An Exploration of Hidden Data: Identifying and Physicalizing Personal Virtual Data to Extend Co-located Communication

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ABSTRACT

Communication is crucial for interpersonal connection, but sometimes we simply cannot find the right words. Some data, such as complex emotions, are either hard to quantify or are otherwise difficult to communicate. We have access to numerous personal statistics from quantified self devices, but *hidden data* are either untracked or require abstraction. In this paper, we explore physicalizations to communicate hidden data between couples. We recruited six couples (*N*=12 participants, 163 telegram responses) to participate in a two-week sensitization diary study followed by two participatory co-design sessions. We then hosted a one-day expert prototyping workshop (*N*=5) to create tangible artifacts based on the findings of the participatory phase. By iterating on the topic in three ways, we contribute (i) a design framework for understanding and tangibly representing hidden data, (ii) a discussion on the appropriateness of these methodologies, and (iii) open research questions to guide future research in the field.

CCS CONCEPTS

• **Human-centered computing** → **Interaction devices**; **Interaction design**.

KEYWORDS

Hidden Data, Communication, Tangible Interaction, Physicalization

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1 INTRODUCTION

Communication is one of the cornerstone abilities that make us human. We communicate information to build relationships, accomplish tasks, and learn from one another. However, some information is difficult to communicate either due to a lack of language or an inability to conceptualize the information. We call this information *hidden data*. Hidden data may be intangible because it cannot be directly measured (e.g., stress or emotions [36, 47]), it is not considered (e.g. feminist data [18]), or it is otherwise hard to communicate (e.g., *why* we feel an emotion). In this work, we explore how data physicalizations can be used to make hidden data tangible to enhance interpersonal communication.

Data physicalization has predominantly been explored for enhancing data understanding [29, 62] or self-tracking [37, 40, 59]. However, in co-located settings, the physicalization of personal data can act as an extension of human communication. For example, two people in a partnership who share a home may benefit from sharing their personal data with each other. If one partner has had a stressful day, the other one could choose to engage in a more mindful way. Traditionally this type of data is shared orally in a private setting – at a shared home or even at couples counseling with an expert. Such data can also be communicated virtually to the other partner by means of data tracking apps. In this paper, we aim to extend traditional oral communication by enhancing it with intelligent physical artifacts. Integrating physical artifacts to convey complex information — such as using dolls for dementia therapy [42], art therapy [1], and ambient light to visualize menstrual cycle data [32] — has been proven to benefit personal communication. For these reasons, our study focuses on physicalizing hidden data to extend co-located personal communication between couples.

In this paper, we present a multi-method explorative study to identify, understand, and physicalize hidden data in the context of co-located personal communication between couples. We explored this problem space with two separate groups of participants: physicalization novices and experts. First, each group set out to identify hidden data in real-life contexts, and then they explored how to physicalize it through tangible prototypes. We recruited six pairs (*N*=12) of novices in existing co-located relationships who completed a two-week sensitization diary study followed by two participatory co-design sessions. Subsequently, we completed a workshop with experts (*N*=5) who first identified hidden data in scenarios generated based on the initial diary study and then created physicalizations.

Our results demonstrate that hidden data can be identified and physicalized in the context of co-located personal communication. We identified 6 key communication patterns which lead to communication problems and propose a framework of solution concepts. We also established design dimensions that impact the development of future systems to physicalize hidden data. Overall, this paper contributes: (1) a framework, design dimensions, and guiding design considerations for creating hidden data physicalizations, (2) a discussion and reflection on methodologies to understand and tangibly represent hidden data, and (3) concrete research questions to guide future research in the field.

2 RELATED WORK

We build on prior work from three different research areas: First, we review works related to the concept of hidden data. We then discuss co-located communication and, finally, introduce data physicalization. In this paper, we amalgamate these three research areas to explore whether hidden data can be systematically derived and subsequently embedded in physical artifacts through a participatory, user-centered process.

2.1 Hidden Data

We define Hidden data as data that are difficult to perceive either due to lack of measurement, lack of ability to measure, lack of consideration, or complexity in abstraction. We track a multitude of personal data with technology. For example, bio-physiological data [3, 5], environmental data of a person's surrounding [61], and contextual and situational data [8] are already considered in HCI research. In many cases, hidden data are a level of abstraction above measurable data. For example, a person may be able to detect the heart rate and galvanic skin response of someone and determine that they have heightened arousal and are potentially nervous, but they will not be able to measure *why* this person is nervous.

Some data are hidden because they are intentionally ignored. D'Ignazio and Klein [14] note that "what gets counted counts" in society. Data from females, for example, has been historically excluded from medical studies and systematically biased [48]. Work on feminist data visualization aims to combat such systemic underrepresentation [18]. This category of hidden data is not the main focus of our work, but of interest is an understanding that just because the information is not collected does not mean that it does not exist.

In this paper, we focus on a subset of hidden data that is relevant to personal communication. These hidden data are best described as data types that have direct or indirect implications for the relationships between individuals but are difficult to communicate due to a lack of appropriate language or an inability to measure. As an example, one communication partner might have had a stressful day without necessarily knowing why it was stressful. They may act stressed or even say that they are stressed – but they are not sure why. In this scenario, the *why* would be hidden data. Thus, hidden data may include feelings, such as stress or pain, but it also includes abstract information, such as why one feels stress or pain. Since hidden data tends to be difficult to communicate with others or even with oneself, there might be additional types of hidden data that prior work has not considered. In this paper, we explore methods of identifying hidden data by means of situation sampling and representing it with participatory data physicalization.

2.2 Co-located Communication

We conceptualize communication generally as the transfer of information. This aligns with a technical understanding of communication associated with the infamous Shannon-Weaver communication model [55]. This model describes information transmission as a sender (full information) transmitting (noise is introduced) to a receiver (flawed information). However, social scientists and psychologists have recognized that human communication is more than just the simple act of transmitting information via the medium of words. The Shannon-Weaver model is, therefore, not sufficient to describe communication in its entire complexity.

"*One cannot not communicate*" [63] — even the act of saying nothing when asked a question communicates some information. Human communication also depends on more than just verbal aspects, [41], we also communicate with body language, tone, context, subtext, and others. These factors are especially of interest and influence when considering co-located communication since participants can interpret non-verbal signals due to their spacial relationship.

We understand communication also as a bidirectional exchange of information, which may be a dialogue between multiple individuals or an individual and themselves. Many prior data physicalization projects involve a unidirectional exchange of information, designed with the user as the receiver of information from others (one-way communication) [29] or themselves (self-reflection) [59], or with the user as the sender of information (self-expression) [22]. Affective visualizations have also been used to help users to physiologically communicate with themselves through biofeedback [13].

Past work in HCI has investigated technology-mediated communication for long-distance relationships using tangibles. Kowalski et al. [39] developed a prototype that uses color, vibration, and thermal signals to communicate between long-distance partners, They found that a hybrid approach, using the prototype and a mobile phone, encouraged users to communicate more often. Similar projects (c.f. [12, 57]) used colored light to mediate communication, while others used technology to re-create haptic communication such as hugging [16], stroking [20], and kissing [52]. Although mimicking such physical interactions may not be necessary for co-located partners, the concept of technology-mediated communication of intimate feelings generalizes to our work.

2.2.1 Understanding Emotions in Interpersonal Interaction. Research in both cognitive neuroscience [6] and philosophy [26, 27] argue that our understanding of interpersonal emotions is best represented by the "Interaction Theory" of social cognition. Gallagher [26, 27] suggests that we understand each other through interactions and narratives. Barrett [9] similarly argues that emotions are both biologically evident and socially constructed. We cannot understand emotions, therefore, without considering interactions.

Reisenzein [51] suggests a computational theory of cognitive emotions based on beliefs and desires in an effort to fully model and predict emotional reactions. However, prior work in HCI cautions

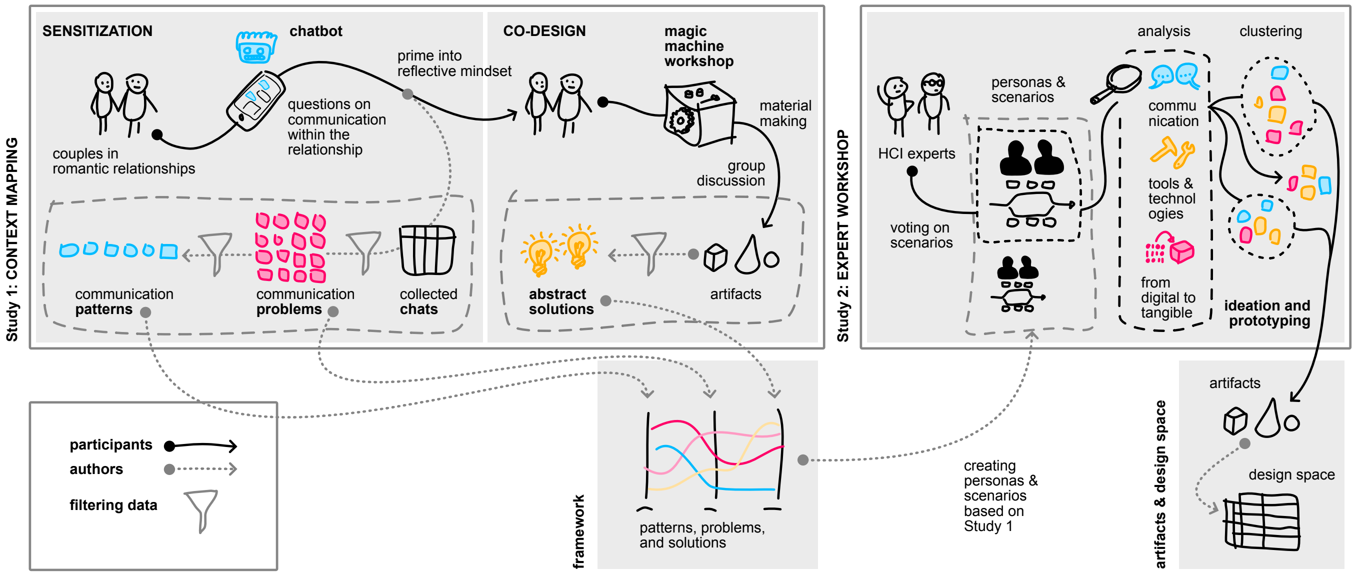

Figure 1: An overview of our multi-method approach to identifying and physicalizing hidden data. Study 1 (Context Mapping) consists of a sensitization diary study and two co-design workshop sessions. After creating a design framework, we put it to practice in Study 2 (Expert Workshop), which was a prototyping workshop with experienced participants.

against using computational emotion models in design [28], and questions whether we should be designing for emotions at all due to the inherent privacy issues and potential impact on our relationships. Boehner et al. [11] advocate for an interaction approach to emotions, in line with Gallagher [26, 27], suggesting that we focus on helping users understand their own emotions rather than helping computers to accurately detect human emotions. In our work, we focus on emotions only insomuch as they can be considered hidden data that could potentially improve communication and understanding. Interactions between individuals are the primary focus of our work, so in this sense, our approach is aligned with prior work [11, 26].

2.3 Data Physicalization

Data physicalizations are physical artifacts "whose geometry or material properties encode data" [34]. As such, they provide opportunities to leverage the full range of human perceptual exploration skills [34] in contrast to common data visualizations, which use only the visual sense. Researchers ascribe to data physicalizations the ability to make data accessible, make use of humans' cognitive abilities, and bring data off of screens and directly into the human world. Prior work on embodied cognition has also highlighted the intrinsic links between physical or sensory experiences and higher-level cognitive constructs, such as emotions and interpretations [15, 45, 64]

Data physicalizations have been employed for analytical purposes to physically represent scientific or statistical data in order to enhance understanding of complex topics [31, 34]. Prior work has also used physicalizations to communicate information through self-explorative interaction [29]. Further, physicalizations have been used to make data more accessible for individuals with sensory impairments since physicalizations make use of multiple senses like touch and hearing [34, 43]. Of particular relevance to our study is the use of physicalizations for self-analysis (e.g., quantified self [58]) and for sending out information to others [17]. A recent relevant study communicated breathing signals between users using visual and haptic modalities while collaborating on tasks, creating a 'social breath' [21].

Offenhuber [46] proposed a two-dimensional data physicalization framework. One dimension is the relationship between data and the mind, from epistemological to ontological, while the other is the relationship between data and the world, from relational to representational. Moere [43] proposed another framework consisting of five categories of data physicalization: ambient display, pixel sculptures, object augmentation, data sculptures, and alternative modalities. We reflect on both of these frameworks when discussing the physicalizations developed in our study.

3 METHODOLOGY

We used a two-study multi-method approach to identify hidden data and subsequently explore tangible representations. We first applied context mapping [60], where participants complete a sensitization stage to discover hidden data in real scenarios followed by participatory co-design sessions. Following this, we conducted an expert prototyping workshop based on the results of the context mapping study. Figure 1 shows each step in the methodology and highlights the flow of information from one step to the next, as well as how each step informed the resulting design framework.

The participants were all couples in romantic relationships. We focused on couples because they have established channels of communication, and we assume that they are likely to communicate

Figure 2: The materials used in the co-design session. Each package included plasticine, CDs, beads, pipe cleaners, wire, aluminum foil, toothpicks, stickers, post-its, rubber bands, wool, paper, cardboard, scissors, tape, glue, pencils, color pencils, and an eraser.

about personal and emotional topics. Open communication about personal topics has been shown to correlate with happier relationships [38, 53], so there is a clear benefit to enhancing communication in this context.

4 STUDY 1: CONTEXT MAPPING STUDY WITH COUPLES

We conducted the first study using context mapping [60], which consists of a two-week sensitization period to prime the participants into a reflective mindset before engaging in co-design sessions.

4.1 Participants

We recruited six couples, N=12 individuals (6 female, 6 male), aged 19-33, M=25, through a university email list and snowball sampling. The participants were mostly knowledge workers (information technology, civil engineering, automotive, and teaching) or students. The participants were in relationships ranging from 1-7 years, with a majority between 3-5 years, and cohabitated between 6 months and 5 years, with a majority between 1-3 years. None of the participants were married. The compensation was based on a rate of 10€/hour, resulting in 40€ per participant. All of the participants took part in both the sensitization and co-design phases.

4.2 Method

After obtaining informed consent, we provided the participants with a personal identification token and a link to an initial demographics questionnaire. We then provided initial instructions for the sensitization and co-design steps.

4.2.1 Sensitization. We implemented a chatbot using the Telegram messenger app[1] to automatically send questions to each participant on a daily basis. The participants were instructed to respond directly in the messenger with their identification tokens as their names to preserve anonymity. The participants were asked five questions per day in week one that focused on their own feelings. In week two, the questions shifted to three questions per day which focused on their partner's feelings. A complete list of the chatbot questions can be found in the supplementary material. There was no specified minimum response length, and participants were allowed to submit answers for a previous day if they missed a day of questions. Participants were told that if they missed two days in a row, we would consider them to have dropped out, and we would pay them proportionally for the amount that they participated.

4.2.2 Co-Design Sessions. We hosted two virtual co-design sessions using Zoom[2], as participants were located in multiple cities. We mailed packages of craft materials to the participants in advance, shown in Figure 2. Each session lasted approximately one hour.

After an initial welcome and overview of the process, each couple was given their own breakout room to complete tasks independently. They were encouraged to think out loud and talk openly. Each participant recorded their own breakout room and uploaded the video to a shared drive for the researchers to collect after the session, which ensured that the participants could not access the videos of other participants. Tasks were provided simultaneously to all groups using the chat function, and the host researcher circulated through the breakout rooms to answer questions. The researcher acted only as a host and did not take part in the creation process.

[1]https://telegram.org/
[2]https://zoom.us/

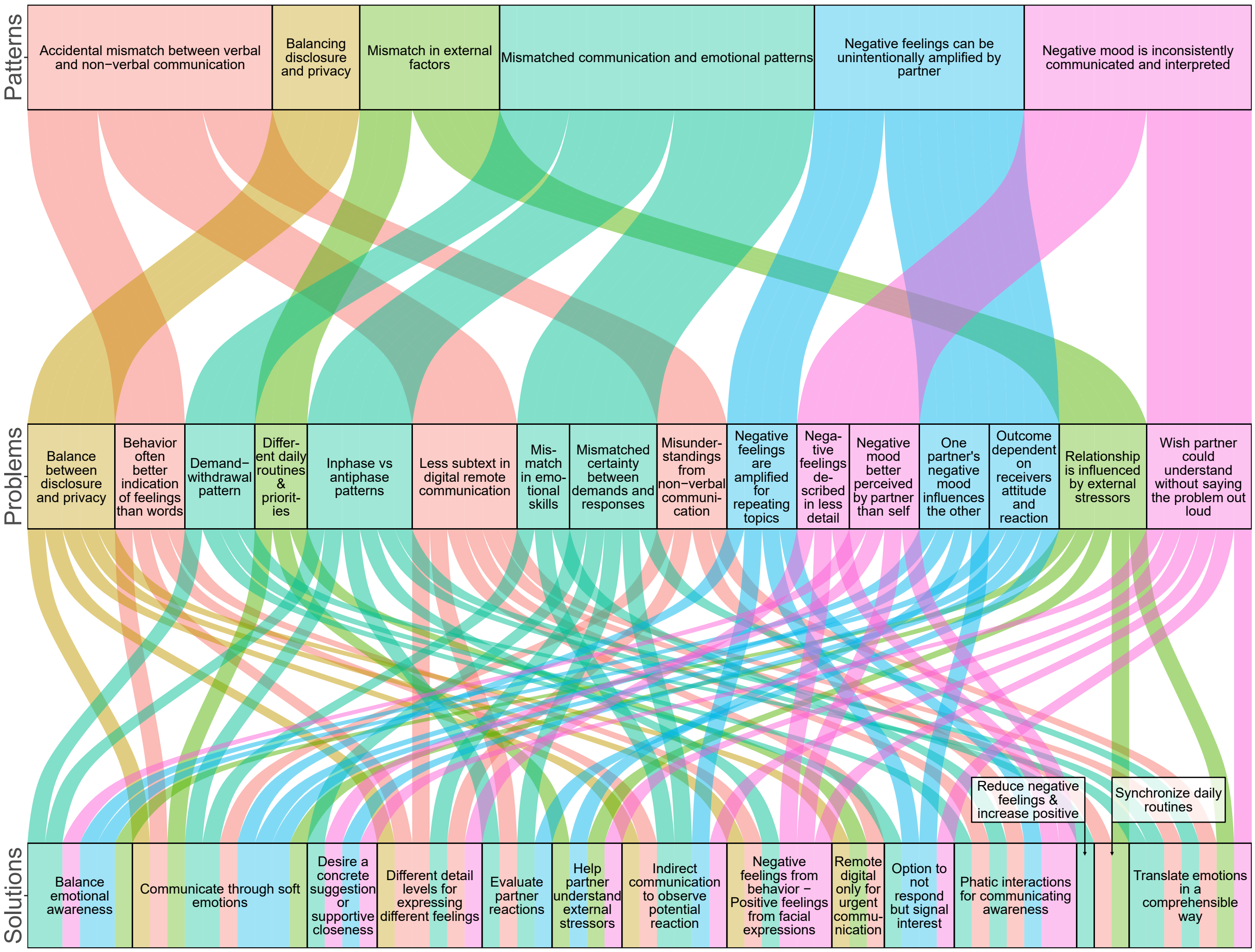

Figure 3: This alluvial diagram represents our framework of hidden data for interpersonal communication — showing connections between Communication Patterns, Problems, and Solutions identified in the sensitization study and co-design sessions.

The co-design sessions were based on the Magic Machine Workshop [4] and thus, had five sequential tasks: (1) **Introduction**: The participants were asked to think about their communication over the previous two weeks (reflection on sensitization) and consider points of tension and moments where they held back feelings; (2) **Prompt**: The couples were asked to individually imagine a magical object to help them communicate their feelings and to draw or write down their responses; (3) **Material making**: The couples were asked to create a physical representation of their magical object which could be one of the previous ideas, a combination of ideas, or a new one; (4) **Description**: The couples reconvened in the main room of the video call and presented their solutions to the larger group; (5) **Group discussion**: The participants each gave constructive feedback on the objects presented by the other groups.

4.3 Analysis

The Telegram responses were exported and coded using MaxQDA software. The recordings from the co-design sessions were transcribed verbatim and also coded using MaxQDA. One researcher conducted an initial round of open coding followed by a discussion with three other researchers. The initial researcher then conducted a second iteration of the initial codes with a focus on Communication Problems. We chose to emphasize problems since they represent areas where communication could be enhanced. Following the principles of Thematic Network Analysis [7], the codes were analyzed to generate basic, organizing, and global themes. Four authors discussed and agreed on the final themes.

4.4 Study 1 Results

We received a total of 163 responses through the Telegram chatbot, with an average of 122 words per response, resulting in a total of 19,980 words over the two-week period for all participants. No

Figure 4: The co-design prototypes (top-left to bottom-right) are: (1) a toy where partners convey feelings with emojis, squeeze to say sorry, and indicate when they are ready to talk; (2) a humanoid device that translates between communication styles; (3) a wearable that measures one partner's emotions and displays them to the other; (4) an edible magic pizza that displays emotion proportions; (5) a helmet that measures and logs emotions to a shared journal; (6) a box that translates between communication styles.

participants dropped out, and only 3 participants missed a single day of responses.

Based on the chatbot responses, we identified 16 Communication Problems, which can be clustered into six Communication Patterns. The six Patterns, summarized in Table 1, are high-level representations of the sources for Communication Problems among the participants. The idea of conceptual mismatches appears often in the themes. The connections between the Patterns and Problems are visualized in the left two columns of the alluvial diagram in Figure 3. The original thematic network for these Patterns and Problems is included in the supplementary material for additional clarity.

As an example, theme T5, "Mismatch in external factors" describes situations where interactions, obligations, and other scenarios outside of the relationship impact communication between the couples. One participant described a scenario where they were unable to fulfill a promise because their day was unexpectedly tiring, which led to a disagreement because their partner failed to understand the external factors:

> *I said yesterday that I would take care of something today, but I was busy all day and came home tired in the evening [...] I had been busy and wanted to relax first, which I told my partner, but she was annoyed because I said I'd do it.* (P8)

The influence of external factors (T5) was one of the most common patterns in the responses. The impact was at times explicit, as in the previous example, but in other examples, the influence was more subtle. One participant reported that they communicated in an aggressive manner that they later regretted because they realized that part of their anger stemmed from the fact that their partner had time to talk about their issue with others:

> *When I left the room, I cursed and slammed the door extra loud. Which, in retrospect, I was sorry about, but my partner didn't realize that the whole thing constricted me, and I barely had time to think about it, unlike him,*

Table 1: Communication Patterns identified as global themes in the sensitization study and co-design session.

ID	Pattern
T1	Mismatched communication and emotional patterns.
T2	Accidental mismatch between verbal and non-verbal communication.
T3	Negative mood is inconsistently communicated and interpreted.
T4	Negative feelings can be unintentionally amplified by partner.
T5	Mismatch in external factors.
T6	Balance between disclosure and privacy.

> *who spent the whole afternoon talking about it with his family.* (P5)

Some communication issues were independent of external factors and rather resulted from different communication styles (T1). One participant reported that they prefer to talk for a long time at once rather than communicating for a small amount every day:

> *At some point, he just wants to be left alone because he doesn't feel the issues are as relevant as I do. I kept talking anyway because it was important, and I'd rather talk for a long time than every day.* (P1)

The rightmost column of the alluvial diagram in Figure 3 is primarily based on the co-design sessions and will thus be explained in more detail in the following section.

4.4.1 Participant Creations. The prototypes generated in the co-design sessions are shown in Figure 4. The themes created in our analysis led to the creation of clusters of "Abstract Solutions." The solutions, and how they connect to the Communication Patterns and Problems introduced in the previous section, are represented in Figure 3. The thematic network for the co-design sessions is also included in the supplementary material.

As a concrete example, consider the prototype in the top-middle of Figure 4. The prototype listens to both partners and translates between their communication styles. In the rightmost column of the alluvial diagram (Figure 3), this corresponds with "Translate emotions in a comprehensible way." The participants who created this prototype reported that they have different abilities and styles in expressing their emotions, which explains the connection to the Communication Problem "Mismatch in emotional skills" and subsequently to the Communication Pattern "Mismatch in communication and emotional patterns." This example illustrates how our analysis led to the connections in the alluvial diagram. In Section 4.5, we will discuss how to employ this in practice.

4.5 Study 1 Discussion

The framework developed in Study 1 is represented by the alluvial diagram in Figure 3. The diagram visualizes the connections between the identified Communication Patterns, Communication Problems, and Abstract Solution mechanisms that were identified in our analysis. A designer wishing to use the framework should first identify communication patterns and problems in the scenario for which they are designing. They should then look at the Patterns and Problems columns of the alluvial diagram and find matches for their scenario. Finally, they should follow the connections to the Abstract Solutions column to identify relevant aspects to use as a starting point for their own designs. For example, if a designer identifies a pattern where users are constantly communicating via digital means and experiencing misunderstandings, they would follow the connection from the Pattern "Accidental mismatch between verbal and non-verbal communication" to the Problem "Less subtext in digital remote communication." They could then trace the connections to six potential Abstract Solution mechanisms and use those as a starting point for their designs. We used Study 2 to put this framework into practice.

We acknowledge that the list of patterns, problems, and solutions presented here is not exhaustive. Rather, this is intended to be a first iteration of a framework for hidden data in interpersonal communication. Future studies which identify different dimensions of hidden data in the context of communication could validate, add to, or otherwise modify our framework.

4.5.1 Participants had difficulty thinking of physicalizations and moving beyond existing technologies. Although we gained valuable insights about communication issues and potential solution approaches, most of the participants' creations would not be strictly categorized as physicalizations. Based on Offenhuber's two-dimensional framework [46], many of the solutions are in the quadrant of epistemic and representational. Beyond this, the solutions tend to use screens (or screen-like systems) to display data, rather than encoding that data in physical properties. Most of the solutions would not find a place in Moere's five categories of data physicalizations [43]. We expect that this is due to the fact that the participants had little to no prior experience with physicalizations or tangible user interactions.

Interestingly, while many related works in HCI aim to communicate physical signals, such as hugs [16, 25] and kisses [52], this was not present in any of our participants' creations. The wearable display and symbol-based communication creations are both reminiscent of work by Jarusriboonchai et al. [35], indicating that findings from long-distance communication may also apply to co-located couples.

One key aspect of the Magic Machine workshop [4] is encouraging participants to think outside of existing technologies. Our participants thought up intelligent devices that, for example, automatically interpreted emotions. However, representations and visualizations used by the prototypes were often tied directly to existing technologies such as tablets and smartwatches. These limitations motivated us to conduct a second Study using expert participants to generate physical prototypes, which is the focus of Study 2.

5 STUDY 2: EXPERT PROTOTYPING WORKSHOP

We conducted an expert prototyping workshop to explore the scenarios and opportunities identified in Study 1. The workshop was exploratory and intended to provide an example of how to employ the framework from the first Study.

5.1 Participants

We conducted the workshop with N=5 participants from four different research labs in three universities with expertise in fields relating to tangible prototyping and data visualization. An overview of the participants is shown in Table 2.

5.2 Method

Prior to the workshop, one of the authors created personas and scenarios for two fictional couples. The scenarios both took place over a single day and involved the couples having an argument, which was based on situations mentioned by the participants in Study 1.

All of the workshop participants read the scenarios at the beginning of the workshop and voted on a single scenario to be the focus of the workshop. The scenarios are included in the supplementary

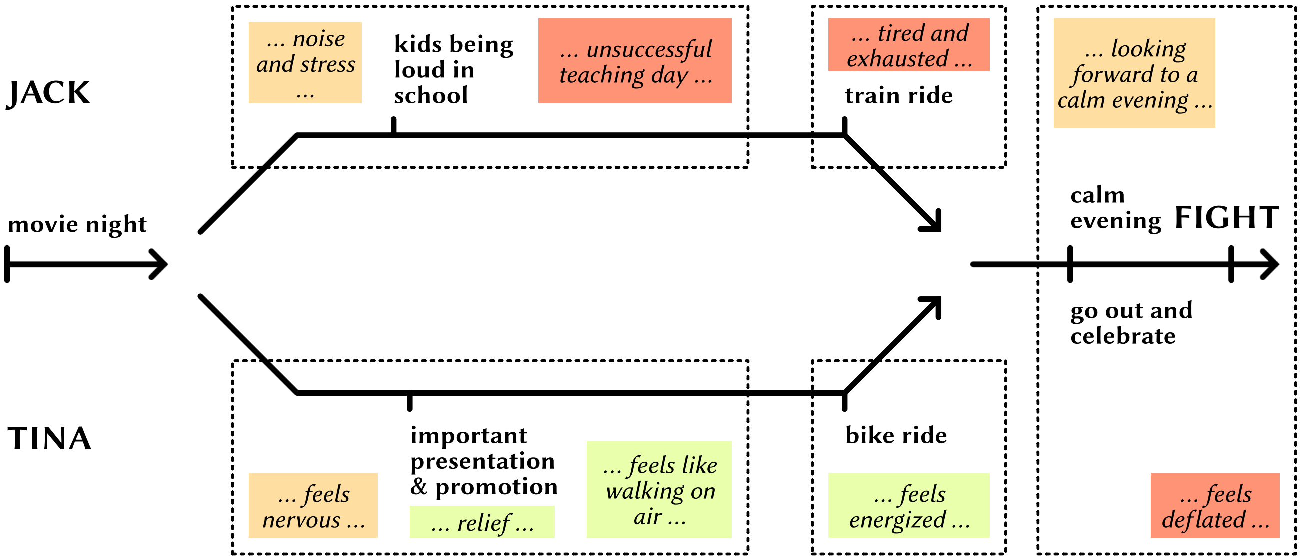

Figure 5: A high-level overview of the prototyping workshop scenario. The two characters, Jack and Tina, have separate experiences during the day and eventually have an argument. Some events in each character's day are shown in black along their respective timelines. Example sticky note responses from the workshop participants are shown in colored boxes.

Table 2: Overview of the participants in the expert prototyping workshop.

ID	Gender	Expertise
E1	Male	Mechanical Engineering & physical prototyping
E2	Female	Virtual-Physical reality & data continua
E3	Male	Tangible devices & physical prototyping
E4	Female	Physicalizations & tangible interaction
E5	Male	Physicalizations & tangible interaction

material, along with the associated personas. After choosing a scenario, the workshop participants were given prompting questions to identify hidden data and communication patterns within the scenario and eventually develop physical prototypes. The participants were given sticky notes and large flip chart paper to respond to the following questions, with one round per point:

(1) Where in the scenarios can communication be extended? What type of data are participants communicating? What type of data do participants need to communicate better?
(2) Where in the scenarios do/can existing tools/technology support this effort to extend communication?
(3) How can purely virtual technology be replaced with tangible artifacts for each of these situations?

Following these three rounds, the responses were clustered, and the participants voted on two aspects to focus on. The participants were then divided into two groups and used clay and other prototyping materials to create tangible artifacts. The participants discussed their ideas and reflected on the workshop after the session.

Following the workshop, two of the authors read through the notes to identify themes and create clusters of potential solutions. Three authors analyzed the features of the prototypes created in the workshop to identify patterns related to communication and data transfer.

5.2.1 Workshop Scenario. A few key events in the storylines of the two characters in the chosen scenario are shown at a high level in Figure 5. The two characters have different emotional experiences throughout their day and eventually have an argument. The workshop participants identified major events in the day, hidden data that were generated, and opportunities for extended communication. The colored boxes in the figure represent examples of responses written on sticky notes by participants identifying the characters' emotions at different points in the day.

5.3 Study 2 Results

In the following, we present an overview of the prototypes developed in the workshop and design dimensions of potential solutions which resulted from our analysis.

5.3.1 Prototypes. The participants produced physical prototypes of four solutions, shown in Figure 6. The concepts are as follows:

(1) *Haptic Entry Mat*: a doormat at the entrance to a house that adjusts in stiffness, texture, and stability. The user stands on the doormat before entering their house to receive information about their partner's emotions and experiences from the day, encoded in and transmitted via the physical properties.
(2) *Flexible Furniture*: smart furniture in the user's house can adjust in stiffness and stability (e.g., by inflating). The user receives signals about their partner's affective state or other hidden data while sitting on the furniture.
(3) *Two-way Stress Ball*: each partner has a stress ball that mimics the shape and behavior of the other's stress ball. If one

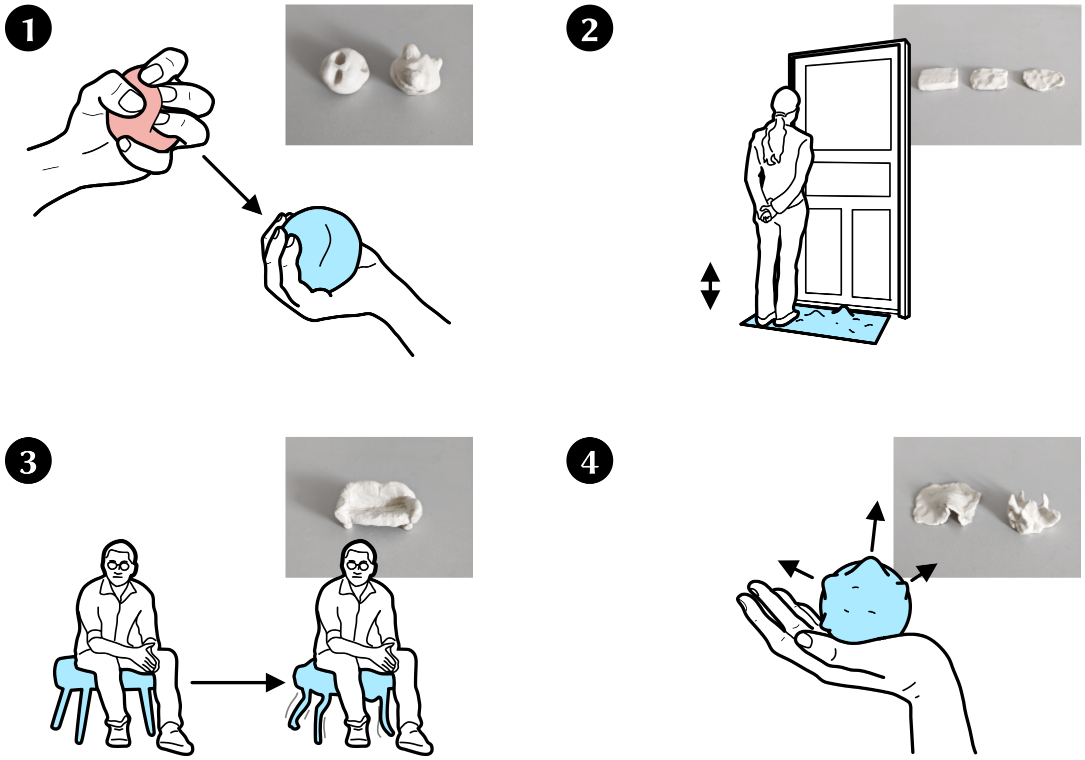

Figure 6: The prototypes created in the expert prototyping workshop: (1) the two way stress ball, (2) the Haptic Entry Mat, (3) the flexible furniture, and (5) the intelligent matter ball.

partner squeezes or pokes their ball, the partner's ball will correspondingly change shape. Partners can use this to send non-verbal messages to one another.

(4) *Intelligent Matter Ball*: the user carries a small ball that can change shape on its own. It changes continuously based on the affective state of their partner. The ball uses shape and texture to communicate hidden data.

5.3.2 Design dimensions of potential solutions. Three of the authors analyzed the features of all of the example solutions generated in the workshop and clustered them based on commonalities in communication patterns and how they interact with data. Through this clustering, we created three dimensions describing important aspects of the solutions:

(1) Data Representation: *Abstract — Literal*
(2) Receiving Partner Signal: *Always Receive — Choose to Receive*
(3) Sharing Partner Signal: *Always Share — Choose to Share*

The Data Representation dimension describes a continuum between communicating abstract, interpreted signals (e.g., mood) and communicating literal signals (e.g., location). The Receiving Partner Signal dimension is a continuum between always receiving a signal from a partner and choosing to check in to receive a signal. Finally, Sharing Partner Signal describes a continuum between continuously sharing data with a device and choosing when and which data to share. Table 3 shows example solutions for each combination. The example solutions were generated by the workshop participants, but not all of the solutions were developed into the physical prototypes outlined in subsubsection 5.3.1.

5.4 Study 2 Discussion

In the following, we discuss using the hidden data framework in practice, temporality in data transfer, choice in data sharing, tangible and embodied representations, and the use of metaphors.

5.4.1 Using the hidden data framework in practice. We used the workshop to explore the framework (Figure 3) that we created in Study 1. The workshop participants used the framework as intended: they analyzed the presented scenario and identified Communication Patterns and Problems, then used the Abstract Solutions in the alluvial diagram as inspiration. As an example, the characters in the scenario had different experiences throughout the day, which led to an argument. In Figure 3 this corresponds with the Communication Pattern "mismatch in external factors," which is connected to the Problems "relationship is influenced by external factors" and "different daily routines and priorities." One of the connected Abstract Solutions, "help partner understand external stressors," is embedded in the Haptic Entry Mat, which gives one partner information about the other's affective state as they are arriving home.

However, rather than using the framework solely to generate solution ideas, it was also used to evaluate the solution concepts and prioritize them for further physicalization. This suggests the opportunity to use the framework as a heuristic evaluation tool for

Table 3: Design dimensions and example solutions generated by the workshop participants.

		Always Receive	Choose to Receive
Abstract	Always share	Flexible Furniture: changes stiffness to provide subtle continuous signals to the user representing hidden data from their partner.	Haptic Entry Mat: changes stiffness to let the user check in on their partner's affective state before entering their home.
	Choose to share	There were no prototypes created for this category.	Tangible mood diary: the user creates physical shapes each day that correspond to their mood or other hidden data. The data builds up over time.
Literal	Always share	Hormone Pump: each user is given hormones to make them feel the stress or emotional experience of their partner.	Sandbox bike trails: paths are generated in a box of sand that represent the movements of the users. One partner can get information about the other by looking at the sand trails.
	Choose to share	Tandem Bike at a distance: if one partner climbs a hill, the other partner can transfer some of their pedaling energy to make the ride easier. The partners can take turns sharing the load.	Two-way Stress Ball: each partner has a stress ball and they are paired together. Any shape change on one is immediately represented on the other, so the partners can send tangible messages.

existing prototypes in order to determine whether they are usable for physicalizing hidden data.

As outlined in Table 3, we also identified three additional dimensions to be considered when creating prototypes to communicate hidden data. After using the alluvial diagram to generate initial solution ideas, a designer would then decide if the data should be represented literally or abstracted through the use of a metaphor. In using this system, a designer should also choose how each partner will input their data into the system and receive data from the system, whether that be continuously (implicitly), intentionally, or a combination.

5.4.2 Temporality in data reception ranges from embodiment to intention. Temporality in data communication was a prominent discussion point in the workshop. For the partner receiving a signal, temporality is the difference between a continuous signal and an opportunity to check in. Some of our prototypes, such as the Flexible Furniture, involve one partner receiving a continuous stream of data. On the other hand, solutions like the Haptic Entry Mat enable partners to choose to check in periodically. As a designer of communication technologies, the spectrum from continuous to intentional data reception should be considered for different scenarios. Continuous reception ensures that partners are constantly updated, and they will be continuously aware of their partners' hidden data. Such a coupled signal could be embodied, so partners could be aware of each others' affective states without conscious effort. Heightened awareness can enhance empathy [50], which improves communication [56]. On the other hand, choosing when to check in and receive a signal requires that the users intentionally view and reflect on the data. Intention and reflection have been shown to improve understanding, focus, and meta-cognition [23, 24].

5.4.3 Choice in data sharing may mean that hidden data are missed. Choosing when to share data is also an important design consideration. Some of the prototypes, such as the Haptic Entry Mat, involve one partner continuously sharing data with the other. Others, such as the Two-way Stress Ball, require the user to choose when to share data. Continuous sharing is a central aspect of ubiquitous capture [54], which is increasing in prevalence as data storage becomes less expensive. There are issues with privacy and autonomy when data are continuously shared, and users should be explicitly aware of how their data are being recorded and communicated. However, users may not always be aware of all of their hidden data. In a system where users choose when to share their data and which data to share, they may miss out on communicating important hidden data. Continuously capturing data may be recommended to identify hidden data that a user is not aware of themselves, although sharing this data continuously could lead to miscommunication if the user is not able to add context to the communication or reflect on its meaning. On the other hand, intentional sharing would be particularly appropriate to communicate something that the user cannot find the words to say. It is important for the users to understand the role and scope of the technology in the relationship, whether as a mediator, a translator, a reflection tool, or another role. Establishing this role is important to determine how much influence the users choose to give the technology within their relationship.

5.4.4 Physicalizations should include fully tangible and embodied representations. Throughout the prototyping workshop, the participants often discussed the nature of physicalizations. Solutions such as the Hormone Pump, where the signal is fully embodied, and the user may not even be aware of receiving it, called into question the traditional definition of a physicalization. Physcalizations are generally described as physical artifacts that encode data through geometry or material properties [34]. In the workshop, participants asked: *Is having a physical experience a physicalization?* Several solutions proposed throughout the workshop involved wearables, such as a weight-changing vest that would represent feelings of stress and relief. We can communicate data physically through wearables and they are a named category in Moere's framework for data physicalizations [43]. The boundary between physicalizations, wearables, haptics, tangibles, and visualizations is blurry in some edge cases. It may be appropriate for the definition of physicalizations to expand to include fully tangible or embodied representations.

5.4.5 Metaphors are important for aggregating and interpreting data. Many quantified self systems provide users with raw, uninterpreted data, such as heart rate [49]. In our exploration of hidden data, we identified complex signals and emotions that require abstraction from raw signals. Tangible experiences, such as temperature or texture, inherently have lower bandwidth than traditional visualizations, so communicating hidden data tangibly requires careful design decisions. In the workshop, the participants often used metaphors to communicate emotions. As an example, the phrase "walking on air" was used to represent a feeling of relief after stress. Metaphors are a debated topic in HCI, but they remain common practice in the design industry and useful tools [10]. Designers should be aware of metaphors that users could employ and could harness these metaphors to embed complex data into low-bandwidth signals.

5.4.6 Summary: Expanding the framework. Based on our analysis and the above discussion, the framework presented in Study 1 can be expanded by including results from the prototyping workshop. In particular, the following design variables should be considered: (1) the continuum between abstract and literal data representation, (2) the continuum from continuous to intentional data reception, (3) the continuum from continuous to intentional data sharing, and (4) the use of metaphors in designing data interpretation and representation.

6 DISCUSSION

In this paper, we set out to explore (1) whether hidden data can be identified through participatory HCI design methods and (2) whether hidden data can be represented using physicalizations to extend communication. In this section, we discuss combined insights from both Study 1 and 2.

6.1 Design Framework

We constructed a design framework, shown in Figure 3, based on the sensitization study and co-design sessions in Study 1. The diagram depicts *Patterns* and *Problems* in communication as well as *Abstract Solutions* that we identified with our participants. The solutions are intentionally conceptual so as to apply to a wide number of scenarios. Designers of future communication technologies can use the diagram by mapping Communication Patterns or Problems from their own user scenarios onto the diagram and using the connected Abstract Solutions as starting points for their designs.

We employed the framework in the prototyping workshop in Study 2 by identifying Patterns and Problems, which is in line with user-centered design processes [2]. The participants created physical prototypes using a combination of brainstorming and Abstract Solutions from the framework. Unexpectedly, participants also used the framework at the end to re-evaluate whether the prototypes (see Figure 6) matched the initial goals. With this in mind, there is an opportunity to adapt and use the framework as a heuristic evaluation tool. However, further analysis is necessary in order to investigate how the physicalization framework for co-located communication differs from previous ones for physicalization of self-tracking data, such as by Khot et al. [37].

6.2 Temporality and Choice

In Section 5.4, we discuss intentional and continuous data transfer in terms of both sharing and receiving data. The spectrum ranging from fully continuous to fully intentional is a design variable for future creators of communication technologies. Systems designed for continuous data reception may allow for embodiment and more intuitive understanding while intentional data reception would enable users to check in on their partner periodically. On the other hand, continuous data sharing may be more appropriate to capture data that are hidden from the user, at the risk of miscommunication, while intentional data sharing would enable users to use the system to communicate something they cannot find the words to say.

Prior work exists at multiple points along the spectrum between continuous and intentional data sharing and reception. Hemmert et al. [29] continuously display information to users, but data must be intentionally added to the system. Waldschütz et al. [62], on the other hand, created a radiation physicalization that constantly senses new data and continuously displays it.

Our study has identified the range of opportunities for sharing and receiving data, but future research should be guided by the following open research questions:

- **RQ1** How should intentional or continuous data *sharing* be balanced to facilitate communicating hidden data?
- **RQ2** How should intentional or continuous data *reception* be balanced to facilitate communicating hidden data?

6.3 Context-Dependency

Hidden data are highly context-dependent. We focused on couples in our study because they have frequent in-depth communication, established communication patterns, and effective communication is a key aspect of relationships [38, 53]. Although our study was focused on a specific context, we created the design framework with broad categories that should be applicable to multiple scenarios. In order to extend our work to other contexts, it is crucial to analyze communication patterns and identify problems in the chosen scenario.

One specific context that is important to HCI is self-tracking. Research in quantified self, as well as an increased focus on mindfulness and self-reflection, make self-tracking an interesting area to apply our approach of physicalizing hidden data. Although our work focuses on communication between couples, some aspects of our approach could be extended to reflection and communication with oneself. In one prior work on creating data physicalizations for self-reflection by Thudt et al. [59], some of the physicalizations focused on hidden data, such as mood or enjoyment, but most of the projects focused on measures that would not be considered hidden data, such as places visited or workouts. However, insights regarding the creation of personal physicalizations could be combined with our design framework to extend our findings to physicalizations for self-reflection.

Future research is required to confirm whether our approach can be extended to other scenarios, which can be guided by the following open research questions:

- **RQ3** How can we design a tangible device that facilitates communicating hidden data in any context?

RQ4 Which contexts benefit the most from tangible communication of hidden data?

RQ5 How can physicalizations be used to identify hidden data within oneself and aid in self-reflection?

6.4 Tangibility and Data Physicalization

The concepts developed by the experts in Study 2 demonstrate the strong coupling of tangibility and data physicalization. Here, tangibility goes beyond the pure physicality and materiality of objects in the real world and instead stresses the non-generic character of tangible user interfaces. This means that the data physicalizations are more than interfaces through which any type of information can be accessed, but instead are specialized representations of a specific subset of virtual data which can be interacted with and accessed via a real-world object. As such, a tangible data physicalization becomes a device that discloses otherwise hidden data and creates a human-technology relation [33]. This enables either hermeneutic access (mediated via reading), such as in the case of the Haptic Entry Mat and the Intelligent Matter Ball concepts, or an embodied relation (mediated via experiencing), as in the case of Flexible Furniture and the Two-way Stress Ball. Therefore, we see the physicalization of hidden data as a fascinating field for applying tangible interaction research and a suitable example to discuss the overlap of tangibility, embodiment, and physicalization within the research community. We see potential in including even more modalities, such as heat or scent, in physicalizations for hidden data in future work.

6.5 Learning From Long-Distance Technologies

Past work in HCI has investigated technology-mediated communications for couples in long-distance relationships. These projects aim to connect people over a distance through wearables [35] and recreate physical touch through tangible hugs [16] and kisses [52]. While our study focused on couples who cohabitate and are therefore often co-located, the findings in long-distance communication are linked to our study. In particular, our findings show that miscommunication often begins or builds while partners are apart, for example at work. This is reflected in the influence of external factors in Figure 3. While the participants in Study 1 developed some prototype solutions reminiscent of related work using wearables [35], they did not aim to replicate physical communication (e.g., hugging) as we see in the long-distance technologies. Rather, the co-located couples developed solutions to help mediate their own interactions, such as 'translators.' While there is clearly an overlap in communication issues faced by cohabitating and long-distance couples, the pressing problems apparent in the proposed solutions appear to diverge somewhat.

6.6 Critical Reflection: Should Data Remain Hidden?

In this study, we explored physicalizing hidden data to augment co-located personal communication. Our methods encouraged a neutral, non-judgmental lens in order to encourage diffuse thought processes and free ideation. Our approach aligns with the interactional approach suggested by Boehner et al. [11] in that we encourage individuals to reflect on their emotions and attempt to gain a deeper understanding of one another. However, just as it is critical to consider ethical consequences before exploring personal informatics data [30, 44], it is equally valuable to reflect in hindsight on whether the suggested solutions are appropriate and ethical. Our work demonstrates that it is possible to identify and physicalize hidden data. However, just because we can translate feelings, emotions, motivations, and other personal and subtle aspects of the human psyche into data, does that mean we should?

For example, consider a solution that enables partners to choose when to share hidden data with one another. In some scenarios, the additional insights provided by the shared data may lead to more fruitful conversations or a deeper understanding between the two individuals. But consider the consequences of one partner choosing not to share; this may lead to distrust, worry, or other breaks in privacy. Such a system also has the potential to be abused in a relationship with a power imbalance.

These results also beg the question: *Do we need technology to solve this problem?* In some cases, users may be better served by improving their communication skills and emotional intelligence so that they have a greater ability to communicate data that was previously hidden. However, we continue to hypothesize that there is a lack of language to communicate some feelings, and having an (intelligent) physical medium to aid in conversation has been shown to be effective in breaking down communication barriers in practice [1, 42]. Combining a physical communication aid with intelligent data interpretation may further break down barriers by adding additional insights and context.

Communication in relationships can be complex, and we do not propose that physicalizing hidden data is guaranteed to improve this communication. However, now that we have explored the space and created a framework for identifying hidden data and then developing tangible representations, there is an opportunity to research how these tangible representations impact relationships and communication. Future studies should investigate whether these tangible artifacts can improve understanding and enhance communication and how these impacts change over the long term.

6.7 Reflection on Methodology

The Study 1 participants had little to no prior experience with physicalizations or tangible interfaces. We chose to include physicalization novices in the first study because hidden data are, to date, not well-defined or well-understood, so we aimed to understand them in real scenarios. However, we found that the participants in the first study had difficulty conceptualizing solutions that would be categorized as physicalizations based on Moere's framework [43] and our own understanding. We initially expected that this was a consequence of their inexperience with the field, but the experts in Study 2 also had difficulty creating solutions that could be firmly defined as physicalizations. Our interpretation is that conceptualizing physicalizations is, in fact, difficult since there is an added layer of difficulty, novelty, and abstraction.

In the future, it may be useful to create an opportunity for novice participants to interact with experts in the field to combine the value of both the participatory and expert methods. This could be realized by integrating context mapping with an iterative human-centered design process, whereby novice participants provide situational data, which experts use in a rapid prototyping process. These prototypes can then be returned to the novice for testing. Situational data may be captured in the form of a diary study over a week, and at the end of the week the rapid prototyping can be completed. We acknowledge that there may be alternative approaches, however, repeating this method over multiple weeks can lead to a common understanding of hidden data, which we found to be a critical aspect in the physicalization process.

6.8 Limitations and Future Work

One potential limitation of our study is that the co-design sessions in Study 1 were held virtually. We hosted the sessions over Zoom because the participants were located in multiple cities. The virtual setup meant that the participants had less spontaneous interaction between groups than would have occurred if the session was held in person. However, since participants were discussing communication patterns within their relationships, the added privacy of breakout rooms may have encouraged them to speak more openly with one another. We assembled packages of creative materials and sent them to the participants in advance, so they were not limited in terms of prototyping materials despite the remote setting.

One other potential limitation is the homogeneity of our sample. All of the couples in Study 1 were heterosexual couples living in Germany, with a relatively small age range. This may impact how well our results and framework generalize to users with different characteristics and should be considered with our results.

Another potential limitation is that we conducted purely qualitative evaluations. We did not conduct an evaluation of a fully implemented physicalization prototype that aimed to extend personal communication. This was intentional as the scope of this paper was to understand hidden data and explore the space of physicalizations in this context. We propose that future research should implement systems of physicalizations and evaluate their effectiveness and usability in the context of extending personal communication. The design recommendations and constructive knowledge that this paper contributes should be used as a basis for future work that quantifies the impact of such a system.

Finally, we did not instruct participants in either study to explicitly consider security or privacy. Many of the potential solutions that were suggested involve accessing and sharing highly personal data, so privacy is a relevant consideration. We intentionally did not want to limit the creative process in our study due to its exploratory nature, but we acknowledge that privacy and security of hidden data artifacts (e.g. visual attacks by someone who is an intruder [19]) is an aspect that is crucial for a working prototype. Future work focusing on real-world implementation should include input from usable security and privacy experts and careful consideration of these aspects.

7 CONCLUSION

We conducted two exploratory studies on physicalizing hidden data in the context of extending co-located personal communication. We conducted a two-week sensitization diary study and two participatory co-design sessions with six couples (N=12) to understand sources of hidden data and explore physical representations. We created a design framework based on our findings in the first study and then hosted an expert prototyping workshop (N=5). The workshop is an exemplary implementation and exploration of our findings in the first study. We incorporated insights from the workshop and generated design dimensions, recommendations, and open research questions for the community to spark future designers to create physical representations of hidden data. This study provides a first exploration into the topic of hidden data using a novel combination of methods and creates a foundation for further work in the field.

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