the other hand, are more easily and unobtrusively accessed on the smartwatch than on other platforms. For example, smartphone apps that record heart rate require users to place their finger on the phone's camera for measurement, while smartwatches with heart rate sensors can record heart rate passively and continuously, only requiring users to wear the watch. Moreover, while emojis are the most common non-textual cue, there are hundreds of emojis with continuously evolving definitions [197, 213, 313], which increases the cost of communication when selecting one on a watch. Biosignals represent our body's immediate response to situations, and thus could provide more authentic and expressive cue by capturing the body's underlying state at specific moments.

5.4 Animo System

Design

Animo is a smartwatch app where two people can send mood representations, or "animos" (lower case), to each other. We referenced existing frameworks for augmented mobile messaging systems [51, 119] to inform the design of Animo. Though this prior work focused on augmenting text messaging for the phone, many of the same concepts can apply to non-textual smartwatch communication.

Content from Sender Buschek and colleagues' design space for augmented mobile messaging includes the "Sender Context" dimension, describing context as "information and cues beyond text" [51] to be included with a text message. Animo does not use text; therefore, we describe its communication *content*. Since our focus is biosignals, heart rate is the content type. Heart rate sensors are a common feature of many smartwatches, and people already associate heart rate with different psychological states, such as mood [266].

Previous studies demonstrate that simply showing heart rate as a raw value can limit expressiveness and appeal, and can be difficult to understand [51, 190]. Thus, inspired by the popularity of mood rings, we chose to represent heart rate as "mood," to guide engagement and understanding.

The *system* is the *content provider*, where Animo shows a mood representation (animo) to a user; a user cannot choose the animo. We base mood loosely on the valence-arousal circumplex, which separates emotion into two dimensions: valence (positive/negative) and physiological arousal (high/low) [238]. Given the constraints of information available on smartwatches, we focused on mood related to physiological arousal determined by users' heart rate (e.g., excitement as a high-arousal mood vs. calmness as a low-arousal mood), and left valence open to users' interpretations.

Sharing Users can view their animo on their smartwatch, and tap on it to send it to their partner. Their partner, who must also be running Animo, will feel a subtle vibration on their watch when they receive the animo. The animo then "peeks" into the side of their watch screen. Tapping on it will play its animation. Given privacy concerns around sharing biosignals [189, 190], users can *explicitly* and *sporadically* share their animos as they please. To encourage sharing, the watch occasionally vibrates when their animo state changes.

Presentation Abstraction We chose a *high* abstraction representation for mood derived from heart rate. To enhance expressiveness and playfulness, animos are animated shapes.

We designed different animos to cover a variety of moods. For some designs, we drew from elements of kinetic typography that were tested in Kim and colleague's work on Yo [159]. The animos varied in three ways:

- **Shape:** In a dyad, one person has circle animos while the other has diamond animos. Shapes are assigned during onboarding and do not change.
- **Motion:** We designed animos with different levels of energy to represent arousal. High energy motions (e.g., bouncing) represent higher heart rate; low energy motions (e.g., swaying) represent lower heart rate.
- **Color:** As with mood rings, some degree of mystery can encourage playful discovery. Therefore, we designed animos to change colors semi-randomly in order to encourage users (who would not be aware of the randomness) to question and interpret their animos. High energy animos are randomly yellow or red, whereas low energy animos are randomly blue or green. Animos in between high and low energy levels are white. We chose these colors according to their existing associations with emotions [152], loosely basing them on their relation to the valence dimension of mood but still leaving them up to interpretation.

We pretested the animos we designed on the crowdsourcing platform Amazon Mechanical Turk to ensure general agreement that they represented expected moods and their associated arousal levels. We tested a total of 26 different animos across three rounds of surveys[1]. In each round, 20 participants viewed a subset of animos presented in a randomized counter-balanced order and rated them on their “mood” and “energy” [180] (see Appendix D for the survey questions). We selected the best performing animos per round to include in the Animo app, which led to a total of 18 animos (see Appendix D for the pretest analysis and results, and a video of the selected animos). Four sets of three animos were chosen to cover different quadrants of the valence-arousal circumplex, where they differed significantly in mood and energy ratings ($p \leq 0.05$). We also included two animos that differed significantly in only energy ratings, in order to introduce some ambiguity that could spark different interpretations. Finally, we included four “neutral” animos that were not significantly high or low in mood or energy ratings.

Presentation Granularity Animo is *person-based*, meaning each user has their own animo. Users can view their own animo on their smartwatch, and their partner’s if they send it to them. Users can have one, and only one, partner. We made this decision to focus on the simplest communication on a smartwatch—one-to-one. Animo is also *message-based*: each sent animo is based on a user’s current state.

Presentation Persistence Sent animos are *ephemeral*: they disappear in 10 seconds if the receiver ignores them by not tapping on them. This emphasizes animos’ weightlessness, and aims to avoid having yet another feed to check. We chose 10 seconds based on early pilot tests we conducted to ensure that receivers would have enough time to notice and tap the animo if desired.

[1]We ran multiple rounds of surveys in order to collect a diverse set of animos that would cover the quadrants of the valence-arousal circumplex. In between rounds, we created new animos when we did not have enough animos that performed well in certain quadrants (e.g., designing for the positive/low arousal quadrant was particularly challenging)

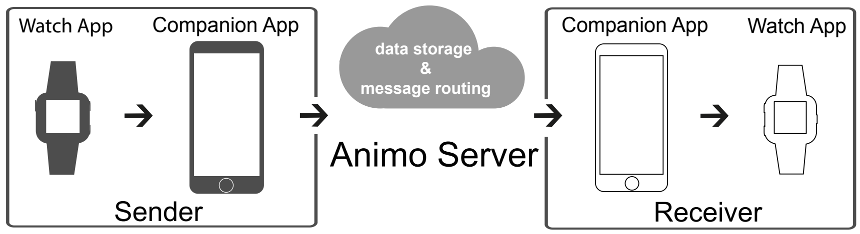


Figure 5.1: Components of the Animo system.

Implementation

We implemented Animo as a "clock face" app for the Fitbit Versa smartwatch, which allowed it to stay on the default screen of the smartwatch. We chose the Fitbit platform because of its compatibility with both Android and iOS, and its "mass appeal," with over 25 million active users in 2017 [5, 229]. The Fitbit Versa has an LCD touchscreen, Bluetooth communication, and a heart rate sensor, among other sensors.

The Animo system is composed of a smartwatch app, a server-side app running on the cloud, and a "companion app" that runs within the Fitbit smartphone app (see Figure 5.1). The companion app enables communication between the Fitbit Versa and a user's smartphone via Bluetooth, which is used when a user sends an animo. The companion app sends the animo to the backend service, which routes the animo to the user's partner. This alerts the receiver's smartwatch that an animo is available, triggering a vibration. The animations are displayed only on the smartwatch and implemented using vector graphics. Animo requires the sender and receiver to both have the Fitbit Versa and the Fitbit app running on their phone with Bluetooth and data connection on.

5.5 Methodology

To test Animo *in situ*, we deployed the app in a two-week field study, allowing participants to freely use the app in order to observe patterns of usage that naturally emerge.

Table 5.1: Animo participant dyads. Includes drop outs (†). Some friends (*) reported also being coworkers.

dyads					animos		
participants		**genders**		**relationship**	**sent**	**read (%)**	**replied (%)**
P1†	P2†	M	M	friends*	—	—	—
P3	P4	M	M	friends*	220	40 (18%)	18 (8%)
P5	P6	F	F	friends*	127	65 (51%)	25 (20%)
P7†	P8†	F	F	friends	—	—	
P9	P10	M	M	friends	175	115 (66%)	59 (34%)
P11	P12	F	F	friends*	173	101 (58%)	43 (25%)
P13	P14	M	F	significant others	258	77 (30%)	66 (26%)
P15	P16	M	F	spouses	68	34 (50%)	7 (10%)
P17	P18	F	M	significant others	45	14 (31%)	6 (17%)
P19†	P20†	F	F	friends	—	—	—
P21	P22	M	F	significant others	210	113 (54%)	60 (29%)
P23	P24	M	F	spouses	77	35 (45%)	16 (21%)
P25	P26	F	F	roommates	108	43 (40%)	6 (6%)
P27	P28	F	M	spouses	33	3 (9%)	2 (6%)
P31	P32	F	F	friends*	168	87 (52%)	39 (23%)
P33	P34	M	M	coworkers	375	159 (42%)	35 (9%)
P35	P36	M	F	spouses	181	43 (24%)	25 (14%)
P37	P38	M	F	spouses	115	49 (43%)	29 (25%)
P39	P40	F	F	roommates	90	27 (30%)	8 (9%)
P41	P42	F	M	coworkers	67	35 (52%)	4 (6%)

Participants

We recruited 20 dyads, or 40 participants. We removed data from three dyads, leaving a total of 17 dyads (see Table 5.1). Participants were removed either because they experienced major technical issues (e.g., loss of connection between their phone and the smartwatch), or because they were traveling without connectivity for most of the study.

We recruited participants through the mailing lists of a technology company, inviting people to participate in a two-week experiment about "mood." We did not pay participants. We asked participants to choose a partner to join them in the study. This partner did not have to be affiliated with the company. In order to have a diverse sample, we recruited participants from three different offices in the United States: New York City, Seattle, and Los Angeles.

Participants varied in their backgrounds and demographics. Their occupations included homemaker, professional server, program manager, business recruiter, software engineer, neuroscientist, and others. Their ages ranged from 19 to 48 years old (M_{age} = 30.4 years, SD_{age} = 6.0 years). Participants' gender and relationship breakdown can be seen in Table 5.1. Sixteen participants identified as Asian, 12 as White/Caucasian, two as Hispanic, and three as mixed White/Caucasian and Asian or White/Caucasian and Hispanic. Fifteen participants owned a smartwatch (e.g., Apple Watch, Google Wear OS), with nine of them using it frequently for activity tracking, phone notifications, or heart rate monitoring. Participants' prior usage of smartwatches did not influence our results, therefore we included all participants who owned smartwatches in our final analyses.

Procedure

Onboarding Each dyad was onboarded together in one of the offices of the technology company. Participants first created a Fitbit account and added each other as friends on Fitbit, then individually completed a questionnaire to describe their backgrounds (see Appendix D for the questionnaire).

Next, experimenters equipped participants with a smartwatch, and took their heart rates during a calming task (individually watch a breathing exercise video[2]) and during a stressful task (count down from 1022 in steps of 13 [39] in front of their partner and the experimenters). We used the average of the heart rates recorded during each task to determine animo arousal, i.e., high and low heart rate baselines.

After recording the heart rates, experimenters explained to participants how to use Animo, including how to send and view received animos. Experimenters purposefully *did*

[2]Video available at `https://www.youtube.com/watch?v=5f5N6YFjvVc`

not explain the meaning behind the different animos, and instead instructed participants to interpret the animos themselves. We made this decision to inform our research questions, allowing participants to flexibly define the animos to understand how they would create those definitions. Additionally, prior work highlights the importance of allowing people to create meaning together from their biosignals [190]. Finally, participants could leave and use Animo freely for two weeks.

Animo Usage We recorded a variety of data to capture participants' Animo usage throughout the study. This included heart rate data, animo states, and animos sent, received, viewed, and sent as responses. Additionally, inspired by diary studies [223], we sent brief daily surveys about their usage. After one week, participants completed a mid-study survey to clarify responses in their daily surveys and provide initial thoughts on Animo.

Offboarding After two weeks, participants returned their watches and were individually interviewed. The interview was semi-structured and elicited participants' thoughts and feedback on their experiences with Animo. To help participants recall their experiences, we showed them the five animos they sent the most and the five animos received the most. In the feedback section, we also showed example sketches and mock-ups for future Animo designs, to probe participants on specific aspects of Animo that they enjoyed or wanted to improve (e.g., what animos looked like, how often they should be sent).

Analysis

We analyzed the responses to the daily surveys, mid-study surveys, and transcriptions of the audio-recorded exit interviews, using participants as the unit of analysis. Two researchers independently performed open-coding to label responses from a random sample of participants. They developed codes according to similarities in participants' overall usage of Animo, experiences sending/receiving animos and subsequent reactions, process of understanding the animos, and feedback for Animo. The researchers met frequently to discuss these codes and create a codebook. Once they agreed on the codebook, one researcher used the codebook to code the rest of the participants. Next, we grouped related codes together and formed themes around participants' communication patterns and how their understanding of the animos affected those patterns and their attitudes towards Animo. During the writing process of the paper, we refined the themes around our main research questions.

5.6 Results

Participants used Animo frequently throughout the study, averaging *five animos sent per user per day* despite not being required to do so and not receiving compensation for participating. Four participants even continued using Animo after completing the study. Across all participants, a total of 2,490 animos were sent, and 1,040 (41%) were read (participants received their partner's animo, and tapped on it to view the animation). Of the animos read, 43% received a reply on average (participants sent an animo back within 10 minutes after reading one). Of the animos sent, 5.6% were lost due to connectivity issues, such as unstable Bluetooth connection between users' phones and the smartwatch or participants traveling to areas with limited network connectivity.

In the following, we describe our results from participants' responses to the surveys and interviews, providing a richer view into the reasons behind participants' Animo usage. We detail the common themes that emerged in our results, and within those themes, include interesting examples of Animo usage that participants shared.

5.6.1 Connecting in New Moments

Animo's design allowed participants to more easily stay connected with each other. Its convenience and constant physical access afforded communication when they typically did not or were not able to communicate with their partner.

Seeing Animo is a Reminder to Communicate

Participants found that looking at their watch reminded them of their partner, and made their partner more *salient*. Since the smartwatch is easily accessible on their wrist, participants only needed to glance down to see their animo. They found themselves doing so not only by haptic prompting (i.e., the watch vibrating when the animo state changes or when receiving an animo), but when they were bored, had "down time," or simply wanted to check the time.

For instance, P22 was traveling in a different city than P21, her significant other, during the first week of the study. She noted that while she was away from P21, the "*watch represented a connection to [him]*", and "*increased communication when there wouldn't normally have been communication*":

> "*...because, like,the thing on my wrist was [him]. It, like, reminded me that, like, there was a prompt to communicate.*" —P22

Looking at Animo thus prompted participants to think of their partner, and sending animos let their partner know that. As a result, participants described feeling happy and nice whenever they received their partner's animo:

> "*It's, like, kind of like getting a 'like' on Twitter or on Instagram. You're, like, 'Oh, somebody thought about me!' And they're not really thinking about you, but they're trying to, like, show you your existence. I like that you're there.*" —P11

Communication is Convenient through Animo

Participants also used Animo when they were already thinking of their partner but unable to communicate through other means. Tapping on their watch was more convenient than "*patiently typing a message*" (P24) on the phone or "*[having] a computer ready to go*" (P15). Animo sending occurred frequently when participants were too busy attending to something else to communicate otherwise. For example, even when P22 was busy traveling, her partner (P21) felt he could easily keep in touch:

> "*I think she was out with her... parents and not necessarily able to text back and forth, but you could still send each other animos...*" —P21

Similarly, participants felt that they were able to send animos during their busy work day, when they typically were not physically co-located with their partners. Our data on Animo usage supports this (Figure 5.2), with the highest number of animos sent and read during work days (Monday-Friday) and work hours (9am-6pm).

Since tapping on a watch is less noticeable than taking out a phone or speaking, Animo provided a private communication channel while in public. For example, when P5 and P6 were in a stressful work meeting together with other colleagues, P6 used Animo to communicate with P5 whenever she thought they would both be annoyed. She described sending animos to let P5 know she was "*thinking about her without being obvious in [the] meeting*."

Our results suggest that Animo may enhance the salience of partners and increase communication. Animo's unobtrusiveness and ease of interaction on the smartwatch allowed participants to connect in moments they were not together, were too busy, or needed privacy in a public space.

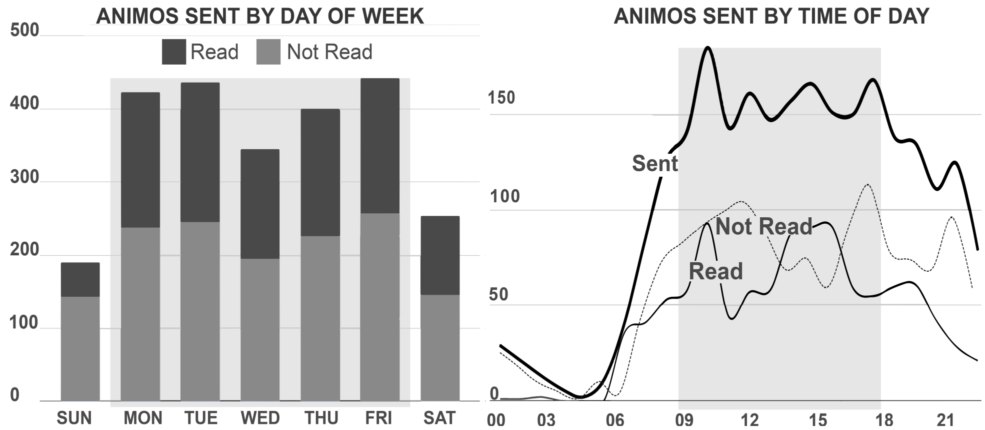


Figure 5.2: Usage patterns by time of day. Working hours are highlighted in gray.

5.6.2 Creating New Understanding

Through Animo, participants felt they could elicit new information from their partners about their states. Receiving animos gave participants insight on their partner's state and opened up new pathways for them to discuss and understand each other's state. This insight aligns with prior research on sharing heart rate [119, 190], where participants felt that shared biosignals functioned as an emotional expression or status update. Our work extends this prior work by detailing how status awareness develops through shared biosignals.

Animo can Start Conversations about Your Day

Animo triggered participants to start *new conversations* with each other, where they checked in with each other based on the animos they saw throughout the day. For example, P13 and P14, who were in a long-distance relationship and only saw each other every few weeks, used animos as a conversation starter while they were apart:

"*She'd get one that was white. She's like, 'You're relaxing right now?' I said, 'Yeah, I'm at home right now.' I was just reading and it prompted other conversation...to check in with each other and see what we're up to.*" —P13

Even when participants were too busy to have these kinds of conversations during the day, the animos provided a "*tapestry*" or "*glimpse*" (P18) of their day. Participants then talked about the animos with their partners when they later saw them face-to-face. This was especially common for participants that lived together (i.e., significant others and roommates). For example, P25 and P26 were roommates who usually briefed each other on the upcoming events of their day before they left for work. P25 once sent an animo to express that she was stressed before an interview. P26 described following-up on that animo:

"*[W]hen we saw each other in the evening, uh, we would like mention that we had sent them...so I like asked if she was in the interview when she sent it to me so we talked about that. So it just kind of prompted discussions about our day.*" —P26

When participants received an animo that triggered their concern, they would start conversations immediately. This occurred when participants thought their partner was stressed. For example, P14 learned that her partner had a frustrating experience with his car. Soon after hearing about it, she received a red animo (which she interpreted as stress), and called her partner immediately because she was worried.

While Animo helped start conversations, participants felt it could not support full conversations on its own. For instance, when participants received animos, sending an animo back only represented an acknowledgement of receipt. P15 felt that Animo acted as a "*first level of communication*," to start conversation, and desired a way to easily access or inform the next level of communication, where conversations could actually take place:

"*[If] I see this yellow jumping dot, it probably means that you know my wife wants to talk about something fun and then oh let me try to call her. So, if there was something, like, oh whenever I share this I want my wife to be able to call me back.... If there was some way to establish this...second level communication would be nice.*" —P15

Animo can Clarify Ambiguous Conversations

In a less common yet interesting case, Animo helped participants understand their partner's feelings when they had difficulties interpreting their behavior. P42, who had a coworker/work-friend relationship with P41, used Animo to validate his thoughts on how P41 felt. After an in-person conversation with P41 where she seemed "*riled up*," P42 checked the animos she sent:

"*It was interesting to see if...one of us was more upset about something...it was good to know if this person was actually worked up or if this was a show, like a front.*" —P42

Though P42's experience was a unique example in our results, it reveals Animo's potential to prompt deeper understanding between people by starting new kinds of conversations and clarifying ambiguous feelings. This finding supports and extends results from prior research showing that shared heart rate can provide emotional status cues and open up communication about those cues [190].

5.6.3 Navigating Open-Ended Interpretation

The Animo system provides an abstracted representation of sensed mood. Given the level of ambiguity we imbued in the animos (e.g., random colors) and the lack of provided definitions, participants' understanding of that abstraction varied. We found that participants' interpretations did not necessarily align with the results of our pretest of the animos–instead, participants situated animos in social contexts. Participants' interpretations affected whether they found the animos *meaningful*, and determined their engagement with Animo. Below, we detail how Animo's open-ended nature impacted participants' ability to meaningfully communicate.

Playful Imagination and Discussion

Participants enjoyed having free reign to understand the animos for themselves. In particular, they appreciated that Animo did not necessarily tell them their mood, but encouraged them to reflect on their mood themselves. P15 compared this to emojis:

> "*I like that animos...looked unintentional in a way that they don't necessarily imply something you know, whereas like an emoji definitely implies something. It doesn't make me feel I'm being forced in feeling something in some way*." —P15

Participants found it fun to not only think about how their own animo could relate to their mood, but also imagine what their partner might be doing, and why they chose to send the animo they did. For example, P21 felt that because the animos were not always accurate, there was more meaning to the ones they selected:

> "*It's just fun to receive them because...she looked at it and then she thought that that reflected her mood and then chose to send it. So, it feels meaningful because of that...she chose that one specifically*." —P21

Participants also enjoyed the process of decoding the animos with their partners. They noted that they became more aware of each other's feelings, "*not just with the animos but...in talking to each other*" (P6). Even seeing less accurate animos spurred these discussions:

"*I mean, like, sometimes we were just, like, laughing about it. I think, like, it allowed us to kind of just have conversations based on our feelings and how we were feeling in the moment.*" —P37

Finding Mismatched Meanings

Though most participants found meaning in the animos, where they felt that their animos reflected or somewhat reflected their state, the meaning they gleaned did not always match the meaning their partner gleaned.

Missing a shared language Participants were not always able to have conversations to jointly reflect on animos with their partner. When this happened, they would be unable to determine whether they agreed on the meanings they attributed to the animos. Instead, they tended to reflect according to their own beliefs.

For example, P11 and P12 were close friends and coworkers who would send animos to each other both as a "poke" and to show that something interesting was happening. P11, who would send her animo to let P12 know what her mood was, stated, "*I wanted her to know that it was matching my mood but, um, I don't think she knew.*" Indeed, P12, who believed the animos were more related to physical activity rather than mood, instead reflected on P11's activity:

"*So, like, for the white ones... she's probably just lying in bed or sitting around somewhere doing something. For active ones.. .maybe she's like jumping around or dancing or, like, walking about or exercising when she sent it.*" —P12

Unintended interpretations Diverging opinions on the meaning of the animos sometimes led to unintended interpretations. For example, P42 viewed animos as representative of his mood–to the extent that he felt Animo was making him more aware of it. He similarly believed P41's animos represented her mood, and thought she sent her animos to show him her mood. In actuality, P41 did not find meaning in the animos and sent them at random times. This suggests that an animo could reveal more information than a sender expects (recall that P42 used Animo to validate his thoughts on P41's feelings), and that a receiver can interpret an animo in ways that stray from a sender's intentions.

Giving animos context Some participants realized their partner might interpret their animos differently than intended. To counter this, they would send additional information through other communication channels to clarify animos they sent. For example, P38 sent his partner a red animo to show that he is excited. However, he recognized that red could be interpreted as an angry color; therefore, he sent his partner a video to give them more clarifying context.

Animo as Content-Less Notification

Ten participants could not find meaning in the animos, and subsequently felt Animo had limited communicative ability. These participants sent animos to simply connect and say "hi" to their partner.

Dyads who believed their animos lacked meaning quickly got bored of Animo and used it less. P39 and P40, for instance, were roommates who both felt frustrated with the system because it made no sense to them and did not seem to match their how they felt (e.g., seeing red animos they view as angry when they actually feel happy). They would send their animo even when it did not match their feelings because their partner "*wouldn't care, wouldn't realize, or wouldn't read into it*" (P39). They instead sent animos randomly as a "hi." Communicating in this way had limitations, as there are only so many times people will say "hi" back and forth:

> "*...I just did not want to keep it going. I was like uh, 'hi,' 'hi', and 'hi' is fine.*"
> —P39

Overall, we found that Animo's open-endedness had benefits and tradeoffs. Participants could decide what the animos meant to them, and reflect on those meanings as part of new conversations. However, not all participants were able to interpret animos, and even when they did, their interpretations did not always match their partner's without a clarifying conversation. This suggests a need to convey the intention of messages sent in systems like Animo, while maintaining the value brought by their brevity.

5.7 Discussion

Our results show that Animo enabled *lightweight social connection*, where participants found it fun and easy to keep in touch and attuned to each other's presence and state. However, Animo experienced some challenges in functioning as a full communication platform, due to its minimal and somewhat ambiguous nature. Repurposing and expanding Bushek and colleagues' design space for augmented mobile messaging [51], we discuss design implications for biosignals smartwatch communication systems based on opportunities and challenges we saw in Animo features. We summarize recommendations for this new design space in Table 5.2.

Content and Presentation: Being Expressive yet Interpretable

Bushek and colleagues describe a design space for augmenting text messaging with different types of context [51]. As a related but tangential form of messaging, biosignals smartwatch communication focuses on biosignals as the content of the message itself. Our results show that Animo promoted lightweight social connection through the *content provider* and its *presentation* to users, where some randomness and abstractness allowed users to have fun creating and discussing their own meanings together. At the same

Table 5.2: Recommendations for the biosignals smartwatch communication design space. Adapted from [51].

Dimension		Recommendation	Support from Animo
Insights on existing design dimensions			
Content	Provider: System | User | Mixed	Combine system- and user-provided content, to help users create their own meaning from their biosignals rather than solely relying on the system.	Developing meaning for animos gave users creative liberty rather than being "forced" into feeling a certain way based on what the system told them.
Presentation	Abstraction: Low | Med | High	For limited content, explore expressive yet simple representations that contain clear and distinct information.	Expressing oneself through the open-ended animos was fun, but also inhibited developing a shared language because they could mean different things.
	Granularity: Person | Message | Communication	Communication-based granularity may promote playfulness, connectedness, and shared meaning. Example: messages that jump around each other when communication is exciting.	Animos were cute and playful, but primarily represented individual users' moods, which users had to convey to their partner.
Suggested new design dimensions			
Sharing	Receiver: One | Many	Single-receiver is more intimate, and watch becomes a reminder of that person. Multi-receiver allows for keeping in touch with more people.	Having one partner made animos feel like a personal and private way to communicate. Some mentioned wanting multiple partners to check in on.
Response	Richness: Simple | Rich	Explore richer opportunities for receiver responses, beyond just sending a message back. Example: simple response could be an acknowledgement of message receipt; richer response could be in-app short text or animation.	Just sending an animo back was limited. Participants wanted more unique and richer responses that are inherently tied to the original sent message.
	Channel: Single | Multiple	Link the watch to other channels for deeper conversation. Watch can act as a lightweight first level of communication, e.g., initiating conversation or simply "being there."	Since Animo communication was lightweight, participants typically followed-up in later conversations in-person, through text, or on the phone. Participants wanted a way to more smoothly enter those conversations directly from the watch.

time, being too abstract and ambiguous can lead to challenges in finding meaning in the content.

Expressive Meaning-Making Animo enabled participants to express themselves, even though the system intentionally provided them with a partially random mood representation. Participants found the process of interpretation fun and meaningful, both when they saw animos that did and did not reflect their mood. The ambiguity allowed them to be expressive by developing their "*own vernacular*" (P27), as opposed to using pre-existing ones. This supports recent research on approaches to emotional biosensing, which questions systems that use biosignals in attempt to determine and tell people how they feel according to predefined emotional categories [133], and suggests potential for people to have meaningful discussions around biosignals instead [190]. In the same vein, our results demonstrate the importance of enabling people to reflect on their biosignals and create their own meanings for them, rather than a system simply telling them what they mean. Additionally, the playfulness and expressiveness of Animo supported *collective* meaning-making experiences for participants and their partners, which can ultimately facilitate communication and social connectedness [136, 316].

Limitations of Abstraction While participants enjoyed being expressive through the highly abstract animo designs, animos were sometimes difficult to interpret. We provided animos as the sole content to reinforce Animo's lightweight nature; however, when that content was not understandable, communication became meaningless. Prior work suggests that communication that lacks content is limited: while it can contain a "symbolic" message (e.g., "hi"), it has less value and impact on relationships [49]. Based on our results, two factors appeared to affect the meaning of the content:

Cognitive effort Decoding the information provided within the animos required more cognitive effort than expected. Though we had designed animos to convey mood through color and motion, most participants focused on only color. Using both color and motion to track animo states proved difficult when participants saw only one state at a time. Subsequently, they often assigned meaning to animos according to only one dimension of the valence-arousal circumplex [238] (e.g., red animos representing high heart rate, rather than negative high heart rate), which negatively impacted their ability to interpret mood from the animos.

Limited context Participants were able to express themselves by creating their own meanings for the animos; however, they did not always converge on those meanings, causing them to miss the sender's intentions. Participants lacked a *shared language* in which to communicate with the animos.

Recommendations for Content and Presentation

Content Provider To promote expressiveness, designers should consider a "mixed" content provider with tools for users to subjectively interpret their biosignals, rather than solely focus efforts towards a system that accurately infers information from biosignals. Users could identify with a message more if they have the ability to define what it means to them, and receivers could likewise recognize that it has meaning for them. In the following chapter, I explore a "mixed" content provider design that enables people to determine their state from a list of recommended states.

Presentation Abstraction High abstraction in presentation can encourage playfulness and expressiveness, but can be difficult to understand. For lightweight communication, simplifying the presentation is important. We recommend minimizing the number of changes a user needs to attend to. Adding small context cues could help distinguish between different meanings. For instance, participants suggested including short captions, such as "hi" or "good morning" (P14), as well as using activity- and emotion-specific animos (P24) to distinguish between biosignals affected by physical or emotional stimuli, which we test in the next chapter. We also recommend exploring non-visual language. For example, a single tap could represent a "hi," while a long press or double-tap could represent a "heavier" event that requires response, such as something stressful.

Presentation Granularity An animo represents the mood of an individual; thus, participants needed to convey how their animo reflected their mood to their partner. To encourage the development of meanings shared between partners, we recommend exploring *communication-based*[3] presentation granularity, to represent how communication

[3]Unlike in [51], we use "communication" instead of "conversation" since conversation may not necessarily occur through the smartwatch.

develops between two users. For instance, participants suggested exploring playful ways to highlight that users are connected through the system and "*convey a sense of togetherness*" (P9). Thus, in the next chapter, I design a new expressive biosignal system that includes animations that interact with each other, such as by hugging. Other examples could include enhancing messages according to communication frequency, or leaving behind "gifts" that serve as a reminder of communication that occurred.

Sharing

Animo used the smartwatch as a *sharing* channel, and allowed participants to directly share their heart rate with each other. This enabled a new way for people to connect by physically sharing information from their body. Our results suggest that this form of sharing enhanced social presence between participants.

Social Presence Social presence is "the sense of being with another" [38], and has components of *immediacy* and *intimacy* [114, 115]. Promoting social presence should promote feelings of connectedness [138].

Past research shows that even with minimal communication content, people can feel as if the other person is present [56, 153]. Participants felt that their partners were "there" on their wrist, especially when they were not physically together. This stemmed from several factors:

Mediated touch The smartwatch is worn on the wrist. When a user receives an animo, they can physically feel it through haptic feedback. Participants mentioned using Animo as a "poke"; haptic feedback can make them feel like they are being poked. Our results suggest the haptic features of the smartwatch in communication can act as a "mediated social touch," which can increase social presence [31, 293].

Immediacy Immediacy is already valued in smartwatches: users enjoy notifications for their ability to quickly check incoming calls and messages [144]. Animo leverages this immediacy for two-way communication: participants found that their partners were more immediately accessible to them. They could easily initiate or respond to communication by tapping on the watch to send or recieve an animo, without reaching for their phone or computer, or typing a message out. Animo's form factor and simple design made it "*effortless*" (P16) to use, helping participants communicate more frequently, even during busy times.

Intimacy In addition to the affordances of the smartwatch, Animo's sharing design affords intimate communication between close-ties, such as significant others and close friends. Specifically, Animo is one-to-one. As P11 mentioned, this makes communicating feel "*more personal*" because only one other person can send animos; they act like a "*hidden message*" (P27). Moreover, the message sent is "mood" derived from heart rate, personal and private information that can increase feelings of intimacy and vulnerability when shared [142, 190, 266]. Similar to prior work [119, 189], participants noted they would prefer to share Animos with their closest contacts. P25 mentioned that she had only known her partner for a few months, and would have liked to participate with her best friend instead.

Recommendations for Sharing We suggest a new design dimension in biosignals smartwatch communication: *sharing receiver*. Animo allowed only one receiver, which created an intimate communication experience preferred by close partners. Given this finding, I focus on significant others in the final stage of my thesis. However, outside of the scope of this thesis, designers might consider multiple receivers for an experience geared towards relationships with varying degrees of closeness, such that senders can keep in touch with several people at once.

Response: Triggering Conversation.

Similar to prior work, sending and receiving animos helped participants feel more aware of and connected with their partners [119, 190]. This supports research suggesting that keeping in touch with a partner's activities can facilitate feelings of connectedness, especially when remote [23, 195]. At the same time, since Animo was so minimal, it was unable to go beyond these short status updates to support full conversations between partners. Instead, participants used the animos they saw as opportunities to converse with each other through other channels, such as through text when they received animos or face-to-face at later times when they physically met.

Our results suggest that systems like Animo are best used as *conversation starters*, rather than platforms for conversation. For a seamless communication experience, future work should consider how these systems can smoothly transition between a lightweight conversation starter to actual heavier conversation. In particular, we suggest exploring how receivers can better *respond* to biosignals messages to inform or initiate future conversations.

Recommendations for Response We recommend *response* as a new design dimension with two sub-dimensions: *response richness* and *response channel*. The former refers to determining situations in which simple or rich responses are appropriate. Animo only enabled simple responses, where participants could send animos back to acknowledge they received their partner's animo. Richer and more diverse responses in-app could better clarify the intent behind the received animo, and guide follow-up conversation (e.g., if a receiver recognizes a sender's animo as an expression of stress, they can provide support in a phone call). For example, P18 suggested enabling short-form replies:

> “*Like, if I received an Animo and I could just respond with, like, three or four questions without having to type anything, but it'd just be like, 'Sad, smiley, question mark*'” —P18

Response channel refers to the channel through which users can respond to a biosignals message. Animo used a single channel, where participants responded to animos within the app on the smartwatch. Another option is to link the app to other communication channels, such as an in-app call button to link to the phone, or pinned animos that users can send in text conversations as a reference. Having multiple linked communication channels could support smoother entry into full conversations from lightweight systems like Animo. In the following chapter, I investigate this new design dimension by testing in-app response animations that can be used as short-form replies or cues to jump onto separate communication channels.

5.8 Limitations

Our research provides valuable insights for using smartwatches as a communication platform with biosignals as content. However, our work has some limitations.

We focused on understanding how people would use a mood-sharing smartwatch app and the opportunities and challenges that would arise. Therefore, we chose to create Animo as the minimal viable prototype, putting our efforts towards the design of the system, rather than incorporating accurate mood detection. Future work should investigate how to incorporate enhanced mood detection. For example, in our work, we represented mood based primarily on physiological arousal, but did not determine whether that mood was positive or negative. One way to incorporate valence is to provide options for users to select valence for their mood representation. Providing manual valence options could affect how people understand and find meaning in their biosignals, and subsequently reveal different communication patterns. I explore this design in the following chapter, enabling users to share their hybrid system-sensed and manually-selected animated states to a communication partner.

Additionally, the demographics of our sample may have biased our results. While the average age of our participants aligns with those who are more likely to own smartwatches, our sample does not include younger adults or children (e.g., 18 and below). Participants were also self-selected, and more than half of them worked at technology companies (and the rest had a partner who did). They likely have more familiarity with technology and may have shown a greater interest in wearables and biosignals than the general public. In the following chapter, I run a study on a new expressive biosignals smartwatch app with participants from a broader range of backgrounds, including people with careers in banking, healthcare, physical labor, and more.

Chapter 6

HedgeHugs: Clarifying the Role of Biosignals in Communication

While my works thus far have demonstrated the potential for biosignals to facilitate social connection in dyadic communication, they have not clarified the central *role* that biosignals play when they are integrated into communication. For instance, people already communicate and connect with each other extensively through verbal conversations or use of emojis [194]. Prior worked has not yet illustrated the *value* that expressive biosignals add to communication with these existing modes of expression.

The previous chapters suggest several possibilities for expressive biosignals to improve the way we interact today. In *communication*, biosignals could be a new way to express oneself emotionally and understand those expressions directly from the body itself, as an objective cue that validates one's feelings. As new emotional expressions, they could facilitate *social connection* by disclosing and recognizing deep and authentic feelings. They could also present opportunities for *social support*, such as by signaling a need for support through biosignals-backed feelings, and by providing support in responses and discussions around the sender's biosignals.

To determine the value of expressive biosignals in communication, I ran a field study to compare how people communicate with and without biosignals. Only a few works have made similar comparisons, including my work in Chapter 4.2 and research from Janssen and colleagues [142], which demonstrate that the presence of biosignals can increase emotional perspective-taking and felt intimacy, respectively. However, neither of these works have tested dyadic communication with and without biosignals in real-world settings. In the final stage of my dissertation work, I sought to address this gap by investigating how integrating biosignals affects all stages of dyadic communication, and subsequently, feelings of connection and social support:

- **RQ7**: How does the integration of expressive biosignals in dyadic communication affect the stages of communication?
- **RQ8**: How does the integration of expressive biosignals in dyadic communication affect feelings of connection?
- **RQ9**: How does the integration of expressive biosignals in dyadic communication affect social support?

6.1 Summary

To understand the role of biosignals in communication, I designed and deployed HedgeHugs, an Apple Watch and iPhone app that enables romantic partners to share and respond to each other's biosignals in the form of animated hedgehog avatars. In a one-month within-subjects study with 20 couples, participants used HedgeHugs with biosignals sensing OFF and ON. I found that while sensing OFF enabled an easy way for couples to keep in touch, sensing ON enabled even easier as well as more authentic communication that enhanced social connection and responsiveness. At the same time, the addition of biosignals revealed concerns over the autonomy and agency over the messages that participants sent. I discuss design implications and future directions for communication systems that recommend states based on interactants' biosignals.

6.2 Introduction

In the present work, I aim to elucidate the value of expressive biosignals by understanding the effects of shifting from communication *without* biosignals to communication *with* biosignals. I build directly on my Animo research in the previous chapter, focusing on the integration of expressive biosignals into smartwatch communication systems. I expand on this prior work by disentangling the effects of *biosignals* from other features present in the app. For instance, Animo participants reported felt presence with their partner, which may have stemmed from the addition of biosignals, by conveying a sense of intimacy necessary for presence [142], or from the watch itself, by enabling mediated touch [31, 293]. Similarly, Animo participants kept in touch with their partner's emotions and activities, which could be possible through biosignals, as discussed in previous chapters, or the emoji or sticker-like animos [194, 281].

To clarify the effects of integrating expressive biosignals as a feature, I collaborated with Snap Inc. to study two versions of HedgeHugs[1], an Apple Watch and iPhone app for couples inspired by our Animo research. HedgeHugs enables couples to send biosignals-driven hedgehog animations as messages to each other. I explore how people use and shift from a sensing OFF version, where sensing in the app was turned "off" and therefore no biosignals were sensed, to a sensing ON version, where sensing was turned "on" with biosignals sensed.

[1]HedgeHugs is an alternate name for the app we studied. Since the app is an actual product, I am unable to use the name or screenshots of the app due to confidentiality restrictions. Instead, I created the HedgeHugs app name and HedgeHugs mockups, which are close representations of the actual app, solely for presenting this research. The descriptions of the system design are also accurate to the actual app.

For the purposes of this study, I focus on communication with HedgeHugs between romantic partners. HedgeHugs was designed with a product mindset with couples as the target population. This decision was based on results from Animo, where participants indicated a strong desire to use apps like Animo with their significant other. Indeed, results my previous chapters and prior research [142] show that biosignals are intimate cues, which people feel most comfortable sharing with their closest others. Moreover, since biosignals can function as status updates, significant others may be the most interested and equipped to understand them despite their ambiguity. That is, people are inherently interested in knowing how their partner is doing, and have existing knowledge about their partner to interpret limited contextual cues from them [33, 112]. Thus, I investigate the following research questions in the context of romantic relationships.

RQ7: How does the integration of expressive biosignals in dyadic communication affect the stages of communication? I explore the effects of expressive biosignals on the different components of communication, including sending a message, understanding and responding with feedback for a message, and understanding the feedback (based on the interactional model of communication [308]). Since Chapter 3 showed that biosignals can express both emotions and daily activities, messages in HedgeHugs are hedgehog animations that represent a variety of emotion and activity states related to biosignals (e.g., anger, exercise). As sticker-like animations, the hedgehogs can be used to express emotions and activities even without biosignals. However, as suggested by Chapter 3, with biosignals, the sender could potentially express their emotions and activities more vividly, since they represent their body's physical state. Similarly, receivers could better interpret and recognize the sender's actual state, as seen in Chapter 4. Thus, I investigate the following sub-research questions on the *sending* and *receiving* stages of communication:

- **RQ7a**: How does shifting from sensing OFF to sensing ON affect sending a message to a romantic partner?
- **RQ7b**: How does shifting from sensing OFF to sensing ON affect the understanding of a romantic partner's message?

HedgeHugs also enables users to *respond* to state animations that they receive with react-specific animations. Though prior expressive biosignals systems that I built did not incorporate response features, I observed that receivers desired to respond by acknowledging and discussing their partner's biosignals. For example, Animo participants often jumped to other platforms like messaging apps or in-person conversation to ask their partner to elaborate on their biosignals and make sure they were OK. Thus, biosignals may impact the way people respond with feedback to their partner's messages and, subsequently, how the sender understands that feedback. Thus, I investigate the following sub-research questions on the *feedback* stage of communication, through responses both within and outside of the HedgeHugs app:

- **RQ7c**: How does shifting from sensing OFF to sensing ON affect responding with feedback to a romantic partner's message?
- **RQ7d**: How does shifting from sensing OFF to sensing ON affect the understanding of a romantic partner's feedback?

RQ8: How does the integration of expressive biosignals in dyadic communication affect feelings of connection? Slovák and colleagues propose two ways that expressive biosignals, specifically shared heart rate, may promote connectedness between people. First, they suggest that expressive biosignals are a form of emotional self-disclosure. Self-disclosure is crucial for people to connect with each other, where it can improve the quality of interactions and closeness in relationships [17, 178]. Though emotional self-disclosure is possible through verbal conversation or nonverbal expression of emojis or stickers [194, 281], biosignals may be perceived as more objective and intimate disclosures of our internal experiences, since they stem from our bodies [142, 190, 266]. Thus, my first sub-question for feelings of connection focuses on disclosure:

- **RQ8a**: How does shifting from sensing OFF to sensing ON affect disclosure between romantic partners?

Second, Slovák and colleagues suggest that biosignals indicate a person's physical being, thereby creating feelings of presence in absence [266]. Social presence can be defined as "the sense of being with another" [38], and has long been studied in computer-mediated communication research. For instance, cues like mediated touch [31, 293] and contextual information [23, 32, 70, 112, 116, 160] can heighten felt presence. In the previous chapter, I discussed how Animo may have similarly enabled mediated touch and shared contextual information through the smartwatch and biosignals, respectively, where the watch can be physically felt and noticed on the body and biosignals can provide context on one's state throughout the day [119, 191]. To explore this further and clarify the effects of biosignals, specifically, I investigate the following sub-research question through HedgeHugs:

- **RQ8b**: How does shifting from sensing OFF to sensing ON affect social presence between romantic partners?

RQ9: How does the integration of expressive biosignals in dyadic communication affect social support? Most work on expressive biosignals has focused on sharing and understanding biosignals, and not how people respond to biosignals. Chapter 3 suggests that people may signal a need for support through their shared biosignals, such as when they seek validation for their feelings. People may also attempt to respond in supportive ways when they view someone else's biosignals. For example, in the previous chapter, Animo participants described immediately jumping to platforms like calling when they thought their partner might be stressed or feeling down. Though close partners are already motivated to provide support for each other [65], biosignals may enhance their desire to provide support or the way in which they provide support as an emotional signal tied to the body. To explore this possibility, I focus on the following sub-research question in this work:

- **RQ9a**: How does shifting from sensing OFF to sensing ON affect support provided for romantic partners?

6.3 HedgeHugs System

HedgeHugs is an iPhone and Apple Watch app for couples that enables two people to send animated hedgehog characters to each other based on their biosignals. HedgeHugs was inspired by the concept of "daemons" in the movie *The Golden Compass*, where daemons are animals that represent a person's "inner self." Like daemons, a user's hedgehog reflects the user's inner state, which can be sent to their partner to let them know how they are doing. HedgeHugs is designed to provide a delightful and playful way for couples to communicate, and includes dialogue, animations, and assets created by professional game designers, animators, and graphic designers. The app has been in production since November 2019, and over 49 thousand people have installed it as of September 2020.

To investigate my research questions, I created two study versions of the HedgeHugs app: sensing ON and sensing OFF, where biosignals are either sensed or not sensed, respectively. In the sensing ON version, users can send hedgehog animations from a list of *sensed* state animations, suggested based on their biosignals. In the sensing OFF version, users can send hedgehog animations from a list of *random* state animations, randomly selected by the system. For both versions of the app, participants are prompted to name their hedgehog and pair with the partner. The sensing ON version requires users to accept HealthKit and Motion & Fitness permissions to access sensed heart rate and activity data from the watch. After naming their hedgehog and accepting any permissions,

Figure 6.1: HedgeHugs on the iPhone and Apple Watch.

users can view their hedgehog on either their phone[2] or watch and scroll through the list of animated states. Users can then send their hedgehog to their partner, who can respond with their own hedgehog.

Pilot Studies

I ran two pilot studies to test the two versions of HedgeHugs app. The first pilot study tested users' understanding of the sensing ON version of the app, to ensure that users would recognize that their heart rate is sensed and connected to the animations. The pilot included seven couples (employees of a technology company and their significant

[2] HedgeHugs was developed as a watch-first app, but we included a phone version of the app for usability.

others) who used the app freely for one week and were asked about how they used the app and how they thought it worked. Based on their responses, I made iterations to the app to improve its usability. For instance, I determined the final list of animations based on the pilot results, where participants described expecting to see certain state animations related to their heart rate that were originally unavailable (e.g., exercise), as well as showed a tendency to select responses from only the top of the react animation list. The second pilot study tested users' ability to smoothly transition from the sensing OFF to sensing ON versions of the app, as well as the logistics and materials for the main deployment study. I ran this pilot for three weeks with three couples (employees of a technology company and their significant others). The results confirmed that users viewed the sensing ON version as a feature update that included biosignals, and provided initial insights that informed the development of the study materials (e.g., survey and interview questions). Moreover, I ran this pilot during the early stages of the COVID-19 lockdown for many states in the United States, which informed ways to address different possible COVID-19 related circumstances (e.g., living situations) for the main study. The final versions of the study app and study design are described in the follow sections.

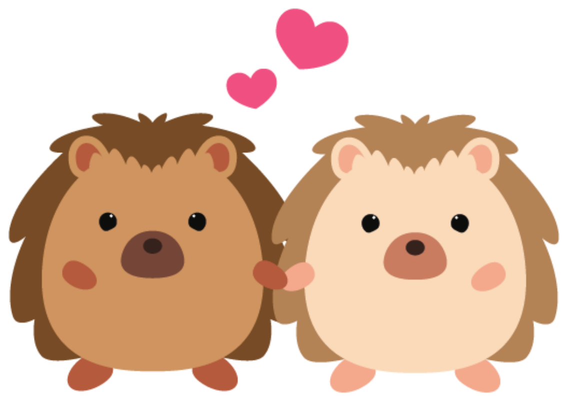
Hedgehog Animations

HedgeHugs users can send two types of animations to their partner: **state** and **react** hedgehog animations. State animations represent "states" that users can send to their partner to initiate communication. Users can select from a subset of states (randomly determined by the system for sensing OFF and sensed for sensing ON) to send to their partner. React animations, or simply, reacts, represent reactions that participants can use to respond to their partner's state hedgehog animations. Reacts are different from simply sending a state hedgehog back, as they are only available when a user receives their partner's hedgehog and are not sensed in either version of the app. Users can select from

(a) Emotions (excited)

(b) Activities (sleeping)

(c) Greetings (waving)



(d) Interaction (holding hands)

Feelings (sensed by biosignals)	**Activities** (sensed by biosignals, motion, time)	**Greetings**	**Interactions**
excited	eating	waving	hugging
happy	sleeping		handholding
angry	walking		
sad	running		
surprised	exercise		
bored			
neutral			

(e) Table of states.

Figure 6.2: Examples and table of hedgehog states.

all possible reacts after viewing their partner's state. Both state and react animations have corresponding emojis that are used to represent the animations in app notifications (explained in the Notifications section below). The study versions of the app contain a subset of the animations available in the production version, in order to focus on states that could be interpreted from biosignals.

State animations HedgeHugs presents an *interpreted* representation for biosignals: animated avatars that correspond to different emotional and physical states. That is, the system determines an interpretation for a user's heart rate by mapping it to multiple possible states, as opposed to presenting *raw* biosignals data (e.g., a heart rate number) [119]. I made this decision based on my prior work (see Chapter 3), which shows that raw data is less engaging and requires additional contextual clarification that may not be feasible on a lightweight smartwatch communication app. Additionally, the avatar is an animated hedgehog representing different types of states in order to increase product appeal and reduce ambiguity, which was an issue in the highly abstract animos seen in Chapter 5.

There are four types of state animations: emotions, activities, greetings, and "interactions." I chose emotion and activity animations based on how participants in Chapter 3 expressed themselves through biosignals. Additionally, inspired by Animo participants' desires to express "hi" and "I'm thinking of you" to their partners, I included greeting and "interaction" animations for users to simply send loving messages to their partner.

Emotions. These include excited, angry, calm, sad, and neutral hedgehog animations. I chose these states to represent each quadrant of the valence-arousal model of emotion [238]. The sensing ON version senses these states using heart rate data extracted from HealthKit. Since valence cannot be determined from the heart rate data, HedgeHugs presents states together based on arousal. That is, excited and angry states are available when a user has a high heart rate, the neutral state is available when the user has a neutral heart rate, and the calm and sad states are available when the user has a low heart rate.

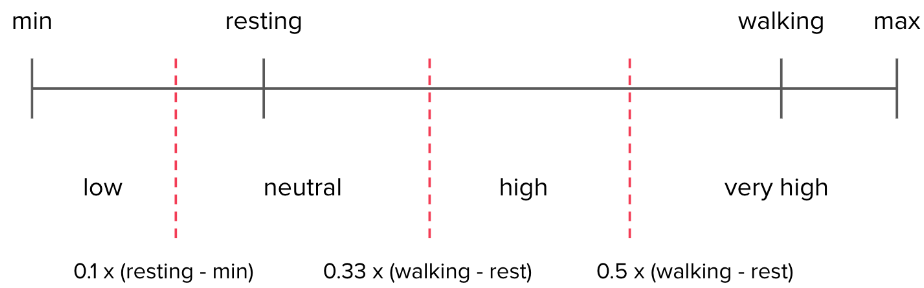


Figure 6.3: Thresholds for heart rate state sensing.

HedgeHugs determines different ranges of heart rate based on a user's min, max, walking, and resting heart rates from HealthKit, which Apple updates daily. The ranges are shown in Figure 6.3, and were determined through empirical testing within the research team.

Activities. These animations represent the variety of daily activities that the user could be engaged in. These include eating, exercising, and sleeping, as well as motion activities such as walking and running. In the sensing ON version, eating is detected based on time (11AM-2PM and 5PM-8PM) and neutral or high heart rate. Sleeping is detected based on time (10PM-8AM), exercising is detected based on high or very high heart rate, and walking and running are detected using motion classification from Apple's Core Motion.

Greetings. This category simply contains one waving hedgehog animation, meant to represent a "hi." In the sensing ON version, we do not use any sensed information for this category, as users may want to greet their partner at any moment. Instead, it rotates availability with the interaction animations such that the user can always convey either "hi" or "thinking of you" to their partner.

Interactions. This category shows animations where the couple's two hedgehogs are interacting. These animations highlight users' affection for each other as a couple, such as hugging and holding hands. In the sensing ON version, we do not use any sensed information for this category, as users may think of their partner at any moment. Instead, these animations randomly rotate with greetings, as described above.

React animations In order to explore my research questions on how people respond to biosignals with feedback and potentially social support, I included 14 different react animations to cover a variety of responses users could have to their partner's state. HedgeHugs initially had 22 react animations, which were designed based on existing react systems (e.g., Facebook Reactions [285]) as well as social support literature. For the latter, I focused on emotional support, or providing caring and concern, as other types of support typically require more information or details, which would not be suitable for a lightweight communication platform [50, 148, 198].

Since the first pilot study suggested that 22 reacts are too many to scroll through, I ran a survey on Mechanical Turk to reduce the number of reacts and increase usability. Through this survey, I aimed to understand how people would interpret and use the react animations in communication in order to select the most relevant ones. 45 participants answered questions about how they interpreted each react animation (e.g., valence, arousal, extent of emotional support it provides), provided an example text message that would prompt them to use the animation as a response, and wrote the message that they believed the animation conveys in words (see Appendix E for survey materials). I selected the final set of reacts to cover diverse possible responses to the HedgeHugs states, focusing on animations that ranged in interpretations (e.g., different types of messages they conveyed). The final reacts included feelings (which were the same as the state feelings), acknowledging the sender's state or receipt of their state (e.g., "I agree" or "OK"), showing caring and affection for the sender (e.g., "I'm here for you" or "I love you"), and indicating a desire for follow-up on a different platform (e.g., "Call me ASAP"). I removed animations that participants described using as responses for messages that the state animations were not designed to convey (e.g., removing the laugh react, since participants felt they would use it for "funny jokes"), or were ambiguous with conflicting meanings (e.g., removing the concern react, which participants perceived as either "I'm sick" or "It'll be OK").

(a) Acknowledgement (thumbs up)

(b) Caring (pat on the back)

(c) Follow-up (question)

Feelings	**Acknowledgement**	**Caring**	**Follow-up**
excited	thumbs up	hugging	question
happy	nodding	handholding	call me
angry		love	
sad		pat on the back	
surprised			
bored			

(d) Table of reacts.

Figure 6.4: Examples and table of hedgehog reacts.

Sharing Hedgehog States

Participants can share their hedgehog state through the main screen of the HedgeHugs app on their watch or phone. Users can enter the main screen through notification prompts to view their hedgehog (explained in the Notifications section below), or by opening the app on their own. Like in Animo, users can simply tap on their hedgehog to send it to their partner, and their partner can view the hedgehog's animated state on their own device. However, unlike Animo, users can scroll to view and send other possible states, using the crown of the Apple Watch or swiping up/down on the phone. In the sensing ON version, the list of states is based on a user's sensed state from their heart rate and motion activity data, and will change as the user's state changes throughout the day. Similar

(a) App notification that comes periodically during the day

(b) Opening the notification shows an emoji representing the current sensed state (pictured: sad).

(c) Opening the app (through notification or manually) shows the current sensed state animation. Scrolling the crown shows other sensed states.

(d) Tapping sends the state animation to your partner.

Figure 6.5: Sending state hedgehog animations on the Apple Watch.

states based on arousal are shown together (e.g., excited and angry states will appear in the same list for high arousal). I made this decision both due to limitations in being able to detect valence and recommendations from the Animo research to explore systems where the user can work together with the system to determine their state. By providing a limited set of other possible states, users can reflect on their subjective feelings alongside the app's suggestions, and then select one of the recommended states. Therefore, states that users send are partially automated and partially manually determined by the user (as opposed to fully automated, as in Animo). Additionally, at least one interaction or greeting state is always included in the sensed state list, such that they are available for anytime the user wants to convey that they are thinking of their partner. In the sensing OFF version, the list is restricted to two to five randomly selected states to match the possible sizes of the sensed state list in the sensing ON version.

Reacting to a Hedgehog State

When users receive their partner's hedgehog, they can react within the app itself. I include react options within the app in order to capture and explore people's behaviors in determining a response for their partner's state. First, users can respond by opening the app to view their partner's state animation. After the animation plays out, the app will automatically enter the react mode, where users can scroll through all 14 possible reacts (using the Apple Watch crown or swiping up/down on the phone) and tap on one of the animations to send it as a response to their partner. The react mode includes all possible react animations in order to understand people's preferences and decisions in reacting with certain animations. Second, users can react through "quick reacts" (pictured in Figure 6.6a), selecting from one of four possible reacts shown in the notification they receive without needing to open the app. Quick reacts are only featured on the watch and are primarily included for usability, as a lightweight way to respond when the user

(a) Receiving partner's state (pictured: sad). Quick react buttons at the bottom.

(b) Viewing partner's state animation after opening the notification.

(c) Entering in-app react mode after viewing partner's state animation. Scroll using the crown to view other possible reacts (pictured: hugging).

(d) Tapping the react animation will send it to your partner.

(e) Partner receives notification of react.

(f) Opening the notification opens the app to view the react animation.

Figure 6.6: React flow on the Apple Watch.

wants to react without viewing the full animation. The four available quick reacts are fixed and selected based on the most frequently used reacts in the production version of the app (love, nodding, hand-holding, and hugging). Finally, users can choose not to react by selecting "Don't react" in the app after viewing the animation, or dismissing the notification. Reacts are the same between both versions of the app in order to explore potential differences in how people react to their partner's state when that state is sensed or not sensed. Users cannot react to a react animation. After a user views a react animation, the app will simply return to the main screen with the list of state animations.

Notifications

Users can receive three different types of notifications from the app.

Partner's state hedgehog visit Users are notified when their partner sends them their state hedgehog. This notification includes an hedgehog emoji representing their partner's state hedgehog, as well as the four quick react hedgehogs. The emojis are designed to act as short-form representations for the larger animated states. They can support lightweight communication such that users can glance to see which state they received and dismiss or quick react to it without viewing the animation, if desired. Tapping on the hedgehog emoji opens the app to play the animation of the hedgehog they received, and then enter the in-app react mode. A mockup of this notification can be seen in 6.6a.

Partner's react hedgehog This is similar to the partner's state hedgehog visit, where users are notified when their partner reacts to the state hedgehog that they originally sent. This notification includes an hedgehog emoji representing their partner's react hedgehog. Tapping on the hedgehog emoji opens the app to play the animation of the hedgehog they received, alongside an emoji representing the original state hedgehog they sent to remind them of the state to which their partner is reacting. A mockup of this notification can be seen in 6.6e.

(a) Opening the "Message from your otter" notification without sensing will show an emoji of a randomly available state (pictured: sad).

(b) Partner visit notification without sensing icon.

Figure 6.7: Mockups for notifications in the sensing OFF version of HedgeHugs.

User's own state hedgehog Users are notified periodically during the day (at least 45 minutes apart) with a "Message from your hedgehog" notification (see Figure 6.5a. Opening the notification shows an emoji of one of their available state hedgehog animations. I include these notifications as a nudge to make users aware of their current state and encourage them to share it with their partner. I chose 45 minutes based on prior work (see Chapter 3) to insure that the notifications would not be too intrusive. Notifications are time-based and thus appear *regardless* of if the user's state changed. This is due to (1) limitations of the Apple Watch, which does not enable real-time heart rate sensing necessary for recording in-the-moment state changes, and (2) my desire to control differences in the notifications between the two versions of the app, as the sensing OFF version would not be able to record state changes without sensing. Tapping on the emoji allows the user to view the animation in the app. Users can also press the "Share" button in the notification to directly share that state hedgehog with their partner without opening the app. In the sensing ON version, the available state animation is randomly selected from the list of sensed states (not including the greetings or interactions). The sensing ON notification also shows a heart icon[3] and the text "Sensed" to indicate that the state is sensed (see Figure 6.5b. In the sensing OFF version, the available state animation is randomly selected from the list of random states (see Figure 6.7a).

6.4 Methodology

To test HedgeHugs, we deployed two versions of the app in a one month field study.

Participants

I recruited participants from late March to early April 2020, a period when many states were issuing stay-at-home orders due to COVID-19, which required that people only leave their residences for essential activities such as for health or getting supplies for daily living. I recruited 21 romantic couples; however, one couple was removed at the start of the study due to failing to meet the minimum participation requirement (explained in the Procedure below). This left a total of 20 couples (N=40 participants). Participants were recruited through Reddit posts on the SampleSize and Apple Watch subreddits, recruitment posts for about 30 cities on Craigslist (including major cities in different areas of the US to account for differences in state responses to COVID-19), and snowball sampling (ads posted on social media).

Participants were required to take a screening survey to ensure that they met the study requirements. This included being in an exclusive romantic relationship, living in the

[3]heart rate by Souvik Bhattacharjee from the Noun Project

Table 6.1: HedgeHugs participant couples.

participants		genders		age		relationship length	married	cohabitating	US state
P1	P2	F	M	36	36	1-3 years	No	No	NY
P3	P4	F	M	25	38	1-3 years	No	Yes	MD
P7	P8	F	M	22	27	1-3 years	No	Yes	CA
P9	P10	M	F	24	24	1-3 years	No	No	CA
P11	P12	M	NB	24	27	1-3 years	No	Yes	IN
P13	P14	M	F	32	37	> 6 years	Yes	Yes	CA
P15	P16	M	F	22	20	1-3 years	No	Yes	GA
P17	P18	M	F	25	25	1-3 years	No	No	CA
P19	P20	M	F	33	30	> 6 years	Yes	Yes	AZ
P21	P22	M	F	49	51	4-6 years	Yes	Yes	OR
P23	P24	M	F	33	35	> 6 years	Yes	Yes	TX
P25	P26	M	F	20	20	4-6 years	No	No	MA
P27	P28	M	F	26	28	1-3 years	No	No	CA
P29	P30	F	M	24	26	1-3 years	No	No	VA
P31	P32	F	M	32	27	1-3 years	No	No	CA
P33	P34	M	F	22	21	1-3 years	No	No	AL
P35	P36	M	F	19	18	11 months	No	No	MO / IA
P37	P38	F	M	29	31	> 6 years	Yes	Yes	TX
P39	P40	F	F	33	37	1-3 years	No	Yes	TX
P41	P42	M	F	25	26	> 6 years	No	Yes	AZ

United States, being able to participate in onboarding and interview sessions via video call, and both partners owning an Apple Watch Series 3 or above that they used for at least two weeks, to ensure familiarity with the watch. Participants described using their Apple Watch for a variety of reasons, most predominantly fitness tracking, but also music, news, weather, short texting, and checking notifications. The screening survey also included several questions about participants' circumstances concerning COVID-19, including their living situation with their partner. Results from the second pilot study that I ran suggested that people will not engage with the app at all when they are together with their partner for most of the day (e.g., if they were both working from home); therefore, I recruited couples who either were not living with each other or were living together with one person or both people spending most of their working time outside.

The 20 couples I recruited were diverse in several dimensions, including their backgrounds, careers, demographics, and length of relationship with their partner. About half of the couples were not living together, including one couple in a long-distance relationship. The rest of the couples were living together with at least one person working outside as an essential worker. Fifteen couples were dating and five couples were married, with relationship lengths that ranged from 11 months to 15 years. Their ages ranged from 18 to 51 years old ($M_{\text{age}} = 28.23$, $SD_{\text{age}} = 7.29$). Unfortunately, our sample was not diverse in sexual orientation, where most couples were heterosexual. 20 participants identified as female, 19 as male, and one as non-binary. 13 participants identified as Hispanic, Latino or Spanish, 11 as White/Caucasian, 9 as Asian, 4 as Black/African-American, 1 as Native Hawaiian or other Pacific Islander, 1 as Asian/Hispanic, and 1 as Biracial. Participants ranged in employment as well, including students, healthcare professionals, personal trainers, technicians, customer representatives, restaurant workers, and analysts. Some participants were unemployed or furloughed due to COVID-19. Table 6.1 summarizes the demographic information per couple.

Procedure

I conducted a one month within-subjects study deploying the two versions of HedgeHugs (sensing OFF and sensing ON) in the wild with couples who were Apple Watch users. All participants used sensing OFF version for the first two weeks of the study and the sensing ON version for the latter two weeks of the study. I intentionally did not counterbalance the order of the versions, as my research questions focused on how shifting from the status quo of communicating without biosignals (sensing OFF) to communicating with biosignals (sensing ON) affects communication behaviors and social outcomes. Moreover, the removal of "sensing" as a feature in a counterbalanced study could disrupt participants' mental model of the app, as opposed to a feature update when switching from sensing OFF to sensing ON. The one month study consisted of the following sessions:

Onboarding Session Each couple completed a 30 minute onboarding session together with one of the researchers over a video call. During this session, participants installed the sensing OFF version of HedgeHugs on their iPhone and Apple Watch through TestFlight. While the app was installing, participants completed a short questionnaire about their background, relationship and communication with their partner, and well-being. For example, the questionnaire included questions about their general experiences in close relationships [305], closeness with their partner [17], their frequency of communication with their partner (e.g., number of messages recently exchanged), and perceptions of social support from their partner [254] (see full survey in Appendix E). Then, I explained the app, including the availability of different types of animated hedgehog messages (state and react), and the ability to send these messages back and forth with each other on their phone and watch. Participants were asked to pair with each other in the app and test these features during the session to ensure that the app was installed and working correctly. Given the effort and time involved with filling out a survey every day, I required participants to fill out a minimum of three daily surveys per week to be considered participating in the study.

Daily Usage of HedgeHugs Participants could freely use the sensing OFF and sensing ON versions HedgeHugs however they wanted during the study, including as little or as much as they wanted. In order to capture participants' perceptions of the app and behaviors throughout the study, I asked participants to complete brief daily surveys about how they used the app (see full survey in Appendix E), which I emailed to them around 9-10pm every night. The first daily survey included comprehension questions to ensure that participants understood how to use HedgeHugs. All surveys included questions on any noteworthy experiences they had with the app that day, their reasons for sending certain state and react hedgehog animations to their partner (randomly selected from the data we collected) or their reasons for not sending hedgehog animations to their partner if they did not send any that day, and their perceptions of the state and react hedgehog animations they received from their partner (randomly selected from the data we collected). Given the effort and time involved with filling out a survey every day, I required participants to fill out a minimum of three daily surveys per week to be considered participating in the study.

Mid-Study Session Around two weeks after their onboarding session, each participant individually completed a 30-60 minute mid-study session with the same researcher over video call. Before the session, I asked participants to individually complete a mid-study questionnaire (see Appendix E). The questionnaire was similar to the onboarding questionnaire, with the addition of questions about social presence through the app [114, 171, 221] and any COVID-19-related changes in participants' circumstances since the start of the study. During the call, the researcher conducted a semi-structured interview about participants' experiences with the sensing OFF version of the app. The interview included questions about participants' overall thoughts and perceptions about the app and its different features (e.g., usage on each device, reactions to the notifications), and how they used the app with their partner (e.g., when and why they sent their own hedgehog, what they thought of their partner's visiting hedgehog, and how they responded to their partner's hedgehog) (see Appendix E for the full list of interview questions). To help participants recall their experiences, I prompted them with GIFs of the top 5 state and react hedgehog animations that they sent and received from their partner. After completing the interview, participants uninstalled the sensing OFF version and installed the sensing ON version. I explained that the sensing ON version displays state hedgehog animations that are sensed based on the participant's heart rate using Health data from the Apple

Watch. After the session, participants given mid-point compensation – a $75 Amazon gift card for participating in the study up until this point.

Exit Session Two weeks after they completed the mid-study session, each participant individually completed a final 30-60 minute exit session with me over video call. Before the session, participants were asked to individually complete another questionnaire, which had the same questions as the mid-study questionnaire. During the call, I conducted a semi-structured interview about participants' experiences with the sensing ON version of the app. The interview contained similar questions as during the mid-study interview, with the addition of questions about how they understood and perceived sensing in the app (see Appendix E). At the end of the interview, participants were asked to uninstall the HedgeHugs app. Since multiple participants expressed interest in continuing to use the app during the study, I provided links to the production version of the app in the Apple App Store, which participants could freely download. After the session, participants were compensated with another $75 Amazon gift card for completing the study.

Adjustments and Issues During the Study During the study, I made updates to both the app and certain study materials to address issues that emerged as participants used the app. Participants installed bug fixes (e.g., for missing state animations) by uninstalling and reinstalling the app through TestFlight. I also adjusted the explanation for the sensing ON version during the mid-study session, after some participants expressed confusion around how sensing worked (e.g., if it was only through notifications and not when they opened the app). I added comprehension questions to the first daily survey after the mid-study session to ensure that participants understood the second version of the app. Since couples had staggered start dates, participants who started later experienced less bugs and confusion around the sensing ON version than participants who started earlier. Finally, several participants had issues receiving the app notifications, where they may not have received any during the first or second half of the study. This is a limitation of the Apple Watch OS, which restricts when and how often apps can send push notifications. Since I was unable to address this issue, different participants received notifications at different frequencies.

Analysis

Together with the research team, I analyzed transcripts of the mid-study and exit interviews using a grounded theory approach [273], focused on how participants' perceptions and behaviors shifted between the two versions of the app. First, we segmented the transcripts into high-level categories according to our interview protocol, which highlighted the different components of communication (e.g., content of what they sent, thoughts about their partners' sent state, feedback provided, etc.). This segmentation enabled us to analyze similar concepts together. Categories were the same for the mid-study and exit interviews, with the addition of three sensing-specific categories for the exit interviews (how sensing worked, experience interacting with sensing, and preferences between versions). Next, we developed open codes for each category based on a subset of transcripts, labeling them according to similarities in participants' perceptions of the app and experiences using the app with their partner. Three coders validated the subsequent codebook by independently coding another subset of transcripts, meeting frequently to discuss the codes and ensure high inter-rater reliability. They achieved fuzzy Fleiss' kappas [161] above 0.7. After validating the codebook, the three coders divided and coded the rest of the segments. we performed axial coding by grouping similar open codes together and analyzing them to form cross-cutting themes. Finally, we refined these themes according to the focus of our research questions: communication, feelings of connection, and social support.

Additionally, I conducted quantitative analysis on the pre-, mid-, and exit-survey data as well as participants' recorded app usage data, using dyads as the unit of analysis (taking

Table 6.2: Example codes from the qualitative analysis codebook.

App Version	Category: code	Description	Example Quote
Sensing OFF	*Initiating Sending*: wanting attention	P wants attention/a response from their partner or wants to indicate their desire or availability to talk. They send their hedgehog to start an interaction with them, explicitly to get a response.	P1: "Sometimes, like for instance, the 'hi' one and the bored one, it's me kind of letting him know I want to talk."
Sensing ON	*Initiating Sending*: easier to send	P felt that it was easier to send their hedgehog with sensing than without sensing.	P17: "Because I did enjoy the message from my otter with the share button and quick reacts. I thought like, it made my use of the app more efficient...'cause I thought [with sensing OFF]...it did take a while to like be in the app and like look for a hedgehog, and think about which one to send."
Sensing ON	*How Sensing Worked*: feeling/activity accuracy	P either thought the sensing was not accurate (-1) or accurate (1) to their (or their partner's) feelings and/or activities	P8: "It was accurate a lot of the times...I went out to go to lunch once. The one with the fork and the spoon, right literally when I was going to lunch, it was a little freaky sometimes. But it was interesting." (1)

the average of responses for each couple). I ran a repeated measures ANCOVA for each of the survey measures and the number of sent messages, controlling for age, relationship length, and anxiety and avoidance scores from the experiences in close relationships scale (see Appendix E), as well as a CHI-square analysis for sent messages that received a response. However, I did not find significant differences between the sensing OFF and sensing ON versions of the app. Based on the interviews, this seemed to be due to limitations of the study including differences in the way people understood the sensing ON version of the app and a lack of consistency in how the app worked for each participant (described in the section above), and a variety of COVID-19-related circumstances that each participant experienced (described in the section below). Unfortunately, since the sample size is not large enough to account for these differences, the quantitative data is difficult to interpret. Subsequently, I will only focus on the qualitative findings for the results.

6.5 Study considerations during COVID-19

It is important to note that our study was conducted in the US during the COVID-19 pandemic, a time where participants experienced unusual situations that affected their usage and perceptions of the app. Our data collection period started on April 6, 2020 and ended on May 23, 2020 (participants had staggered start times). During this period, many states in the US issued stay-at-home orders, and some states rescinded those orders partway through the study. Stay-at-home orders required people to not to leave their residences other than for essential trips, such as for health purposes, to get supplies for daily living such as food, or if they were essential workers (e.g., life-sustaining occupations, including employees in healthcare, food retail, and public transportation). Subsequently, participants had to adjust to changes in their life circumstances throughout the study. To account for COVID-19-related effects on the study, I asked participants to describe the changes they experienced and whether/how it affected their use of the app in the pre-, mid-, and exit surveys, as well as the mid- and exit interviews. Below, I detail their responses in order to contextualize the study and our findings.

Communication with each other. Responses from the screening survey showed that eleven couples experienced changes to their frequency of communicating with each other since the start of the study. Of these couples, those who lived together saw each other more often due to changes in their work schedules, such as reduced work hours and shifts.

Those who lived apart saw each other less often due to social distancing, including one couple (P31 and P32) who typically lived together but were staying with their individual families during the study. Participants who were primarily at home and apart from their partner (i.e., if their partner was an essential worker or did not live with them) described communicating with their partner more than usual, because they were bored or because they missed their partner. However, this changed during the second half the study, where participants were more adjusted to their living situation or lived in a state that ended the stay-at-home order. With these changes in communication, some of these participants described using the app less in the second half of the study when they were more able to go outside and meet up with their partner again.

Job changes. Almost all participants experienced changes in their work lives due to COVID-19. Six participants were unemployed, furloughed, or had to temporarily shut down their business around the start of the study, and were adjusting to staying at home without work. Two participants worked in healthcare, and experienced a significant increase in the amount of work they had due to COVID-19-related cases. The rest of the participants either continued to work outside as essential workers with reduced shifts, or worked at home during the study. In the latter half of the study, with states beginning to reopen, participants found themselves working more regular shifts again, as well as returning to work outside. Subsequently, many participants described using the app less in the latter half of the study because they were busier with work.

Mood shifts. Almost all participants experienced a negative shift in their mood at the start of the study due to COVID-19. Many participants described being stressed and unhappy about the changes to their daily routine and their ability to go outside, concerned for the health of their family members and people they knew who could be affected by the virus, and frustrated with the uncertainty in how the situation will affect their lives in the long-term. With these mood shifts, participants noted that the content of their communication with their partner changed, with some people conveying more negativity than usual, and others conveying more positivity than usual to keep each other in good health. Many people viewed the app as a new and welcome venue to express these feelings, given the fun and playful nature of the animations. Some participants also noted that they felt more positive in the second half of the study, after some time adjusting to their new life circumstances.

Overall, participants described pandemic-related changes to their lives that may have decreased their use of the app in the second half of the study (due to seeing their partner more or becoming busy with work), and affected the content they were communicating over the app (focusing on positivity in the first half of the study). These patterns did not significantly affect the qualitative findings, other than the themes around social support, which I explain in Section 6.6.3 below.

6.6 Results

In this section, I describe how participants used HedgeHugs during the study and provide detailed insights around the reasons behind their usage for both versions of the app. Overall, participants sent a total of 2474 states and 987 reacts (39.9% of states) during the study. Participants were engaged with HedgeHugs daily, sending an average of 1.66 states and 0.71 reacts (42.8% of states) per day with the sensing OFF version (week 2) and an average of 1.54 states and 0.54 reacts (36.4% of states) with the sensing ON version (week 4)[4]. As expected based on COVID-19-related changes in the latter half of the study (described above), there was a slight non-significant drop in usage from the sensing OFF to the sensing ON version. Despite using the sensing ON version less, 30 out of 40 participants preferred it over the sensing OFF version for enhancing their ability to

[4]I report usage data from weeks 2 and 4 only, due to significant novelty effects that participants described experiencing in weeks 1 and 3, after they first installed the sensing OFF and sensing ON versions of the app.

communicate and connect with their partner. At the same time, participants experienced challenges in using both versions of the app to communicate what they wanted to their partner. I describe these results in more detail below, structured around themes for each of our research questions on communication, feelings of connection, and social support.

For each theme, I first describe how participants perceived the app with sensing OFF and established their baseline usage, before highlighting the changes they experienced when they switched to sensing ON. Note that participants' perceptions and patterns of behaviors established with the sensing OFF version continued with sensing ON unless explicitly discussed otherwise.

6.6.1 Effects on communication between romantic partners

Participants described using both versions of HedgeHugs to quickly communicate with their partner throughout the day through its notification feature and low-effort interface. However, with sensing OFF, while participants could easily contact each other, they faced limitations in what they could communicate. Sensing ON mitigated some of these issues and supported even easier communication.

Sensing OFF: Easily keeping in touch

Participants described keeping in touch with their partner with HedgeHugs even without sensing, particularly when they were apart from each other. They felt that the HedgeHugs interface and readily available, unintrusive messages helped them quickly communicate back and forth with their partner.

Noticing the app prompts communication With sensing OFF, participants felt that HedgeHugs helped them keep in touch by prompting them to reach out to each other. Participants were prompted when the app notifications suggested an available state hedgehog to them, as well as when they noticed the app on their watch complication (i.e., when they glance at their wrist) or phone (i.e., when they scrolled through apps during breaks or when they were bored). These features became a reminder for participants to engage with their partner through the app, leading them to reach out when they might not otherwise have thought to or been able to:

> "*[The notifications were] like a quick reminder of...her. If I'm working or something...I stop and look at it and I'll think of it for a second and respond to that⋯..it's very helpful if we're both distracted. It helps us reconnect really quickly.*" - P25

When participants sent and received hedgehog animations, they also started new conversations with each other. This included both in the moment or at a later time when they were free or would be seeing their partner. These conversations would take place on other channels like texting or phone calls. While they were primarily follow-ups to the state hedgehogs sent, they could also be unrelated to the hedgehogs:

> **Related conversations:** "*I usually know that behind...every one of his hedgehogs, there's a long drawn out story. [If I] knew that that day he had something coming up and he sent me an angry hedgehog, then I would text him, 'Hey, what happened? Tell me all the details.'*" - P16

> **Unrelated conversations:** "*[Using HedgeHugs] is normally just a kind of quick like one-hitter type situation. Where it's just something that I would use to...nudge to move to those other modes of communication.*" - P30

Sending pre-made messages is easier than figuring out what to say With sensing OFF, the state and react animations functioned as pre-made messages that participants could use to communicate with each other, similar to emojis and stickers. With the hedgehog animations, participants expressed their current feelings and activities, as well as greetings ("hello") and affection ("love you") towards their partner. Participants described being able to quickly and easily express these messages to their partner because they were embedded in the animations, and reduced friction in communicating with their partner:

> "*[It's] easier to show via picture versus words, like it's quicker to be like, 'Hey, I'm hungry,'' or 'I love you,' 'I'm thinking about you,' with that picture than typing it out.*" - P12

Participants who used the watch in the first half of the study felt that sharing the pre-made messages was especially easy on the watch, which afforded a convenient tap-and-send interface. These participants enjoyed not having to take out their phone, open an app, and figure out the words to convey what they wanted to say:

> "*It takes like a lot of energy or effort to open the messaging app and figure out what I want to say, or send a text⋯. When the notifications showed up on my watch, it felt simple to just do [a] quick share, if it matches the mood, because it's almost the same work as closing the notification.*" - P17

Participants similarly found it easy to respond to their partner's hedgehog through the react hedgehog animations, which also functioned as pre-made messages. For participants who noticed the quick react feature on the watch notifications, reacting was even easier through the tap-and-send interface and reduced the options they needed to consider.

By sending and responding to their partner with pre-made messages, couples could send hedgehogs back and forth as a form of conversation within HedgeHugs. These hedgehog conversations typically took place when the couples were apart, and did not require additional follow-up or clarification outside of the app. One couples described these as "hedgehog streaks," where they sent more than two hedgehogs back and forth within up to 15 minutes as a nonverbal, animated conversation, similar to sending memes or emojis without text. Within a hedgehog streak, couples sent an average of 12 and a max of 33 hedgehogs to each other.

Though participants mostly used the app when they were apart, some participants found the pre-made messages useful when they were physically together and unable to communicate through other channels. For example, P15 and P16 were a couple who worked at the same place, but were not allowed to communicate with each other or use their phones during work. P16 described being able to send a hedgehog animation to her partner to greet her partner when she would not have otherwise been able to:

> "*I was right across him at my work, but I was busy. So I just clicked on the state hedgehogs really quick and scrolled to the hi hedgehog. And I was able to send it within like two seconds rather than pulling out my phone, [which] I can't do] at work.*" - P16

Messages can be unintrusive with low pressure to respond Couples felt they could keep in touch with each other through the app not only because they could easily send and react with hedgehog animations, but also because the animations themselves were unintrusive upon receipt. Similar to sending their hedgehog, participants could easily tap on notifications when they received their partner's hedgehog and view the short animation. Given the lightweight nature of the message, nine participants described having low expectations for their partner's response, such as not expecting an immediate response or any response at all. Subsequently, participants felt they were not taking up time in their partner's busy day or pressuring their partner to respond when they sent their hedgehog:

> "*It kind of removes...the urgency or stress from a message. It's like I can convey an emotion without the other person saying, 'oh I need to read this and respond like as soon as I can,'... like you can convey something without it taking up as much time [whereas] if I see a text [it's like] we're having a conversation already.*" - P35

Aligned with this view, after seeing their partner's lightweight state hedgehog, some participants chose to not respond or to only acknowledge that they received the hedgehog:

> "*[It doesn't always] necessitate a response whenever we say things. So I think whenever I get [her hedgehog], I'm like, 'Oh, that's nice. She's thinking about me.' But I don't necessarily have to open it up and respond.*" - P33

At the same time, if participants did want to have those longer conversations, they could gauge their partner's availability to have those conversations through their hedgehog. P15, for example, had wanted to tell his partner a story, and inferred that his partner was able to chat because she sent him a hedgehog:

> "*I decided to tell her [the story] through text...unrelated [to the hedgehog she sent]...but I guess it would relate in the way that if I saw that notification [of her hedgehog] recently, then that means like, she may or may not be on her phone and have the time to reply to it, you know?*" - P15

Sensing OFF: Fitting in with existing communication practices

As participants used HedgeHugs, the app became integrated into their daily interactions and communication patterns with their partner. Even without sensing, the app was a lightweight communication channel that supplemented and even replaced participants' other communication channels with their partner, using known context from their relationship to fill in the details.

Understanding messages based on context from their relationship Participants adapted HedgeHugs to how they typically communicate in their relationship with their partner, where existing context from their relationship was embedded in the hedgehog animations they sent. For example, during the study, 17 participants sent their hedgehog to represent routine communication with their partner that they had engaged in prior to the study, such as to say "good morning," "good night," and "how's it going" at certain

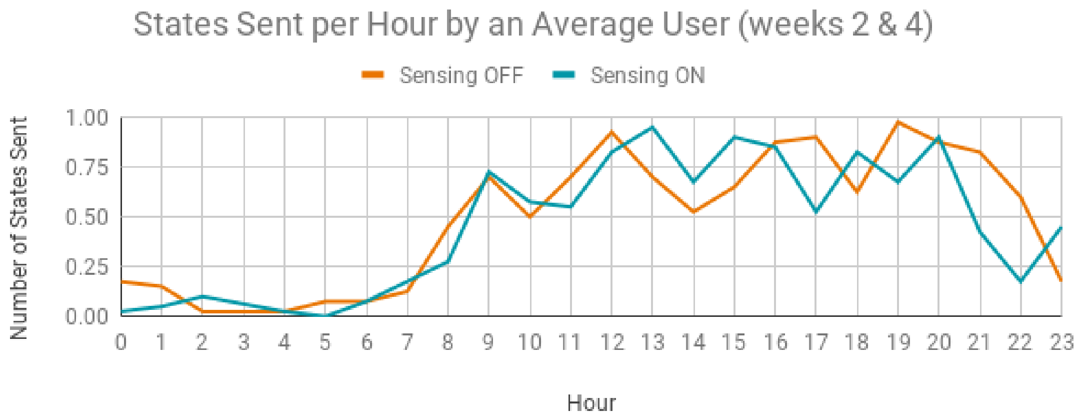


Figure 6.8: Average number of states sent for HedgeHugs by time of day.

times of the day (i.e., mornings, nights, breaks). This aligns with participants' usage data for both versions of the app (see Figure 6.8), which shows peaks at the start and end of the day (9AM and 8PM) and common break times (12-1PM around lunch and 4PM towards the end of the work day).

> "*I was thinking to communicate [with the hedgehog] because first thing in the morning, that's what we do. Whenever one of us wakes up, it's always just, communicate [with each other].*" - P10

> "*So around twelve is when I put my laptop down and then I start thinking about what I'm going to make for lunch. And then I'm on Instagram, and that's when I use the app...and send [my hedgehog] to...my partner on the app.*" - P1

Participants also expected that their relationship context would help them convey their intended message through the provided animations. 16 participants claimed that they and their partner knew each other well enough to understand what they meant by a particular hedgehog animation. P23 and P24, for instance, described drawing from their communication and inside jokes with each other over their 13 years of being in a relationship:

"*We've been together for a long time. There's a lot of hand signals, emojis, and just moods for the most part. I understand her pretty well.*" - P23

"*[My partner] and I have an inside joke [about our dog]. And so when I saw that hedgehog, I sent it to him because it was just a reminder of pretty much what the dog was doing.... Like I said, we have a really strong connection. Like he doesn't even have to say anything. I don't have to say anything.*" - P24

Understanding messages based on existing conversations Participants used HedgeHugs to supplement their conversations and shared activities with their partners, even without sensing. That is, participants could send their hedgehog during a conversation or activity they were already engaged in with their partner, and their partner could use that conversation as context to interpret the hedgehog. For example, P1 and P2 were a couple who often watched TV together remotely. While watching the news with her partner, P1 sent her hedgehog to express her sarcastic surprise to the news content:

"*Like the sarcasm 'wow' [hedgehog], that was [sent] during conversation...like I would text him and be like, 'ok Cuomo is talking or this clown is on doing his speech.' And then Trump would talk about something [and say] something crazy and I would respond with 'w-o-o-o-w!'*" - P1

Participants also used hedgehog animations as a way to reference conversations after they've ended, such as to follow-up without starting a new conversation or as an expression or reaction to the conversation they just had:

"*If it's a situation where it's like a sad one...you feel the [hedgehog] emoji more if it's sent after the conversation because then it's like, okay, we talked about it and now I really know how you feel...as opposed to...[if] you're getting it immediately, [it can be] perceived as...you're sending it before fully understanding why I sent mine.*" - P2

Becoming a daily communication channel All of the participants already used a variety of applications to communicate with their partner, including texts, FaceTime, Instagram, and Snapchat. They described allocating different roles for these platforms, such as having detailed conversation over texts and calls on FaceTime, sending memes and articles over Instagram, and sharing quick pictures over Snapchat. Several participants described HedgeHugs as taking a new role dedicated to quickly conveying feelings to their partner, similar to the quick communication of Snapchat and emotions in various forms of emojis (e.g., Bitmojis, stickers) but faster:

> "*This is more feelings-based than just finding a random something off the Internet to send.*" - P3

> "*Just because on Snapchat, there's also a lot of different emojis. But now that we have [HedgeHugs], it's a lot more easier to just use one sort of emoji to convey emotions [than choosing from] like a variety of them on Snapchat, and like different shapes, sizes and things of that sort. This just makes it more simple and efficient⋯*. - P29

Five participants, including P29, noticed that the hedgehog animations actually *replaced* Snapchat as one of their means of daily routine communication with their partners:

> "*Whenever I feel texting or something or if someone isn't responding then the first go-to thing is to send the hedgehogs instead compared to like sending [a snap on] Snapchat or anything else....*" - P29

Sensing OFF: Limitations to lightweight communication

While participants engaged in easy and lightweight communication with their partner through HedgeHugs with sensing OFF, they experienced some challenges with the app being *too* lightweight for them to communicate meaningfully with their partner. Moreover, participants used to accessing long lists of emojis or GIFs to express their states nonverbally were frustrated by the short randomized list of states.

Some animations feel less meaningful to send Participants did not always send their hedgehog when they noticed it, as they sometimes felt the available animations would be meaningless to send to their partner. Most participants would not send state hedgehog animations when they did not see any animations in the randomized list that were related to what they were doing or how they were feeling. They pointed out that sending an unrelated hedgehog would require additional explanation outside of the app to clarify its meaning, which felt unnecessary and contrary to a lightweight channel.

> "*I think...having only like two options to choose from...I am not as big of a fan of that, because I feel like a lot of times they don't necessarily apply to how you're feeling in that situation. So you just end up not using it.*" - P38

Additionally, participants did not want to send hedgehogs that were redundant. They felt that sending hedgehogs over and over again might result in those animations being less interesting or exciting, and unnecessary because they already sent that message to their partner or their partner already knows what they're doing from their prior message.

> "*But it's in my opinion better to not overuse those ones because then...you're using the same one over and over. If we had like the standard that if she sends something neutral, there's going to be something neutral back...you can include something like this where...she thinks it's cute...like a deviation from what's expected but in a good way.*" - P35

> "*I think he got the point that I am bored. So I don't have to always send it.*" - P26

> "*Well, you already sent it in the beginning. So I feel like if you send it again, it just would be kind of repetitive. I guess it would make more sense if you are changing from that activity to a different one to send a hedgehog.*" - P27

Animations without words can be ambiguous While participants felt that it was easier to not use words for their hedgehog message, they sometimes found the wordless animations too ambiguous to fully communicate what they wanted to their partner. In fact, one of the most requested features for the sensing OFF version was to add short captions for the animations. Participants described some concerns over multiple potential meanings for the animations they sent or limited details for the message, which could lead to misunderstanding or necessitate off-app clarification (again, defeating the purpose of a lightweight communicating channel). Moreover, participants often sent random hedgehog animations with no meaning, such as sending just to send them or because they happened to like how they looked.

> "*Like that walking hedgehog...she might [react with a] thumbs up, but that doesn't necessarily mean that...she's understanding that the walking hedgehog means that I would like to go for a walk...the thumbs up could be, 'yes, I want to go for a walk too." It could be like, 'walking is good.' So I mean, there's not a lot of clarity with just having the simplistic reaction.*" - P38

> "*Well, he would have no idea probably what I was trying to get at if I just randomly sent a hedgehog that wasn't super happy. Whereas in person I could just be like, 'hey, this annoyed me, I need you to do this more.' And I can't do that with the app.*" - P37

On the receiver's end, participants also described being unsure about what their partner wanted to communicate through their state hedgehog, if they were trying to communicate anything at all. Subsequently, participants were unsure how to respond. They described sending "safe" responses back that were generally positive (such as their own state, a thumbs up acknowledgement, or a loving one), a randomly selected react hedgehog just to respond at all, or simply not responding.

> "*I was confused about that hedgehog.... I remember out of my confusion I replied with him because he looked pretty chill.... I was just trying to say no hostility as well, 'cause I didn't know what the other hedgehog was doing. So that was a pretty safe response.*" - P33

Many participants did send their state hedgehog with an expectation of an appropriate response, and were disappointed that they received only a best guess or random responses back from their partner. For example, P34, who was P33's partner, had expectations for receiving certain responses from her partner when she sent state hedgehog animations representing her feelings:

> "*I feel like it was a kind of crummy reply··· So if I'm sitting here looking like this bored hedgehog and then he's just like, 'yeah,' I feel like it doesn't answer my need for more than just a 'yes.' So to me that feels a little crummy.*" - P34

Sensing ON: Easier communication depending on sensing accuracy

Most participants felt that communication became *even easier* through HedgeHugs with sensing ON compared to sensing OFF, where they engaged more with the convenient watch app and could more easily determine which animations to send to their partner. They felt that the addition of biosignals helped mitigate some of the issues around the meaning of the animations they sent to and received from their partner, thereby aiding their ability to express their current state, and understand and react to their partner's state. However, these benefits were only possible if participants perceived that the sensed state options accurately reflected themselves or their partner most of the time.

Sensing gives a reason to use the watch app Participants used their watch much more often during the second half of the study due to the addition of sensing in the app (see Figure 6.9). Many participants defaulted to their phones in the first half of the study,

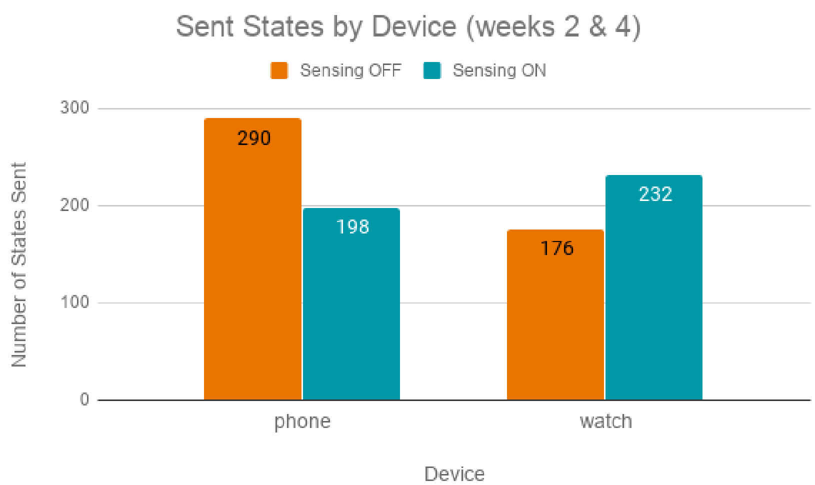


Figure 6.9: Total states sent in HedgeHugs by device.

often because they were not wearing their watch (for many, due to being at home during lockdown and seeing no need to wear it) or because they only used their watch to check notifications. In the second half of the study, participants were told that they needed to wear the watch in order for the sensing feature to work, but that they could still use both the phone and watch app to view the sensed states. Though most participants initially wore the watch to test the feature, they found themselves engaging with the app more on their watch than they had before. As their usage shifted to the watch, participants enjoyed the sensed states and notifications as well as the convenience of having the watch on their wrist. P14 noted that the sensing feature gave him a reason to use his watch:

> "*I have the watch and I use it but you know, I'm not really like, super attached to this watch compared to my phone.... So I think having a reason to want to use the watch for this app and its sensing my vitals and things like that is, I think it's a good thing to include in this type of app.*" - P14

Sensing provides a better pre-made message 24 participants felt that sensing ON improved the pre-made messages that they could send to their partner. These participants appreciated the automated state suggestions that the app provided, which gave them a better list of state hedgehog options. This simplified the process of selecting a state to send, as they no longer had to pick the next closest one to what they wanted, or close the app and wait for the randomized states to change.

> "*The sense state hedgehogs in the second app hit closer to home than the first app, where they were just like random hedgehogs. So it narrowed it down better.*" - P3

> "*I think I actually prefer the second [version of the app]. Just because, it sounds a little weird, but it's like less work...it kind of already does the searching for you. Whereas with the state hedgehogs on the first [version]...if I didn't see one I wanted...then I would just like wait for the next round.*" - P34

Participants who noticed the sensed notifications from the app felt that they could more easily send their hedgehog through the notifications. They became more engaged with the notifications, which shifted from being a nudge to use the app to a suggestion to share their current sensed state. When they felt the suggested state was accurate, they could simply share from the notification without opening the app. Five participants described simply sending their state hedgehog whenever they got a notification without thinking about it or even knowing which animation they were sending, because they trusted the app to know how they were feeling and suggest an accurate state.

> "*Because it knows exactly how you're feeling versus like me having to look through it and kinda of tick something. Because sometimes I don't even know how I'm feeling...you don't really think about how you're feeling until you have to...sit and think about it.*" - P9

> "*The first two or three times [that I got the sensed notifications] they were on target as far as...the way I was feeling⋯. That would be the hedgehog*

that I was trying to send anyway, for the most part⋯. So once I realized that that's what was happening, I wouldn't think too much about it anymore as far as opening up the app and seeing if it was the hedgehog I wanted to send or anything like that." - P23

Participants also felt that the app with sensing ON helped to mitigate some of the issues in lightweight communication that they faced with sensing OFF. With sensing ON, participants described sharing more meaningful and less random hedgehog animations to their partner. Since the hedgehog animations became tied to participants' personal data, it was automatically representative of participants' physical state and what they were actually doing or feeling. This reduced the ambiguity of the animation as a message, because the message would always be about their own state rather than something random or unrelated to themselves:

"*Just because it kind of reflected a little bit of what I was doing on a day-to-day basis. It was just more of what I was actually doing [as opposed to] just sending a random hedgehog that was just given to me*." - P7

"*When I was sending the message, my intent behind it wasn't, 'Oh, I'm reminding you to do something.' I'm sharing my mood with you. So I would say I definitely saw that change in version two. [Version one] was just more inclined to him and [version two] was more inclined to me*." - P36

On the receiver's end, participants who recognized that their partner's state was sensed[5] also felt they could better understand their partners' sent state hedgehogs. The message they received felt less random and more relevant to what their partner was doing

[5]We noticed that many of our earlier participants did not recognize their partner's sensed states, where they instead focused on how the sensing feature worked for themselves. This may have been due to the individual nature of sensing, where they more readily reflected on their own physical state, or a need for a more prominent indicator that their partner's visiting hedgehog was also sensed. We added additional instructions during the mid-study session to ensure that they understood that their partner was being sensed. Ultimately, about half of the participants did not recognize their partner's sensed state. These participants understood and reacted to their partner's state in the same way as when they used the sensing OFF version.

or feeling. For example, knowing that his partner was being sensed by the app, P4 would reflect on his partner's shared sensed state, as opposed to thinking that she just sent a random one like in the first half of the study.

> "*So it did make me take [a second to] pause and think to myself okay, what could she be doing at this time that will make the state hedgehog show this? [The first version] was just more of as a random one whereas this one was more of like a targeted…estimation you can call it.*" - P4

Since participants had a better understanding of their partner's state, they could provide better reactions, rather than resort to "safe" or random reactions:

> "*I think it's different in so far that I felt like she really wasn't sending random ones. I feel like they were kind of more based on what she was doing. So, you know, I felt, for that reason I felt like my reactions were more consistent.*" - P39

At the same time, some participants lowered their expectations for responses due to the shift in the nature of the message they sent. For example, P34 noted that since she no longer needed to prescribe complex meaning to the state animations she sent, which would now represent her state, she felt more satisfied with her partner's feedback simply acknowledging her state to show that he understood it:

> "*[In the second half] instead of having these crazy, intricate meanings to it, it was just how I was feeling or what I was doing…. So he would get that…then from there, he would reply back with like, aw, thinking of you too, like smiley hedgehog.*" - P34

Challenges of recommending a sensed message Participants' understanding of how sensing worked in the app and how it can relate to feelings and activities affected their ability to use the app. We designed the system to recommend a set of states; therefore, the states that participants sent to their partners were partially automated by the system and partially manually selected by the user. Though most participants accepted this design, a few participants felt that it did not meet their expectations or understanding for how sensing or emotions work. These participants typically tried to use the sensing ON version in the same way as the sensing OFF version.

Regarding the automation in suggested states, while some participants gave the system room for error (e.g., "*I could see how it could think that*" - P34), others felt frustrated with the system if they felt their sensed state was inaccurate or if they believed it impossible to fully sense their mood or activity from their heart rate. Six participants who experienced these issues believed that the set of states available with sensing ON were worse than with sensing OFF, as they felt the set was still randomized by even more limited since only certain animations were shown together based on their state. As a result, they preferred sensing OFF, because they would get more variety to choose from to reflect their state:

> "*Whenever it would send something I would usually get the same hedgehogs. So I wish when it was sensing something I would be able to get like a variety of hedgehogs at different times whenever it was sensing something in particular compared to like just one all the time.*" - P29

Regarding manual user selection from the suggested states, while we originally intended this design to reduce being constrained to one possibly inaccurate state, some participants *expected* the system to recommend exactly one state. They found the multiple states unnecessary or confusing, especially if they did not want to think about which one best matched them. These participants subsequently focused on interacting with the app through solely the notifications, such as those who trusted the system to know their exact state, or focused on the top hedgehog animation in the list of options:

> "*I just never knew which one was the most accurate.... I really just thought it was that first on [in the state list and] the other ones could have been random [or] maybe a second best choice. I just didn't really figure out which one to*

go with, you know? I'm like betraying my heart rate if I choose a different one [than the first one] or something." - P15

On the other hand, some participants believed that they could experience multiple feelings at once, and were satisfied with having multiple state options as long as one of them matched them:

"*Most people at any given time throughout the day, you might be feeling a lot of different things...at least with the sensed version, you know...at least one of the things that it was showing you [matches].*" *- P38*

Finally, while sensing reduced the ambiguity of the message people could send, two participants found the new, clearer message too restricting. P13, for example, had used version one of the app to send hedgehog animations that made her partner smile without necessarily relating to her feelings. Since the sensing ON options were restricted to her own state, she struggled to find animations that conveyed what she wanted:

"*[There aren't] very many to pick from because...I don't always want to send out what I'm feeling, sometimes I just want to send out a funny one or send out something for him to make him smile or laugh.*" - P13

6.6.2 Effects on social connection between romantic partners

Participants felt that HedgeHugs was more intimate and personal than other communication apps because it was unique to them and their partner. Participants used both versions of this intimate application to connect with their partner, where sharing their state helped them be more aware of each other and feel like they were together while apart. As participants shifted to the sensing ON version, they felt an enhanced connection with their partner where the hedgehogs became more authentic and representative of each other. At the same time, sensing ON introduced new tensions in communicating through the app, due to the system's influence on what users communicate.

Sensing OFF: Self-disclosing states through HedgeHugs

Participants used HedgeHugs to disclose their current state, including their feelings and activities, to their partner, even with sensing OFF. These included some states they might not have otherwise shared with their partner prior to using the app, where they were more willing to share those states due to the visual appearance of the hedgehog animation.

Cute hedgehogs make it easier to disclose Eight participants found that HedgeHugs with sensing OFF made them more willing to disclose their state to their partner because the cute and playful hedgehog animations were disarming. In particular, they felt more compelled to share negative or more mundane emotions or activities that they typically would not communicate to their partner over other channels:

> "*I probably wouldn't send a text saying I'm sad...but somehow I feel better sending it as the sad [hedgehog] than me sending a text saying I'm sad...sending it in the cute little hedgehog feels like I'm revealing emotions or I feel more protected doing it that way*." - P2

> "*It provides a different avenue of communication to express certain things that I normally wouldn't do in the other apps. For example, I like to...open the app like when I'm eating [and send] the knife and fork...state hedgehog. [It] provides like a nice way to...send her that notice every day...without it feeling awkward. Because [if every time I ate] I just send her a message saying like, 'I'm eating'...like every single day, it'd be weird and awkward. But when I send it through the app, it feels a lot less invasive or intrusive*." - P17

Participants also pointed out that sometimes the visual animation could better express what they wanted to express compared to words. P24, for example, experienced a health issue during the study and described being in a state that she could not express in words, so she turned to the hedgehog animations:

> "*I really haven't been wanting to talk too much to anybody. Even though [my partner] is the closest person to me, sometimes it's hard because I don't know if I want to be sad, angry, mad. And so sometimes I just want to just show my emotion without actually speaking it. It's very important to not always have to tell somebody how you're feeling.*" - P24

Participants felt the hedgehog animations facilitated not only expressing their own states, but asking about or discussing their partner's states. Since the animations themselves represented participants' states, they provided unsaid answers to the "how are you doing?" check-in questions typically asked when initiating conversation. Since their partner already disclosed their state, they simply had to ask more details about it.

> "*One of the benefits of the hedgehogs too is [that] you've already communicated to me that you're angry [or] that you're sad. So we don't have to dig around with each other. It adds a kind of preliminary 'hey how are you doing,' you don't have to tell me you're fine, because you've already told me that you're sad or angry or that kind of thing.*" - P39

> "*I just find it that it would be easier to approach someone by asking them, 'why did you send me that?' or 'what did you mean by that reaction?' As opposed to saying like, 'hey, are you mad?' or 'hey, did I do something?'*" - P41

Sharing states to know what each other's up to Participants expressed their current state with each other even with sensing OFF, disclosing what they were doing and how they were feeling to their partner through the hedgehog animations they sent. These states included "extreme" or atypical feelings and activities that they wanted their partner to know about, as well as "ordinary" feelings and activities that were common to their daily lives. Several participants explained that since the hedgehog animations themselves did not provide details, they conveyed a general sense of their mood. Five participants felt this use case would be more applicable to younger audiences or people earlier in their relationship, who may desire interaction but not conversation:

> "*When you're [married and] living together, you have a lot of decisions in things that you need to make together on a daily basis versus if you're just dating...there's not necessarily a need to communicate every day, multiple times a day. There's a desire [to but] you might not necessarily have something to say to that person all the time, but you might still want to interact with them on some basis. [So] I think the more general communication...just sending a hedgehog to be like, 'hey, I'm thinking about you' would be good in that dating stage where you're not necessarily with the person all the time.*" - P38

P35 and P36, the youngest participants (18-19 years old) who had been together for 11 months, seemed to agree with this sentiment, noting that they have observed others their age struggle with meaningless conversations to keep in touch. After some trial-and-error with the sensing OFF version, they established a new pattern of communication where they used HedgeHugs to convey their baseline, broad feeling, and other apps for more specific or extreme feelings and situations that required full conversation:

> "*Because [people my age who are dating are] sort of bored or want to check in, there's always like convos that are just like, 'Hey, hey, what's up? Not much. How about you? Not much. Like, what are you doing? Later.' ...Replacing that sort of platonic conversation with the hedgehog app, and just having a cute, exciting, newer way to check in..that sort of changed our mentality on texting because now texting [warrants] a full conversation or it's about something important. And I think that the hedgehog app...helped*

take stress off of conversation [and] made it a lot easier to find meaningful conversation." - P35

Participants also noticed that they became more aware of their partner's current state when they received their partner's hedgehog. For example, P13 and P14 were a married couple who got into an argument during the first half of the study. The day after the argument, P13 sent angry hedgehog animations to her partner to indicate that she was still angry, and her partner noticed:

"*The hedgehog kind of makes me realize more like oh, I guess she's mad at me for some reason or like what we fought about a while ago or like even like a day ago or a few days ago I guess, it's still bothering her even now.*" - P14

Sensing OFF: Feeling like they're there with nonverbal cues

As in much of remote communication [282], when couples were not physically together they had less access to each other's nonverbal cues, such as gestures or facial expressions. Participants used the hedgehog animations, which were expressive and full-bodied, as a way to supplement the lack of nonverbal communication.

"*It's a supplement to that nonverbal communication when…they're not able to act on those verbal communications or directly respond to those emotions in person.*" - P11

Participants described typically using emojis, Bitmojis, GIFs, and selfies to express those missing nonverbal behaviors.

Thirteen participants felt that the hedgehog animations were a more vivid and simple means to express themselves emotionally compared to their typical means outside of the app, including emojis, Bitmojis, GIFs, and selfies. When they received their partner's hedgehog, they could also imagine their partner through the hedgehog animation.

"It's kind of like seeing emojis. They're not like animated like these. So it's like something about using specifically hedgehogs and seeing their movements. It kind of enhances the emotion." - P2

"It's like I love you too or...I know what she's saying but I can't put into words, like one of those. Like I see her doing [that reaction] you know." - P4

Sensing ON: More authentic messages with less agency

For most participants, shifting from sensing OFF to sensing ON enhanced feelings of connection with their partner. With sensing ON, they shared not only more relevant states, but also more honest states through the app, where they and their partner were more open and genuine with each other.

Sharing sensed states to know what each other is actually up to As discussed in previous sections, participants who felt the sensing was accurate with sensing ON were better able to express themselves compared to with sensing OFF as a result of having better matched options to their actual state. Subsequently, participants could both better disclose how they were feeling or what they were doing and better understand their partner's state, since the animations would be more meaningful as their actual states and not just random. Finally, with a better understanding of their partner's state, they could respond in more relevant and appropriate ways.

Sensed messages are more authentic and representative of you Though participants considered HedgeHugs with sensing OFF already fairly personal, 27 participants described the app with sensing ON even more personal. With sensing ON, they felt the available hedgehog options were personalized to themselves and their body's physical state, backed by their own data. Participants felt more connected to their hedgehog, as it became a representation for themselves. P35, for instance, said that sending the hedgehog animation felt as if he was the hedgehog visiting his partner, rather than selecting a hedgehog animation as if it was an emoji or sticker:

> "*Like, it's personal to me because it's reading what I'm doing...it's almost as if you could go through like the phone yourself and like wave or like something like that....[In version one, it] could have just been a sticker app, an iMessage where you're just sending from a collection of animated stickers. Once it [sensed] what you were doing throughout the day, it [became] a more personal experience...because it's sensing what you're wanting to say throughout the day.*" - P35

On the receiver's end, participants who recognized that their partner was sharing their sensed state also felt more connected to their partner. Their partner's sensed hedgehog gave them access to their partner's physical responses, which they would typically only perceive if they were physically together:

> "*It was interesting that both of our body's responses were being recorded. That's what I mean by feeling connected like we're not physically together, but you're still able to get a sense of their actual bodily responses through the app, like through technology, and that was cool.*" - P31

Nine participants also described becoming more aware of their own state through the app, which encouraged them to express themselves more honestly. P14, for instance, found that he often put up a front for his feelings – both to himself and to his partner. When the app indicated that he was stressed, he realized that he was actually feeling that way and felt more compelled to share that with his partner:

> "*I'm pretty open with my feelings overall in life and with my partner, [but with HedgeHugs] I'm more open to be like, honest, I guess, like totally 100% honest compared to 95% honest⋯the 5% can sometimes make a big differ-*

ence⋯. I would send the [stressed hedgehog] instead of being like, 'Oh, I don't want to look weak right now by showing that I am stressed.'" - P14

Likewise, participants who recognized their partner was sharing their sensed state felt that their partner was being honest with them through the app. With sensing OFF, their partner could pick any hedgehog animation for their state, even if they were not feeling that way. With sensing ON, since the state hedgehogs were automatically tied to their partner's data, participants felt they could tell how their partner was *actually* feeling.

"*I feel like in the first version...I wouldn' t know if that was actually how he was feeling or if he just picked [a smiley one]...just to send something nice. So like knowing that he actually felt that way and probably like a little bit happy and so that was good.*" - P37

Three participants were compelled to be more responsive and thoughtful about their responses to their partner's more honest and authentic sensed states. For example, P31, who tended not to respond immediately to her partner's state with sensing OFF, felt more urgency to respond with sensing ON:

" *I feel like [the hedgehog's] a way of him reaching out. So for me to just wait [to] respond and not really think much of i, it feels rude not to validate whatever he sent out, because that is...an extension of him like a virtual extension of him. So I felt like I needed to respond to it as soon as I saw.*" - P31

P36, who frequently used the quick reacts during the first half of the study, used them less during the second half of the study. She explained that since her partner was sharing his emotions with her, she felt "responsibility" to put more effort into reacting by opening up the app and deciding which react animation would be the most appropriate response.

[asked about quick reacts for sensing ON] "*Although very convenient, I just felt more of a responsibility this time to [open the app]. Just because I felt* *like my partner was sending me state hedgehogs off his emotion. [Doing] a quick react hedgehog...it was kind of dismissing the notification in a sense. Opening up the app and like scrolling through all reacts so I could choose the right one made me feel like I was more connected with my partner in the interaction.*" - P36

Sensing may take away control over the message While more than half of the participants felt the system provided a more personal communication experience, eight participants expressed concerns over the system recommending their current state. Most of these participants felt the system was inaccurate or incapable of sensing their feelings or emotions, and believed that they knew their own feelings better than a system could. They wanted control over sharing how they felt, such as by selecting from all possible states, similar to emoji keyboards, in order to most accurately represent themselves:

"*Like, I feel like I know what I feel like...this thing is guessing how I feel based on I don't know what my heartbeat or...I don't think that's like accurate.*" - P1

"*[Picking from an expanded list of animations] would be exactly what I was doing at the time...I mean it's like 100% accuracy, I can just select from a list. And I'm given more options versus having to pick between like 2-5.*" - P30

The system's state suggestions may have controlled not only what participants could share, but also how participants understood their own feelings. For instance, P18 brought up concerns that the system may have influenced her to feel a certain way or share with her partner that she was feeling that way, even if she was not actually feeling that way:

"*I guess like with [sensing ON] it was like always asking yourself whether or not you really felt that way before sending it. And so I don't know if sometimes that would influence you to send it anyways or influence you to maybe feel that way. Yeah so, I do prefer the first one that way whatever* *you're feeling…you're able to just think of it on your own and just send it.*" - P18

As previously mentioned, some people readily gave up their control to the system because it made communication easier. They trusted the system to know how they felt better than they did and often sent the sensed state without thinking about it or even knowing what animation they were sending. However, one participant pointed out that while this made communication easier, it also made it more impersonal. Though the message itself was personalized to himself, he no longer took the time and effort to consider what to send:

"*I think with the second half it was me sending stuff based on what I think the watch read that I felt. So it wasn't me taking the time and going through and saying, yeah, this is the one. It was like, the watch said this is how I feel. So I guess this is how I feel. Let me send it. It was like [sensing ON] was almost more impersonal, even though it was reading off of my data.*" - P2

6.6.3 Effects on social support between romantic partners

Participants used both versions of HedgeHugs to provide social support to their partner through both their state and react hedgehogs, aiming to bring their partner to a more positive state. For more serious negative states, they often jumped to other platforms to have a more immediate, detailed discussion to make sure their partner was doing alright. With sensing ON, participants were able to improve the social support they sent to their partner, such as by recognizing and appropriately responding to their partner's actual feelings.

Sensing OFF: Keeping my partner in good spirits

Sending positive messages and emotional support Participants sent both state and react hedgehog animations to ensure their partner was in a positive state. Eight participants, for instance, sent certain state hedgehogs to put a smile on their partner's face by showing that they were thinking of them or because they knew their partner liked or found that particular animation funny. These participants noted that due to the COVID-19 lockdown (which was still in its early stages during the study), they were especially concerned about their partner's mood. Indeed, several participants noted mood shifts caused by their adjusted life circumstances (detailed in Section 6.5). P14, for instance, faced unemployment at the start of the study and described frequently being in a negative state during the first half of the study. Therefore, his partner, P13, sent hedgehog animations primarily to make him feel better:

> "*He's been kinda down lately with this whole COVID thing...he's been calling EDD a lot so it's been frustrating him. So, sometimes I just want to send a funny one to make him kind of smile and feel better in the moment*." - P13

Since participants also experienced changes in their diet and exercise during the lockdown, their partners also used their state hedgehog animations to suggest activities for them, like eating or walking, to make sure they were in good physical health:

> "*So since I'm a lazy person I have to be reminded to work out so that was just one of the reminders to get my exercise done*." - P20

Participants also appreciated being attended to and thought of, as their partner took a moment out of their busy day to send something nice and to care for them. Since the hedgehog animations were cute and loving, they usually successfully put a smile on their face:

> “*I always liked [receiving my partner’s state hedgehog]. They’re cute. I mean, it brings little smile to your face especially if I was like really busy in the moment and then I looked on my phone to see what he sent me and be like, oh, okay, I can be less stressed now.*” - P13

> “*It made me smile. ’Cause like, I mean…we’ve been together for almost eleven years now, so he doesn’t always send me lovey stuff. So I thought it was cute that they were holding hands. It was like more…romantic. I thought it was sweet ’cause he doesn’t often send me like love emojis stuff.*” - P37

Participants also provided emotional support to their partner when they received their state hedgehog, looking for appropriate responses that would show that they cared for their partner. This included acknowledging their partner’s state, reciprocating their feelings (e.g., affection or showing similar excitement), and showing concern for their partner. Aligned with this, the most common react hedgehogs sent in response to neutral and positive states were the thumbs up and love hedgehogs. The most common reacts for negative states (anger, boredom, sad) were pat on the back and question hedgehogs to indicate consoling and the desire to follow-up. One participant noted that use of the react animations helped ensure positive communication with their partner, even when they sent more negative states:

> “*You can’t really use the app in a negative way at all. So I think whenever we’re using the app it’s very positive. …Because there’s like a sad state hedgehog. And if you send that, there’s also a consoling your state hedgehog. So it cancels each other out. It’s cute.*” - P26

Many participants decided to follow-up on their partner’s state by starting a new conversation with their partner over text or a phone call, or mentally preparing themselves to support them in person if they were going to see them later. Through all of these different reactions, participants aimed to make their partner feel better:

> "*Text me, talk to me about it or the hug one. Like if she's frustrated, there's something going on at home or at school. I would you know, send her the hug reaction just to you know, hopefully push her for some good spirits.*" - P32

> "*It sort of like altered my way of asking her how her day was in a way...like going into that conversation thinking, it was a bad day and I'm going to have to console her in a way. So I guess it just prepared my mental state for the conversation we were going to have once you got home.*" - P15

Participants also mentioned that their partner's responses through react hedgehogs or conversations did help them feel better:

> "*That particular one always reminds me [of my partner] because she always says, 'there, there.' That's kind of like her little like, 'it's gonna be fine.' It reminds me almost exactly. So it's kind of one of my favorite ones, because I can just hear her saying it.*" - P40

Sensing ON: Validation and responsiveness

Validating feelings Participants felt that they better provided and received social support when they shifted to the sensing ON version. As previously mentioned, sensing helped participants become more aware of their own feelings, and they sometimes expressed those feelings in order to validate and discuss it with their partner:

> "*So I think that was important when I would get those messages just to kinda be like, man you know it really read me, I had a bad attitude at work. It's like it initiated a conversation that 'hey what's bothering you type of thing.*"' - P40

When participants received their partner's sensed state, they described better understanding their partner's actual feelings than for the randomized states, as it stemmed from their partner's body. As previously mentioned, participants could then provide better matched or more thoughtful responses to provide support.

P9 noted that he provided better feedback for his partner with sensing ON because he felt he could shift his focus to his partner's state when reacting. In the first half of the study, a few participants sometimes repurposed the react hedgehog animations to send their own state rather than react to their partner's state, because there were simply more react options available than the state hedgehog animation list. With the sensed state list, P9 felt he had more relevant state options to share his state, and could use the react hedgehogs as intended.

> "*Before [with sensing OFF] I wouldn't see that many that matched how I was feeling. Because when I would get something from her I would send something back that I was feeling because then I would finally see something that I guess matched.*" - P9

Finally, participants appreciated receiving more thoughtful responses, particularly if they had expectations to receive a react animation that would match with their sent state:

> "*I kind of felt like [her reacts were] more in context. [With sensing OFF] I think she would occasionally send the random thumbs up⋯. [It's] kind of like when you text...you have the ability to send a thumbs up [that] a lot of people do now. I feel like it's less personal than responding with a text...that thumbs up hedgehog is literally like a thumbs up you would receive in a text message. [So] actually having something that fits the context of what you sent, makes it a little bit more personal.*" - P39

Using sensing for self-reflection rather than communication Four participants mentioned that they viewed the sensign ON version as an opportunity to track their own mood, without needing to send it to their partner. These participants were interested to understand how they truly felt, and would consider changing their behaviors in order to improve their well-being. They viewed sensing as a more "selfish" feature that did not require sharing with their partner:

> "*[The sensing ON version] kind of focuses on you a little bit more, which may sound selfish, but...it does bring it to your attention if there's something going on with your heart rate, which I think is good for you as an individual.*"
> - P39

6.7 Discussion

6.7.1 Summary of Results

Perceptions of HedgeHugs

Overall, participants viewed both versions of HedgeHugs as a lightweight communication channel that enabled them to easily to keep in touch with their partner and let each other know how they are doing. With sensing OFF, participants felt the hedgehog animations were an easy way to communicate without words, using them to convey their current state, suggest activities, and show caring and affection towards their partner. This communication was especially convenient over the watch, since they could quickly tap to send their hedgehog as a new message or response to their partner. However, this communication was also limited because a simple animation could mean multiple things or required more detail. For most participants, HedgeHugs with sensing ON mitigated some of these issues and enhanced participants' ability to connect with each other. The addition of biosignals created a more personal experience with the app and with their partner, where the app curated possible messages for them to send with more specific, authentic meaning because they were tied to their own physiological responses. At the same time, biosignals introduced new concerns around accuracy and agency over the message, where some participants felt the system was overly suggestive on how they were feeling or what to communicate to their partner.

Interaction Patterns using HedgeHugs

Participants adapted HedgeHugs into their own communication practices in a variety of ways, summarized in Table 6.3. *Non-conversational status updates* were state hedgehog animations that participants sent in order to update their partner on their current status, just to let them know and not necessarily in order to receive a response from their partner. *Conversation starters* occurred when participants sent their hedgehog and then started verbal conversations on other platforms such as over text or a phone call. These conversations could be related or unrelated to the sent hedgehogs, as well as happen immediately or at later times (e.g., if they knew they were going to see their partner later in the day and planned to discuss it in person). Hedgehog messages that were *integrated into existing conversations* were sent as a way to react to or reference something said on a different platform. This included messages sent alongside conversations that were already happening or after the conversation ended. Finally, *conversations through the hedgehogs themselves* were hedgehogs sent back and forth with no additional communication outside of the app.

Participants often engaged in multiple interaction patterns with their partner throughout the study, but most commonly described using HedgeHugs as a non-conversational status update or conversation starter. Integration into existing conversations may not have been as frequent due to HedgeHugs being its own app separate from the platforms on which existing conversations occurred. Similarly, conversation through the hedgehogs themselves may have been limited due to the lack of detail provided by the wordless hedge-

Table 6.3: Types of interaction patterns observed in HedgeHugs, with examples based on participant interviews

Pattern	Description	Example
Non-conversational status updates	Updating your partner to let them know what you are up to without needing a response	User sends a calm hedgehog to let their partner know their general mood
Conversation starters	Jumping onto another platform to have verbal conversation related or unrelated to a sent hedgehog	User sends an angry hedgehog and their partner responds over text to discuss what happened
Integrated into existing conversations	Using your hedgehog to reference or react to a conversation on another platform	User sends a surprised hedgehog while on the phone with their partner (alongside conversation), user sends a hugging hedgehog after having a serious conversation with their partner (after conversation)
Conversations through the hedgehogs themselves	Sending hedgehogs back and forth without jumping onto another platform	User sends a hugging hedgehog in the morning to show they're thinking of their partner, partner sends a love hedgehog to acknowledge and reciprocate their affection, user sends an eating one because they're hungry after waking up, partner sends a nodding hedgehug knowing that they will eat soon

hog animations. With sensing ON, participants continued to engage in the same patterns. However, some participants noted that they began engaging in more non-conversational status updates compared to the conversation starter. This may have been due to less ambiguity in the meaning of the sent hedgehogs, such that participants did not need to engage in follow-up conversation for clarification (e.g., asking their partner what their hedgehog meant).

6.7.2 Integrating Biosignals into Communication

The results demonstrate opportunities in augmenting communication through the sharing of sensed states, as well as challenges in recommending sensed states to share. Most participants (75%) felt that sensing ON was an exciting feature update that improved their overall experience using the app. However, the benefits they saw in sensing were dependent on their perception of its accuracy. Participants who preferred HedgeHugs with sensing OFF were distrustful, confused, or frustrated by the sensed state recommendations that the app made. In this section, I discuss these potential opportunities and challenges in integrating sensing into communication.

Opportunities for Biosignals: "Enhanced Emojis"

The results suggest that sharing sensed states can promote efficient and personal communication between couples, and help them feel connected with each other. This aligns with my prior work on Animo (Chapter 5), which similarly showed that people can easily keep in touch through sharing biosignals-driven animated shapes on their smartwatch. I build on this work by further exploring the ways in which biosignals can support lightweight communication, particularly when they are present in sensed state recommendations compared to randomized state recommendations. Specifically, based on participants' usage of HedgeHugs with sensing OFF and ON, we suggest that the app with sensing OFF functioned similarly as emojis, stickers, and GIFs, while sensing ON introduced a new, enhanced form of communication.

Easier communication First, participants felt that sharing from sensed state suggestions was easier than sharing from a randomized list of animations. With sensing OFF, participants would scroll through the list of state animations as if they were scrolling through a shorter emoji/sticker/GIF keyboard. Some participants were frustrated with access to only two to five random states as they expected a wider and more expressive variety, while others appreciated that they did not need to spend time looking through hundreds of options for a specific emoji or GIF. After updating to sensing ON, participants felt less like they were scrolling through a collection of random animations at all, as the list they were provided was personalized to their state. These participants felt that the sensed states they saw were more accurate to how they were feeling or what they were doing than the randomized states. Thus, their hedgehog became more representative of them and was easier to send to their partner. This was reinforced by the smartwatch, which participants were more compelled to use with sensing ON in order for the sensing feature to work. The smartwatch prompted participants with notifications that became personalized suggestions about how they were feeling with sensing ON, rather than dismissable nudges to use the app with sensing OFF. Through the notifications, participants simply had to make "yes or no" decisions to share their hedgehog, without needing to scroll through emoji-like options or even think to send their hedgehog on their own.

Less ambiguity Sharing a sensed hedgehog was also less ambiguous than sharing a randomized hedgehog. With sensing OFF, participants assigned various meanings to the hedgehog animations. The meanings they described included those that the animations were not originally designed for, such as suggestions ("let's go for a walk"), needs ("text me back"), and inside jokes. Participants would even send animations with no intended meaning, just to send one to their partner. This flexibility in the hedgehog animations aligns with the flexibility of emojis, where an emoji can be used to convey numerous possible messages [213, 313]. Emojis are thus known to be expressive yet ambiguous, and even when used in textual contexts [212]. Some participants did describe following-up over verbal conversation to clarify the animations they sent, or struggling to interpret and respond to the animations they received from their partner with sensing OFF. Our results suggest that biosignals helped reduce this ambiguity, where participants no longer assigned different meanings to the animations. Instead, the animations became meaningful on their own, where participants understood them as simply representative of their or their partner's general current state. This facilitated sharing state hedgehog animations, because participants no longer had to think about what they could mean. It also facilitated responding to those animations, because they could appropriately react when they understood what they meant.

Authenticity Finally, participants felt that sharing sensed hedgehog animations enabled more open and genuine communication with their partner. While couples used both versions of the app to keep in touch with each other's current state, they felt that sensing ON enabled a more personal experience with each other because it was backed by data. Participants described feeling more connected to their hedgehog because it was tied to their body's physical state, as if they were the hedgehog itself. Seeing their sensed state also encouraged them to reflect on how they were feeling, and be more honest with both themselves and their partner by sharing it with them. Participants subsequently felt more connected to their partner when they received their hedgehog, as they felt the hedgehog was their partner, who was conveying their honest state with them. Some couples noted that even if they are fairly open with their partner, they appreciated knowing that their partner's state was backed by data and that their partner was not just putting up a front. Moreover, this motivated a few participants to be more thoughtful and responsive in their reactions to their partner, such as reacting more quickly or more deliberately.

Challenges for Biosignals: Me vs the System

As a system that recommends a user's current state, the sensing ON version of HedgeHugs experienced challenges in how participants perceived and trusted the sensed states. Though most participants felt that their sensed hedgehog accurately reflected their feelings and activities, eight participants were skeptical of the system's ability to sense states and disagreed with the suggestions they saw. The sensed states were also restrictive, where the participants believed they were less likely to find an animation they wanted to send, since randomization presented equal probability of seeing all states. These participants stated that they would have preferred a list of states with more variety to choose from.

Subjective understandings of sensing and emotions While perceptions of inaccuracy were a major barrier for some participants, participants ranged in their definition of accuracy. Given the limitations of detecting emotions from the signals available on the watch (e.g., low granularity of heart rate, inability to determine valence), we designed the app to present a small set of *possible* sensed states. This also enabled us to explore a hybrid system/user-determined message design. Some participants were accepting of this design and gave the app room for error. They did not expect the sensed states to be 100% accurate and reasoned why the app would suggest states that did not quite match them, based on their knowledge of their own heart rate or physical state (e.g., the app thinking they are angry because their own heart rate increased while walking up the stairs). These participants also described typically being satisfied with at least one state in the list of suggested states, and did not mind if the other states did not fully match them. Conversely, participants who perceived the app as inaccurate tended to expect exactly one accurate state most of the time, giving less flexibility for the app to suggest other states that may not match their feelings. These discrepancies in perceptions of accuracy appear to stem from participants' different lay understanding of emotions and how they relate to heart rate. For instance, P15 described differences in how his mind feels (how he thinks he feels) as opposed to how his body feels (what the app suggested to him), and being conflicted on following his mind or his heart. On the other hand, P14 felt his heart was an indicator of how he truly felt, as opposed to how he thought he felt in his mind. Thus, systems like HedgeHugs that recommend emotions according to physiological signals should consider how to address different definitions of "accurate" emotions. I elaborate on possible directions for this in the following section.

Agency and effort in communicating feelings On the other extreme, a few participants described blindly trusting the system and sending their hedgehog from the sensed state notifications even if they did not know which animation they were sending. Though the sensing feature was not designed to be highly accurate, these participants felt the system knew their feelings better than they did, and helped them to convey those feelings to their partner. One participant (P18) warned against this "power of suggestion," where the system could influence them into thinking they felt a certain way. This aligns with prior work by Hollis and colleagues [128], which suggests that people may overly trust emotion sensing systems and be influenced by the system's interpretations of their emotions. Another participant (P2) noticed that by simply accepting and sharing the system's recommendation, he put less thought into curating a message to send to his partner. Though the reduced effort made keeping in touch easier, effort is an important quality of communication that contributes to meaningful and close relationships [154, 155]. Moreover, recent work on AI-mediated communication suggests that systems that generate messages for communication, such as HedgeHugs' sensed state animations, can affect perceptions of authenticity [216] and trustworthiness [141] in person sending the message. Thus, despite sensed states being inherently more personal and intimate through biosignals, they could potentially prompt less personal ways of communicating if the system has more agency over communication than the user. Below, I recommend future research directions and system designs to explore how to reconcile this tension.

6.7.3 Design Implications and Future Directions

Below, I detail implications and propose future directions for researchers and practitioners exploring expressive biosignals.

Sharing sensed states on existing platforms

While having a separate platform like HedgeHugs dedicated to sharing states can create an intimate experience for couples, the sensed hedgehog animations could easily integrate with existing platforms as "enhanced emojis." People already increasingly need to navigate multiple communication apps, which can cause "expression breakdowns" when they are unable to consistently express themselves across those apps [111]. By integrating biosignals into existing platforms, users could benefit from centralized communication with their partners while expressing themselves in more authentic ways through the sensed states. In platforms such as texting and mobile messaging, they could also could easily start new conversations about the states they share, a common pattern we observed in our study.

As part of existing platforms, biosignals would primarily function as a means to augment communication as opposed to acting as standalone messages like in HedgeHugs. Rather than relying on relationship context, users would reference the augmented communication content to interpret the biosignals (e.g., text in mobile messaging in Chapter 3 or in an online narrative in Chapter 4.2). Researchers and designers of communication platforms could explore how biosignals could augment various types of communication content, such as images, videos, or emojis, and the new interaction patterns that may emerge. For example, biosignals could become new types of "emojis" or integrate with existing emojis (or stickers/GIFs/other forms of expression). For the latter, biosignals could suggest specific emojis or limit the available options. This could help people navigate the ever growing list of emojis, as well as clarify potentially ambiguous emojis. Suggested emojis could be annotated in order to designate them as sensed states (e.g., a heart symbol, beats per minute, or special effect or badge attached to the image).

Addressing user expectations for sensing

I found that varying perceptions of accuracy and agency over the animations affected participants' ability to use the sensing ON version of the app. Given people's own subjective understanding of their state as well as ongoing research on emotion detection, designers need to consider how to present and incorporate sensing technology both in its current and future levels of accuracy. That is, even if the system claims to be accurate based on the user's physical state, the detected emotion may conflict with how the user subjectively believes they feel. This is hinted by my prior work on Animo, where some participants distrusted and felt restricted by the fully automated message meant to represent their state (see Chapter 5). For HedgeHugs, I took a hybrid approach, where the app suggested both a single state in notifications and a list of possible states within the app. However, some participants continued to be skeptical of the suggested states, having strong beliefs about how they are feeling, while others were confused by this design, believing that they should see only one recommendation.

Future directions in this area should investigate new ways for expressive biosignals systems to collaborate with users' subjective understanding of their own state. For example, researchers could explore systems that support different lay theories of emotions and how they affect perceptions of the system's accuracy, such as whether the user interprets emotions based on external contextual cues or internal physiological experiences [288, 322]. Designers of these systems should clearly and carefully introduce how sensing in the system works. For example, onboarding steps could detail the system's approach to emotion (e.g., its relationship to the body's physiological state, why the system might suggest multiple possible emotions), or provide adjustable settings that match user's personal understanding of their own state. Future work could also explore to involve the user in system recommendations, such that user can have more control over what they are feeling and how they share those feelings. For example, the system could allow users to provide feedback on their state in order to improve the system and feel involved in the system's suggestions, or prompt them to interpret the suggested state before sharing it with their partner. This could also encourage users to engage in more effort and meaning-making with their partner, and enhance the authenticity of the system-suggested message.

Sharing sensed states in romantic relationships

We purposefully designed HedgeHugs for romantic couples, given the intimacy of sharing biosignals (see Chapter 3) and couples' existing interest in knowing each other's current state [112, 195]. Aligned with these works, we found that most couples did not have concerns about sharing their sensed state with their partner, and also relied on their knowledge about their partner to interpret their sensed state. Within these relationships, participants engaged in a variety of interaction patterns that integrated HedgeHugs into their intimate communication practices (see Table 6.3).

Future directions could further explore how to design sensing systems to support these different intimate interaction patterns. For example, since couples used multiple patterns within their communication with each other, systems could indicate which pattern users intend to engage in when they send their state. For example, messages could differentiate between different patterns using separate state animations or badges attached to the animations. Systems could also cater to specific patterns; for instance, for conversation starters, applications could preview a user's state similar to the Knock Knock feature on Google Duo, which previews a user's video before a call. Researchers could also explore whether relationship characteristics affect the patterns that couples use most frequently. For instance, some participants described wanting to connect with their partner but not start new conversations during the earlier stages of their relationship, which the state hedgehogs could support as general status updates or short conversations themselves. In later relationship stages, such as during cohabitation or marriage, participants described needing more detailed communication for decision-making, which the state hedgehogs could support as conversation starters or integrated into existing conversations. Thus, future work could investigate the interaction patterns that are most common in different types of relationships, such as earlier and later-stage relationships.

6.7.4 Limitations

Though our findings elucidate the value of expressive biosignals in communication, there are several limitations to this work.

First, we ran a non-counterbalanced within-subjects study in order to reduce confusion in participants' mental model of the app, where sensing was a "feature update" rather than a feature being removed. Most participants did perceive sensing ON as a feature update that enhanced their use of the app; however, a few participants were strongly influenced by their mental model of the app with sensing OFF and expected it to work the same way. Moreover, novelty effects were much stronger for sensing OFF than for sensing ON. The number of sent messages dropped by 605 messages between the first and second week of using sensing OFF, compared to a drop of 77 messages between the first and second week of using sensing ON. Many participants also described getting used to the app during the second half of the study. We took these differences into consideration during both our interviews and analyses; however, future work should consider either a between-subjects design or longer longitudinal study to reduce potential order or novelty effects.

Second, we deployed the app *in situ* on participants' own smartwatches for use in their everyday lives, in order to achieve high ecological validity. Given the differences in participants' lifestyles, especially during the COVID-19 pandemic, as well as tendencies towards different devices (e.g., participants with large hands mentioning that it was difficult for them to interact with the app on the watch), participants naturally had diverse experiences with the app. Limitations of the Apple Watch OS also affected whether the app worked as intended for all participants, where some participants received no notifications while others felt that they received too many. Thus, while our qualitative findings present a variety of interesting communication patterns that stem from participants' diverse usage, studies with greater levels of control are necessary to clarify potential causal effects that biosignals may have on communication.

Finally, while we recruited a diverse sample of participants from different backgrounds, participants were self-selected and may have shown a greater interest in wearable and couple-specific technologies. Additionally, the shortest relationship length among participants was 11 months. As described in the last section, the participants we recruited integrated biosignals into their communication using a variety of interaction patterns. People in earlier stages of their relationship or without established communication practices with each other may engage in specific patterns or use the app in different ways. Given stay-at-home orders, we also restricted recruitment to people who were living apart from their partner or living together if one or both of them were essential workers. Thus, we were unable to capture how people that did not match these criteria might use the app outside of these unusual circumstances. It is also possible that our participants would engage with the app differently outside of these circumstances, as many of them had to adjust to changes in their daily routine during the study.

6.7.5 Conclusion

I ran a month-long within-subjects field study on HedgeHugs to explore the role of biosignals in communication by comparing communication with and without biosignals. Results showed that biosignals can support easier and more authentic communication, while presenting concerns around accuracy and agency over the communication content based on participants' diverse understandings of emotions. I discussed the opportunities and challenges around integrating biosignals sensing into communication, and made recommendations for future research and design. These include suggestions around applying biosignals to existing platforms and romantic relationships, as well as user expectations for sensing. In the following chapter, I synthesize the results and implications from this work and my prior work to discuss expressive biosignals theory and design, along with future directions for this area of research.

Chapter 7

General Discussion and Conclusion

7.1 Summary

My dissertation work investigates expressive biosignals, or the display of sensed physiological data as social cues, as a novel means to foster social connection between people. I designed, developed, and deployed five expressive biosignals systems in empirical studies to understand how they apply to communication and explore the design space for integrating them into communication.

In the first stage of my thesis, described in Chapter 3, I investigated people's motivations and concerns in *sharing* biosignals (**RQ1**), and how they can meaningfully share their biosignals with others (**RQ2**). I ran a two-week field study with 13 participants who used an Android app that enabled them to text their heart rate to any of their contacts. From experience sampling questionnaires and interviews, I learned that people are willing to share their biosignals with close others as a way to express their emotions and activities, and engage in playful interactions. At the same time, participants described concerns around how the receiver would interpret their biosignals, where they may unwittingly signal intimacy and vulnerability. Participants thus engaged in meaning-making with the receiver, providing clarifying context through text and images and discussing factors that may have influenced their heart rate number.

Next, I sought to understand how people interpret *receiving* biosignals and, subsequently, perceive the sender. Since traditional nonverbal cues like body language or facial expressions can affect the impressions we form of others, I first investigated how biosignals affect impression formation as a new type of social cue (**RQ3**). In Chapter 4.1, I created and tested six visualizations to represent a relatively unexplored expressive biosignal: brain activity, from which my findings showed that people are willing to interpret emotional and cognitive states. However, I found that different design features of the representations, such as how dynamic the changes in the visualizations were, significantly affected people's interpretations. Despite this ambiguity, some participants felt connected with the target, as if they knew them deeply. Others were concerned about privacy, where viewing someone else's brain activity felt too personal or even invasive, aligning with sender's concerns in sharing their data in Chapter 3.

Since Chapter 4.1 suggested that people interpret emotional states and feel connected through visualized biosignals, Chapter 4.2 explored receivers' ability to empathize with the sender, or understand their feelings (**RQ4-5**). I ran a controlled study based on existing experimental research that showed that instructions to consider someone else's feelings can increase empathy for stigmatized group members, for whom people typically have difficulty empathizing [29]. Using the same narrative, I investigated whether expressive biosignals could similarly affect empathy for the narrator when they are present and when they are visualized. Given the ambiguity of the brain activity visualizations in the previous study, I displayed the narrator's heart rate data as a graph alongside their story, as heart rate is the most accessible and familiar biosignal, and is commonly visualized as a graph. Responses from 62 participants showed that expressive biosignals *can* increase empathy in two ways: the presence of biosignals increased emotional perspective-taking, or perceptions of the narrator's feelings, and visualizing biosignals increased felt closeness with the narrator.

In Chapter 5, I expanded on my previous studies, which had isolated sending and receiving in one-way sharing, by exploring *dyadic communication patterns* afforded by expressive biosignals in two-way sharing (**RQ6**). I developed Animo, a smartwatch app that enabled users to send animos, or animated mood representations based on heart rate, to one other person. Drawing from the implications of my previous studies, I designed Animo to encourage playful interactions around biosignals, represented as abstract, emotionally expressive animated shapes that users can choose to share. Animo also leveraged the smartwatch as a new platform for communication that can unobtrusively sense and display people's heart rate. I deployed Animo in a two-week field study with 34 participants, and found that the app afforded a lighweight way for people to connect with each other when they were apart. Partners could keep in touch with each other's status and mood throughout the day, which helped support a sense of presence and start new conversations about their feelings. At the same time, some people felt that the animos did not accurately reflect their mood and sent them only to say "hi" to their partner. This showed that biosignals can promote lightweight social connection, but face issues in perceptions of accuracy.

While these prior works illuminated the potential for biosignals to help people connect with each other, they did not address *the role of biosignals in communication*, as they did not compare communication with and without biosignals. Chapter 6 addresses this gap, where I aimed to understand the value of integrating biosignals into communication, including their effects on the stages of communication, feelings of connection, and social support (**RQ7-9**). Building directly on my Animo work, I designed and developed HedgeHugs, a smartwatch app that enabled romantic partners to interact through hedgehog animations, which they selected from a list of recommendations based on their heart rate. Similar to Chapter 4.2, I compared two versions of HedgeHugs where biosignals were present, with sensing turned ON, or absent, with sensing turned OFF. In a one-month field study, 20 couples used HedgeHugs with sensing OFF for the first two weeks and with sensing ON for the last two weeks. Results from interviews showed that communicating with sensing ON felt easier, more personal, and more authentic than with sensing OFF. At the same time, sensing ON introduced concerns around accuracy and agency over the messages they were sending to each other. For some participants, the suggested states conflicted with how they understood emotions or took away meaningful effort in communicating with their partner.

In summary, these studies address important research questions around the communication and design of expressive biosignals. On the sender's end of communication, I explored people's intentions behind sharing their biosignals (**RQ1-2**), and learned that people share to express their emotions and activities, but have concerns around how receivers might interpret their biosignals. Thus, on the receiver's end, I investigated receivers' ability to interpret the sender's biosignals (**RQ3-5**). I found that people will form impressions about the sender's emotional and cognitive states and empathize with the sender, albeit with some ambiguity depending on the biosignals representation. I next expanded these findings to dyadic communication, exploring the dynamics of exchanging biosignals within pairs (**RQ6**). I observed that people can keep in touch with each other's moods and activities through biosignals, depending on their perceptions of the accuracy of the system's recommendations. Finally, I studied how these dynamics broadly affect dyadic communication (**RQ7-9**). I showed that communication with biosignals, compared to without them, supports easier and more authentic communication, but elicits concerns around not only system accuracy, but the agency and effort over the feelings they convey.

Taken together, my work demonstrates that biosignals can foster social connection between people as authentic social cues that stem from our body's reactions to everyday experiences. At the same time, the accuracy and agency of these systems, as well as the context and representations for shared biosignals, can affect people's decisions to share and their understanding of each other's data. Thus, expressive biosignals systems require careful design for how they recommend emotional states and enable sharing them. In the following sections, I synthesize these findings to present an initial theory and design space for expressive biosignals. I discuss important implications for both researchers and practitioners, and propose future directions to expand on expressive biosignals research.

Table 7.1: Summary of Studies

Chapter	Expressive Biosignals	Findings
3	Android app connected to the Mio Alpha 2 that enabled heart rate texting through mobile messaging	People share biosignals to express emotions, activities, and playfulness. Relevance and intimacy can be barriers to sharing biosignals.
4.1	Six raw/interpreted brain activity visualizations, including graph, emojis, and ambient light	People are willing to interpet emotional and cognitive states from biosignals, but their interpretations are affected by the representation. Concerns around cognitive load and privacy in viewing someone else's biosignals.
4.2	Heart rate caption or graph alongside a text narrative	Presence of biosignals increases emotional perspective-taking, visualizing biosignals increases closeness.
5	Animo, a smartwatch app for sharing animated shapes based on heart rate between two people	Communicating biosignals on a smartwatch can support lightweight connection and new conversations. Perceptions of inaccuracy limit interpretation and ability to communicate.
6	HedgeHugs, an Apple Watch and iPhone app for sharing animated hedgehogs that represent emotions and activities based on heart rate between romantic partners	Communication with biosignals, compared to without, is an easier and more authentic means to quickly convey one's current state, directly from the body. State recommendations may face issues in accuracy, agency, and effort in communicating those states.

7.2 Causal Model for Expressive Biosignals

In this section, I propose causal relationships involved in expressive biosignals that describe how expressive biosignals influence social behaviors and perceptions. This model is based on my thesis work and prior expressive biosignals research, focusing on factors that may influence the likelihood of sharing biosignals with another person, as well as potential social outcomes after sharing biosignals. Since this area of research is still new and has largely been exploratory (including in my own research), there may be relationships outside of this model that have not yet been uncovered. I describe potential future studies that can test these proposed relationships and explore possible new relationships.

Likelihood of Sharing Biosignals

We share our daily events and emotional reactions to express ourselves to other people. By disclosing our personal experiences, we can convey important information about our intentions and needs to others. Research shows that disclosing expressive biosignals can similarly convey this information as representations of our physiological responses during these experiences. In my own work, I observed that people share biosignals like heart rate to convey both general moods (e.g., feeling blue) and intense emotional experiences (e.g., stress during conflict with another person). Drawing from Omarzu's Disclosure Decision Model (DDM) [225], I propose that the presence of biosignals will affect the likelihood of disclosing our state in three ways.

Perceived value of sharing. The DDM suggests that people are more likely to disclose if they view disclosing as valuable according to their goals for disclosure. Based on prior research, biosignals may support social goals of intimacy (building relationships), relief of distress (expressing negative emotions), and identity clarification (conveying accurate information and ideas about oneself) [225].

Since biosignals can reveal our internal emotional states, people may perceive sharing them as a way to build closeness with others and achieve intimacy goals. Certain biosignals, such as those tied to the heart, the universal symbol of love, are also widely recognized as intimate. Listening to audio of a person's heart beating can be as intimate as mutual gaze or physical closeness [142]. Additionally, people view expressive biosignals as a form of emotional self-disclosure, where they reveal objective and authentic information about our emotions backed by data (see Chapters 3 and 6, and [132, 266]). Emotional self-disclosure, moreso than other types of self-disclosure, is crucial for developing intimacy because emotions can reveal our core experiences and provide opportunities for us to be understood [178].

Expressive biosignals could also support goals of relieving distress, as biosignals can express negative emotions. Expressing negative emotions can reduce distress by eliciting support from others [157]. Chapter 3 showed that biosignals can be used to signal a need for support, where study participants shared their heart rate in order for their contacts to recognize their negative emotions and console them. Chapter 6 similarly showed that while using HedgeHugs, participants would express negative emotions such as stress and sadness knowing that their partner could validate or care for them. Participants also reported becoming more aware of their own emotions through biosignals, and shared them to discuss and understand them with their partner.

Finally, biosignals can be valuable in conveying information about oneself, contributing to identify clarification goals. Chapter 3 showed that biosignals can convey information about both emotions and daily activities like eating and working. Chapters 5 and 6 showed that over smartwatches, people share their biosignals with the intention to simply let their partner know how they are feeling and what they are up to. By accessing their own biosignals, they can also become more self-aware and share to demonstrate what they learn about their own feelings. Findings from Chapter 6 suggest that people feel they can convey this information accurately through biosignals, because they represent their actual state. Study participants were subsequently more honest in the information they shared with their partner through their biosignals, wanting to be true to their actual feelings rather than putting up a front.

While the presence of biosignals in communication may increase the value of disclosure relative to different social goals, my prior work suggests that perceptions of the system's accuracy would moderate this relationship. In Chapters 5 and 6, I observed that people's subjective understanding of their own state can conflict with the system's recommendations for their state, depending on their lay theories of emotions. Participants had different opinions on whether their heart rate suggests anything about their feelings at all, whether their mind or body is more influential over their feelings, and whether one could feel multiple emotions at once. Moreover, people varied in their ability to understand their own emotions: some participants trusted the system's interpretations more than their own, while others were confident about how they felt. Participants who disagreed with the system typically did not share their recommended state because they felt it was an inaccurate representation of themselves that would confuse their partner. Thus, sharing in these cases would oppose identity clarification goals, because biosignals would not convey accurate information about themselves. As such, I propose that perceptions of the system's accuracy will moderate the effects of the presence of biosignals in communication on the value of sharing, subsequently impacting the likelihood of sharing.

> ***P1.*** *Presence of biosignals increases perceived value of sharing, moderated by perceptions of the system's accuracy, subsequently increasing the likelihood of sharing.*

To test this hypothesis, future work should further explore perceptions of the value of sharing biosignals while accounting for different lay theories of emotions and individual differences in emotional intelligence. For example, a participatory design workshop that prompts people to describe an ideal expressive biosignals system could illustrate different expectations for how sensed state recommendations should work, and how they relate to people's social goals. To determine how to best match users' perceptions of accuracy, participants could co-design the number of states they expect the system to recommend (e.g., one or multiple), when sensed notifications should appear (e.g., on state change or periodically), and how they would navigate the sensed states in different situations.

Additionally, controlled studies that compare the likelihood of sharing biosignals during interactions with different social goals could reveal people's perceptions of the goals that expressive biosignals would best support. I predict that people would be more likely to share their biosignals during a task focused on intimacy, such as getting to know a potential friend or romantic partner, as opposed to one focused on social control (strategic self-presentation [225]), such as a job interview.

Perceived interpretability Based on the DDM, if the receiver cannot interpret the sender's message, disclosure may not be an appropriate strategy for achieving the sender's social goals [225]. As representations of our internal experiences, biosignals could enhance perceived interpretability of the sender's state, especially when the sender has difficulties conveying their state to others. In the HedgeHugs study in Chapter 6, participants felt that sharing biosignals could express their emotions when they struggled or did not have the means to describe them in words or gestures, similar to emojis and stickers. However, unlike emojis and stickers, which tend to contain multiple evolving meanings [213, 313], the presence of biosignals in a message inherently ties the meaning of the message to the sender's state.

At the same time, perceptions of interpretability may depend on whether and how the system makes inferences from biosignals. Though everyone has biosignals, they change according to the characteristics of each person's body (e.g., each person having different resting heart rates) and are highly contextual. My research shows that people recognize this, and may provide additional information when the data is in raw form to aid interpretation. In Chapter 3, when heart rate was presented as a raw number, participants texted the number alongside details that clarified its significance, such as whether it was higher or lower than usual or if it related to an event that took place. On the other hand, if the system infers and presents the sender's state from biosignals, the interpretability of the biosignals will depend on the interpretability of the inferred presentation. For example, Chapter 4.1 showed that receivers form different impressions of the sender when viewing different visualizations of the same brain activity data, depending on the design features of each visualization. Differences in results from Chapters 5 and 6 illustrate that more abstract representations, like colored animated shapes, may be less interpretable than concrete ones, such as avatars with recognizable facial expressions and body movements. Thus, I propose that the system's inference of biosignals, particularly in how it represents them, will moderate the effects of biosignals in communication on perceived interpretability of the sender's state.

> ***P2.*** *Presence of biosignals increases perceived interpretability of the sender's state, moderated by the system's inferences from the biosignals, subsequently increasing the likelihood of sharing.*

To test this proposition, future work could directly compare the interpretability of the sender's state in messages with and without biosignals. Researchers could run a controlled study modeled after work by Kruger and colleagues, who tested perceptions of emotions, such as sarcasm and anger, over email [172]. The study could be designed to compare the extent to which a sender's intended message and a receiver's understanding of that message match when biosignals are present or absent, using measures such as ratings of emotional content or different message types (e.g., conveying state vs making a suggestion). Researchers could also vary the biosignals representation, including those that are more raw or more interpreted (see Chapter 4.1) to test effects of the system's inferences. For example, in emails, biosignals could be presented as raw numbers or interpreted through kinetic typography (e.g., jumping text for high arousal detected by skin conductance [302]). Assuming they agree with the system's inference, people may perceive the latter as more interpretable given the emotional quality of kinetic typography [159, 180].

Privacy concerns The DDM suggests that disclosure comes with subjective risks, including loss of control for the sender, or rejection or discomfort from the receiver. As a cue for private inner thoughts and feelings, biosignals may increase these risks. In Chapter 3, one of the main barriers to sharing heart rate was perceptions that it would be *too* intimate or vulnerable. Given the heart's cultural tie to love, sharing heart rate may be an unintended sign of closeness or flirting with another person. Biosignals are also connected to health, and could invite judgment or unwanted concern for one's health. Some study participants were even deceptive when sharing their biosignals, describing them as elevated due to walking rather than stress to avoid worrying others. Biosignals are also more difficult to control than other modes of expression, such as verbal or facial expressions; thus, sharing them could threaten impression management by revealing too much about one's inner experiences [266]. Aligned with this, study participants in Chapter 4.1 likened viewing brain activity data to "intruding" on someone's thoughts.

At the same time, people tend to be more willing to disclose to close others [231]; therefore the effects of biosignals on privacy concerns may depend on the sender's relationship with the receiver. In Chapter 3, when study participants had the option to share with anyone through text messaging, they primarily chose to share with close contacts. In Chapter 5, participants who partnered with roommates and co-workers regretted choosing not to participate with a best friend or significant other, the people to whom they felt most comfortable disclosing. Participants in Chapter 6 agreed with this sentiment: as romantic partners, they described being open with each other and not hesitant to share their biosignals. Thus, senders who share their biosignals with close others will likely have less privacy concerns because they already share the most with them.

> ***P3.*** *Presence of biosignals increases privacy concerns in sending a message, moderated by the relationship between the sender and receiver, subsequently decreasing the likelihood of sharing.*

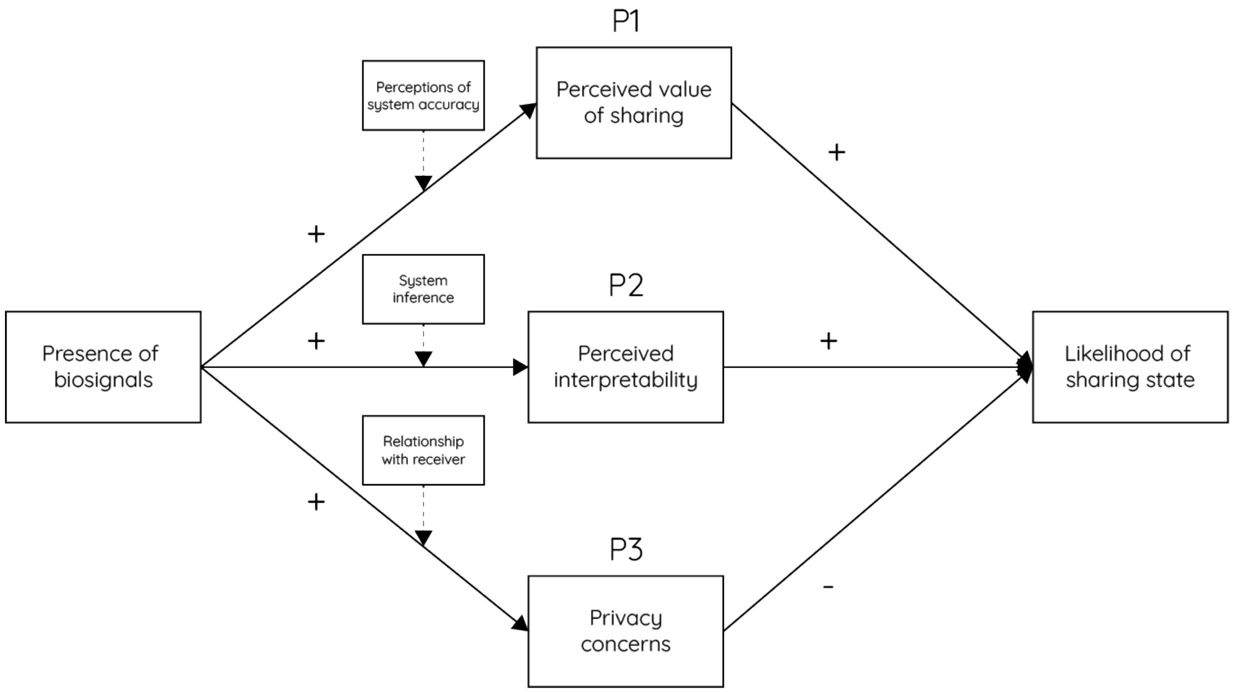


Figure 7.1: Causal model for likelihood of sharing biosignals (P1-P3)

Future work could test this proposition through controlled studies that compare the number of shared biosignals messages between people in different relationship types (e.g., significant others, friends, acquaintances, strangers) or in different relationship contexts (e.g., personal or professional). According to the above discussion, I predict that the number of messages shared in a system like HedgeHugs will be greater for partners sharing with significant others compared to close friends. Researchers should also consider the characteristics of the platforms on which biosignals are shared, where certain designs may invite more or less privacy concerns. For example, a social media platform that normalizes broadcasting biosignals amongst members (e.g., similar to displaying heart rate during a Twitch stream [244]) may reduce perceptions of being overly intimate compared to sharing biosignals with only one other person (e.g., through a direct message), therefore increasing the likelihood of sharing.

Social Outcomes of Expressive Biosignals

We can better connect with people when we recognize and understand their personal experiences [262]. Recognizing and understanding shared biosignals could also lead to social connection by increasing our awareness of others and their underlying thoughts and feelings [119, 132, 189]. Slovák and colleagues described two potential categories for these effects: biosignals as information and biosignals as connection [266]. I propose that the presence of biosignals, functioning in these two ways, can lead to social outcomes such as social presence, cognitive perspective-taking, and closeness.

Social Presence Social presence is defined as the "sense of being with another" [38], and involves components of intimacy and immediacy in an interaction [114, 115]. I propose that the presence of biosignals can increase feelings of social presence, both as information and as connection to the other person.

As information, the presence of biosignals could increase the accuracy of interpreting the sender's state as a cue into how the sender is feeling or what they are up to. In Chapter 6, study participants felt they could more accurately interpret their partner's state selected from a sensed rather than randomized list. However, similar to the relationship between the presence of biosignals and perceptions of interpretability, perceptions of the system accuracy may affect the receiver's ability to accurately interpret the message. As seen in Chapter 6, people who believe that the system suggests inaccurate states are likely to believe that it does the same for everyone. Their perceptions of accuracy could also be influenced by others who experience inaccurate suggestions. Subsequently, they may be skeptical of their partner's state message, perceiving it as random or not representative of their partner's state. Thus, receivers who perceive the system as accurate are more likely to accurately interpret the sender's state.

Accurately interpreting the sender's state could subsequently increase social presence by filling in for essential nonverbal and contextual cues that are often missing over mediated communication channels [300]. In Chapters 5 and 6, study participants felt that their partner was more salient when they received their biosignals. They became more aware of them throughout the day and even imagined their partner's behaviors through their partner's biosignals. When receivers interpret the sender's biosignals, the sender may become more vivid and immediate because they have access to their body's reactions to everyday experiences in the moment. Aligned with this, participants described feeling a greater urgency to view their partner's biosignals, because it represented their current ephemeral state.

The presence of biosignals could directly affect social presence even without information. Prior work shows that minimal cues are capable of enhancing feelings of presence [56, 153]. Biosignals could similarly act as a minimal cue that represents a sense of being alive [135], as the daily physiological workings of our heart, brain, and other organs are necessary for our existence. In Chapters 5 and 6, study participants described shared biosignals as representative of their partner, as if their partner was there was them on their wrist through the smartwatch apps. Since the biosignals were connected to their partner's physical self, they were reflective of their partner. However, different modalities in which the biosignals are communicated may moderate these effects on social presence. Study participants were prompted to think of their partner when they noticed the watch on their wrist or felt haptic feedback from incoming app notifications. While these characteristics are not specific to biosignals sharing, they may extend to different representations of biosignals, such as haptic or audio feedback. For instance, haptic vibrations of the heart beating may simulate mediated touch, as one would typically need to touch another person to feel their pulse, subsequently enhancing social presence [31, 293].

Increased social presence through biosignals may also lead to increased responsiveness. In Chapters 5 and 6, study participants felt a greater urgency than other messages to not only view their partner's biosignals, but also respond to them because they represented their partner. One participant felt that ignoring a biosignals message until later would be like dismissing her partner, since the message felt like her partner was visiting her in that moment through the app. This behavior suggests that the presence of biosignals may have downstream effects of greater responsiveness from a receiver, through greater social presence.

> ***P4a.*** *Presence of biosignals increases accuracy in interpreting the sender's state, moderated by perceptions of the system's accuracy, subsequently increasing social presence.*
>
> ***P4b.*** *Presence of biosignals increases social presence, moderated by communication modality.*
>
> ***P4c.*** *Presence of biosignals increases responsiveness through increased social presence.*

While I propose a relationship between the presence of biosignals and social presence, findings in Chapters 4.2 and 6 did not show significant effects of biosignals on social presence measures. In the discussion of results for Chapter 4.2, I postulated that the visualizations we chose for biosignals (a text caption and a graph) may have been too "clinical" (as suggested in Chapter 4.1) to affect social presence. Additionally, while I found qualitative evidence for effects on social presence in Chapter 6, there were too many confounding variables during the study to interpret our quantitative presence measures (e.g., irregularities in how the app functioned on the Apple Watch OS, different understandings of how sensing worked, unusual circumstances during a global pandemic).

Future work should consider more controlled studies with larger sample sizes to clarify the relationship between expressive biosignals and social presence suggested by qualitative findings. For example, a laboratory experiment could compare felt social presence during a remote communication task (e.g., getting to know a stranger) with and without the presence of interactants' biosignals. Information interpreted from the biosignals could also be manipulated in order to test direct and indirect effects on social presence, such as comparing displays of neutral, non-fluctuating heart rate to elevated heart rate. Researchers should also explore the effects of different modalities for communicating biosignals, such as by comparing visual, audio, and haptic representations (e.g., an image of a pulsing heart vs sound of a heart beating vs vibrations of a heart beating). To test potential downstream effects on responsiveness, these studies could incorporate different means or measures for responding to biosignals, such as time taken to initiate a response or effort taken in constructing a response. For example, if asked to write a text message response, people may be more likely to write longer messages when they can view the other person's biosignals.

Cognitive perspective-taking I propose that the presence of biosignals can lead to increased cognitive perspective-taking when a receiver accurately interprets the sender's state. I define cognitive perspective-taking according to Batson and Ahmed's description of the imagine-other perspective for empathy: "imagining how another thinks or feels given their situation" [26]. By accurately interpreting the sender's message as their internal state (see previous section), a receiver may be more likely to imagine the sender's thoughts or feelings, as well as their relevant context. Chapter 4.2 provides evidence for this, where I ran a controlled study that showed that the presence of biosignals significantly increases perceptions of a target's emotions. The qualitative findings in Chapter 6 also support this in everyday settings, where study participants described reflecting on their partner's biosignals and how their partner's context would have affected them.

Cognitive perspective-taking through biosignals may also lead to greater responsiveness. Prior literature shows that perspective-taking can lead to both instrumental (tangible aid) and emotional support (caring and concern) for others [27, 63, 80, 228]. Findings in Chapter 6 suggest that people may engage in more supportive responses [198] to close partners when receiving their biosignals, as opposed to states selected from a randomized list. Through biosignals, study participants could better understand their partner's state and attempt to respond appropriately and positively, such as by asking for elaboration, being encouraging for positive states, and consoling negative states. One participant described being more thoughtful in determining an appropriate response to her partner's biosignals compared to when he sent his state from a randomized list, because she felt more "responsibility" for her partner's sensed state.

P5a. *Presence of biosignals increases accuracy in interpreting the sender's state, moderated by perceptions of the system's accuracy, subsequently increasing cognitive perspective-taking.*

P5b. *Presence of biosignals increases responsiveness through increased cognitive perspective-taking.*

While I propose effects on responsiveness through cognitive perspective-taking, findings from Chapter 4.2 do not support this, as I did not observe significant effects on responsiveness in the form of social support for stigmatized groups. I postulated that this may have been due to limitations in our measures for support, which included monetary donations to an organization rather than the individual who shared their biosignals and whether people wrote a message of support. As suggested for social presence, future work should further explore potential downstream effects that biosignals may have on other measures of responsiveness. In addition to the aforementioned measures, researchers could measure the quality or perceived quality of response provided; for example, based on the discussion above, biosignals may increase the sender's satisfaction with the response they receive, and the receiver's self-report of thoughtfulness behind their response.

Closeness Prior work shows that the presence of biosignals can directly increase closeness between people. Janssen and colleagues found that people perceive the sound of a person's heartbeat as significantly more intimate than an artificial heartbeat or silence [142]. Since the heartbeat matched the average heart rate of sitting and did not

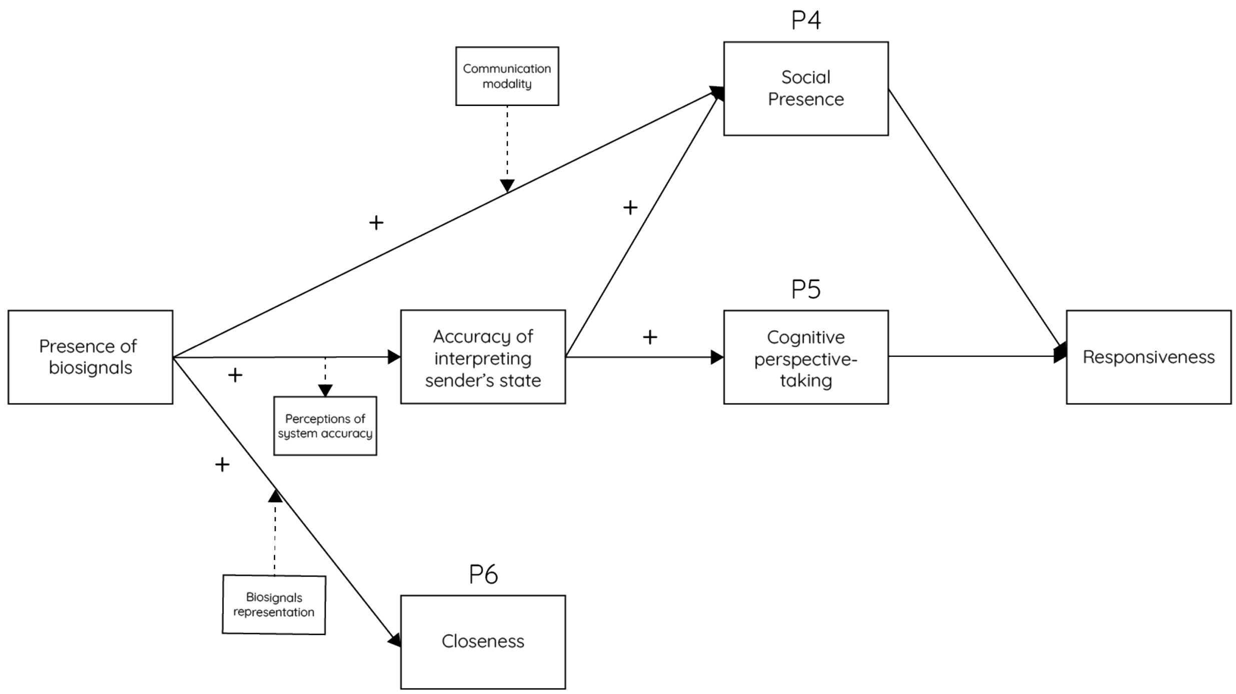


Figure 7.2: Causal model for understanding biosignals (P4-P6)

vary during the experiment, I propose that biosignals directly affected closeness, as they did not convey emotional information during the participants' interactions. Chapter 4.2 showed that the representation of biosignals can moderate this relationship. Specifically, visualizing biosignals as a graph can lead to significantly greater closeness with the sender compared to describing them in text. More dynamic or animated representations, as opposed to plain text, can help receivers become more aware of and closer to the sender.

> ***P6.*** *Presence of biosignals increases closeness, moderated by representation of the biosignals.*

7.3 Design Space of Expressive Biosignals

Research on expressive biosignals thus far has explored a variety of expressive biosignals designs, ranging from intimate direct messaging systems between romantic partners to public displays broadcasted to strangers. In this section, I articulate a design space for expressive biosignals, including different dimensions that existing research systems have explored and that researchers and practitioners can expand on in future work. While the list of dimensions is not exhaustive, it covers major factors that can affect the way biosignals are shared and understood between communication partners.

Data Type

Wearable sensor devices can record a variety of physiological responses, including heart rate, brain activity, and skin conductance (see Chapter 2.2). Prior expressive biosignals work, including my own, has heavily focused on heart rate due its accessibility in popular consumer-grade products, like smartwatches and fitness bands, and people's greater familiarity with the data. However, several works have shown that other types of signals can be expressive as well. For example, Chapter 4.1 demonstrated that people are willing to interpret emotional and cognitive states from brain activity, which are becoming more available on commercial headsets like the Muse and EMOTIV Insight. Researchers have also explored skin conductance as a social cue, using custom and commercial devices to understand how it is interpreted in conversation [132, 270] and virtual reality narratives [73]. Tan and colleagues investigated the combined effects of multiple biosignals in one display, including heart rate, skin conductance, and respiration, on stress in collaboration [278]. As advancements in sensor technologies expand our everyday access to various physiological signals, future work should consider how people interpret and react to these different signals in various social contexts.

Audience

Since biosignals are fairly personal and private data, designers should consider the audiences with whom people feel comfortable sharing. Different relationship contexts may affect a sender's motivation to share as well as the receiver's understanding of the data. Prior literature has investigated sharing within a variety of relationship types, ranging from close others to strangers. In Chapters 3 and 5, I observed that people are most comfortable sharing with their closest others, due to the intimacy of the data and vulnerability felt in sharing them. Chapter 6 showed that receivers also use their existing relationship context (e.g., knowledge of their sender's schedule, inside jokes, etc.) to help them interpret the sender's biosignals. At the same time, Chapter 4.2 showed that people can empathize with anonymous others after viewing their biosignals, including members of stigmatized groups, with whom people typically experience difficulty empathizing. This suggests that biosignals could facilitate connection between people with varying levels of closeness and familiarity with each other.

Researchers could explore different ways that expressive biosignals systems could support these different relationships. For example, anonymity could help reduce feelings of vulnerability, but would require interactants to provide detailed stories or engage in shared experiences to clarify the meaning of their sensed state, given the lack of an existing relationship to provide that context. Systems could also include varying levels of control over sharing. In the systems I designed, sharing was always opt-in; however, people who are highly comfortable sharing with each other may desire automatic or unrestricted access to each other's biosignals. Future directions could also expand this dimension by investigating sharing between audiences that are known to experience barriers to social connection, such as polarized groups or people with social orders who face difficulties in emotional expression and understanding.

Representation

The representation of biosignals can have a significant impact on how people understand the data. In my work, I have studied a variety of raw and interpreted representations for biosignals, including numbers, graphs, ambient light, and animated avatars, and found that they can be ambiguous in different ways. Raw representations, which display data close to its raw numerical form, require user effort to interpret how they are relevant to them (e.g., a user appending text to a heart rate number to explain what their biosignals mean to them). Interpreted representations, which manipulate or add meaning to the data, can face issues if the system's interpretations do not match the user's (e.g., a user disagreeing with an emoji that the system recommends for their state). Interpreted representations have more opportunity to be engaging and appealing, given the diverse ways that the data could be manipulated, but need to be carefully designed to address accuracy concerns.

Researchers should explore how to present interpreted representations for biosignals such that the system and the user can work *together* in a more effective human-AI interaction as sensing technologies continue to advance [319]. Researchers should consider different types and levels of user involvement in the system's interpretation of their state. For example, in Chapter 5, I designed Animo to recommend one sensed state, therefore giving agency to the system to determine the user's state. In Chapter 6, I designed HedgeHugs to recommend a set of sensed states from which the users select to send to their partner, therefore giving partial agency to both the system and the user. An alternative design for partial agency could include the user choosing from different representations, as opposed to choosing from the same representation of different states (e.g., if a user feels that a color better represents them at that moment than a jaunty avatar). Users could also explicitly override the system's state recommendations by inputting their perceived state, in order to have full agency over their final shared state.

Future work should also explore new, non-visual ways to represent expressive biosignals. Most research has focused on visual representations, which are perhaps the most widely used form of expression over computer-mediated communication, but audio and haptic representations could present interesting new directions for expressing one's internal state. A few systems have incorporated more raw audio and haptic representations, such as the sound or vibration of heartbeats (e.g., [135, 142] and the Apple Watch Digital Touch), but designers could consider interpreted representations, such as sound effects and movie soundtracks [264], or different intensities and patterns of haptic feedback. Recent work by Alfaras and colleagues has explored possible non-visual directions for biosignals, including sonic output and changes in temperature [9].

Communication platforms

Researchers have built expressive biosignals systems on platforms such as laptops [266], ambient light [270], apparel [132, 134, 298], smartwatches (see Chapters 5 and **??**), and public benches [135]. The different form factors of these platforms can have major effects on people's experiences sharing and understanding expressive biosignals. For instance, apparel is physically on the body and therefore conveniently accessible in everyday life, but vary in whether they are broadcasted (e.g., easily visible to others like a shirt or helmet) or meant to be viewed only by the wearer (e.g., smartwatches). Platforms like benches and ambient lights are situated in environments, and could be affected by features of the environment such as the public or private nature, or other lifeforms in the environment [135]. Future directions can expand this dimension by explore different platforms that enable new ways to interact with and share biosignals with others in different social contexts. For example, a shared public screen displaying aggregate biosignals (e.g., similar to Mood Meter [123]) could provide an interesting means to raise awareness of stress in workplaces or exciting events at nearby locations.

Feedback mechanisms

Though less research has explored feedback mechanisms for expressive biosignals, it is important to consider the types of responses that are desirable or appropriate after viewing

Table 7.2: Design space explored in this thesis.

Chapter	Data Type	Audience	Representation	Platform	Feedback
3	heart rate	phone contacts	number (bpm)	phone	none
4.1	brain activity	anonymous stranger	raw (graphs) and interpreted (colors, emojis, swirling lines) visualizations	desktop screen, lightbulb	none
4.2	heart rate	stigmatized group member	caption or graph	storytelling platform	none
5	heart rate	close others	abstract shapes animating emotions	smartwatch	send back one's own biosignals
6	heart rate	significant other	hedgehog avatars animating emotions and activities	smartwatch, phone	response hedgehogs

someone else's biosignals. In Chapter 5, I observed that people respond to biosignals over their typical communication channels, such as text and in-person conversations, to discuss and create meaning around those biosignals. In Chapter 6, where I enabled a feedback mechanism through lightweight react animations, I found that certain biosignals, such as those meant to convey the sender's general mood or a status update, may require only a simple acknowledgement of receipt or even no response at all. Future work should further characterize the different situations that favor certain types of feedback, and consider ways for expressive biosignals systems to highlight the sender's expectations for those feedback. Researchers and designers could also explore other possible feedback mechanisms, such as responding with one's own biosignals or providing different forms of social support.

7.4 Future Areas for Research

My research demonstrates that biosignals can be used to express emotions and connect with others in interpersonal computer-mediated settings. In the previous section, I suggested future directions to further develop theory around biosignals and their specific social impact, as well as approaches to explore system design. In addition to these directions, I propose several broader areas for exploring the social potential for expressive biosignals.

Expressive biosignals can be applied to a number of social settings. In my work, I focused primarily on interpersonal communication as a foundation for understanding expressive biosignals. Other researchers have also explored expressive biosignals in the contexts of entertainment [97, 244, 258, 298] and collaboration [209, 278]. In addition to expanding on these areas, researchers should also consider integrating biosignals into health and education settings. For example, biosignals could support more effective communication between doctors and patients and subsequently better health outcomes, or between teachers and students for better learning outcomes.

My dissertation work has focused on communication at a distance, but future work could explore opportunities for biosignals to be integrated into in-person communication. Expressive biosignals could be used as an additional nonverbal cue that reveals our internal responses and vividly conveys our feelings in moments when it is difficult to express or understand them, such as during interpersonal conflict. In fact, some participants in my studies shared their biosignals while collocated with the intended receiver, particularly when they were physically together but unable to communicate through other means (e.g., being unable to talk with each other during a stressful work meeting). Future work could further explore people's motivations to share biosignals with each other in these situations, and ways to support them.

Since biosignals can express highly emotional experiences, both negative and positive, future work could further explore their ability to encourage social support. My work showed initial findings for their potential to impact support in terms of increased responsiveness, such as greater immediacy or thoughtfulness of response. Future work should explore whether there are specific categories of support that expressive biosignals can promote and contexts in which they could be supportive, as well as potential downstream effects on well-being. In particular, social support through expressive biosignals may be especially beneficial in the context of marginalized groups, who often experience highly stressful situations. Members of these groups may not be aware of or able to express their stressful experiences to others, and others outside of those groups may not fully understand or appropriately respond to that stress.

In my future work, I plan to explore how expressive biosignals could support recognition, expression, and understanding for the experiences of marginalized group members. In a first step in this direction, I plan to design a new expressive biosignals system for facilitating supportive communication between anonymous marginalized student peers. The system will be embedded in a community for sharing and responding to personal stories, with the goal of relieving student distress and building feelings of connection amongst community members. I will explore new devices to reveal stressful moments (both positive and negative) through biosignals; for example, the Scosche Rhythm 24 enables heart rate variability sensing that could yield more accurate detection [250, 275]. To build on prior research in this new context, I will investigate how to design features that (1) reveal the sensed state to the sender while avoiding additional stress that may come with awareness, such as by delaying the reveal or using subtle indicators, (2) give the sender agency over the state they share, such as through prompts that ask them to reflect on and contextualize the system's recommendation as part of the sharing process, (3) represent the sender's state in an interpretable and unobtrusive way, such as haptic feedback representing the intensity of their feelings or need for support, and (4) enable the receiver to provide meaningful feedback, such as by sending tokens of support that could be passed to other members of the community to “pay it forward.” Inspired by personal experience, I will deploy the system with freshmen women in computer science, a marginalized population known to experience issues in belongingness, stress, and high attrition rates [30, 196]. Similar to Chapter 6, I will compare use of the system with and without biosignals in order to understand their effects on communication within marginalized groups, feelings of connection with a broader community, and individual well-being. Through this work, I will contribute to expressive biosignals research by expanding on our understanding of the effects of expressive biosignals in communication and the design of expressive biosignals systems in the context of marginalized groups.

7.5 Conclusion

My dissertation on expressive biosignals leverages commercial sensing technologies to develop new forms of communication at a distance that help people understand each other at a deeper, physiological level. I formalize expressive biosignals as an emerging area of research in Human-Computer Interaction that lies at the intersection of social computing and ubiquitous computing. I contribute five expressive biosignals systems as novel interventions for social connection that enable emotional expression and empathy between people. Based on my research on these systems, as well as prior related work, I present a mapping of the design space for expressive biosignals that describes different dimensions for researchers and practitions to consider in building new systems. I propose a theoretical model that hypothesizes the relationship between expressive biosignals and social connection, including the motivations behind people’s decisions to share their biosignals and consequences to viewing others’ biosignals. Finally, I suggest several areas for future work to expand on expressive biosignals research in the domains of not only interpersonal relationships, but also education and well-being. Altogether, my thesis work presents the opportunity to advance the state-of-the-art of communication tools through expressive biosignals, and ultimately promote a closer, more connected society.

Appendix A

Chapter 3 Materials

A.1 Mid-Study Interview Questions

1. What was your experience with the app and watch like this week?

Heart Rate

1. When you were notified about changes in your heart rate, did you expect those changes?
2. Were there times you weren't notified where you thought you would be?
3. What did you think about your heart rate?
4. Were there instances you held back or were not able to fully express what you wanted to say?

Sharing Behavior

1. Have you shared your HR?
2. If yes:
   (a) At what times did you choose to share your data?
   (b) What was that decision like for you?
   (c) How did you feel about sharing?
   (d) Did you add any contextual information (text, image, video)?
   (e) Who did you choose to share your HR with/how did you choose them?
   (f) Did you get any responses from sharing?
   (g) What do you think they thought when they got the message?

3. If no (or if there were times they chose not to share):
   (a) At what times were these?
   (b) Why did you not want to share?
4. Have you broadcasted your HR?
   (a) Did you check the graph at the provided URL?
   (b) Did you watch the graph throughout your streaming period?
   (c) Did you share the URL with anyone?
   (d) Who did you choose/how did you choose them?
   (e) Did you get any responses from broadcasting to those people?
   (f) How did you choose those periods to broadcast?

External Sharing

1. Were there any situations you would have liked to share your HR but couldn't?
2. Were there any situations you would have liked to broadcast your HR but couldn't?
3. Did you share anything with anyone outside of broadcast/notifications?
4. Did you show anyone your heart rate face-to-face?

A.2 Exit Interview Questions

These questions were the same as the mid-study interview questions, with the addition of the following:

Heart Rate

1. Can you show and describe to me at least 5 direct share cases that you recall from the last two weeks?

Broadcasting

1. Can you show and describe to me at least 2 broadcast texts that you recall from the last two weeks?

Communication Changes

1. Did you experience any changes in the quantity of communication with your contacts?
2. Did you experience any changes in the quality of communication with your contacts?

Feedback

1. What do you think the limitations of the app were?
2. Where there times where you felt blocked or frustrated (not including bugs/crashes)?
3. What would you have liked to change about the app? About sharing?
4. Is there other information you would have liked to see?

Appendix B

Chapter 4.1 Materials

B.1 Visualizations

https://youtu.be/njClA-pZMXI

B.2 Questionnaire

Instructions

We have collected brain activity from participants who listened to a music clip while wearing an electroencephalography (EEG) headset. We will show you six different visualizations of participant data and ask your opinions on them after each. Several seconds of brain activity was recorded before the stimulus was presented, which is reflected in each visualization. The music that was used will play automatically with the recording, matching the time that the participant had heard the music. After you watch all of the visualizations, we would like you to fill out a short survey about yourself. This study will take about 60 minutes.

EEG Activity Meaning

For each visualization, you will be shown delta, alpha, and beta waves.

- Delta waves are associated with deep sleep.
- Alpha waves are associated with relaxation and disengagement.
- Beta waves are associated with focused concentration and active thinking.

Questions per visualization

1. What did you notice in the visualization?
2. What meaningful changes, if any, did you perceive in the brain activity?
3. What is your impression of the person whose brain activity you just watched? Please answer to the best of your ability.
4. How do you think the person felt as they listened to the audio?
5. If you were able to view your own or another person's brain activity in this manner while speaking to that other person face-to-face, how would you feel? Why?
6. If you were able to view your own or another person's brain activity in this manner while speaking to that other person online, such as through text or video chat, how would you feel? Why?

The questions below are based on [282].
Please indicate how much you agree or disagree with the following statements about your impression of the person whose brain activity you just viewed. (Strongly disagree - Strongly agree, 7pt likert scale)

1. I have a clear impression of what this person might be like.
2. I have a clear impression of how well I would get along with this person.
3. I have a clear impression of how well I would work with this person on a collaborative task.
4. I have a positive impression of this person.
5. I feel connected to this person.
6. I feel similar to this person.

The questions below are from the TIPI scale [106].
Please rate the extent to which you think each pair of traits apply to the person whose brain activity you just viewed, even if one characteristic applies more strongly than the other. (Strongly disagree - Strongly agree, 7pt likert scale)

1. Extraverted, enthusiastic
2. Critical, quarrelsome
3. Dependable, self-disciplined
4. Anxious, easily upset
5. Open to new experiences, complex
6. Reserved, quiet
7. Sympathetic, warm

8. Disorganized, careless
9. Calm, emotionally stable
10. Conventional, uncreative

The questions below are from [169].
Please indicate how much you agree or disagree with the following statements about the person whose brain activity you viewed. (Strongly disagree - Strongly agree, 7pt likert scale)

1. This person is capable of planned actions.
2. This person has complex feelings.
3. This person can engage in a great deal of thought.
4. This person can experience pain.
5. This person is capable of doing things on purpose.
6. This person is capable of emotion.
7. This person has goals.
8. This person is highly conscious.
9. This person can experience pleasure.
10. This person has a good memory.

The questions below are from [201].
Please describe how you felt about the brain activity visualization and the feedback it gave: (Strongly disagree - Strongly agree, 5pt likert scale)

1. The visualization provided sufficient information, not too much.
2. Changes in the visualization were clear and easy to observe.
3. It was easy to understand the current state of the visualization.
4. The design of the visualization was aesthetically pleasing.
5. The visualization provided sufficient information, not too little.
6. The visualization was intuitive to understand, and required little to no explanation.

Questions after viewing all visualizations

You have now finished watching and answering questions about each visualization. Please answer the following questions about them as a whole.

1. As you were watching the visualization, did any of them (line graph, emoji, swirl, color gradient, LED light, sliding circles) match what you would think your own brain activity would be while listening to the music clip? Which one(s) and why?

2. How do you think your brain activity (the delta, alpha, and beta waves) would change as you listen to the given music?
3. If you had to choose one of these visualizations to provide an impression of yourself to another person, which one would you choose?
   (a) Line Graph
   (b) Emoji
   (c) Swirl
   (d) Color Gradient
   (e) LED Light
   (f) Sliding Circles
4. Why would you choose the above visualization to provide an impression of yourself to another person?
5. If you had to choose one of these visualizations to form an impression about another person based solely on their brain activity, which one would you choose?
   (a) Line Graph
   (b) Emoji
   (c) Swirl
   (d) Color Gradient
   (e) LED Light
   (f) Sliding Circles
6. Why would you choose the above visualization to form an impression about another person?
7. If you had to choose one of these visualizations to predict how well you would get along with another person, which one would you choose?
   (a) Line Graph
   (b) Emoji
   (c) Swirl
   (d) Color Gradient
   (e) LED Light
   (f) Sliding Circles
8. Why would you choose the above visualization to predict how well you would get along with another person?

9. If you had to choose one of these visualizations to predict how well you would work with another person, which one would you choose?
   (a) Line Graph
   (b) Emoji
   (c) Swirl
   (d) Color Gradient
   (e) LED Light
   (f) Sliding Circles
10. Why would you choose the above visualization to predict how well you would work with another person?
11. Did you perceive that the brain activity data behind each visualization were from the same person? (Yes/No) Why or why not?

Please rate the extent to which you think each pair of traits applies to yourself, even if one characteristic applies more strongly than the other. (Strongly disagree - Strongly agree, 7pt likert scale)

1. Extraverted, enthusiastic
2. Critical, quarrelsome
3. Dependable, self-disciplined
4. Anxious, easily upset
5. Open to new experiences, complex
6. Reserved, quiet
7. Sympathetic, warm
8. Disorganized, careless
9. Calm, emotionally stable
10. Conventional, uncreative

The following questions were used to check for biosignals familiarity.

1. Do you have any prior experience with EEG or brain sensing headsets? (Yes/No)
2. (If yes) What brain sensing headsets do you have experience with?
3. (If yes) Please describe the nature of your prior experience with EEG or brain sensing headsets.

Appendix C

Chapter 4.2 Materials

C.1 Questionnaire

Experience reading the transcripts

Please answer the questions about your experience reading the interview excerpts to the best of your ability. Jared is the person who was interviewed.

The questions below are from [171, 221].
Please rate how applicable the statements below are to your experience reading the interview excerpts. (Not applicable at all - Totally applicable, 5pt likert scale)

1. While reading these excerpts, I could imagine Jared in my mind.
2. While reading the excerpts about Jared, I felt that I was dealing with a very real person and not an abstract anonymous person.
3. I felt I was able to assess Jared's reactions to the situations described in the excerpts.
4. I felt I could get to know Jared through these excerpts.

The questions below are from [114].
Please use the scale below to indicate your feelings about the interview transcript that you read. Please answer based on the excerpts you read, and not the interviewee. (5pt bipolar scale)

1. Not vivid-vivid
2. Distant-Close
3. Cold-Warm
4. Not intimate-Intimate

5. Unsociable-Sociable
6. Impersonal-Personal
7. Not immediate-Immediate

The questions below are from the Experience-Taking Scale [150].
Please rate the extent to which you agree with the following statements about how you felt while reading the interview transcript. (Strongly disagree - Strongly agree, 7pt likert scale)

1. I felt like I could put myself in the shoes of the poster.
2. I found myself thinking what the poster was thinking.
3. I found myself feeling what the poster was feeling.
4. I could empathize with the situation of the poster.
5. I understood the events of the story as though I were the poster.
6. I was not able to get inside the poster's head.
7. While reading the posts, I felt I knew what the poster was going through.

The questions below are based on [28].
Please rate how much you experienced the following feelings while reading the interview excerpts. (Not at all - Extremely, 7pt likert scale)

1. Troubled
2. Apathetic
3. Moved
4. Anxious
5. Sad
6. Warm
7. Cheerful
8. Fearful
9. Uneasy
10. Softhearted
11. Infuriated
12. Compassionate
13. Sympathetic
14. Stressed
15. Tender

Perceptions of the interview transcripts

Please answer the following questions about your perceptions of the interview excerpts.

The questions below are from the Inclusion of Other in the Self Scale [17], with Self and Other replaced with You and Jared, respectively.

1. Please choose the picture (shown below) that best represents how you see yourself in relation to Jared.
2. Please choose the picture (shown below) that best represents how similar you feel to Jared.

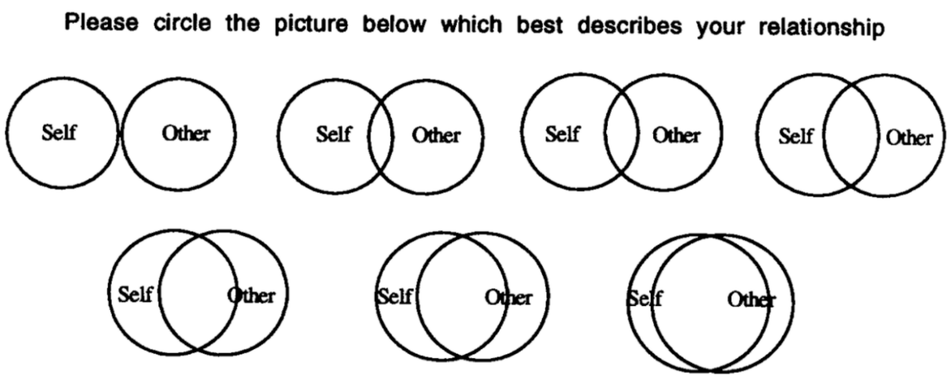


Figure 1. The Inclusion of Other in the Self (IOS) Scale.

1. What do you think of Jared?

The questions below are based on [185]. Participants were paid $3 total.
For our previous study, we received a number of potential interview contacts from a local Addiction Counseling Service, which is designed to help local individuals who were addicted to hard drugs (heroin, cocaine, etc.). While our interviewee, Jared, was not connected to this service, we are collecting donations to support this program.

If you would be interested in donating some of your reward for this HIT to our local Addiction Counseling Service, please indicate the amount below (instructions for your donation will be included at the end of the survey).

1. 0
2. 0.50
3. 1.00
4. 1.50
5. 2.00
6. 2.50

We are still in contact with Jared and have been gathering messages to send him that support his goals to stay clean. Are you interested in writing a short message of support for Jared? (Yes/No) If Yes: Please write your message here.

The questions below are based on [29, 46].
Please rate to what extent you agree or disagree with the following statements. (Strongly disagree - Strongly agree, 7pt likert scale)

1. People addicted to hard drugs lack self-control and inner strength.
2. People who end up addicted to hard drugs only have themselves to blame.
3. Many people addicted to hard drugs exaggerate their troubles to get sympathy.
4. I would see people addicted to hard drugs more as criminals than victims.

The question below checked for familiarity with hard drugs.

1. Do you or any loved ones (e.g., friends, family) have any experience with hard drugs? (Yes/No)

Questions about Interview Content

Please answer the following questions about the content of the interview excerpts you read.

The following questions were used as manipulation checks.

1. What drug was Jared addicted to?
   (a) Cocaine
   (b) Alcohol
   (c) Heroin
2. Jared did not try to stop his drug addiction.
   (a) True.
   (b) False.
   (c) Not sure.
3. What is Jared planning to do after finishing his prison sentence?
4. (For HR Graph condition) What was the graph plotting?
5. (For HR Graph and Caption conditions) Jared's heart rate was...
   (a) elevated.
   (b) normal.

    (c) low.
    (d) I'm not sure.
6. What do you think caused the changes in Jared's heart rate?

The question below is from [303].
To what extent was Jared feeling... (Not at all - Extremely, 5pt likert scale)

1. Distressed
2. Excited
3. Strong
4. Scared
5. Hostile
6. Enthusiastic
7. Proud
8. Ashamed
9. Nervous
10. Determined

The following questions were used as believability checks.

1. Did you believe the interview transcripts were... (Yes/No/I don't know.)
    (a) From an actual interview we conducted with Jared.
    (b) Created for the purposes of this study.
    (c) Based on someone's true experiences.
2. What do you think is the purpose of this study?

The following questions were used to check for biosignals familiarity.

1. Do you own any sensors that measure physiological data (e.g., heart rate, respiration)?
2. If yes:
    (a) Which physiological sensors do you own?
    (b) How frequently do you use these sensors to measure your physiological data (Very frequently - Never, 6pt likert)
    (c) For what reason do you own these sensors?
    (d) How familiar are you with physiological data (e.g., heart rate, respiration?) (Not at all - extremely, 5pt likert)

Debriefing

The purpose of this research is to understand the impact of different channels of communication on participants' reactions to an ambiguous story about a stigmatized group member. In this study, we asked participants to read fictional interviews that were created by our lab members, and whether you would donate to a fictional organization. The results from this study will help us understand whether certain channels can increase empathy and reduce biases when engaging with someone's personal story.

Appendix D

Chapter 5 Materials

All supplemental materials, including animo animation videos, Mechanical Turk surveys, and daily survey and interview questions can be downloaded at this link: https://dl.acm.org/doi/10.1145/3314405

Appendix E

Chapter 6 Materials

E.1 React Survey

Instructions

For the following questions, you will rate 17 ***reaction animations***. Imagine using the animations you see as a standalone reaction to an animated message that a close partner sent (e.g., significant other, best friend, family member), as described on the previous page. In some animations, your partner will be represented by a light brown hedgehog. Please answer the questions based on your first instinct.

Questions per animation

1. To what extent do you believe this animation expresses a ***negative*** versus ***positive*** reaction? (Negative - Positive, 5pt likert scale)
2. To what extent do you believe this animation expresses a ***low energy*** versus ***high energy*** reaction? (Low energy - High energy, 5pt likert scale)
3. To what extent do you believe this animation demonstrates ***closeness*** **(*i.e., intimacy and familiarity*)** towards your partner? (Not at all - Very much, 5pt likert scale)
4. To what extent do you believe this animation shows ***caring and concern towards your partner*?** (Not at all - Very much, 5pt likert scale)
5. To what extent do you believe this animation demonstrates ***understanding of your partner's feelings*?** (Not at all - Very much, 5pt likert scale)

6. To what extent do you believe this animation requests ***follow-up action*** (***after you've sent the animation***) ***from your partner***? (Not at all - Very much, 5pt likert scale)
7. To what extent do you believe this animation shows that ***your partner is valued***? (Not at all - Very much, 5pt likert scale)
8. Please write one possible message that this animation conveys in words.
9. Imagine a message you received ***from your partner*** that would prompt you to respond with this animation. Please describe that message.

E.2 Pre-Study Questionnaire

Your Experience in Relationships

These questions were part of the screening survey only, and were taken from the Experiences in Close Relationships Scale ECR-SF [305].
Please rate the extent to which you agree or disagree with the following statements about how you experience romantic relationships in general, NOT just specific to your current relationship. (Strongly disagree to Strongly agree, 7pt likert scale)

1. It helps to turn to my romantic partner in times of need.
2. I need a lot of reassurance that I am loved by my partner.
3. I want to get close to my partner, but I keep pulling back.
4. I find that my partner(s) don't want to get as close as I would like.
5. I turn to my partner for many things, including comfort and reassurance.
6. My desire to be close sometimes scares people away.
7. I try to avoid getting too close to my partner.
8. I do not often worry about being abandoned.
9. I usually discuss my problems and concerns with my partner.
10. I get frustrated if romantic partners are not available when I need them.
11. I am nervous when partners get too close to me.
12. I worry that romantic partners won't care about me as much as I care about them.

Apple Watch Usage

1. How often do you use your Apple Watch?
2. What do you use your Apple Watch for?

3. What self-tracking apps have you used (on your phone or watch)?
   (a) Strava
   (b) MyFitnessPal
   (c) Apple Health
   (d) Google Fit
   (e) Fitbit App
   (f) I have not used any self-tracking apps.
   (g) Other: (please describe)

Your Relationship with Your Partner

Please answer the following questions about the nature of your relationship with your partner.

1. Looking at your text and mobile messages from yesterday (including stickers, images, videos) about how many messages did you SEND to YOUR PARTNER? If yesterday was atypical, please answer according to the most recent typical day you can recall in the last week.
2. Looking at your text and mobile messages from yesterday (including stickers, images, videos) about how many messages did you RECEIVE from YOUR PARTNER? If yesterday was atypical, please answer according to the most recent typical day you can recall in the last week.
3. Looking at your text and mobile messages from yesterday (including stickers, images, videos) about how many conversations did you have with YOUR PARTNER? We consider a conversation when a new "timestamp" appears by messages from you or your partner. If yesterday was atypical, please answer according to the most recent typical day you can recall in the last week.
4. Thinking about yesterday, about how many voice or video calls did you exchange with your partner? If yesterday was atypical, please answer according to the most recent typical day you can recall in the last week.

The questions below are from the Relationship Assessment Scale [122].

1. How well does your partner meet your needs? (Poorly - Extremely well, 5pt likert scale)
2. In general, how satisfied are you with your relationship? (Unsatisfied - Extremely satisfied, 5pt likert scale)
3. How good is your relationship compared to most? (Poor - Excellent, 5pt likert scale)

4. How many problems are there in your relationship? (Very few - Very many, 5pt likert scale)

The questions below are from the Love Scale [248].
Please rate the extent to which you agree or disagree with the following statements. (Strongly disagree - Strongly agree, 7pt likert scale)

1. If my partner were feeling badly, my first duty would be to cheer them up.
2. I feel that I can confide in my partner about virtually everything.
3. I find it easy to ignore my partner's faults.
4. I would do almost anything for my partner.
5. If I were lonely, my first thought would be to seek out my partner.
6. I feel responsible for my partner's well-being.
7. I would greatly enjoy being confided in by my partner.

The question below is from the Inclusion of Other in the Self Scale [17], with Self and Other replaced with Me and My Partner, respectively.

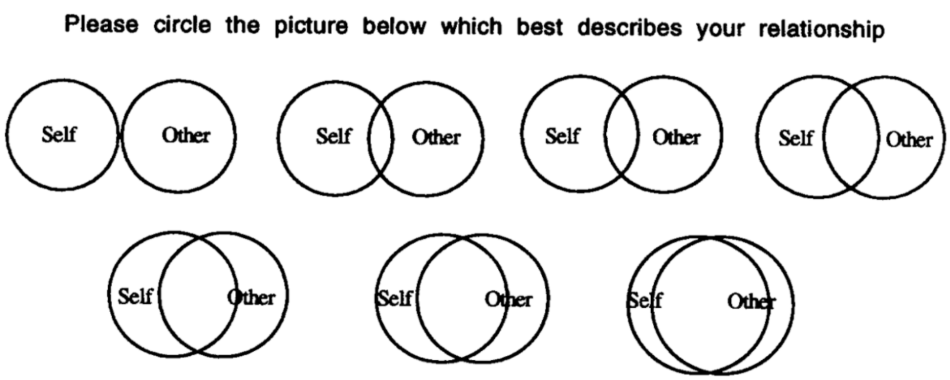


Figure 1. The Inclusion of Other in the Self (IOS) Scale.

The questions below are from the Emotional Self-Disclosure Scale ESDS [269].
How often do you express the following feelings to your partner? (Never - Always, 5pt likert scale)

1. Excited
2. Relaxed
3. Anxiety
4. Indifference
5. Calm

6. Apathy
7. Happy
8. Sad
9. Tired
10. Anger

The questions below are from the Social Support Questionnaire SSQ6 [254]. (*Not at all - Extremely, 5pt likert scale*)

1. To what extent can you count on your partner to be dependable when you need help?
2. To what extent can you count on your partner to help you feel more relaxed when you are under pressure or tense?
3. To what extent does your partner accept you totally, including both your worst and best points?
4. To what extent can you count on your partner to care about you, regardless of what is happening to you?
5. To what extent can you count on your partner to help you feel better when you are feeling generally down-in-the-dumps?
6. To what extent can you count on your partner to console you when you are very upset?

The questions below are from the Perceived Stress Scale [64].
The questions in this scale as you about your feelings and thoughts during the LAST MONTH. Please indicate your response representing HOW OFTEN you felt or thought a certain way. (Never - Very Often, 5pt likert scale)

1. In the last month, how often have you felt that you were unable to control the important things in your life?
2. In the last month, how often have you felt confident about your ability to handle your personal problems?
3. In the last month, how often have you felt that things were going your way?
4. In the last month, how often have you felt difficulties were piling up so high that you could not overcome them?

E.3 Mid-Study and Exit Questionnaire

These questionnaires were the same as the pre-study questionnaire, with the addition of the following, from [114, 171, 221].

1. While using the app, to what extent did you feel you were able to assess your partner's responses to different situations IN THE APP (e.g., receiving your hedgehogs, sending hedgehogs)? (Not at all - Very much, 5pt likert scale)
2. Please explain your rating above.
3. While using the app, to what extent did you feel you were able to assess your partner's responses to different situations OUTSIDE OF THE APP (e.g., what they were doing, what was happening around them)? (Not at all - Very much, 5pt likert scale)
4. Please explain your rating above.
5. To what extent did you imagine your partner in your mind's eye while you used the app? (Not at all - Very much, 5pt likert scale)
6. Please explain your rating above.
7. My experience interacting with my partner using the app was...(5pt bipolar scales)
   (a) Personal-Impersonal
   (b) Sociable-Unsociable
   (c) Warm-Cold
   (d) Immediate-Non-immediate
   (e) Close-Distant
   (f) Intimate-Not intimate
   (g) Vivid-Not vivid

E.4 Daily Survey Questions

1. Please describe one noteworthy experience you had with the app today (e.g., whether you noticed anything new, learned a new function, used the app in a new way).

Sending your State Hedgehog

STATE hedgehogs are the hedgehogs you see on your main app screen that you can send to your partner to "initiate" an interaction. REACT hedgehogs are the ones on the "Tap to React" screen that you can send to your partner to "respond" to their hedgehog.

Our records indicate that you sent the following state hedgehog animation today, around (time). Please answer the questions below about this animation.

1. How did you first notice this state hedgehog animation?
   (a) "Message from your hedgehog" notification" on my WATCH.
   (b) I opened the app on my WATCH and saw it.
   (c) I opened the app on my PHONE and saw it.
   (d) Other: (please describe)
2. What were you doing when you noticed this animation?
3. What message you were trying to convey with this animation to your partner?
4. What kind of reaction to this animation were you expecting from your partner, if any?

Our records indicate that your partner reacted to the state hedgehog above with this react hedgehog.

1. What did you think of this react hedgehog, if you recall seeing it?
2. Did your partner react to your state hedgehog above in any other way through the app or outside of the app (e.g., through other apps, in-person conversation)? If yes, please explain.
3. Were there any state hedgehogs you saw, either in notifications or in the app, but did not send? If yes, why did you decide not to send those state hedgehogs?

Receiving your Partner's State Hedgehog

Our records indicate that you received the following state hedgehog animation from your partner today around (time). Please answer the questions below about viewing your partner's state hedgehog animation.

1. What did you think of your partner's state hedgehog animation when you received it?
2. What message do you think your partner was trying to convey with this animation?

Our records indicate that you reacted with the following animation:

1. Why did you react in this way?

2. What message were you trying to convey with this reaction?
3. Were there any other ways you wish you could have reacted to your partner's state hedgehog (e.g., other animations or messaging options)?
4. Did you react to your partner's state at all outside of app (e.g., through other apps, in-person conversation, etc.)? If yes, please explain.

E.5 Mid-Study Interview Questions

General

1. What has your experience with the app been like overall so far?

Phone vs Watch

1. Did you find yourself using the app more on your phone or your watch? Why?
2. How did you feel about using one vs the other?
3. Were there any differences in how you used it on the watch vs the phone?

Notifications

1. You mentioned in some of the daily surveys that you've noticed notifications such as (describe notifications they mentioned).
   (a) What did you think of these notifications?
   (b) When did you decide to open them, vs dismiss or ignore them?
2. Did you use the quick react or share button features? When and why?
3. Did you ever look at the app on your own, without first seeing a notification?
4. Was this on your phone or watch? Why?

Sharing Behavior

Now we're going to talk about the state hedgehogs you sent to your partner, that they may or may not have reacted to.

1. Here's an example of a state hedgehog you sent to your partner on (time). They reacted with (describe any react hedgehogs).
   (a) Can you talk about what was happening when you sent it?
   (b) What did you think of your partner's reaction?

2. Here are some examples of the state hedgehogs you've sent over the past two weeks (show slide of top 5), and some examples of the react hedgehogs your partner sent to you. Note that these are not necessarily matched up with each other.
   (a) Do you recall sending these state hedgehogs?
   (b) Can you give me a few examples of those times?
   (c) How did your partner react?
   (d) What did you think about the way they reacted?
3. Were there any state hedgehog animations, provided in the app or not, that you wish you could have sent to your partner? Why or why not?

React Behavior

Now we're going to talk about the hedgehogs you received from your partner, and may or may not have reacted to.

1. Here's an example of a state hedgehog you received from your partner on (time).
   (a) Can you talk about what you thought when you received this hedgehog from your partner?
   (b) Why did you decide to send that react hedgehog? (or not react)
2. Here are some examples of the state hedgehogs you received from your partner over the past two weeks (show slide of top 5), and some examples of react hedgehogs you sent to them. Note that these are not necessarily matched with each other.
   (a) Do you recall seeing these state hedgehogs from your partner?
   (b) Can you give me a few examples of those times?
   (c) What do you think they were trying to convey to you?
   (d) How did you react, if at all?
   (e) Why did you react in this way?
   (f) (if they sent a react hedgehog) How did you decide which hedgehog to react with?
   (g) What were you trying to convey to your partner?
   (h) In the examples you described, were there any ways you wish you could have reacted to your partner, but weren't able to within the app?
3. Were there any hedgehog animations, provided in the app or not, that you wish you could have used to react to your partner? Why or why not?

Communication Behavior

Now I want to ask you about your communication more generally.

1. Please describe any instances in which you and your partner talked about the app.
2. How has using the app been similar or different to other ways in which you communicate with your partner?
3. Do you find you're communicating similar or different things with the app versus other ways you communicate?
4. Did you ever use the app in conjunction with other communication channels, such as in conversation or with any of the apps you just mentioned? For example, sending an hedgehog and then mentioning it in another app, or your partner receiving your hedgehog and then commenting on it in another app.
5. (if mentioned) You mentioned in your daily surveys that your partner reacted to your hedgehog outside of the app as well, for example, (describe their survey response). Could you describe this in more detail?
6. Have there been any changes to the way you communicate with your partner since the start of the study?

E.6 Exit Interview Questions

General

1. What has your experience with the second version been like overall?
2. What did you think about the app update after the mid-study interview?
3. What was your understanding of what the update was?
4. Did you have any expectations for this update?
5. What did you think about the heart rate sensing?
6. Did you notice any differences in the way the app worked?
7. Did you notice any differences in the way you used this version, compared to the first version?
8. Which version do you prefer? Why?
9. Aside from the app changing, was there anything different about your circumstances from the first half of the study (e.g., your location, your job, ways you and your partner communicated)?

10. There are lots of reasons why participation in the study may have changed since the update. For example, life circumstances, or general decline in the novelty or motivation to use the app. Did you notice any differences in your participation in the study, including your use of the app, as the study went on?

Notifications

1. What did you think about the notifications in the second half of the study?
2. How did they compare to the notifications in the first half?

Sharing Behavior

1. How did knowing (if they knew) that the app sensed your state affect the way you sent your hedgehog to your partner, if at all?
2. You mentioned for V1, that you sent your state hedgehog when (describe instances they sent them from the mid-study interview). How did this compare to the times you sent your state hedgehog with V2?
3. You mentioned for V1, that you sent your state hedgehog because (describe reasons they sent them from the mid-study interview) How did this compare to the reasons you sent your state hedgehog with V2?
4. In our last interview, you talked about how you sometimes expected certain reactions from your partner, both within and outside of the app. How did your expectations for your partner's reactions compare when you sent your sensed state hedgehogs in V2, if you had any?
5. Were there any times you saw a state hedgehog that did match your mood that you decided not to send?

React Behavior

1. What did you think about seeing your partner's sensed state hedgehog in V2?
2. How did knowing (if they knew) that you were viewing your partner's sensed state affect the way you reacted to your partner, if at all?
3. You mentioned for V1, that you sent a react hedgehog when (describe instances/reasons for sending them described in mid-study interview). How did this compare to the times you reacted with react hedgehogs with V2?
4. You mentioned for V1, that you sent react hedgehogs that (describe the way they matched react hedgehogs in the mid-study interview). How did this compare to the way you reacted with react hedgehogs with V2?

5. You mentioned for V1, that you reacted on (describe other platforms they used to react stated in the mid-study interview). How did this compare to the times you reacted to your partner in the second half of the study?

Communication Behavior

1. Did you and your partner talk about the new version of the app at all? How did you talk about it? What did you talk about?
2. You mentioned in our last interview that V1 of the app was (describe what they said about how it compared to the other ways they communicate in the mid-study interview). How did V2 compare to the way you communicated with V1?
3. Have there been any changes to the way you communicate with your partner in the last two weeks?

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