Understanding Shared Personal Data Constructive Physicalization Processes

by

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B.Sc., North South University, 2018

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ABSTRACT

Constructing data physicalizations, wherein data is represented using physical tokens, is posited to help people with data-centric decision making. Research has shown that the hands-on nature of this process enables a familiar way for people to collaboratively construct and interact with representations. However, we do not know how people collaborate when constructing a physicalization and subsequently, how they can be supported. We conducted a qualitative study with six couples to better understand how people collaborate to construct a physicalization. We found that participants employed three main styles of collaboration – *mutual*, *exclusive* and *dictator* – when working together to construct a physicalization on their shared personal data. Additionally, we identified that such collaboration styles were facilitated through actions such as discussion, distributing tasks, and preparing and assembling tokens. Informed by our findings, we discuss: a) the differences between previously proposed physicalization workflows in the literature and ours, and b) implications for design to foster collaboration in data physicalization processes.

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DEDICATION

This work is dedicated to the visualization research community who are working relentlessly to make the data tangible and ubiquitous for the lay audience.

Chapter 1

Introduction

Data physicalization entails encoding information, including numbers and relationships, by leveraging the geometric attributes of physical objects, such as shape, size, texture, color, and material [38, 4]. This approach has gained popularity as a way to engage individuals and groups in accessing and understanding information in a memorable and relatively easy manner through physical interactions [87, 27]. In this paper, we focus on the emerging area of inquiry within this area of research that pertains to the collaborative construction of physicalizations and the underlying factors that contribute to successful collaborations [38], in an everyday environment.

1.1 Context & Motivation

Considerable research effort has been dedicated to exploring the collaborative aspects of digital visualizations. This encompasses collaboration in visual analytics [32, 84, 33] and the design of visualizations on tabletop displays [23, 35]. Isenberg and colleagues [31] have presented a set of design guidelines for developing visualization tools that facilitate co-located or distributed collaboration for GUI-based visualizations. However, limited literature exists on collaborative data physicalization, specifically regarding how collaboration unfolds during a *constructive physicalization* process that utilizes tangible tokens [29].

Collaboratively constructing tangible depictions of data is a well-established practice [28, 10, 1, 46]. For instance, architects frequently utilize material techniques to create preliminary or miniature designs, either individually or in collaboration with other peers, with the aim of gaining deeper insights into human perception in re-

lation to environmental experiences [27]. Through continuous interaction with construction and deconstruction processes, they can identify design flaws and generate new ideas [2]. Visualization researchers have explored, for example, the use of micro-robots [44, 43], or investigated participatory physicalization processes [71], to further our understanding of how physicalization can foster collaboration. However, these studies and tools primarily focus on examining aspects of physicalization, such as materiality and fabrication. We still have limited knowledge of how collaboration itself unfolds in the context of data physicalization. Crafting a physical representation of data in a collaborative manner requires considering various design and structural aspects that go beyond conventional collaborative Graphical User Interface (GUI) visualization processes, such as needing to understand how people gather data and select objects to encode data, learning about interaction techniques they may utilize to construct and edit physicalizations, and how they negotiate design aspects such as aesthetic considerations [6].

1.2 Research Questions

To better understand how collaboration unfolds during the construction of data physicalization, the overarching research question of this thesis is: **How do two people collaboratively create physical visualization?**

Our overarching research question consists of two sub-questions, including:

- How do two people collaborate in the same space to create a physicalization of their personal data? Specifically, what types of collaboration occur?
- What types of data-centric actions do two people use when collaborating to create their physicalization?

1.3 Research Approach

To answer these aforementioned queries highlighted in sub-section 1.2, we conducted a qualitative study that engaged six cohabiting couples in the collaborative creation of a data physicalization using their shared personal data within a domestic setting. Cohabiting couples are often involved in joint endeavors encompassing various everyday tasks, ranging from household chores and grocery shopping to bill settlement

and planning outings [7, 82, 25]. This makes cohabiting couples well-suited for our study, given that they know each other well, are likely used to collaborating on many everyday life tasks, might already collect shared data, and would benefit from mutual analysis and understanding of their data. Our goal is to uncover the patterns of collaborative dynamics that emerge when couples collaboratively craft data physicalizations and further explore the nature of discussions and decision-making processes.

Over 2.5 months of study, participants constructed data physicalizations in their homes. We gathered and analyzed data including 21.5 hours of videos, 6 diary responses, 6 pre- and post-study interviews and 6 built data physicalizations. We analyzed the data based on an established collaboration framework [48] that categorizes collaboration working styles in a group setting into three types (*mutual*, *exclusive*, and *dictator* collaboration) and looked at how it might apply to data physicalization. The main findings from our study are as follows:

- We found that couples predominantly engage in mutual collaboration for various visualization-related tasks, including activity selection, externalization, and mapping planning.
- We found that couples exhibit a tendency to allocate tasks based on workload and the inherent characteristics of the chosen construction method when they engaged in the tasks of data collection and construction of physical objects.
- We identified several data-centric strategies that couples employ during discussions and that shape their collaboration dynamics and their data physicalization process.

1.4 Thesis Scope

In this thesis, we aimed to identify and better understand the different collaboration styles people employ within a constructive data physicalization process. Additionally, we wanted to understand specific actions people take when engaging in the specific phases of a constructive data physicalization process such as data gathering, mapping, token construction and others. By recruiting cohabiting couples, we identified various collaboration styles and micro-actions that likely reflect the behaviors of couples with basic visualization skills. Our findings contribute valuable insights into how such pairs interact, make decisions, and divide tasks when creating physical

representations of data. Based on these insights, we compared our approach with the existing workflows of collaborative visualization and data physicalization. Then, we proposed seven areas for future research for developing tools and methods that facilitate effective collaboration in similar contexts: 1) tracking conversations and discussions; 2) collecting and logging shared data, 3) encouraging personalization in the design process, 4) designing tangible tokens, 5) editing and fixing mapping errors, 6) constructing a physicalization, and 7) dividing and tracking tasks.

However, it is important to acknowledge the limitations of our study. Our findings may not be directly applicable to other social groups, such as students, office colleagues, siblings, or housemates, as their collaboration dynamics could differ from cohabiting couples. For example, the level of familiarity and pre-established communication patterns among cohabiting couples may not be present in these other groups.

Chapter 2

Related Work

Inspired by three key areas of visualization research – *data physicalization* [38], *collaborative visualization* [31], and *constructive visualization* [29] – we investigated co-located collaborative data physicalization practices within home settings. This section provides an overview of relevant prior research.

2.1 Visualization and Physicalization Examples in Home Settings

We start by reviewing studies and systems devised to facilitate data visualization and exploration within home settings.

2.1.1 Visualization examples in home settings:

Previous studies have explored the utilization of visualization within home contexts, addressing diverse objectives such as managing household energy consumption [58, 20], promoting family awareness of personal health data [69], and monitoring internet usage [12]. These systems gather data on individual family members or in-home environments, aiming to enhance their daily lifestyles. For instance, researchers have employed digital handheld displays in homes to gauge how residents perceive data and its impact on pro-environmental behaviors [17, 73]. Additionally, Mennicken et al. [57] integrated appliance-specific smart home data into digital calendars to foster family interaction and collaboration, facilitate open discussions, and support decision-making.

2.1.2 Physicalization examples in home settings:

Specific to data physicalization for home environments, researchers have often prioritized designing individual-centric systems. For example, in energy consumption visualization, techniques like ambient displays [5], such as the *power-aware cord* [24] and *energy orb* [11], aesthetically convey energy data to raise awareness of environmental behavior. These tools effectively prompt individuals to change their energy consumption habits.

Other examples include *Physikit* [26], a square-shaped display employing light, vibration, movement and airflow to visualize environmental data; *Motiis* [65] that allows parents to monitor their children's cognitive states when playing video games, fostering discussions on mental well-being; and *Ecorbis* [76] that is designed to enhance understanding of the environmental impact of daily household activities, particularly in food consumption. These tools not only provide visual feedback but also enable direct comprehension, sensory engagement and information connection for household members.

Indoor-oriented physicalizations include installations like *Loop* [70] and *Laina* [56], that track individual physical activity data, offering reflective tools and motivating household members. *Straide* [16] is a spatial interface that presents daily life information and message notifications aesthetically, fostering insightful discussions in homes. Go & Grow [9] is a physicalization that relies on living plants to motivate people to achieve their exercise goals.

Our focus on physicalization in home settings draws from the benefits this body of work has identified.

2.2 Visualization and Physicalization Examples in Co-located Group Settings

Here we provide insights into research on collaborative physicalization experiences.

2.2.1 Visualization Examples in Co-located Group Settings:

Extensive research has focused on *collaborative visualization* in co-located group settings, aiming to uncover workflows and group dynamics when conducting visual analysis [33, 35]. Mark et al. [49, 51] outlined five stages of collaborative visualization:

question parsing, variable mapping, visualization selection, validation, and answer interpretation. Isenberg et al. later broke down this workflow into a sequence of steps, including data browsing, task parsing, collaboration strategy discussion, task establishment, clarification, task selection, perform operations and validation [36]. When completing such tasks, collaborators adapt robust discussions and information sharing, with a closer collaboration style leading to more optimal solutions [34].

2.2.2 Physicalization Examples in Co-located Group Settings:

There is growing acknowledgement in the visualization research community that incorporating physical representations of information enhances engagement and collaboration [75]. For instance, *Bit Planner* [68], is a LEGO-based wall-sized calendar used by office personnel to visualize their daily work schedules. This tool allows individuals to share their individual work plans as well as engage in collaborative scheduling through LEGO block manipulation. It has since been argued that such visualizations are effective in promoting engagement and sense-making, as they can facilitate discussions, constructive disagreements and reflection [72].

Several researchers have investigated the use of physicalizations for data-driven collaboration purposes. For example, *Cairns* [22], *Data Strings* [77] and *Physical Bar Charts* [41] invited participants at public events to add or remove tangible data using strings or colored tokens, with the aim of encouraging personal reflection on community data. *Data Badges* [63] is another example that facilitated personalized conference badge creation, sparking informal discussions and networking interactions among attendees. *Edo* [71] prompted discussions and critical contemplation by physicalizing data about climate impact from dietary choices in communal spaces.

Some physicalizations exhibit shape-changing characteristics (e.g., *inFORM* [18], *EMERGE* [79] and *Zooids* [44]), demonstrating potential for dynamic data visualizations within collaborative settings. For instance, the *Zooids* [44] micro-robots can be reconfigured into various arrangements and support collaborative decision-making scenarios. Similarly, researchers have extended the single-user *EMERGE* technology [80] to explore how groups of users collaborate and engage with it in co-located environments [78]. This latter inquiry revealed a spectrum of interaction techniques employed, underlining the significance of factoring in social dynamics and power structures within co-located groups during collaborative design endeavors.

Building on findings related to collaborative physicalization experiences, our work

delves into the intricate dynamics of collaboration within the context of constructive data physicalization.

2.3 Constructive Data Physicalization

The concept of *constructive data physicalization* [29, 30, 28] entails crafting visualizations manually by associating data to physical tokens such as LEGO blocks. Researchers have suggested that allowing individuals to manipulate data tokens manually not only enhances their understanding of the data, but it also facilitates the reflective creation process of personalized visualizations that hold a meaning for them [60, 83].

Researchers have started to explore co-located collaborative efforts within constructive physicalization. This collaborative approach entails intricate social interactions centered around negotiating and aligning interests related to the data, such as when engaging in data crocheting [59] and data cuisine sessions [86]. A study in which university students created physical visualizations on a shared board in close proximity showed that to surmount obstacles and achieve successful visualization outcomes, individuals use strategies such as peer discussions and the application of interactive techniques throughout the collaborative process [62]. Another study demonstrated that tangible materials can cultivate group cohesion and facilitate the materialization of abstract concepts, and that the manipulation of even loosely related concepts can be realized through deconstruction and token replacement [10]. Building on this knowledge, researchers have developed toolkits for facilitating collaborative construction of physical representations [1].

While collaborative construction of data physicalizations is gaining interest in the field, we lack empirical data to understand how people collaborate when engaging in a constructive physicalization process. To address this gap, our work contributes on understanding the collaboration dynamics.

Chapter 3

Study Methodology

The goal of our qualitative study was to gain insights into how collaboration unfolds and what strategies couples employ to collaboratively build data physicalizations of their personal data.

3.1 Study Design

3.1.1 Pilot Study

To determine the feasibility and limitations of our study design, we recruited three couples for our pilot study. Following each pilot session, we made iterative changes that influenced our final study design.

Initially, the study was designed to take place over a fixed period of time and participants were required to engage in the data physicalization process consistently. However, after conducting our pilot studies, it became apparent that the couples had difficulty finding time from their busy schedules to continuously contribute over consecutive days. Informed by this finding, we decided to ease the duration of the study to make it more flexible for participants and decided not to impose any fixed timelines in the final study but encouraged our participants to complete it within two-three weeks for pragmatic reasons.

Another revision we made informed by our pilots was regarding the participant recruitment criteria. During the pilot sessions, we did not focus on recruiting participants with prior visualization knowledge. However, we observed that one of the pilot participant pair (PC2), who had less familiarity with visualization, encountered challenges regarding understanding basic concepts of data visualization. For exam-

ple, both partners were uncertain about the type of data to collect for their shared activity, prompting the primary researcher to provide a brief explanation over Zoom. Similarly, during planning for physicalization, they had doubts regarding material selection and mapping it with collected data. The primary researcher clarified these concerns through short explanations. As a result, we developed and introduced a pre-screening questionnaire in our revised recruitment criteria and selected only couples with basic visualization knowledge. Also, we introduced a preliminary training session during the study's introduction phase, to ensure all participants had at least the same basic knowledge about data physicalization concepts and had gained some quick hands-on experience in developing a physical data representation collaboratively for fictional dataset and using materials they found in their homes as well as added explanations about *data physicalization* in our study handout with a few instances to make it easier and more specific.

Lastly, a final modification we made to our original study design was to reduce the number of questions participants had to answer during the study period. Two of our pilot couples (PC1 and PC2) complained that writing down answers to questions while engaging in the constructive data physicalization process was quite time-consuming. To address this concern, we prioritized capturing answers to questions that were more specific to ongoing hands-on experiences using the data collection template, and moved some of the more higher-level questions about their overall experiences to the post-study interview. Some example questions are the inspiration of the final physicalization, the collaborative working styles and challenges they encountered while constructing. Based on these modifications, we describe the final study design in detail in the following section.

An unchanged aspect of the study was the remote nature of the study, given the pandemic conditions during the time of the study.

3.1.2 Final Design of the Study

In this study, we used the elicitation diary method [42, Ch. 6] and semi-structured interviews [15] to gather information on the collaborative physicalization process. Our study was divided into four main phases – 1) participant recruitment, 2) preamble, 3) collaborative construction activity and 4) post study interview, as shown in Figure 3.1. In this section, we describe each of these phases in detail.

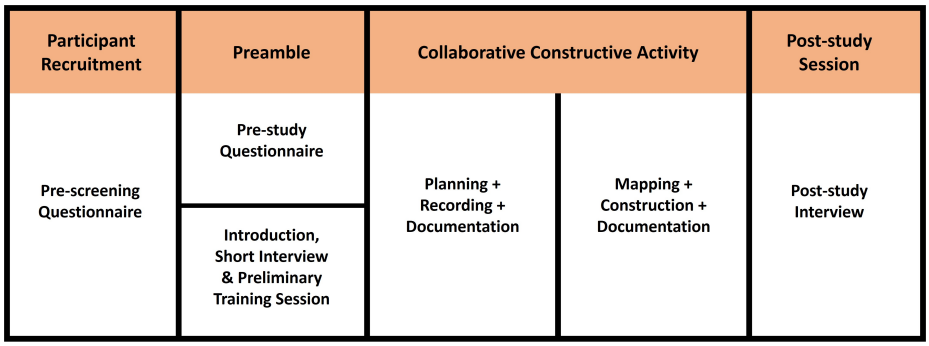

Figure 3.1: Structure of our study, that consisted of four parts: *participant recruitment*, *preamble*, *collaborative constructive activity*, and *post-study session*. In the *participant recruitment* part, interested couples completed pre-screening questionnaires. Recruited couples then attended the *preamble* session, completing pre-study questionnaires and a pre-study session, including an introduction of the study, a short interview and a one-to-one preliminary training session. In the *collaborative constructive activity* part, couples engaged in planning, recording, mapping, constructing, and documentation activities. Lastly, they participated in a *post-study session* to conclude the study.

3.1.3 Participants Recruitment

We recruited participants with basic knowledge of visualization concepts in order to limit the time and effort they would need to spend to learn these basic concepts. We used two variations of a pre-screening questionnaire (see supplemental material) that each member of a couple had to complete individually. Our pre-screening questions were based on questions from the *VLAT* questionnaire [45], which helps assess an individual's ability to perform basic and simple visualization-related tasks such as value retrieval, finding extremum, determining a range, finding correlations and trends, and making comparisons. We picked line chart visualization-based questions for pre-screening as line charts are common and most likely understood by the general public [19]. Each individual in the couple received their own pre-screening questionnaire variation by email after the couple expressed interest in participating in our study. One variation of the questionnaire came directly from *VLAT*, and for the other, we made minor modifications to the questions by inverting the original questions (e.g., we would ask to find the lowest value instead of the largest value). If both individuals of a couple answered all the questions correctly, we recruited them to participate in our study.

3.1.4 Preamble

Upon confirmation of recruitment, the couple signed a consent form. Then, the participants completed a pre-study demographic questionnaire (including their age, gender, and previous experiences with visualizing using software, hardware, or physical materials). After that, each couple participated in an hour and a half long introductory online session where we familiarized them with the study study handout, material document, and diary template that we describe below. To establish foundational knowledge of concepts relevant for our study, we spent 20 minutes reviewing basic visualization concepts such as data types, visual variables, and mappings, by referring to existing visualization examples. These examples were also included in our study handout for participants to review later. Then, we conducted a 15-minute pre-study interview, where we asked them a few questions regarding their previous experiences with collecting data about an individual or a shared personal activity (such as, tracking each others' monthly expenditure), with creating visualizations, and with sharing this information with each other. Then, we conducted a training session in which the couples developed a physical data representation collaboratively using a fictional data set and materials found in their homes (such as cutlery, papers and sticky notes). Through that session, participants learned how to format the data set (such as the expected range of data attributes and data points for the study), how to map those implicitly or explicitly to a physical material, and how to construct a physicalization together using those materials. Participants were also given opportunities to ask questions.

3.1.5 Collaborative Construction Activity

In this phase, couples constructed a physicalization of their own data sets (Figure 3.2) over 1-3 months (average 21 days, excluding the pause in the study for personal or post-interview scheduling reasons). To give participants some structure for the constructive process, we shared with them Thudt et al.'s constructive physicalization workflow steps [83] consisting of phases such as planning and designing, constructing the tokens via mapping data to physical objects, and integrating the tokens to build the data physicalization. We also encouraged them to complete the steps in any order that made sense to them. Regardless of the order, all participants were required to complete the following: planning, recording, mapping, construction, and documentation.

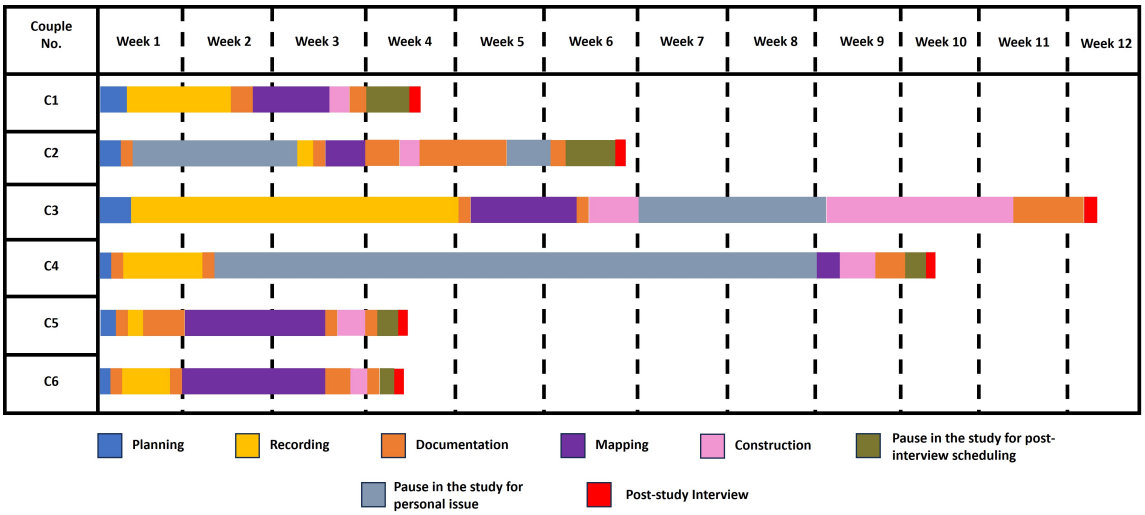

Figure 3.2: Timeline showing the total time taken and the phases couples went through to construct their physicalization. All couples followed a specific sequence of phases, including *planning*, *recording*, *mapping*, *construction*, and attended the *post-study interview*. At the end of each phase, couples documented their progress using a shared digital documentation template provided by the research team. Sometimes, couples had to pause the study for personal reasons, as seen with couples C2, C3, and C4.

For the *planning* and *recording* steps, we asked couples to pick a joint activity and decide what kind of data they wanted to collect. To necessitate constructing a data visualization, we asked that participants gather data multiple times during their chosen activity at different points in time.

For the *mapping* step, we asked couples to decide how they would like to map their collected data in a physical form and to purchase the necessary materials for developing their physicalization. To help participants choose their material, we gave them a document (see supplemental material) which listed some potential strengths and limitations of common art and craft materials from a constructive visualization perspective. For example, we highlighted that beads came in multiple colours but are rigid materials, in contrast, yarn also came in multiple colours but offered more flexibility in how they could be used and shaped. Participants were free to use any materials they wanted and we provided a purchasing budget of $75 per couple.

Once the mapping was complete, the couples started *constructing* physical representations using their chosen materials. In this construction step, couples were encouraged to work together whenever possible. In a situation where constructing together may be difficult (e.g., if one partner is sewing), we asked the other partner

to contribute by taking on other tasks that will eventually lead to the completion of the physicalization.

During the planning, mapping, and construction steps, we asked the couples to *document* their overall progress via a digital documentation template (see supplemental material). Some examples of questions included asking them to list the name and type of the activity for which they were collecting data, the tools they used for data collection, pictures of the materials they purchased and pictures, sketches or descriptions of how they decided to map the data. We also asked couples to video- and audio-record the entire construction period for data analysis purposes.

3.1.6 Post-study Interview

Once they had completed constructing their physicalization, couples took part in a 1-hour post-study interview session on Zoom. In this semi-structured interview, we asked participants to describe how they collaborated to create the physicalization in each step, what inspired them, and how they imagined integrating the physicalization in their home. We tailored the interview questions for each couple based on their documentation responses and the recordings gathered during the construction step.

3.2 Recruited Couples

We circulated our recruitment posters via university mailing lists, postings at local coffee shops, and posts on social media groups (e.g., Facebook, Slack and Twitter). Six couples (12 participants, 18-39 years old, median 31) participated in our study (C1–C6). The couples engaged in shared activities such as cooking, jogging, playing video games and watching movies, and were interested in collecting shared personal data. Slightly more than half the participants were students (7/12), and the remaining were from other occupations (such as data engineer, data analyst, and general laborer). All participants had used software tools to create visualizations, and some had worked with physical objects (6/12) and hardware and electronics (3/12) to create visualizations. Table 3.1 summarizes participants' information.

Table 3.1: Demographics of the Couples

Couple No.	**Participant No.**	**Occupation**	**Previous experience of creating visualization with**
C1	C1a	Master's Student	software; physical objects
	C1b	Master's Student	software; physical objects; hardware & electronics
C2	C2a	Unspecified	software; physical objects
	C2b	Data Engineer	software
C3	C3a	Data Analyst	software
	C3b	Graduate Student	software; hardware & electronics
C4	C4a	PhD Candidate	software
	C4b	PhD Candidate	software; physical objects
C5	C5a	Student	software; physical objects
	C5b	General laborer	software
C6	C6a	MSc Student	software; physical objects; hardware & electronics
	C6b	Engineer/Data Analyst	software; physical objects

3.3 Data Collection and Analysis

Our primary data source included 6 diary entries, which consisted of written responses for 12 questions, images or screenshots of the tools used to record data (a total of 10 images), and images of the materials used to create physicalizations (a total of 10). In addition, each couple sent us their dataset (6 datasets in total), we gathered 23 recorded videos of the construction and visualization explanation sessions (ranging from 1 to 2.5 hours duration in length, 21.5 hours in total) and 23 photos of the final physicalizations. We also gathered 18 hours of pre- and post-study interview recordings.

One researcher transcribed all the pre- and post-interviews and the construction and physicalization explanation videos. The researcher then analyzed this transcript together with the responses submitted via the documentation template using open coding over four rounds. At the end of each round, the codes were discussed by the entire research team, leading to removing duplicates, merging of codes and renaming codes [3]. At the end of four rounds, the code book had a total of 311 codes.

In the first round of open coding, the researcher analyzed one couple's data sources (pre- and post-study interviews, diary entries, construction, and visualization explanation video transcripts). After finishing the first round, the code book comprised of eleven main categories: data, materials, collaboration, physicalization, selected activity, challenges, previous experience, overall collaborative experience, communication, individuality, and future implications. After discussions with the research team, categories such as individuality and previous experience were eliminated to narrow down the analysis to focus on the collaborative data physicalization process on their personal data, which was the goal of the study.

In the second round, the researcher coded data for two other couples. The research team then discussed and agreed to merge categories. For example, physicalization, data, activity, and material merged into one major category named "types of physicalization". Another category was "collaboration practices", comprising collaboration, communication, and associative challenges.

In the third round, the researcher identified three practices that occurred throughout the construction process: couples working together, couples sometimes working separately, and couples working together or separately but with one partner playing a leader role. After discussing these practices as a group, we went back to the literature and identified Maher et al.'s categorization [48] of collaboration as highly

relevant. This categorization proposes three types of collaboration: *mutual collaboration*, where participants *"are busy working with the other"*; *exclusive collaboration*, where participants *"work on separate parts of the problem, negotiating occasionally by asking advice from the other"*; and *dictator collaboration*, where *"collaborators decide a leader who is 'in charge' of leading the process."* [13]. Moreover, previous literature (e.g., [13, 74]) that had research goals similar to ours, have also used this categorization to distinguish between the collaboration styles.

In the fourth and last round, the researcher conducted selective coding based on these three established collaboration styles. As an example of *mutual collaboration*, some couples employed a turn-taking strategy when collecting the data for their shared activity: one partner was reading the data while the other was logging that information in a file. As an example of *exclusive collaboration*, still in the data collection step, some couples collected the same information simultaneously but separately on their own applications, and others divided the task where one person was responsible for collecting certain information while the other collected different information. As an example of *dictator collaboration*, some partners with a strong design sense did take charge and make unilateral decisions during the construction phase.

Chapter 4

Findings

4.1 Summary of the Collaborative Physicalization Projects

In this section, we describe the six unique data physicalizations that the couples created.

4.1.1 C1's Genshin Impact Physicalization

C1, who often plays video games, decided to visualize their video game activity. They wrote in the research template, *"We selected the activity through discussion since this is one activity that we already do together everyday."* They collected 220 minutes (3.6 hours) of their gaming activity data for five consecutive days where they set a timer to ring every 10 minutes while playing *Genshin* to remind them to stop and collect data about their progress in the game. Their data consists of the amount of time played, the number of times their character died, the number of bosses they killed, the number of rewards they achieved, the elements of the character and the weapons they used, and the topics of conversation they had during that time.

Their final representation, shown in Figure 4.1, resembles a temporal bar-chart showing the changes in their gaming experience over five days. In order to construct their physicalization, they used one bamboo skewers with styrofoam placed on top of each skewer for each day they played. The height of each bamboo skewer represents the amount of time they played that day. On top of the styrofoams, they attached drawings of dragons with one toothpicks for each enemy they defeated every 10 min-

Figure 4.1: C1's Genshin Impact Physicalization. C1 created a physical representation resembling a bar chart, using wooden skewers, styrofoam, paper, color pencils, and toothpicks to represent data about their playing of the Genshin video game. They added clouds that depict their most frequent conversations on that day in written form.

utes. They drew small, medium or large dragon icons to show the total number of enemies they killed each day. A small dragon icon meant they had defeated 1-3 enemies, a medium one for 4-6 enemies, and a large one for 7-9 enemies. They encoded the summed number of times they died within each 10 minute interval to day skull drawings in a similar fashion. A small skull meant they had died 1-2 times on average every 10 minutes, a medium one 3-4 times, and a large one 5-6 times.

They represented their in-game characters by drawing the character, with the characted *electro* represented with purple colour and *pyro* with red color. They also drew the weapon on that character (spear, magic book and sword), and represented the number of rewards they received each 10 minutes each day using emoji faces that they taped to the face of the character. Finally, they attached speech balloons containing the topic of conversation they ad that day.

4.1.2 C2's Cooking Physicalization

C2 visualized their cooking experience, an activity they enjoy doing together. Their physicalization shows the contribution each individual made while cooking an item. They collected data from three separate instances of cooking for three dishes (fried rice, fish, and salad) in a single day. Using this data they created the set-like physical-

ization show in Figure 4.2. They encoded the type of dish with the type of cooking utensil they typically use for that dish: a saucepan for fried rice, a fry pan for fish, and a plate for salad (that they later swapped for a used mixing bowl because their plate was too small). They represented one row in their dataset with a strip cut from paper. They represented the ingredients used for each dish using real ingredients. They also represented the type of ingredient (oil, vegetable, protein, carbs and condiments) with shapes made of clay. For example, oil was shown using an orange star, vegetables with a green triangle, and protein with a yellow circle. Finally, they showed who did what part in preparing each dish using colored emoji faces where they carved pink smileys for C2a and blue smileys for C2b using toothpicks.

Figure 4.2: C2's Cooking Physicalization. C2 created a visualization in three parts to display the ingredients and each person's involvement in cooking three dishes. They used cooking utensils (e.g., saucepan, plate, fry pan), edible ingredients (e.g., eggs, prawns, butter, rice, oil, etc.), and modelling clay to represent their cooking data.

4.1.3 C3's Yoga Physicalization

C3 perform yoga regularly and already collect their yoga activity data on a mobile app. They visualized this dataset. The data comprises 15 days of yoga data, containing workout episode number, date and time of the activity, total workout time, yoga trainer, average heart rate, minimum and maximum heart rate, total calories burned and active calories burned. For their physicalization, shown in Figure 4.3, they drew inspiration from nature.

They created one token for each of the 15 days of yoga, hanged from left to right in chronological order. We describe the components of each token from top to bottom. At the very top of a token, the length of the dark-grey colored yarn represents the active calories burned of C3a with the length of the crochet chain (1 braiding of yarn = 10 calories); then the wooden bead represents the type of yoga activity (a light bead means slow flow yoga, a dark bead means energetic flow yoga); and then the light-grey colored yarn the active calories of C3b. The color of the small wooden ring underneath represents the yoga trainer (medium blue for 'Dustin', light blue for 'Molly' and green for 'Jessica'). Next, the size of the large beads and the color of the yarn wrapped around them represent the duration of the yoga activity: a 45mm ring with dark-red yarn corresponds to a 10 minute session and a 55mm ring with lighter-red yarn a 20 minute session. Attached to the large beads are four yarns whose length encodes heart rate values (1 crochet chain represents 10 heart beats per minute). The two light-grey colored yearns show C3b's data and the two dark-grey colored ones C3a's data. Of the two yarns for each participant, the one on the left represents the person's minimum heart rate and the rightmost one their maximum heart rate. After constructing the physicalization, they permanently installed it as a wall-hanging piece at home.

Figure 4.3: C3's Yoga Physicalization. C3 created a physicalization where one token represents the data for one of their 15-day yoga activity. They encoded the data values using yarn of different colors, small colored (light-colored and dark-colored) wooden beads, painted wooden rings, and larger-sized wooden rings covered with yarns.

4.1.4 C4's Rock climbing Physicalization

C4 decided to visualize their rock climbing activity, something they do regularly on weekends. They collected data about climbing attempts over three days. Each

climbing attempt includes date, grade, difficulty, length, time, participant, and tail, where each day is a separate instance.

Their physicalization, shown in Figure 4.4, is a bar-chart like visualization in a wooden frame. Each bar is made of ribbon and represents one climbing attempt. Bars are arranged chronologically from left to right and separated in three groups of four climbing attempts, one group for each of the three days. They used special ribbons (those with printed rockets on them) to separate the three days. The color hue of a ribbon encodes route difficulty, ranging from grey (easy) to green to lighter green to yellow to orange (hard). On each ribbon, they sewed one large button for every minute of climbing and one smaller button for 30 seconds of climbing. At the top of each ribbon, they added a hand-symbol sticker if the route had an overhang section requiring extra grip; and a butterfly sticker for each person they met during that climb. After completing their phyisicalization, they permanently installed it on a wall in their home.

Figure 4.4: C4's Rock climbing Physicalization. C4 physicalized their rock climbing experience through a bar chart-like representation. They used one colored ribbon to represent one climbing route, and the color of the ribbons indicates the difficulty level for that route. Blue ribbons separate the three days over which they climbed. Blue buttons on a ribbon denote time spent climbing the route, hand stickers indicate overhangs, and one butterfly sticker represents one person they met.

4.1.5 C5's Shopping Physicalization

C5 visualized their shopping activity. They collected data about a single shopping day. During that activity, they performed three shopping tasks, and in total they stopped 13 times to observe for 5 minutes and record the time of day, the number of cars on the street, the birds, trees (deciduous, evergreen) and people (female/male) they saw, the weather, and the distance they travelled (calculated using a phone).

Figure 4.5: C5's Shopping Physicalization. C5 created a visualization where one plastic cup represents one shopping task, skewers of varying heights represent the amount of time they spent collecting data. Colored yarn, strings, rings and jingle bells represent the trees, female and male persons, cars and birds they saw. They used modelling clay to encode the weather and pebbles to show the distance they travelled.

Their physicalization is a set-like physicalization where one cup represents the data dimensions associated to one of the three shopping tasks (see Figure 4.5). In each cup, they added one token for each data point collected during that shopping task. Each token is made of a wood stick whose length represents the time they stopped to make their observations (the maximum duration they had was 400seconds). Then, they attached to the wood stick several objects that represent different data values: The length of green and blue yarns encodes the number of deciduous and evergreen trees they saw, respectively (half a centimeter for one tree); the length of white and black strings encodes the number of female and male persons they saw, respectively (one centimeter for one person); one ring on the stick represents five cars; and one jingle bell represents one bird. At the top of the stick, they represented weather with the color of clay (grey for cloudy, blue for rainy, and yellow for sunny). They also

attached stones/pebbles to show distance travelled (large ones represent 500 meters and small ones 50 meters).

4.1.6 C6's Stardew Valley Physicalization

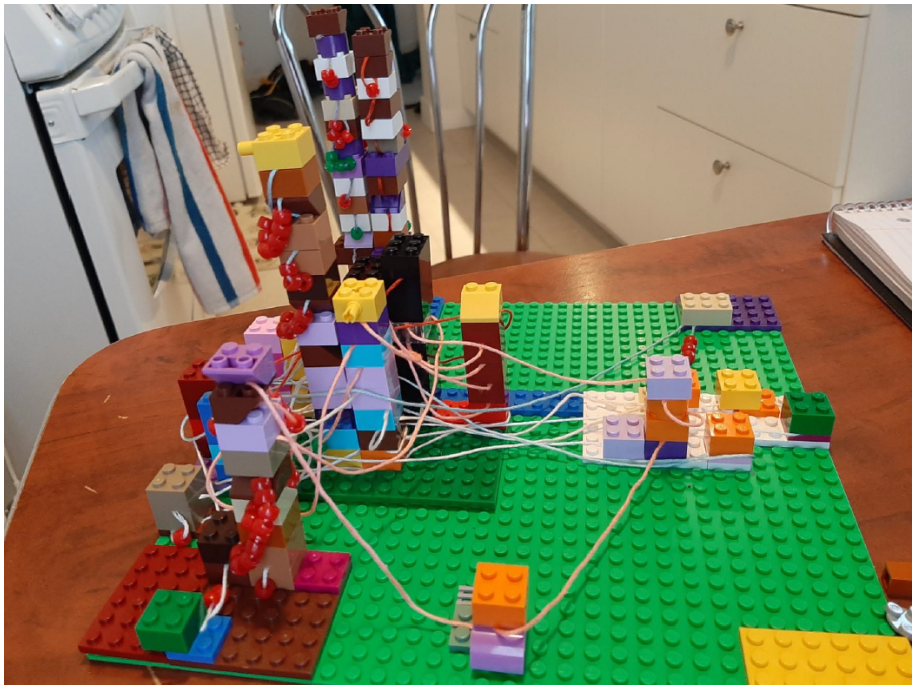

Figure 4.6: C6's Stardew Valley Physicalization. C6 used LEGO blocks, beads, and yarns to create a map-like representation of their gaming activity data. They created small towns using flat LEGO blocks of different colors, and on each flat LEGO block, they showed the activities they completed and the time it took to complete these activities with LEGO blocks (each block representing one hour). They used different colored beads to indicate energy gained (green) or lost (red). Each individual was assigned a different colored yarn (blue for C6b and red for C6a).

Similar to C1, C6 physicalized data about online gaming. They play *Stardew Valley*, an agriculture-simulation game, together regularly. They collected data for one hour for three consecutive days. Their physicalization is a spatio-temporal one based on a map that resembles the map in the game (see Figure 4.6).

The large, flat LEGO blocks represent small towns in the game. The position of LEGO blocks indicate their presence at a particular location on the map (i.e. in a particular town), and their color encodes the type of activity at a specific time at that location. One colored block represents one hour spent on an activity. The strings that connect the LEGO blocks show their movements from one location to another.

The color hue of strings represents each person (red for C6a and blue for C6b), and the color value (from light to medium to dark) indicates if the movement took place on the first, second or third day. Beads on a string indicate the gains and losses of their energy with red and green beads, respectively.

4.2 Study Findings

From applying Maher et al.'s [48] framework of collaborative practices, we identified that our participants often switched between the three styles of collaboration (*mutual*, *exclusive* and *dictator*), during their data physicalization construction process. Although Maher et al.'s framework was applicable for computer-mediated collaborative works, we realized the same applies when couples were engaged throughout the physicalization construction process on their shared personal data. Additionally, we noted that participants employed different strategies that impacted their overall collaboration styles which unfolded within each portion while creating their personal data physicalization. These collaborative behaviours emerged based on their needs to accomplish each activity or task. In this section, we detail how couples worked together to construct their physicalization on their shared personal data.

4.2.1 Activity selection

All six couples engaged in discussion and mutually decided on the shared activity they wanted to visualize. For example, C4a said that *"we began to discuss what activities we do together because daily we engage in some little activities which are unnoticeable or big activities which are not new."* Such mutual selections took three main forms, which are: *a routine shared activity*, *a shared activity for self-understanding*, and *a shared activity unique to them*. In the following paragraphs, we expand these three main forms with evidences from our research results.

Selecting a routine shared activity

Four couples selected an activity they did frequently together or was part of their regular routine (C1, C3, C5 and C6). For example, C6 said, *"We wanted to pick an activity that we were doing fairly consistently. We enjoy participating in (such activity) together everyday, and we felt it would be interesting to analyze this data through this physicalization."*

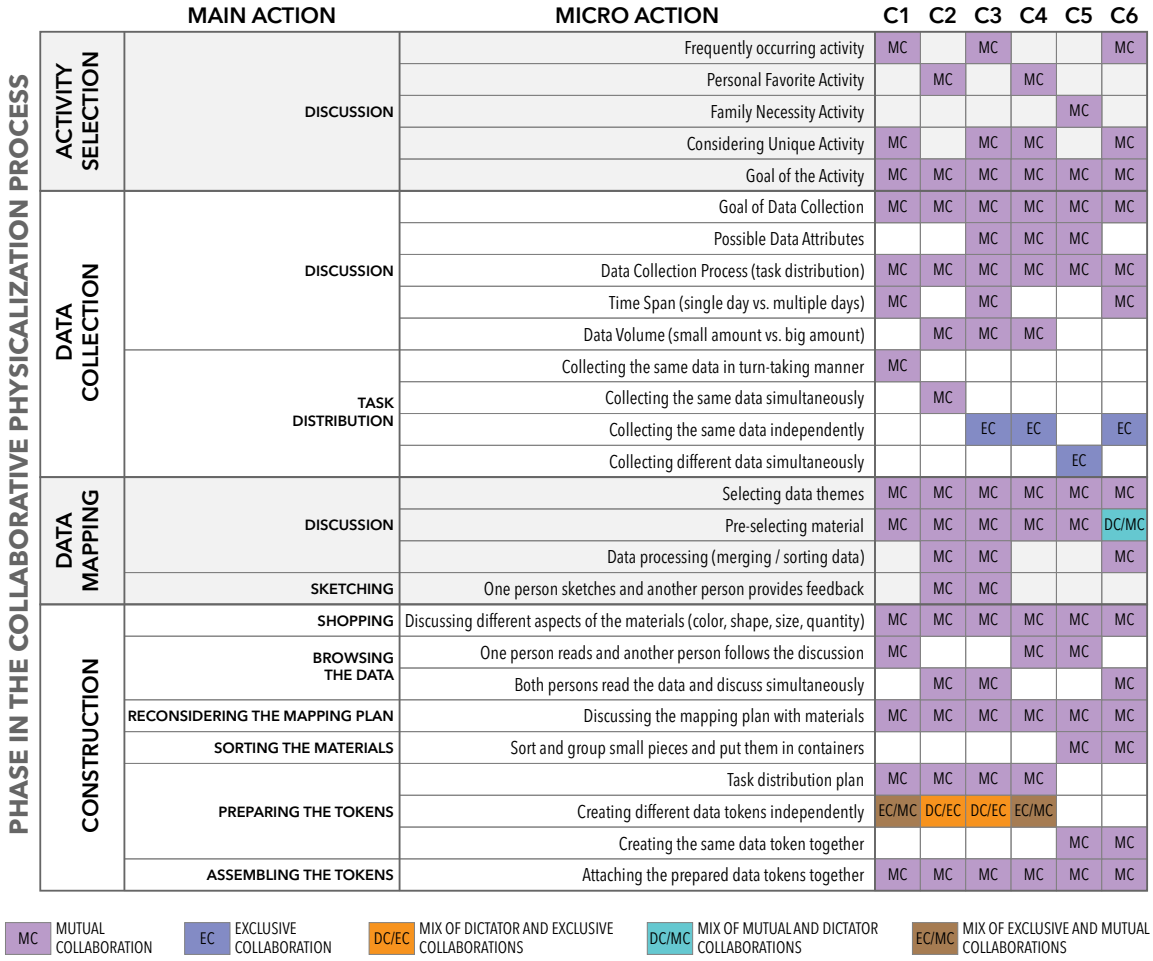

Figure 4.7: Overview of the *collaborative constructive activity* from our participants. Results are broken down into four primary phases: *activity selection*, *data collection*, *data mapping*, and *construction*. Each of these four phases is then further broken down into the main actions that took place during that phase. Each main action is then further broken down into micro-actions. For each micro-action, we show whether couples employed *mutual*, *exclusive*, *mixed of dictator and exclusive*, *mixed of mutual and dictator*, and *mixed of exclusive and mutual* collaboration styles.

Selecting a shared activity for self-understanding

Two couples picked an activity that they did together but for which they wanted to better understand each individual's contribution towards that activity (C2, C4). For example, during the post-study interview, C2a stated that *"it is one of our favorite activities. Plus, we occasionally make the combination of food we selected for this study...we thought, it's nice to have, like, who did what. That way we can see I was doing the most work, or if he was doing the most work."*.

Selecting a shared activity unique to them

Four couples (C1, C3, C4, C6) considered selecting an activity that they thought would be unique to them compared to other couples such as activities that couples rarely involved. From our analysis, we realized that this thought process emerged among them due to the examples that were included in the study protocol. For example, C1a said that *"we wanted to choose something different from the others, because we saw (in the examples) like many couples choose, like cooking or walking in something like very normal, and boring..... So we decided to choose another thing that we like to do together."*. Our study protocol had examples of restaurant and walking activity examples which influenced them to select something different.

4.2.2 Data collection

In the data collection phase, there were two main activities the couples engaged in – discussing on the data design and collection procedure and collaborative data collection process.

Discussing on the data design and collection procedure

In the discussion step, all couples engaged in mutual collaboration. For example, C3b explained *"We sat together and we were discussing if we do this (i.e., activity) which data we could extract and choose which data we felt was most important to visualize and would give (the) best kind of most impact in terms of giving deep information [...] because the main thing is we want to meaningfully gather information from the visual at the final thing."* During this discussion, couples reflected on the type of data they could collect, the length of time for which they wanted to collect the data and the amount of data they wanted to collect. Three couples (C3, C4, C5) considered the

type of data they could collect. For example, C5b explained – *"we start discussing about which data we encounter with that if we want to go for shopping. We may see people, we may see cars, maybe we would see trees and other things like that, so we make a list."* Three couples (C1, C3, C6) considered the length of time for which they want to collect the data (single day vs. multiple days). For example, C1a shared that *"we actually play games together every day, so we thought that it was not a big effort for us to do it like (spending) 10 minutes to collect information for three days."* Lastly, three couples (C2, C3, C4) considered the amount of data they wanted to collect. For example, C2a stated that *"we saw the example dataset and we were like, decided to collect as many data we can. We did not want to collect small data that would be hard for us to visualize."*

Collaborative data collection process

In the data gathering step, two couples (C1 and C2) employed the mutual collaboration. These couples distributed the data collection tasks amongst each other, wherein one partner was responsible for reading the data, and another was responsible for logging that information. Within this style of collaboration, we observed some minor differences between the two couples. C1 gathered data about a video game they were playing and engaged in data gathering over five consecutive days. To log data, they took a turn-taking approach. C1a described their overall process as follows: *"we always try to change sides [...] so if I am [...] reading the data and C1b was inputting like typing, next day I was inputting all the information on the sheet and C1b was reading [...]. So we are like changing."* C2 gathered data about a meal they cooked together. In contrast to C1's approach, C2 did not log data live or engage in turn-taking. They recorded the entire cooking activity first and then logged sat down together to log the data, wherein one person read out details about the gathered data from the recording (e.g., timestamp in the recording) and another person made note. They described their process as follows, *"[...] if we really do that way, like somebody is doing the work and some the other one is recording that would hinder the natural behavior, like how we work together. So what we did was we record the whole activity, like we set up a camera in front of the kitchen, and we just worked and that way we later on sit together and we were looking at the timestamps and we noted down the start time. [...] C2b played the video, and he was telling me, okay, this is the timestamp and you are doing this thing on this ingredient. So I opened a*

Google Doc [...] I just recorded whatever he was telling."

On the other hand, four couples (C3, C4, C5, C6) employed *exclusive collaboration* style, wherein each person was responsible to log data. Among the four, three couples (C3, C4, C6) engaged in the selected activity together but collected data separately about their own performance within those activities and later merged the two separate datasets into a single dataset. For example, C3 chose to visualize their own yoga activity and while they performed yoga at the same time and in the same place, they collected their own data using their own smartwatches. One couple, C5, logged different data attributes while performing the same task and then merged their dataset. For example, C5a mentioned in their post-study session that *"I was counting the deciduous trees which are growing now. And C5b was counting the evergreen trees. First C5b was counting both of them, and then we when we got the bus, we figured out it is hard to count both of them for him. Then I did that."*

4.2.3 Data mapping

In the data mapping phase, participants engaged in two main activities – discussing on the data mapping, and sketching for design verification.

Discussing on the data mapping

In the discussion step, similar to previous phases, all couples engaged in mutual collaboration. The couples began by reviewing the data they had collected, brainstorming ideas on how to present this information best visually, and determining the necessary materials to build the physicalization. For example, C6a explained their data mapping process as follows: *"[...] I guess it was like a lot of back and forth [...] I don't know, C6b might have suggested having the beads reflect something, and like how to do the beads. So it's like a lot of back and forth kind of bouncing ideas and kind of seeing what works."* As part of their discussion, the context from which the data had been collected informed their data mapping strategies (C1, C3, C5). For example, C1b said that *"as we are doing something related to the game we just have discussed among ourselves that our visualization could be thematic to the game as the main theme! So the idea was to create our visualization, just like a game."* On the other hand, two couples (C3, C4) discussed how they would like to present their visualization on their shared data. For example, C3 stated in their documentation *"We wanted to create something that was beautiful and that could potentially be dis-*

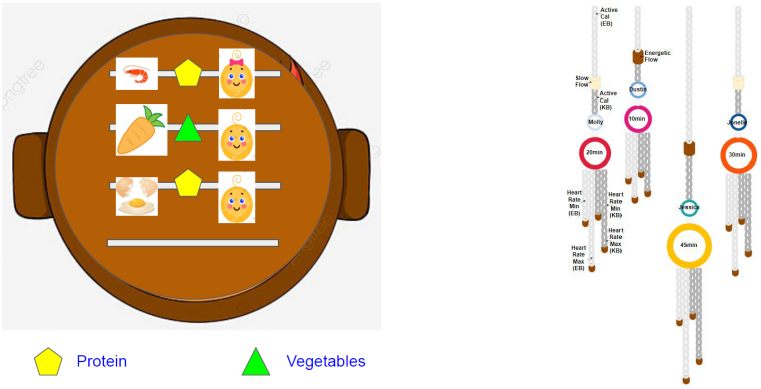

Figure 4.8: Sketches that participants created to depict how (left) C2 were going to use symbols on a saucepan, and (right) C3 were going to map the different data dimensions to different attributes of a token.

played as an art piece on our wall. We also have needlework / crafting (e.g. knitting, crochet, sewing) skills and knew that we wanted to make use of these skills somehow and incorporate them in the construction process." In addition, some couples (C2, C3, C6) deliberated on which data to display and exclude. For example, C3b said: *"[...] so all the data that is collected during each workout by the app automatically on through the watch and the phone, we basically included everything in the table. [...] Except for I think it includes weather data. And so like the weather at the time that we did the workout, but we're doing it all indoors, so we didn't include you know, the temperature outside or, you know, the temperature in [city], which, who knows where they're actually collecting that."* All couples also discussed the materials they would use to map the data. For example, C3a stated that *"we brainstormed together many different visualizations and physical representations of different aspects of the data [...] and carefully considered the nature of the input data and decided what kind of shape, material, and could be used to represent it."*

During the data mapping phase, C6 transitioned from a dictator to a mutual collaboration style. During the post-study interview, C6b mentioned that *"after seeing the data we were kind of 100% sure that we are going go with a map you know but it was C6a idea to use LEGO, because we already (have) a set of LEGO from (his) previous visualization projects and he likes using such stuff. So we had to make (mapping) plans based on the LEGO."* Once they had decided the material, the couple shifted to a mutual and cooperative approach to construction.

Sketching for design verification

Some couples (C2, C3) employed sketching using software tools (e.g., draw.io and PowerPoint) as a way to mutually collaborate and brainstorm (Figure 4.8). For example, C3b said, *"Once we decided upon what kind of actual structure we wanted to work with, in terms of its physical representation, then we went into we actually modelled it. So we used a kind of simple software to just draw out what our different shapes would be to just kind of get a sense of like, what it would look like and would it be? [...] We wanted to get an understanding because we were hanging it, and we were not sure how physically large it would be. So we took data points where they were like, on the high ends of the values, (such as) high calories, long term, long duration, and high range of heart rate, and therefore, longer lines, longer crochet chains. And we took those representative data sets on the high end, and then also the ones on the low end, too. And we modeled them in just to see, and we tried to make it to scale to see like, would they be, would one just be like, so ridiculously long, and with the other one just be like so so small, that it would be kind of awkward [...] So, I think I was making diagrams and [C3a] was sharing her thoughts."* On the other hand, C1 thought about what final physicalization might look like. For example, C1b stated in their post-study session that *"after considering the game as theme, we selected the base, and we tried to make it look like a 2d, actually, like from eight bits. When you're seeing that flat screen, and you can see the platform and the character, the flat character. So that, we are visualizing our gaming activity."*

4.2.4 Construction

Participants engaged in a number of actions as part of the construction phase, which are shopping the materials, browsing data and sorting materials, discussing to reconsider the mapping plan, Preparing the data materials/objects, and assembling the data materials/objects in the final physicalization. The collaboration within these steps varied and included mutual, exclusive and dictator style collaborations as shown in Figure 4.7.

Shopping the materials

After finalizing the physicalization designs, all couples went shopping together to purchase the necessary materials. An example mutual shopping process looked as

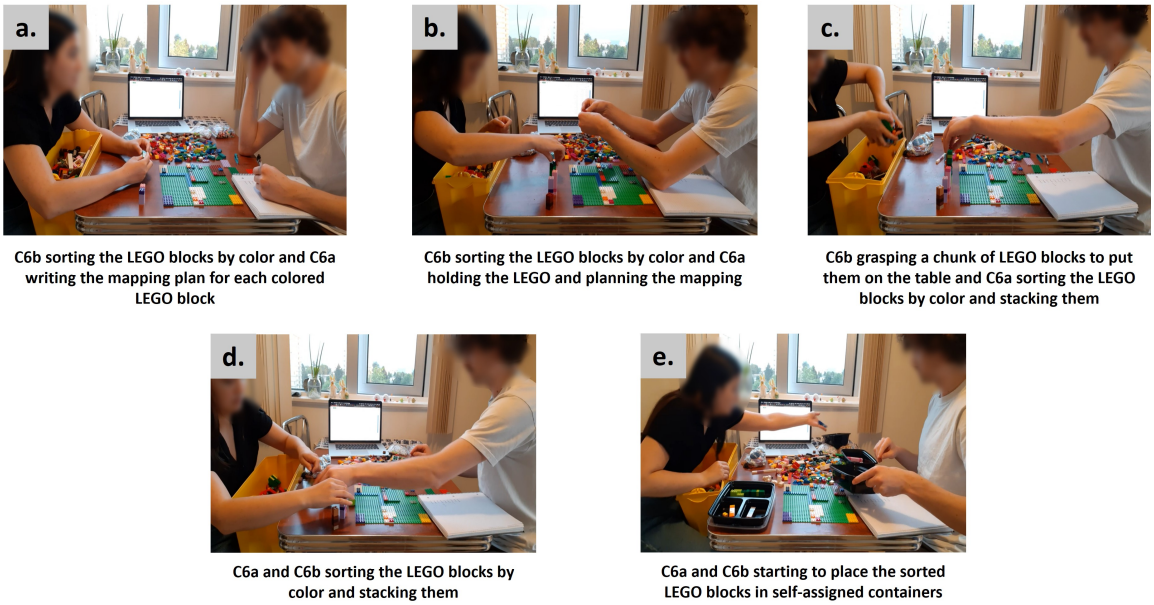

Figure 4.9: C6's mapping planning and LEGO sorting process. This figure depicts the series of steps C6 went through for their LEGO sorting process, which includes (a) C6b sorting the LEGO blocks by color and C6a writing the mapping plan for each colored LEGO block; (b) C6b sorting the LEGO blocks by color and C6a holding the LEGO and planning the mapping; (c) C6b grasping a chunk of LEGO blocks to put them on the table and C6a sorting the LEGO blocks by color and stacking them; (d) C6a and C6b sorting the LEGO blocks by color and stacking them; and (e) C6a and C6b starting to place the sorted LEGO blocks in self-assigned containers.

follows: C4a said, *"there was a separate room (in the shop), so we could stay there and then make our plan [....] So when we went in, we worked with what we have (in the store) [....] we knew what we want to make and this was our guideline in our brain and this was communicated to both of us. Two of us looking around collecting, putting on a table and assembling right on the spot, that's how more or less it happened. Like someone is like, Oh, but I think this will be good for this and this for that. It was very creative process just on the spot. But we knew very well what we want to put down [....] (which) gave us the flexibility."*

Browsing data and sorting materials

Post shopping, couples engaged in constructing the representation using the purchased items and began by revisiting their data and previously developed data mappings. All the couples browsed the data together, which triggered them to discuss how they wanted to show the data using the material. The approach to browsing was

(a) (b)

Figure 4.10: C3 and C5 browsed the data and discussed their plan for next steps. (a) C3 printed their data on paper and used it to track their progress through the data and token creation; here, one person is pointing at a specific data point, and the two participants are discussing. (b) C5 used their laptop, where one person was responsible for reading the data, and the other was following along with the discussion.

similar across all couples: one partner would read the data and initiate the mapping discussion, and the other would share their mapping plan. For example, C5a would point to a data value on their laptop screen and then the couple would discuss how they wanted to map that value, as shown in Figure 4.10 (b). Similarly, C3 printed a physical copy of their data table and C3a would point to specific data values while C3b would share the mapping idea they had previously discussed, as shown in Figure 4.10 (a). In a more elaborate process, two couples (C5 and C6) also sorted their materials during their discussion. For example, we observed C6a and C6b separating LEGO blocks based on shape and colour and placing them in separate boxes, while they discussed their data and data mapping plans (see Figure 4.9).

Couples also browsed their data frequently during construction to keep track of their token creation progress. For instance, C3 used a marker to check the completed items, and C3a said to C3b during the construction task, *"you checked off all the ones that are attached that you have completed."* (Figure 4.10(a)). This tracking process later helped them to figure out where to start if they took break in the middle of the construction process.

Discussing to reconsider the mapping plan

As part of data browsing, four couples altered their data and mapping (C2, C3, C4, C6). Such changes included rounding or scaling values, and adjusting the physical representation plans (e.g., changing colors, filtering data for space limitation or filtering out values that would be hard to visualize). These discussions were informed

by hands-on tinkering with the materials and token construction (see Figure 4.11). For example, C4b said, *"If you put this one (i.e., the ribbon) here right and then we have this wood separated you said use this one to separate them right and then so how many of these [ribbons] can fit? 1, 2, 3 and we can increase the distance this much."* In response, C4a said *"this is how it should look like 1, 2, 3. . . . . .I do like that frame better because we also need to think practicality of how much space it is going to take."*. Likewise, C6 experimented with mapping data by placing small LEGO blocks on a flat LEGO surface to determine how to fit each data point within the available space. During this process, C6 also utilized the option of online tools (such as Google) to get inspiration for their physicalization design (Figure 4.11 (right)).

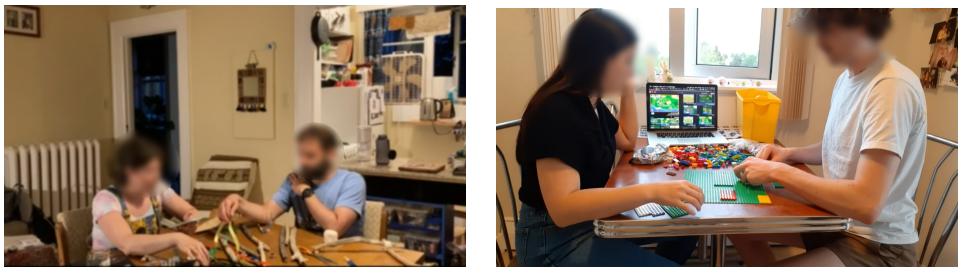

Figure 4.11: Couples C4 (left) and C6 (right) discuss their mapping plan and consider making changes to their initial mapping plan based on material references. During this process, they grab and place their material to check whether they suit the initial mapping plan.

Preparing the data materials/objects

To construct the physical tokens representing their data, we observed that two couples (C5, C6) mutually collaborated. As shown in Figure 4.12, C5 worked together to construct their tokens and divided amongst themselves the smaller steps with the token construction. C5b said, *"[...] For example, I measured and cut and she stick or tie those."* Similarly, C6a worked together and in a turn-taking manner, saying later *"we were working together and taking turns between mapping and looking at the data and placing the LEGO one-by-one on the board"*).

We observed that four couples (C1, C2, C3, C4) came up with a plan on how to prepare the tokens and distributed the task of constructing the token amongst themselves. If the workload was quite labor intensive, we observed that these couples tended to distribute the tasks so that they could complete them faster. For example, C1b said that *"it was a good way to make it faster, because if one of us had to*

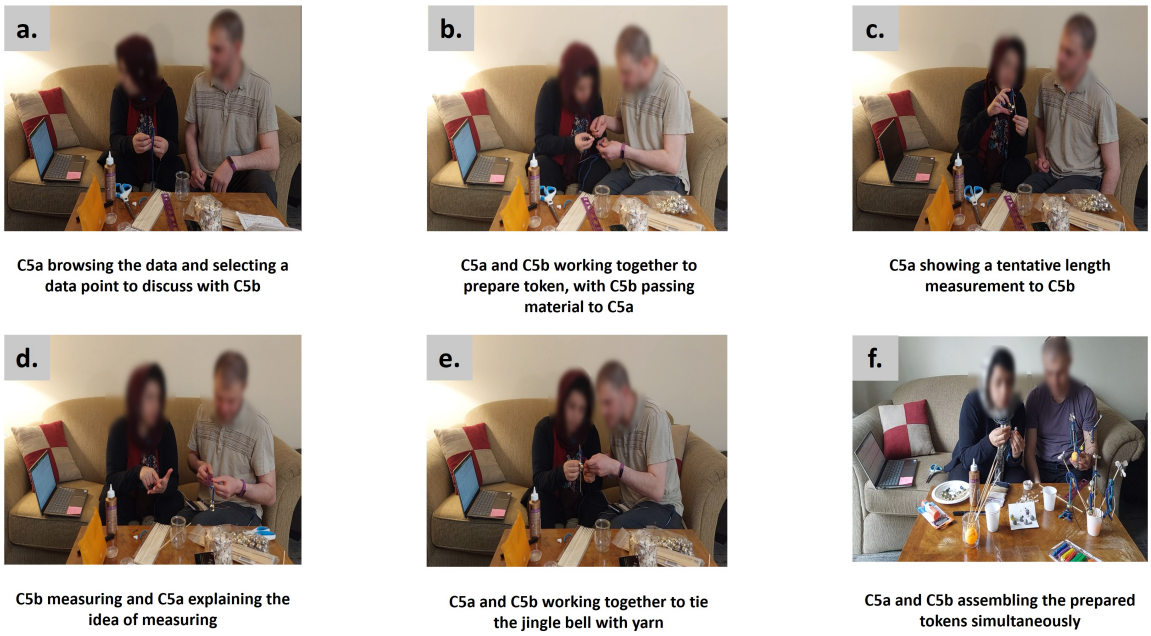

Figure 4.12: C5's token preparation phase. C5 worked mutually to prepare their tokens, following a series of steps: (a) C5a browsing the data and selecting a data point to discuss with C5b; (b) C5a and C5b working together to prepare token, with C5b passing material to C5a; (c) C5a showing a tentative length measurement to C5b; (d) C5b measuring and C5a explaining the idea of measuring; (e) C5a and C5b working together to tie the jingle bell with yarn; and (f) C5a and C5b assembling the prepared tokens simultaneously.

draw everything alone, it will take more time.”. Two of these four couples (C1, C3) also noted distributing token construction tasks based on expertise and skills. For example, C3 said that *“when collaborating, we would likely split up our duties based on skill or expertise in the particular task.”* C1 further sub-divided the same type of tasks (e.g., drawing a token) by the type of crafting skill they liked more, for example, C1a said *“I love drawing more than C1b so I drew characters and C1b drew icons or symbols.”*

We also noticed the transitions in the collaboration style when they were busy in creating the tokens. Two couples (C2, C3) transitioned from an exclusive to a dictator collaboration style. This occurred when couples worked exclusively, but at some point in the process, one partner attempted to dictate the other partner’s actions. For example, C3a stated during their post-study interview that *“there was some points when we were doing the physicalization where, you know, one of us was sort of giving more instructions and the other was doing it.”* In addition to giving instructions, we also observed C3 working exclusively. For example, C3b said that *“I inherently knew that she would be doing more of the crochet, because that she’s a lot better at that. But I think part of it was also just like how we felt in the moment.”* Similarly, C2a said that *“Yeah, he likes cutting stuffs [....] I asked him to cut and I focused on making the emojis (on clay).”*

Figure 4.13: C2a is dictating C2b to follow the instructions. In this process, C2b asked C2a which color of modeling clay they preferred for mapping their data, and later they followed C2a’s instructions.

Another instance of such transition is when C2a asked C2b to create a token for a particular data attribute and when C2b started to explore how to make it, C2a gave

specific directions on how the token should be constructed, saying *"No, you can take pink from here and blue from here and just make some smaller circles so I'll draw the eyes and mouth using a toothpick."* After this short episode of dictator collaboration style, they transitioned to an exclusive collaboration style and continued working independently to prepare different tokens. C2a said *"We aimed to share the workload and collaboratively build the final structure. We both did a bit of all the tasks to get the experience out of the building phase and trust our partners abilities."* (Figure 4.13).

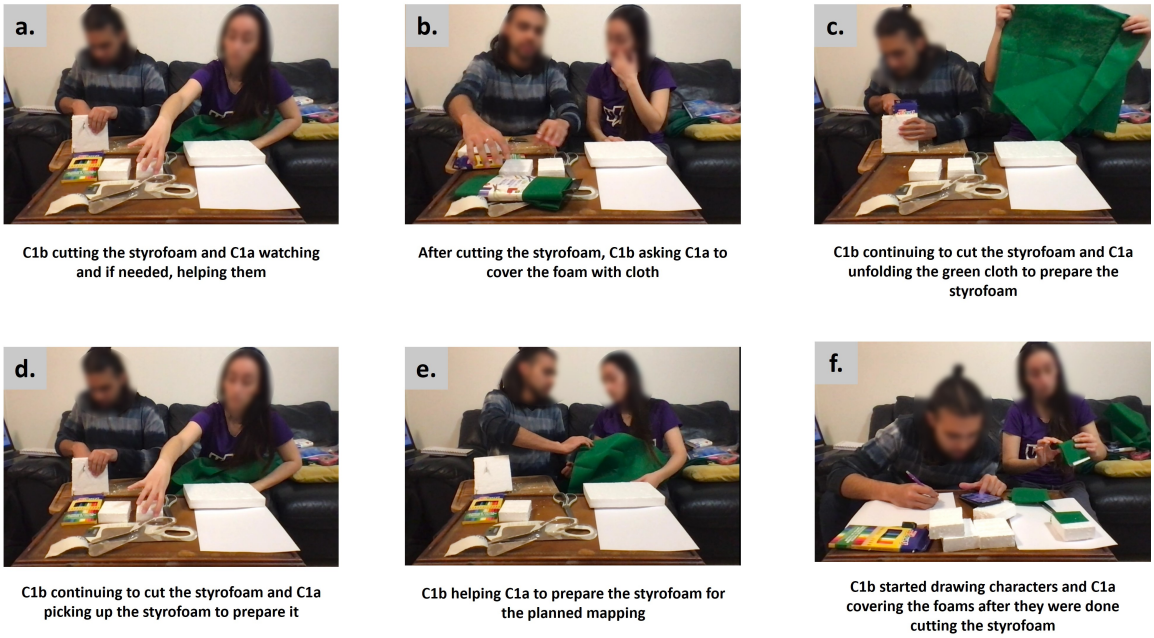

Figure 4.14: Exclusive Collaboration Assembling phase of C1: (a) C1b cutting the styrofoam and C1a watching and if needed, helping them; (b) after cutting the styrofoam, C1b asking C1a to cover the foam with cloth; (c) C1b continuing to cut the styrofoam and C1a unfolding the green cloth to prepare the styrofoam; (d) C1b continuing to cut the styrofoam and C1a picking up the styrofoam to prepare it; (e) C1b helping C1a to prepare the styrofoam for the planned mapping; and (f) C1b started drawing characters and C1a covering the foams after they were done cutting the styrofoam.

During construction, two couples (C1, C4) transitioned from an exclusive to a mutual collaboration style. In these cases, they first worked on constructing different tokens and later decided to assemble them together. For example, C4a said that *"[...] I think I knew how to sew button [...] C4b wanted to make the base using driftwood at the beginning so yeah it was like that [...] Sometimes I was trying to help C4b when*

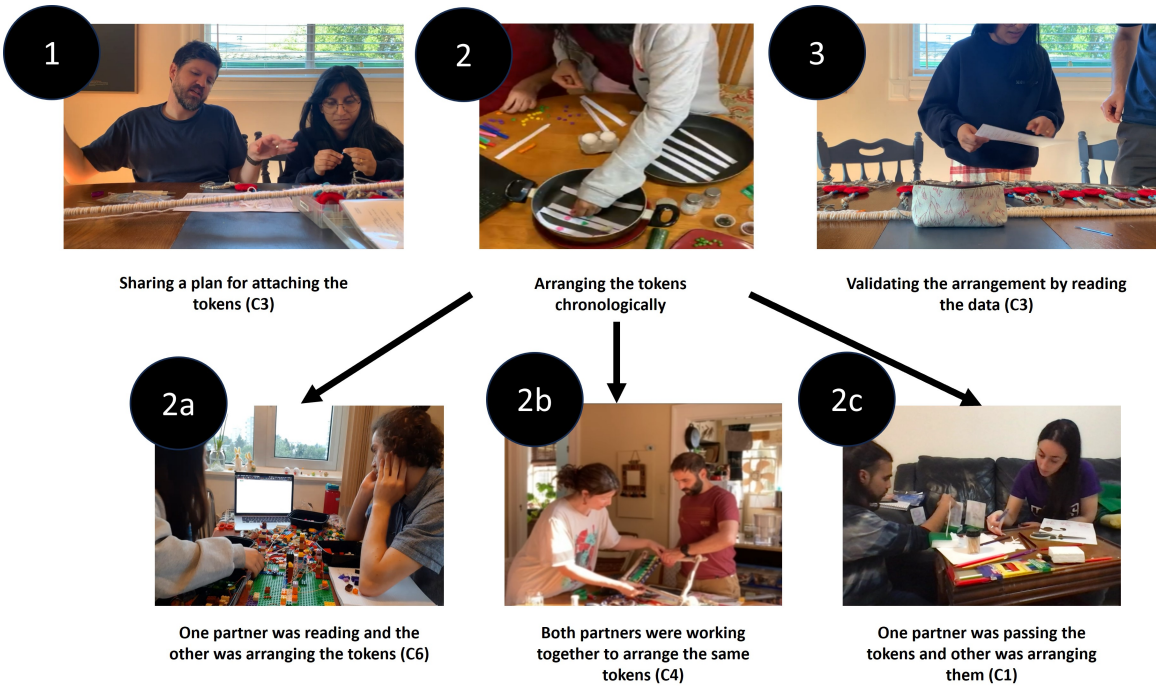

Figure 4.15: Mutual assembling phase. All couples worked together in the assembling process to attach the tokens. They followed the process sequentially, consisting of: (1) sharing a plan for attaching the tokens (C3); (2) arranging the tokens chronologically (C2); and (3) validating the arrangement by reading the data (C3). We observed three strategies for arranging tokens: (2a) one partner was reading and the other was arranging the tokens (C6); (2b) both partners were working together to arrange the same tokens (C4); and (2c) one partner was passing the tokens and other was arranging them (C1).

he asked for my helping hands."

Figure 4.14 shows another such transition, this time by C1, where they prepared tokens independently and then helped each other. For example, C1b started by cutting some styrofoam pieces to make their token. C1b wanted those covered with green cloth and they asked C1a to complete that task; then they helped C1a complete the task.

Assembling the data materials/objects in the final physicalization

After they had crafted the tokens, all six couples discussed how to attach the tokens to construct the final physicalization (see Figure 4.15 (1)). Next, they began assembling the physicalization by placing the tokens one by one, commencing with the first token

they wanted to place (see Figure 4.15 (2)). We observed three variations within this assembling step. The first variation, shown in Figure 4.15 (2a), consisted of only one person attaching the token, while the other read the corresponding data value (e.g., C6). The second variation, shown in Figure 4.15 (2b), consisted of both individuals working together to assemble the physicalization (C3, C4 and C5). The third variation, shown in Figure 4.15 (2c), consisted of couples working together, but where one person picked up and passed a token to another person who then placed it (C1, C2). Lastly, they all validated the completed arrangement by ensuring the selected dataset was represented in its entirety (see Figure 4.15 (3)).

Chapter 5

Discussion

In this discussion chapter, we highlight higher-level comparisons between our model and some existing models relevant to the data visualization process. Based on these differences, we propose some design implications and limitations of our study.

5.1 Comparisons between Collaborative Physicalization Process and other frameworks

As our study revolved around two primary visualization components, collaborative visualization and data physicalization, we discuss our findings, i.e., collaborative physicalization process (CPP) by comparing with the existing of collaborative information visualization workflow (CIVW) and data physicalization pipeline (DPP) beyond desktop systems, highlighting the core differences with our results.

Previous research has demonstrated how collaboration takes place in a data analysis task on digital platforms, including desktop [50], CAVE [64], or tabletop displays [36]. While these models are designed for digital platforms, we have discovered that these collaborative workflow also hold relevance for the constructive physicalization process. Since our recruited couples worked closely and collaborated synchronously on a shared interface (i.e., the physical model), we considered Mark et al.'s collaborative information visualization workflow (referred to as CIVW) [50] to illustrate the similarities and differences compared to ours.

The CIVW model [50] identified a five-stage process for collaboratively analyzing data on a digital computer. These stages are *"parsing the question," "mapping a variable to a program," "locating the correct visualization," "validating the visualization,"*

and *"verifying the entire answer."* Their collaborative process only demonstrated how pairs work together to find and validate the final visualizations to address specific questions related to visualization using a computer. We noticed that some of these actions were partially incorporated into our proposed collaborative physicalization process (referred to as CPP), highlighted in the later sections.

In addition to collaboration, our study explores the realm of data physicalization, specifically constructive data physicalization. It involves selecting shared activities, gathering and formatting data, designing visualizations, prototyping, and constructing tangible data representations. Previously, Thudt et al. demonstrated the overall workflow of constructing data physicalization from a single-user perspective [83], but their observations did not account for the micro-actions required in each step of the process. On the other hand, Jansen and Dragicevic proposed an extended data physicalization pipeline [37] that demonstrated a series of micro-actions that a single user had to consider for creating a physicalization. Although our focus is on the collaborative process in constructive data physicalization, we found that the proposed model of Jansen and Dragicevic (we are referring it as DPP) closely aligns with our process. Therefore, we used their proposed pipeline to identify where collaboration features could be considered in the data physicalization process. All comparisons between DPP and our approach and technical requirements are highlighted in the later sections.

In the following sections, we outline the key similarities and differences between CIVW and DPP using our CPP. Our collaborative physicalization process, CPP, is broken down into four phases: *activity selection (A1)*, *data collection (A2)*, *data mapping (A3)*, and *construction (A4)*. In our findings, we have identified and described specific actions and associated micro-actions for each phase. To visually represent the complete process of collaborative physicalization resulting from our study, please refer to Figure 5.1. Through these comparisons, we will provide technical implications on how and where collaboration can fit into the pipelines. Please note that we use couples as our user group to discuss each phase of CPP.

5.1.1 A1 – Activity Selection

Our CPP model commences with the "activity selection" (A1) phase, in which couples converse briefly regarding several personal aspects for choosing a joint activity, such as the activity's uniqueness and frequency. By considering these discussion points as

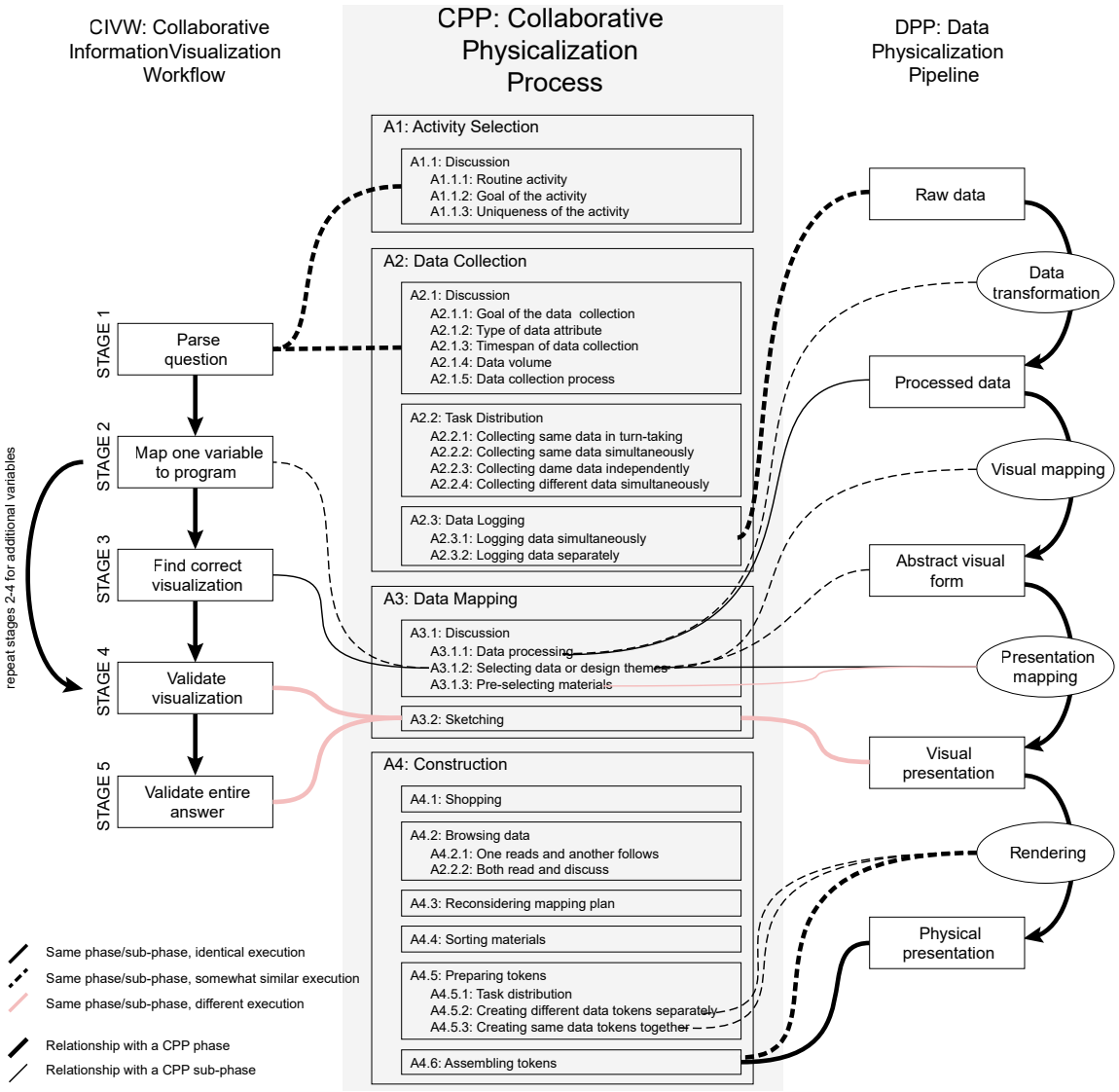

Figure 5.1: The comparisons between our model, Collaborative Physicalization Process (CPP) and Collaborative Information Visualization Workflow (CIVW) and Data Physicalization Pipeline (DPP)

reference factors, couples selected a shared activity that resonates with their personal preferences or goals as a couple.

Collaborative tasks, such as team projects [47], pair programming [67], or reflecting on community practices [14], require valuable discussions at the initial stage between partners. Our CPP model also began with such discussions between couples, which enabled them to establish a higher-level premise and generate ideas to achieve the desired outcome based on the situation and resources. While this initial step is absent in DPP, the CIVW model begins with the "parse question" stage, indicating that it also starts with discussions but with a different focus. Despite this difference, both models (i.e., CPP and CIVW) share the importance of setting up a points of view at the beginning to generate ideas for achieving the desired outcome. These actions aided them in narrowing down the entire design process of their physicalization later. For instance, C2 chose cooking as their shared activity, using vegetables and kitchenery items to visualize their cooking data. Additionally, the constructive physicalization approach, whether an individual or collaborative effort, allows the designer to embed their personal views in their design [83, 46]. For example, C2 chose their personal favorite colors and material to visualize who completed the specific task while cooking a particular dish. Hence, it is useful for the users, who are designing the physicalization, to gain a comprehensive contextual understanding before selecting the appropriate activity, data, design elements (such as data formatting, material selection, and data encoding), placement, and potential audience beforehand. Although not all of these concepts may be explored in the initial phase, they serve as a starting point for the users to gradually engage in the creative process. Similarly, in the context of DPP, individuals must undertake a similar process to construct their physicalizations [83]. However, the micro-actions and interactions from a single-user perspective may differ from our CPP. Thus, integrating this step in DPP would enable users to infuse their personal reflections or perspectives into the design of their physicalization, resulting in a more personalized and meaningful physicalization.

5.1.2 A2 – Data Collection

Next, couples progressed to the "data collection" (A2) phase in CPP after agreeing on a shared activity in the previous phase (i.e., A1 – Activity Selection). During this phase, they deliberated on how to collect the data, what type of data to log, how much data to collect, and for what duration. They ensured that their decisions aligned with

the higher-level goal they were aiming for, which was the physical representation outcome. Subsequently, they distributed the data collection tasks amongst themselves, also known as "task distribution" (A2.2) in CPP. The couples then commenced on collecting the data, known as "data logging" (A2.3), using various methods. While we have detailed these actions and micro-actions in our Findings section, we now focus on how they differ or can be integrated into the CIVW and DPP models in the following paragraphs.

Although the "parse question" stage of the CIVW mainly focused on utilizing pre-existing data, the discussions in the "data collection" phase of CPP centred around the process of collecting and logging data. However, pairs in CIVW carefully observed the available data and deliberated on their approach to address their chosen inquiry through visualization. Interestingly, this aligns with the "discussion" (A2.1) sub-phase of CPP's "data collection" (A2) phase, where pairs briefly conferred on whether their intended data collection aligned with their shared objectives and would yield a meaningful physicalization. Our observations have revealed that having a clear structure or plan in place beforehand, as evidenced by successful pairs like C3 and C4, can aid individuals in devising a solid plan prior to execution and lessen potential stress. While the "discussion" (A2.1) sub-phase is absent in DPP, previous research on constructive data physicalization has shown the importance of making a plan for data collection, even for an individual. It ensures that individuals consider all data collection-related questions before executing. Collecting meaningful data is the primary goal of this phase, so having such a pre-planning and initiating associated micro-actions are equally important when personal data is involved. Failure to collect even a few crucial data points may hinder users from extracting the intended information, resulting in the need to redo the process, which can be time-consuming.

The "task distribution" (A2.2) sub-phase in the "data collection" (A2) of CPP is not present in the CIVW and DPP models. In the CIVW model, pairs worked collaboratively on a single computer interface to depict the data through visualization for analysis purposes, so there was a lack of opportunity to distribute the task among themselves. However, further exploration of the collaborative visualization analysis process revealed that task distribution does occur if the digital system allows them to work independently on the same interface (e.g., tabletop display [36]). On the other hand, the DPP model is designed for a single user and began after raw data had been collected, so this step was irrelevant. While data collection is integral to the constructive data physicalization process, previous researchers demonstrated it

for a single user (e.g., [83, 66]). In the CPP model, we demonstrated how couples collaborated in this phase by planning, distributing the data logging tasks, and then logging their data (i.e., in the "data logging" (A2.3) sub-phase). We noticed how this collaborative planning and synchronization sometimes could impose challenges due to the manual effort involved. Moreover, we have learned from our pre-study interviews that couples sometimes share their personal data (e.g., tracking each other's financial data on a shared spreadsheet) to aid their future planning. In everyday family routines, planning for an activity and distributing tasks for completion are common. We demonstrated how families engage in these practices by employing a data-driven approach to allocate tasks prior to gathering personal data.

In the last sub-phase, referred to as "data logging" (A2.3), couples gather their personal data while engaging in the activity, resulting in final logged data that partially corresponds with DPP's "raw data" stage. Raw data is defined as the data that is generated immediately after logging and prior to any modifications being made. As this action allows couples to generate a raw data that they will use for the rest of their data physicalization process, so collecting effective and meaningful information is the key in this process. For example, identifying what types of data users could aim to collect for their physical representation also requires significant time and effort—something that was a source of frustration among our participants deserving consideration in future research efforts. Also, accuracy of the data maybe another concern in this process, especially who rely on the manual approach of the process. Moreover, couples also had to merge all individually collected raw data which was another time consuming task. A collaborative platform could help by merging or combining individually recorded data into a shared file. This file would include a data table, which the platform could use to provide guidance on formatting the data table to prevent duplicates and frustration.

5.1.3 A3 – Data Mapping

The subsequent stage of our CPP model is the "data mapping" (A3) phase. In this phase, couples processed their data and brainstormed various physical mapping styles by considering factors such as colors, shapes, heights, and materials, assigning each data variable accordingly. This iterative development of individual ideas facilitated the creation of cohesive design themes that aided couples in finalizing the materials and the design of their physical representation. Additionally, two couples (C2 and

C3) producing sketches to verify the overall design and grasp a better visualize of their final representation before buying materials and start constructing.

During this phase, couples undertake micro-actions that align with the final four stages of CIVW's model. These stages include "mapping one variable to program," "finding the correct visualization," "validating visualization" with a loop for additional variables from stage four to stage two, and "validating the entire answer." The "data mapping" phase of CPP involves "data processing" (A3.1) – modifying, merging, or sorting the data, "selecting data or design themes" (A3.2) – designing and presenting the physicalization, choosing visualization variables, and encoding data, and "pre-selecting materials" (A3.3) – determining the types of materials, their usage, and how to embed them into the physicalization design. In contrast, pairs in CIVW did not need to modify the data or engage in detailed discussions about visualization design. They had a fixed set of traditional visualization diagrams and only needed to place each data point within these diagrams.

Using the constructive physicalization approach, couples personalize their data representation, allowing for creative design choices throughout the physicalization process [43]. They adjust their data as needed and thoughtfully select materials to ensure that the resulting physicalization meaningfully reflects their personal aspects. This process requires specific skills in material handling and design, as couples aim to create representations that are both aesthetically pleasing and carry valuable meaning to them.

After completing these steps, couples validate their designs, making adjustments to resolve any errors and ensuring all planned materials fit appropriately. For validation, two couples (C2 and C3) sketched their designs to get an initial sense of how well the design suited their physicalization plan. These discussions on design and data mapping, followed by sketching for validation, helped couples gradually refine their physicalizations to meet their requirements. If any of these steps were not followed carefully, the resulting physicalization could become error-prone, messy, or confusing.

Although not all micro-actions performed during the "data mapping" (A3) phase were present in the CIVW model, they were observed in some form in the DPP model. For example, the "data transformation" of DPP, which later results in "processed data," corresponds to the actions taken by couples during the "data processing" (A3.1.1) of CPP. As couples refined their collected data to retain only relevant information for the physicalization process, they carefully considered each attribute before discarding or combining it with other data attributes. Although this process

required more effort since it was done manually, it ultimately produced a meaningful data format.

Since the data was collaborative, both partners had to reach a consensus before taking any action. For instance, while modifying their collected data, couples considered the type and range of data they wanted to use and how best to utilize it to achieve their personal goals through physicalization. These actions contributed to refining their data mapping process, specifically in the selection of data or design themes ("A3.1.2") and the pre-selection of materials ("A3.1.3") for creating a personalized physicalization design.

Effective discussions are crucial, allowing partners to share their insights and incorporate them into their overall design-making process. This approach adds a personal touch to the physicalization. While personal insights influenced discussions and design decisions throughout every phase of CPP, the "data mapping" phase discussions were particularly vital and often required data-oriented guidance, which could be challenging and time-consuming. Couples utilized various visual variables of physical components, such as color, shape, size, texture, and placement, which could be daunting without the necessary knowledge to create a meaningful physicalization. Therefore, adopting a systematic data-oriented approach to make design decisions could reduce workload and design errors, enhancing the production of more meaningful physical representations.

5.1.4 A4 – Construction

Once the design was finalized, the couples commenced the "construction" (A4) phase, which involved procuring materials by going "shopping" (A4.1) and engaging in activities such as reviewing data (A4.2), adjusting the mapping plan if necessary (A4.3), organizing materials for easy access or tracking purposes (A4.4), creating physical models gradually through preparing tokens (A4.5), and assembling these tokens into the final physical model(A4.6). While absent in CIVW due to its focus on digital visualization systems, this process was detailed in DPP's last two steps – "rendering" and "physical presentation," geared towards physicalization. However, our CPP highlighted constructive aspects of physicalization that were not considered in DPP.

The last two stages in DPP, known as "rendering," involving the use of fabrication technologies like 3D printers or CNC machines to produce models of the physical representation, and "physical model," which refers to the ultimate tangible visualization

formed by assembling modular pieces, correspond to some extent with our activities related to "preparing tokens" (A4.5) and "assembling tokens" (A4.6) within the broader phase of "construction" (A4). In CPP, couples created their models manually by preparing the modular tokens first and then assembling/placing them in the final physicalization model which required a significant amount of time as expected. In this phase, couples displayed a range of collaborative styles, from fully mutual to exclusive collaboration, with occasional variations including elements of dominance or a more dictatorial approach. Styles of collaboration can differ depending on the methods and tools used, as well as the particular task being carried out. As a result, it may be difficult to understand how collaborative physicalization workflow processes vary from our findings without additional details or specific instances. Nevertheless, breaking tasks into smaller actions and gradually producing tangible data tokens could present promising opportunities for future research.

The first four sub-phases of the "construction" phase in the CPP were not present in DPP. The purchasing materials (A4.1) and browsing data (A4.2) did not show significant differences, likely due to the study setup.

5.2 Implications for Design

From our study, it became evident that couples employed diverse collaboration styles and utilized varying actions within these styles to construct their physicalization based on shared personal data. Building upon our findings and drawing insights from existing literature, this section delineates the challenges identified and proposes areas for future research where technology can play a facilitating role in the construction of physicalizations centered around shared personal data: 1) tracking conversations and discussions, 2) collecting and logging shared data, 3) encouraging personalization in the design process, 4) designing modular tangible tokens, 5) editing and fixing mapping errors, 6) assembling the physicalization, and 7) dividing and tracking tasks.

5.2.1 Tracking Conversations and Discussions

From our study, we learned that couples were largely engaged in back and forth communication and discussion across all phases of the data physicalization process, as shown in Figure 4.7. Using discussions as a medium to drive collaboration which is commonly noticed in other group work experiences such as in digital data analysis [81,

36], team project work [47], pair programming [67], and reflecting on community practices [14]. Despite the importance of discussion to enable team work in such collaborative design processes, capturing important parts of such discussions in a systematic manner is a challenging task [85].

In our discussion chapter we discussed, how all couples frequently engaged in brief discussions from activity selection to assembly of their physicalizations as expected. Throughout the process, couples discussed to keep themselves updated either on each other's progress or sharing ideas for next plans. Moreover, couples also solved problems or fixed any emerging facts or confusions through such conversations and negotiations. For example, in the case of data physicalizations, participants in our study (C1–C5) made a list of materials they wanted to purchase for their construction. While some (C1, C2, C5) followed their shopping list closely, others (C3, C4) adapted their shopping list in an ad-hoc way at the time of shopping based on whether the material matched the data they wanted to represent or whether the individuals liked a specific material or not. Additionally, details such as the quantity of materials needed was also often assessed at the store. Such a process while creative and potentially fun, can also be time consuming. For example, C4b said, *"[...]having figured out limitations on the spot, helped us to be more creative in that under the spot and it took longer than expected."* Individuals may also end up purchasing more items than needed or worse, fewer items, requiring additional shopping trips. For example, C2b said that *"we were thinking to use male and female stickers to show us (in the visualization) but we did not have enough [...] Yeah, I said C2a that I could go to shopping next morning but she wanted to finish it on that so we made shapes from clay instead."* A system that can help participants capture such a detailed shopping list along with the rationale for why one wants to purchase specific materials can be a pragmatic way to facilitate the process.

Within a home context, such as in our study, personal devices such as smartphones and smart assistant technologies such as Google Home or Amazon Echo could offer a way to capture information (e.g., GAVIN [39]), if privacy issues [88] are addressed. To filter and capture important information, strategies regarding what type of information to capture, when to capture it (i.e., for which task), and how to refresh the captured information can be useful metrics for design. It would also be useful to offer some form of analysis of the collected data to support decision-making.

5.2.2 Collecting and Logging Shared Data

In our study, couples expressed wanting an automatic data logger to instantly capture their activity data without interruption. For example, C1b mentioned that *"it would have been nice if someone was monitoring our activities and collecting data for us from the back because it was quite annoying to pause each time in the middle of the game and record data [...] we even sometimes forgot to monitor our time as we were so much into the game."* While couples were free to choose their preferred method of data logging, having a system to log shared activity data automatically could ease their data collection process, as has previously be discussed [25].

Some possible solutions for automatic data logging currently exist and can be extended to support data visualization tasks. For example, personal devices like smartwatches and smartphones capture data through sensors for personal use. Users also sometimes share this data with trusted persons. Such applications can be extended to shared data collection by enabling simple features such as collating shared data to create a single file for shared activities. Outside of digital data gathering, for shared physical activities, interfaces such as a shared calendar system [52] could facilitate data logging.

5.2.3 Encouraging Personalization in the Design Process

In the course of our study, we observed couples making deliberate efforts to infuse their distinct personal preferences into the entirety of their physicalization artifact. This encompassed considerations such as color palette, shapes, sizes, materials employed, intended purpose or goal, and the overall design of the finalized assembled physicalization, including the tangible tokens incorporated. Couples demonstrated a conscious endeavor to tailor each element, creating a bespoke representation that authentically reflected their shared experiences and individual tastes.

For example, C2a said that *"we wanted to make it as much as colorful to make it be creative but we have a small idea on how to work with yarns so we thought using such clay we could make some emojis. . . ."* Enabling couples to embed their personalization in the construction process of data physicalization involves incorporating mechanisms that allow for individualized expression within the shared representation. Providing customizable features, such as selecting preferred colors, themes, or visual metaphors that resonate with each partner, fosters a sense of personal connection to the collaborative creation. Additionally, integrating interactive elements that permit

couples to curate and arrange data points based on their unique preferences enhances the personalization aspect. Offering flexibility in the design and layout ensures that the resulting physicalization is not only a joint endeavor but also a reflection of each individual's identity and preferences. This approach not only enhances the overall engagement of couples in the construction process but also contributes to a more meaningful and personalized representation of their shared personal data.

In future, we suggest to have an interface that should allow couples to input and visualize their shared personal data in a manner that resonates with their unique preferences. For example, we have various modern design tools (e.g., TinkerCAD) that enable users to create free-form designs based on their personal preferences. By allowing users to upload their shared personal data and integrating Large Language Model (LLM) features (such as ChatGPT or DALL-E), these CAD modeling tools could generate outputs based on user inputs (i.e., prompts). This integration has the potential to enhance flexibility in generating, scaling, and modifying designs collaboratively while guiding users through a more data-centric approach.

In this approach, when users want to incorporate a certain material into the design, whether individually or combined, it needs to be meaningful based on the context of the activity and the data they are working with. One possible way to achieve this is by assigning specific materials to each data point, along with the attributes of these materials, how users prefer to utilize them, and assessing their feasibility for the final outcome. This approach, observed in constructive digital visualization settings (e.g., ReConstructor [55]), can also be adapted to the physicalization design context.

Furthermore, the system needs to consider each individual's preferences, such as the design theme and how they want the final design of the physicalization to be displayed (e.g., hanging or on a table). This consideration allows users to incorporate their personal aspects into the design.

Additionally, offering flexibility in the selection of data sources and the ability to highlight specific events or memories empowers couples to tailor the physicalization to reflect their shared experiences. Overall, by providing a platform that accommodates individual preferences and collaborative input, couples can actively shape their shared personal data into a meaningful and personalized data physicalization.

5.2.4 Designing Modular Tangible Tokens

In our study, all participants created visualizations that look quite different from traditional visualizations like line charts, bar charts and scatter plots. Previous studies related to data physicalization have also pointed out that constructive physicalization can encourage more creative outcomes, especially when compared to digital visualization [29, 83]. However, a common challenge with constructive physicalization is that designing and constructing tokens is a time consuming process that requires craft and design skills [6]. For example, C3a said *"I think what would have been useful for us, a modeling tool that would allow you to put your data in. I suppose that's what a digital visualization is where you take your dataset and you put it into the software, and it visualizes it for you. But it would be nice to have that concept but with like much more sort of, choice of what type of shapes and things you use because something we found challenging was we were able to sketch up our ideas on Draw.io or by hand and then even digitally on Draw.io, but it was difficult to get proportions you know something and manipulated as well. It was you know, everything was difficult to move around and put together. So if the end goal was to create a physical visualization, having a tool that allowed somebody to sort of do the mapping process in a digital space would be very helpful [...] something like that would have saved us a lot of time and effort that we put after sketching."* Future technologies could help with this process to help people accomplish their design activities more effectively and more efficiently.

Existing design tools such as CAD tools for 3D modelling, could be extended to assist with developing and testing 3D tokens in collaboration. Modelling tools like AutoCAD, JSCAD, Autodesk Maya, TinkerCAD and Unity enable designers to create free-form models using the properties of desired materials (such as material type, weight, height, shape, size and color). Such models can also be simulated with animation and interactive features to better understand how these models behave within the parameters of physics, and thereby help people assess if a token will stand sturdy on a table or if it can be hung from a wall. These models could be also be displayed in augmented or virtual reality, that would allow also people to evaluate how the model will appear within a specific space and how people will interact with it. However, these existing tools are primarily designed for single users or distributed collaborative teams, which does not align with the collocated nature of collaborative physicalization. For example, in an attempt to validate their planned data visualization, two couples (C2 and C3) sketched a draft using software sketching tools. However, we

provided evidence in the study findings that the tools they used did not assist them in their design process. These tools did not support collaboration such as supporting two people creating their designs on the same canvas like prototyping tools like Canva or Figma or ideation software like Miro, demonstrating how they work, and merging their ideas. These tools also do not inform people about the physical rendering procedures required to bring their creation to life [37]. If tools were to provide information about the required physical rendering steps, along with an estimation of the time required to construct the physicalization, people could reconsider their design decisions before they start creating tokens.

The different software we mentioned above also generally lack data-aware tools that are needed to improve precision, aesthetics, and consistency of tokens. Designers often approach data visualization using either a top-down [8] or bottom-up [54] approach. The top-down approach involves creating the design first and then incorporating the data, while the bottom-up approach considers different aspects of the data before designing the visualizations. It has been shown that in constructive physicalization, people tend to prefer the bottom-up approach [54]. One way to support this bottom-up approach would be to support creating models of tokens by following data-driven design guides [40], that they could then use as a backbone for creating and customizing tokens. Such data-driven guides would facilitate the tedious steps of ensuring accuracy of data mappings (e.g., figuring out what the exact size of a clay token should be to represent its associated data value), which would allow participants to focus instead on the more creative and expressive design tasks. Moreover, creating physical tokens manually could be labor-intensive; therefore, we require tools to automate the process and reduce such hands-on operations. For example, we have automated or manual fabrication tools (i.e., 3D printers, 3Doodlers or CNC machines) which enable users to design and print or create physical tokens based on the requirements. This also would enable users to produce tangible tokens quickly and easily.

5.2.5 Editing and Fixing Mapping Errors

Prior studies have shown that correcting physicalization errors or modifying design choices often makes data mapping unnecessarily tedious [66]. We made similar observations in our study. For example C3 who did not anticipate that creating 30 individual tokens might take a significant amount of time, and that the tokens would

not all fit within their designated frame or wall space. After they had finished installing 15 tokens, they faced the problem of space, which led them to a change in the design by leaving out the remaining 15 data tokens. While C3 had sketched out their idea before constructing the physicalization, their sketch was only an incomplete estimate. Having access to a tool such as the ones described in the previous section could offer a way to gain a fuller understanding of the planned physicalization design and could save people time by allowing them to make modifications earlier in the process.

Even with such modelling and simulation tools, mistakes still occur during the manual construction of their physicalization. For example, during the construction of their physicalization, C4 made used the wrong ribbon colour to map the difficulty level of a rock climbing route: although their planned mapping had dark green ribbons to indicate easy routes and grey ones for hard ones, they mistakenly attached a grey ribbon to show one of the easier routes and only realized this when attaching their third ribbon to the wooden frame. At this point and considering the amount of time they had already invested in the construction process, they decided to modify their mapping on the fly. To address such situations, systems could support people in creating a mapping plan in advance and monitoring people's construction to inform them of any deviation or mistake on the go. For example, once the system has enough information to recognize the final design of the physicalization from the users, it can automatically create a mapping plan and estimate the total time required for construction, considering the materials and the workload for data token preparation process. This plan will allow users to have a clear understanding of how data is mapped to specific materials and where each material should be attached. As a result, when users are creating the data tokens, they will be aware of their mapping plan, helping them avoid mistakes such as C3 and C4 encountered.

5.2.6 Assembling the Physicalization

Participants in our study were expected to devote significant time to the construction phase since it was a fully manual activity. Many of them had a hard time determining the total construction time, and this sometimes resulted in frustrations. For example, C3b asked C3a to finish the task that they had taken on because they were getting frustrated by the amount of time it was taking them. They later reflected on it, saying: *"if I was doing something for a long time and it just kind of got very boring*

and tedious to do, to continue to repeat it, then perhaps I would ask C3a to do it and then maybe I'll take on some other tasks." Fabrication tools such as 3D printers and CNC laser cutters could help reduce the construction time. For example, C1b said *"when you are doing the visualization, like in the real life, you don't know how much work you will have to do, so you just start. For example, if we have to do this, the same visualization again, I will do in a super better way. You know, I will not draw the characters, I will just print them. It would be smart."* Access to such specialized fabrication machines remains limited and expensive, and we lack fabrication equipment that would be more accessible, perhaps at the cost of precision.

5.2.7 Dividing and Tracking Tasks

During the data collection and construction phases, we observed couples often divided the task of preparing tokens amongst themselves (see Figure 4.7). Even during the construction phase, we observed as they completed each token, one couple (C3) also marked it off on their datasheet, to keep track of their progress. Prior collaborative visualization studies have shown that pairs often tend to distribute task [36].

Users distribute their tasks based on the relevant working expertise with the material, workload of a specific task (such as, creating a token) and size of the planned physicalization. All of these are interrelated so it depends on the collaborative working style of the users, because they have the freedom to decide where they prefer to contribute and what they like execute in the entire physicalization construction process. In terms of task distribution especially in a collocated environment, digital technologies could help with dividing tasks and tracking their progress, which would be particularly useful for large-scale projects like constructing physicalization. For example, systems that enable self-assignment of tasks based on personal preferences, which can be useful (participants in our study often divided tasks by skill expertise) in such cases. Also, structured task tracking mechanisms would also ease the process, as well as ways to transfer tasks between people, like C3 did in our study. Supporting task transfer would need to aid in the recording of progress made prior to handing off the task to help the other person easily continue that task.

5.3 Limitations and Future Work

Our qualitative study revealed several forms of collaboration styles that couples employ during the physicalization process in a home environment. The objective of this study was not to generalize these collaboration techniques but rather to highlight the various aspects in which couples collaborate and coordinate while building a physical representation of shared data. In this section, we highlight research directions that would contribute to building a more complete understanding of collaborative data physicalization, by addressing some of the limitations of our study.

First, our sample size was small, and most of our participants were young adults with engineering backgrounds. Although this study allowed us to illustrate the complex dynamics that take place when couples collaborate and coordinate during the physicalization process, further research is needed to explore other forms of collaboration that might arise with a broader population and in different contexts. For example, we might want to consider older couples or couples with little visualization knowledge in order to reach a saturation point [21] and arrive at more generalizable findings.

Second, although we drafted a precise protocol, including questions and scripts, the findings from our post-study interviews likely have some bias due to the interviewer's assumptions [61].

Third, the couples completed their physicalization in various and sometimes drastically different amounts of time, as shown in Figure 3.2). This sometimes made it difficult for participants to recall information such as their collaborative decision-making process during post-study interviews. Although we had included the diary-like documentation template for participants to document information on the fly to mitigate this risk, in future studies, we suggest putting time constraints on the completion of each task and measuring whether it influences their collaborative process.

Finally, since we did not continuously collect audio and video data (aside from the construction task), we could not address some tacit information that would have affected the overall collaborative physicalization process. Because collaboration styles differ across individuals [53], future research should investigate these implicit factors that would contribute to designing the next generation of technologies to support collaborative physical visualization.

Chapter 6

Conclusions

This qualitative study provides insight into how collaboration occurs among couples when undertaking a constructive physicalization task in a domestic environment. Our findings revealed that there are no standardized procedure for couples to accomplish individual tasks. However, we identified a consistent pattern characterized by initial deliberations and ideation, followed by planning stages, before they executed their plan. We documented three collaboration styles that couples employed as they worked together to accomplish their objectives: *mutual* cooperation, *exclusive* individual effort, and *dictatorial* decision-making tactics. We pointed out that couples utilized intricate collaborative procedures and techniques to generate creative and distinct representations that embody their personal shared data. Overall, this study highlights the importance of recognizing and understanding the complex collaborative processes that occur in domestic environments when undertaking constructive physicalization tasks. While more research is needed for the community to build a fuller understanding of that space, we have identified a series of design considerations that can inform the development of technology support tool that facilitate the creation of physicalizations in contexts that require collective actions.

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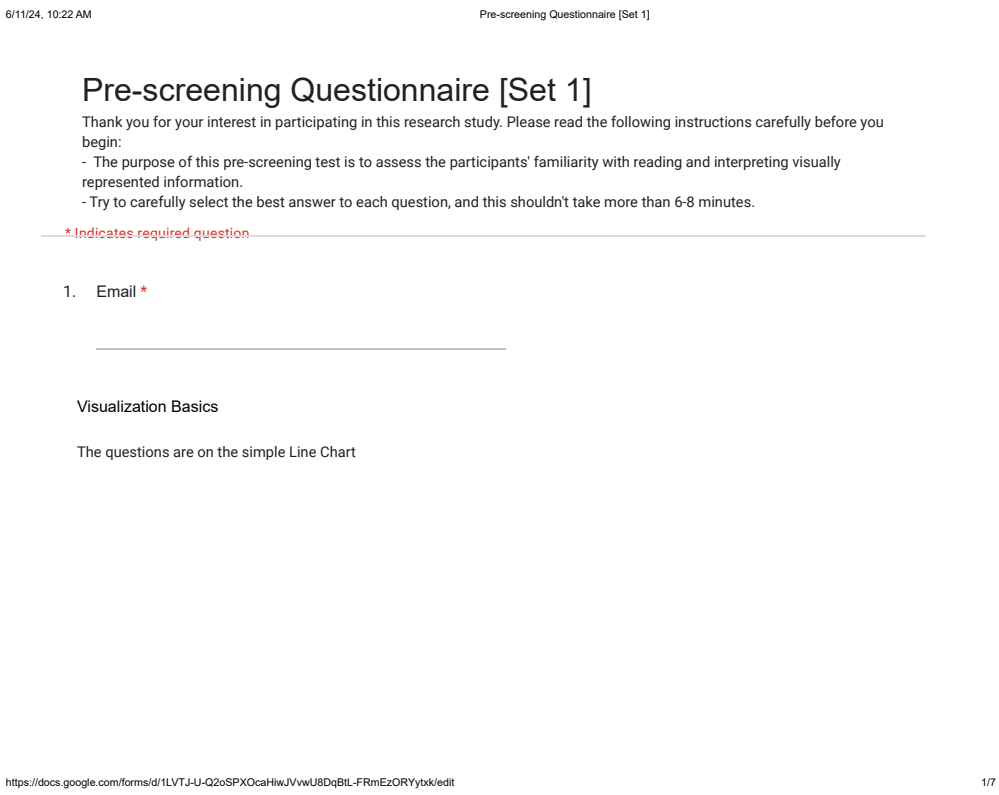
Appendix A

Additional Information

In this appendix, we include the participant recruitment poster, two sets of pre-study questionnaires, a study handout emailed to the participants, a pre-study training document and the diary template.

Figure A.1: Participant Recruitment Poster



6/11/24, 10:22 AM Pre-screening Questionnaire [Set 1]

Pre-screening Questionnaire [Set 1]

Thank you for your interest in participating in this research study. Please read the following instructions carefully before you begin:
- The purpose of this pre-screening test is to assess the participants' familiarity with reading and interpreting visually represented information.
- Try to carefully select the best answer to each question, and this shouldn't take more than 6-8 minutes.

* Indicates required question

1. Email *

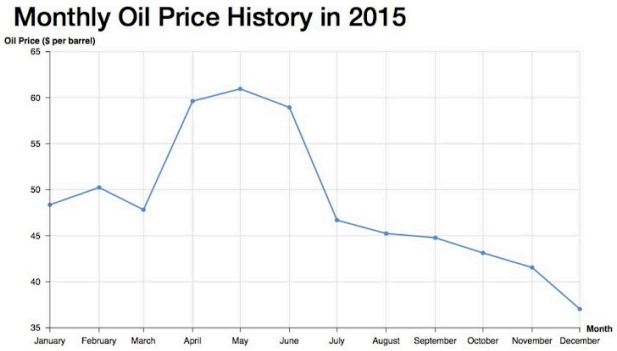
Visualization Basics

The questions are on the simple Line Chart

https://docs.google.com/forms/d/1LVTJ-U-Q2oSPXOcaHiwJVvwU8DqBtL-FRmEzORYytxk/edit 1/7

Figure A.2: Pre-Screening Questionnaire [Set 1] - Page 1

2. What was the price of a barrel of oil in February 2015? *

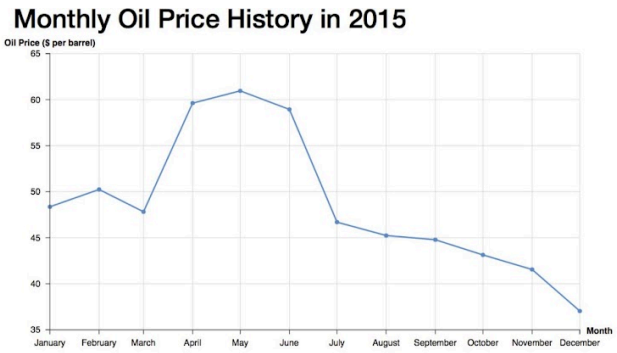


Mark only one oval.

- $57.36
- $47.82
- $50.24
- $39.72

Figure A.3: Pre-Screening Questionnaire [Set 1] - Page 2

3. In which month was the price range of a barrel of oil the lowest in 2015? *

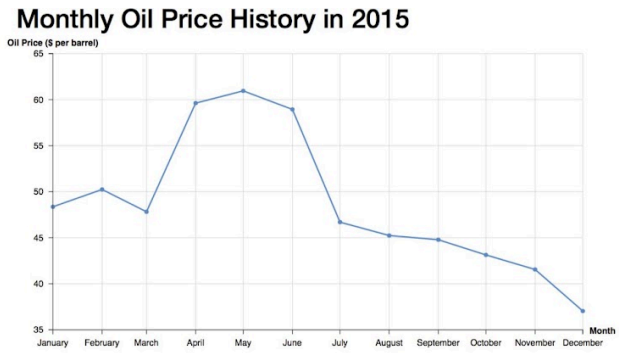


Mark only one oval.

- March
- May
- July
- December

Figure A.4: Pre-Screening Questionnaire [Set 1] - Page 3

4. What was the price range of a barrel of oil in 2015? *

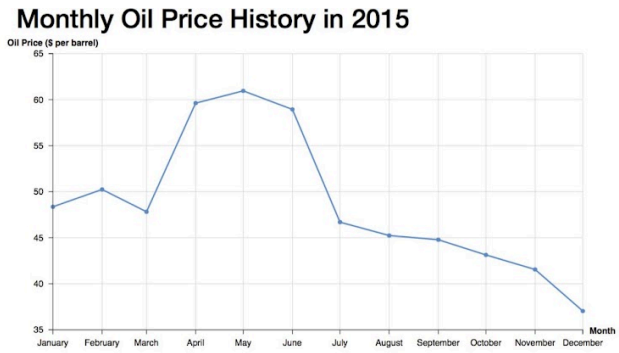


Mark only one oval.

- $35 - $65
- $48.36 - $60.95
- $37.04 - $48.36
- $37.04 - $ 60.95

Figure A.5: Pre-Screening Questionnaire [Set 1] - Page 4

5. Over the course of the second half of 2015, the price of a barrel of oil was _____. *

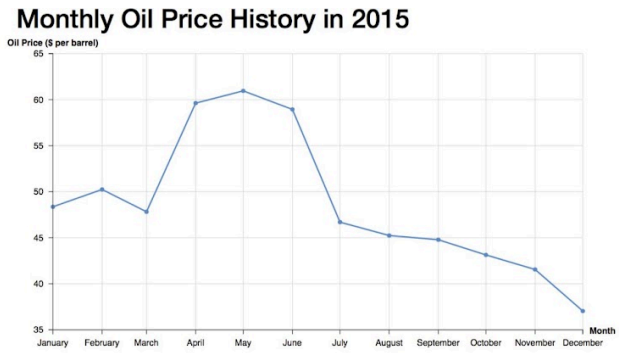


Mark only one oval.

- Rising
- Falling
- Staying

Figure A.6: Pre-Screening Questionnaire [Set 1] - Page 5

6. About how much did the price of a barrel of oil fall from April to September in 2015? *



Mark only one oval.

- $4
- $15
- $17
- $45

Figure A.7: Pre-Screening Questionnaire [Set 1] - Page 6

Pre-screening Questionnaire [Set 2]

Thank you for your interest in participating in this research study. Please read the following instructions carefully before you begin:
- The purpose of this pre-screening test is to assess the participants' familiarity with reading and interpreting visually represented information.
- Try to carefully select the best answer to each question, and this shouldn't take more than 6-8 minutes.

* Indicates required question

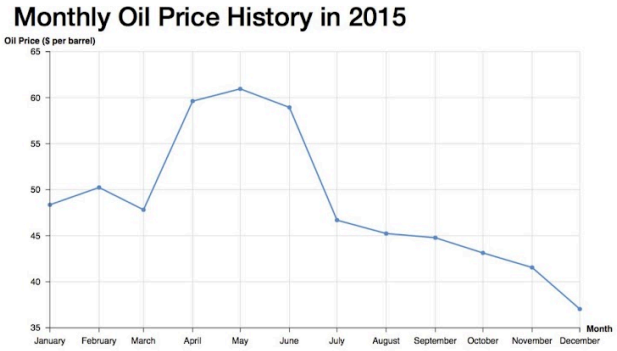
1. Email *

Visualization Basics

The questions are on the simple Line Chart

Figure A.8: Pre-Screening Questionnaire [Set 2] - Page 1

2. What was the price of a barrel of oil in October 2015? *

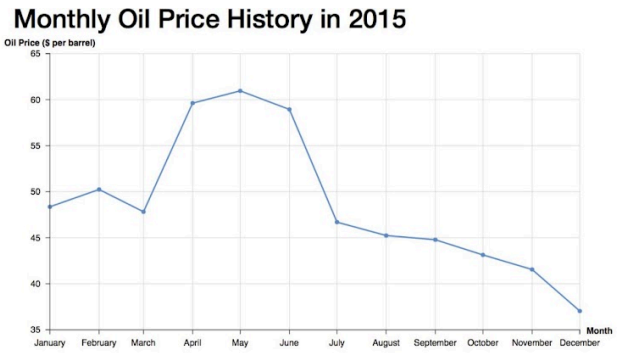


Mark only one oval.

- $52.45
- $47.82
- $39.24
- $43.72

Figure A.9: Pre-Screening Questionnaire [Set 2] - Page 2

3. In which month was the price range of a barrel of oil the highest in 2015? *

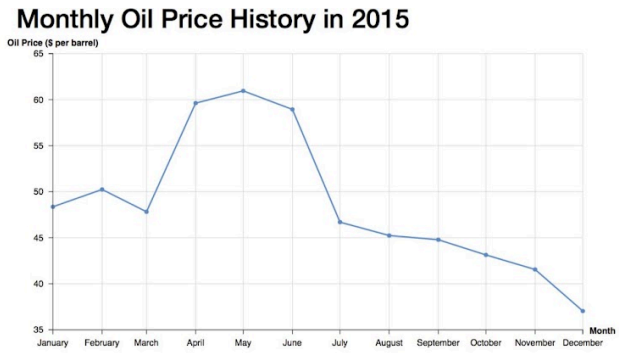


Mark only one oval.

- March
- May
- July
- December

Figure A.10: Pre-Screening Questionnaire [Set 2] - Page 3

4. What was the price range of a barrel of oil in 2015? *

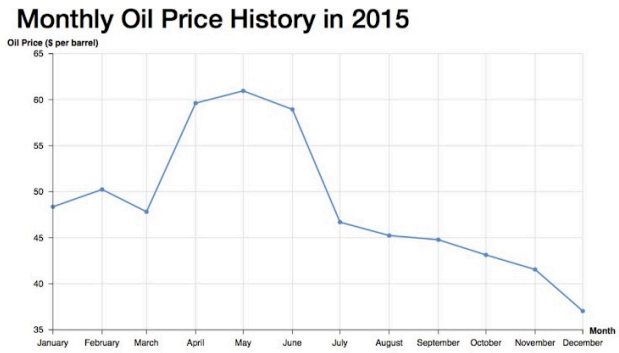


Mark only one oval.

- $35 - $65
- $48.36 - $60.95
- $37.04 - $48.36
- $37.04 - $ 60.95

Figure A.11: Pre-Screening Questionnaire [Set 2] - Page 4

5. Over the course of the first half of 2015, the price of a barrel of oil was _____. *

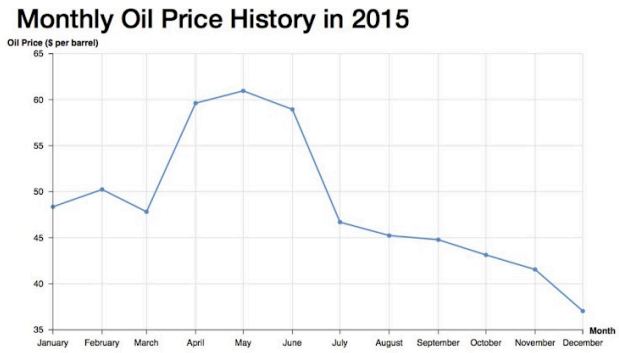


Mark only one oval.

- Rising
- Falling
- Staying

Figure A.12: Pre-Screening Questionnaire [Set 2] - Page 5

6. About how much did the price of a barrel of oil rise from February to April in 2015? *



Mark only one oval.

- ◯ $4
- ◯ $10
- ◯ $17
- ◯ $45

Figure A.13: Pre-Screening Questionnaire [Set 2] - Page 6

University of Victoria

Study Handout
HERB: 21-0310

Co-Visualization in a Family Setting - Study Handout

Study Overview

Objective:

The overarching goal of this research is to understand how pairs of family members (i.e. couples or partners) together create a single physical visualization using a dataset that is meaningful to them. We (the researchers) refer to this process as "co-visualization". Here physical visualization refers to creating a physical representation (such as an object or artifact created using physical materials such as Legos, art and craft supplies, pebbles, or others) of any type of data (e.g., eating habits, exercise routines, hours spent cooking, etc.) that can be utilized by people for a variety of reasons such as understanding self, reflecting on the activity or as a discussion piece. More specifically, the proposed research will explore how couples or partners engage in co-visualization.

Description:

For this study, participants (that is, couples or partners) will create a single physical visualization together for a dataset (e.g., family activity that couples do together) that is meaningful to them. During the visualization construction process, the participants will document their experiences by highlighting things such as how they selected the dataset, materials for constructing the visualization, task distributions (if any), how the individual members contributed to the creation process, feelings expressed during the creation process and final thoughts on the final visualization created.

What is Data Physicalization or Physical Data Visualization?:

"A data physicalization (or simply physicalization) is a physical artifact whose geometry or material properties encode data." [1]

More precisely, data physicalization is a different approach compared to traditional visualizations. It is a process where users engage themselves to give a physical form to data that

Figure A.14: Study Handout - Page 1

can support various aspects like cognition, communication, learning, problem-solving, and decision making [1].

Who can participate:

We are looking for couples or partners who must meet the following criteria:

- Both participants are 18 years of age or older;
- Both participants live in the same home and currently reside in Canada;
- Both participants have some kind of familiarity or knowledge in reading and interpreting data visualizations (i.e., charts, graphs, plots, etc.)

What do participants need for this study:

- A smartphone or any video and audio recording device.
- A Tripod stand
- A device (computer, tablet, phone) with the Zoom video conferencing software installed.
- Access to the internet.

What will be provided for this study:

- To purchase physical materials for constructing the visualization, and a tripod to capture pictures and videos, you will be given a maximum of **$75** budget. You will be compensated upon submission of purchase receipt via e-transfer.
- We will provide participants a template for documenting their study experiences.

Compensation:

- As remuneration for the time spent on the study, you will be given a **$100** e-gift card.

Duration of the study:

- Approximately 7-8 hours (we expect you not to spend more than 2-3 hours per sub-phase, so in total 7-8 hrs over the entire study period).

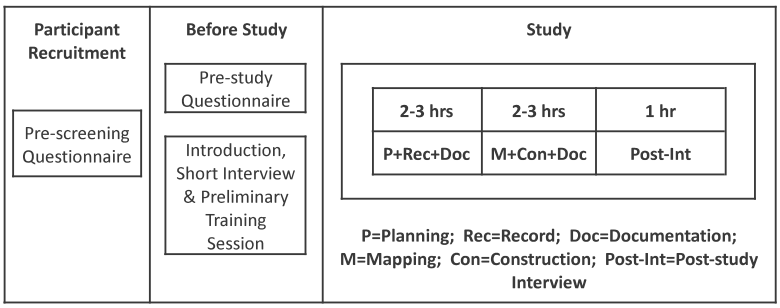
Structure of the study:

It is a single-phase observational study that is divided into a few sub-phases where you (that is, couples or partners) will create one physical visualization together. The below table summarizes the structure of the experimental design:

- In the participant recruitment, we (i.e., researchers) will ask both of you (that is, couples or partners) to fill out two separate pre-screening questionnaires individually that we (i.e., researchers) will use to understand both of your visualization basics.

Figure A.15: Study Handout - Page 2

- After recruitment, we will share a consent form and demographic information questionnaire that both of you will sign the consent form and fill out the questionnaire. Later, we will introduce our study briefly and walk you through a training session where you will create a physical representation collaboratively using a toy dataset. Note that our provided toy dataset is an example of how both of you can collect data in multiple instances. It is important to note that the format of the dataset relies on you, but you need to make sure that you collect data in several instances while performing an activity (i.e., something that lasts a minimum amount of time and with multiple instances of data collection).
- The study consists of a series of sub-phases, indicated with the letters: P (for Planning phase), Rec (for Recording phase), Doc (for Documentation phase), M (for Mapping phase), Con (for Construction phase), and Post-Int (for Post-study Interview phase).



[**NOTE:** This sample table has been provided to give you an overview of our study for this research and represents a typical process for constructing visualizations. However, the order in which the sub-phases are executed can vary based on both of your workflow ideas, but irrespective of the orders of the sub-phases, you will have to ensure that all the sub-phases are completed and documented within the 7-8 hrs timeframe, and you have a physical visualization built by the end of the activity.]

The definitions of the sub-phases:

- ➔ ***Participant recruitment:*** *Both of you (i.e., couples or partners) will fill out two separate pre-screening questionnaires individually where we (the researchers) will try to understand the visualization basics of both of you. Questions are very basic and easy to answer.*
- ➔ ***Before study:*** *Before we conduct the introduction session, you will both sign the consent form and complete the pre-study questionnaire we will share with you. Upon signing the consent form and completing the questionnaire, you will participate in a remote introduction session at your convenience. As part of the introduction session, you will participate in a pre-study interview in order to allow us to gain a better understanding of*

Figure A.16: Study Handout - Page 3

your experiences with data visualization. Later, we will introduce our study briefly and walk you through a training session where you will create a physical representation collaboratively using a toy dataset. Note that our provided toy dataset is an example of how pairs can collect data in multiple instances. It is important to note that the format of the dataset relies on both of you, but you need to collect data several instances while performing an activity (i.e., something that lasts a minimum amount of time and with multiple instances of data collection).

- ➔ ***Planning (P):*** *In this sub-phase, you will select one activity that you like to perform together as a pair e.g., walking, cooking, watching movies, listening to music, etc.*
- ➔ ***Recording (Rec):*** *You will collect data while performing your planned activity together. While collecting data, you can think about many aspects. For example,*

Example Activity	*Example Data Gathered*
Walking	*distance walked, hours spent walking, location of the walk, photos taken during the walk, number of trees spotted in the walking path, how many steps you walked, how many places or areas you covered, how many people you met; are some examples of possible data that can be collected for the activity.* *You are free to collect any data that you find relevant and meaningful*

Below is an example about an activity done in pairs. Note how the dataset relies on you collecting data several times (i.e., something that lasts a minimum amount of time and with multiple instances of data collection).

Instances	Events	Timestamp (YYYY-MM-DD hh:mm:ss)	Photos taken	Number of steps	How many people they met	The topic of the conversation	Distance covered by walking
1	Walking	2021-11-10 07:45:25	x	256	2		0.2 km
1	Walking	2021-11-10 07:46:32	x	351	1		0.27 km
1	Walking & Discussing	2021-11-10 07:48:39	x	417	6	Talking about personal things	0.32 km
1	Walking & Discussing	2021-11-10 07:50:44	1	525	0	Talking about personal things	0.4 km
1	Walking &	2021-11-10	x	643	0	Talking about	0.49 km

Figure A.17: Study Handout - Page 4

	Discussing	07:53:10				personal things	
1	Walking & Discussing	2021-11-10 07:55:12	x	768	0	Talking about family matters	0.59 km
2	Standing & Discussing	2021-11-10 08:15:36	1	1022	2	Talking about professional career	0.78 km
2	Walking	2021-11-10 08:19:15	x	1154	0		0.88 km
2	Standing	2021-11-10 08:21:11	1	1289	0		0.98 km

- ***Documentation (Doc):*** *While performing each sub-phase, you must document your progress in the template that we will share with you. Examples of things to document include: rationale for all the decisions made, any decisions changed, overall experience while gathering the data and constructing the visualization, and anything else you would like to share with the researchers. You must also document each sub-phase with photos and videos that can be attached to the template provided. The documentation must be as detailed as possible, as we (the researchers) will analyze your data for each sub-phase of the research using the documentation files.*
- ***Mapping (M):*** *Once you finish your data collection process, you need to start thinking about how you want to map the collected data to a physical representation together. Two examples are shown below. Based on how you would like to create your visualizations at this stage, you (as a couple or partners) will decide what physical materials you want to purchase using the provided budget or use from their own supplies. You are also free to change or use multiple materials and purchase additional materials (within the budget provided) during the process if you find it important to your visualization process.*

Example Activity	*Example Data gathered*	*Example Materials Purchased*	*Example Mapping*

Figure A.18: Study Handout - Page 5

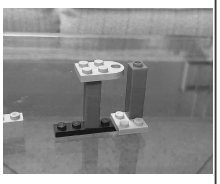
Walking	*- distance walked,* *- hours spent walking,* *- location of the walk*	*- A printout of the geographic map of the locality* *- Wool*	 In this example, the distance walked is mapped to the length of the wool strand, hours spend is depicted by the width of the wool strand (e.g., thicker wool strand means more time than the thin wool strand) and the location of the walking path is indicated by the pins and way the strands are laid out on the map.
Cooking	*- hours spent cooking,* *- types of dishes*	*- LEGO*	 *In this example, each bit of the LEGO brick represents time spent after cooking (each bit represents 15 minutes) and color depicts different types of dishes*

Figure A.19: Study Handout - Page 6

			that are cooked (e.g., brown-colored blocks are for cooking vegetables and white-colored blocks are for cooking chicken curry).

- ➔ ***Construction (Con):*** *Once you are happy with your mapping, you will start to construct the physical visualization together using the selected material. This may take a couple of hours or you can select to spread the construction process over multiple days. You must ensure that the construction process is done as a pair and not individually. The construction of the visualization should be completed within the allocated time frame.*
- ➔ ***Post-study Interview (Post-Int):*** *When you inform us that you finished the construction of the data physicalization, we will connect with you over Zoom and ask about the overall process experiences, any issues they ran into, and things they liked about the process. At this time, please also share with us the data you used for the visualization. This data can be shared with us in any format that is easy for you. For example, in the form of a picture or you can share an excel sheet. You can either paste a link to your data file here or you can send it to us as an email attachment.*

A few important reminders:

- ➔ The format of the dataset relies on them, but you need to collect data from several instances while performing an activity (i.e., something that lasts a minimum amount of time and with multiple instances of data collection).
- ➔ When performing each sub-phase, you need to document everything in the provided template to help us understand and analyze your progress.

Before the study [approx. 1 hour]:

We will take you through the study details and conduct a pre-study interview to learn more about you and your partner's experience with data visualization. A preliminary training session will be held later so that you can understand the collaborative process of creating a meaningful physical visualization. During that session, we will give you a toy dataset about a pair activity to give you a better idea of what is expected from you and the type of data you should collect.

Planning, Recording & Documentation [approx. 2-3 hrs.]:

In this sub-phase, you (as a couple or partner) will plan what you want to visualize and how you want to visualize it. For example, you might consider visualizing the number of hours you spent cooking by assembling a lego-based structure. In this example, the data or "what you want to

Figure A.20: Study Handout - Page 7

visualize" would be hours spent cooking, and the materials used to create the data representation would be "lego".

In this part, the participants will complete the following:

1. Please select one task/activity that you take part in together and will ensure sufficient data collection. Remember that you need to collect data several times (i.e., something that lasts for a reasonable amount of time and with multiple instances of data collection). Some examples include:
    - Hiking
    - Roaming around the city
    - Watching movies in a cinema hall
    - Dining outside
    - Summer camping
    - Fishing
    - Cooking
    - Watching movies (on Netflix, Amazon Prime, etc.)
    - Playing video games
    - Jamming
2. Think about what are the different aspects of the activity you would like to represent (e.g., hiking activity can have several aspects for which you can collect data e.g., hours spent hiking, geographic location of the hike, number of people who went on the hike, pictures taken during the hike). Once you have decided which data you are going to represent, specify the activity in the shared template. Remember that, you will choose a shared activity that you do together as a couple and then collect data several times (i.e., something that lasts a minimum amount of time and with multiple instances of data collection). It is completely up to you and your partner to decide which data to collect. The choice of the data that you as a couple want to visualize should be meaningful that can be used to understand each other better or simply communicate to others. The only mandatory aspect is that the data must contain a reasonable dataset that will have a frequency of 4 to 5 data points (per attempt/instance) with 2 to 4 or 5 data dimensions or attributes.
3. Discuss and record your planned data.
4. Take pictures of the tools and procedures you used to collect the data. Upload them using the template provided.
5. Answer the questions in the provided slides template and explain your processes.

Mapping, Construction & Documentation [approx. 2-3 hrs.]:

In this sub-phase, you (that is, couples or partners) will plan how you want to map your collected data. Based on that, purchase your preferred material(s) and then construct a single

Figure A.21: Study Handout - Page 8

physical visualization using the purchased material(s). You will construct this visualization together. Therefore, you need to sit together, coordinate, communicate, and share information.

In this part, you will complete the following:

1. You will discuss and think about how you want to map your collected data
2. Based on that, purchase materials that you would like to use for constructing a physical representation of the activity. You should use the fixed $75 budget to purchase the materials you need including a tripod stand (if you do not have one). Refer to the List of sample materials for suggestions on the types of materials you can use. Once both of you have decided which materials you are going to use for representing their data, specify the material in the shared template.
3. Upon purchasing the material, you will begin planning your process for constructing the visualization.
4. You are asked to capture pictures and videos of the whole creation process. This includes the materials you select or purchase, as well as the steps of construction, collaboration, and data mapping. You will upload these pictures and videos to the shared slides template as you complete each step in the visualization construction process.

NOTE: In case you speak more than one language at home, please either do the exercise in English or provide a translation in English during the session.

Interview [approx. 1 hr.]:

In this sub-phase, you will inform us that you completed the construction activity, and then we will conduct a post-study interview to understand your feelings and what you have learned from this study.

In this sub-phase, you will complete the following:

1. We will contact you over zoom to have a check-in interview session where we will be asking a few questions to understand your progress and feelings.
2. We will ask you to share with us the data you used for the visualization. This data can be shared with us in any format that is easy for you. For example, in the form of a picture or you can share an excel sheet. You can either paste a link to your data file here or you can send it to us as an email attachment.

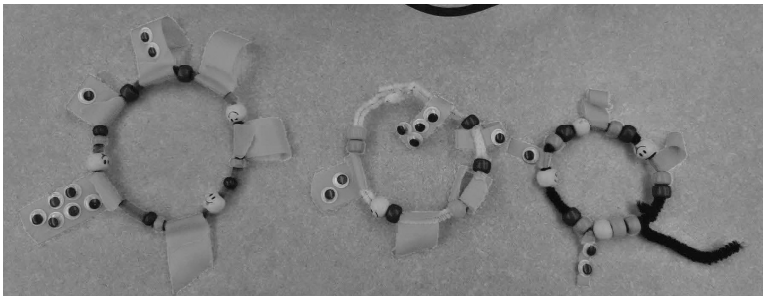
Example of a Physical Data Representation

The following data physicalization examples are shared activity and credible for as a pair, but we encourage you to think beyond these examples and the choices of materials.

Collected Data: Morning Walk

Figure A.22: Study Handout - Page 9

Materials: Pipe cleaners, art materials (i.e., beads with different colors and different emojis), and googly eyes



Layout & Mapping of the visualization: As a couple, they like to go for morning walks every day to keep themselves physically fit, so they decided to visualize their morning walk experience of a particular day.

Each circular loop represents the instances (from left to right), and they tried to show the distance they covered, the number of people they met, and the events for each data point in each instance. They encoded different instances using the circular loops using the pipe cleaners. The size of the circular loops represents the distance they covered in each instance. To calculate the distance for each attempt, they first calculated the total distance walked in that instance and then subtracted it with the total distance covered by the previous instance. The googly eyes represent the number of people they met while walking. They used two different types of beads where colorful beads illustrate the activities they were doing at that moment, and the emoji beads denote the topic of the conversation. The mappings of these beads are as follows:

- Activities they were doing: Walking → Blue; Discussing → Green; Standing → Orange,
- The topic of the conversation: Personal → Emoji with the tongue out; Family → Emoji with a wink; Professional → Emoji with a slight smile

Of course, this is an example that has some interesting degrees of detail, and as a couple, it is up to you to decide what details you will record. It is indeed painful to collect detailed data, but having more detailed data can inspire you to create a more interesting visualization.

N.B.: You are not allowed to create the visualization using a computer. You can use any materials that you think can be helpful to create a visualization collaboratively. Examples of the materials can be plasticine, paper folding, playdoh, clay, wood, sand, water, cardboard, lego blocks, matches, tree leaves, grass - whatever you like as a pair but make sure it supports collaboration.

Figure A.23: Study Handout - Page 10

Preliminary Training Session Dataset
HERB: 21-0310

Co-Visualization in a Family Setting

Preliminary Training Session Dataset

In this session, I (i.e., the researcher) will walk you through a training session, in order to help you understand the process of creating a meaningful physical visualization collaboratively. I am providing below a toy dataset about an example activity done in pairs. Note how the dataset relies on you collecting data several times (i.e., something that lasts a minimum amount of time and with multiple instances of data collection).

Scenario: Jack and Rose are a couple who previously participated in our research study. As part of this research, they had to decide what activity they would like to perform, so they planned to dine out in a Chinese restaurant together during the weekend. They went to the restaurant on the weekend and collected data about their overall restaurant experience. They were requested to collect data multiple times while performing the activity, so they used their cell phone's built-in timer and notes applications as tools for data collection. They decided to set a timer that would alert them every 10 minutes, and each time the timer alerted them, they recorded the data they had decided to record. It includes what they were doing in the restaurants at that time, the food they were eating, the taste of that food, the color of the food, and the pictures they captured. They captured these data in quite a few instances and tried to collect 4 or 5 rows of data (per attempt/instance) by spending 40 min to 50 min at the restaurant.

Data: The table below shows the format that Jack and Rose used to collect their data. Each row in the table has a timestamp and several attributes/dimensions.

Figure A.24: Preliminary Training Dataset - Page 1

	ATTRIBUTES						
DATA POINTS	Instances	What is Happening	Timestamp (YYYY-MM-DD hh:mm:ss)	The name of the food	The taste of the food	The color of the food	Photographs
	1	Eating	2021-11-10 07:45:25	Hot and Sour Soup	Savoury and Spicy	Dark yellow	
	1	Discussing	2021-11-10 07:46:32	Spring Roll	Crispy	Yellowish	
	1	Eating & Discussing	2021-11-10 07:48:39	Hot and Sour Soup	Savoury and Spicy	Dark yellow	
	1	Eating & Discussing	2021-11-10 07:50:44	Hot and Sour Soup	Savoury and Spicy	Dark yellow	
	1	Eating & Discussing	2021-11-10 07:53:10	Spring Roll	Crispy	Yellowish	
	1	Eating & Discussing	2021-11-10 07:55:12	Spring Roll	Crispy	Yellowish	
	2	Discussing	2021-11-10 08:15:36	House Special Chow Mein	Sweet and salty	Dark yellow	
	2	Eating	2021-11-10 08:19:15	Szechuan Vegetables	Spicy	Red and yellow	
	2	Eating & Discussing	2021-11-10 08:21:11	Szechuan Vegetables	Spicy	Red and yellow	
	2	Eating & Discussing	2021-11-10 08:23:33	House Special Chow Mein	Sweet and salty	Dark yellow	

Figure A.25: Preliminary Training Dataset - Page 2

	2	Eating	2021-11-10 08:35:57	House Special Chow Mein	Sweet and salty	Dark yellow	
	3	Drinking & Discussing	2021-11-10 08:55:16	Tangy Strawberry Slush	Sweet	Reddish	
	3	Drinking & Discussing	2021-11-10 08:57:58	Tangy Strawberry Slush	Sweet	Reddish	
	3	Drinking & Discussing	2021-11-10 09:01:49	Tangy Strawberry Slush	Sweet	Reddish	
	3	Drinking & Discussing	2021-11-10 09:03:37	Tangy Strawberry Slush	Sweet	Reddish	
	3	Drinking & Discussing	2021-11-10 09:05:22	Tangy Strawberry Slush	Sweet	Reddish	

Figure A.26: Preliminary Training Dataset - Page 3

University of Victoria

List of Sample Materials
HERB: 21-0310

List of Sample Materials

For this study, you will need access to physical materials such as plasticine, paper, playdoh, clay, wood, sand, water, cardboard, lego blocks, matches, tree leaves, and/or grass to create physical visualizations. You can either purchase some of these materials including a tripod, for which you are given a maximum amount of $75 or you can recycle what you already have at home. You are not allowed to create the visualization simply using a computer and digital tools such as Powerpoint or Excel. The below table offers suggestions on the strengths and limitations of some physical materials that you might consider using for constructing your physical visualization. For example, Lego Bricks are good for representing color and some specific shapes (e.g., square and rectangle), but you cannot easily create a free-form shape like you can with playdoh.

The below list is not exhaustive and comprehensive but serves as a way to think about materials before you select them for engaging in this activity. You are welcome to use materials we do not include in the table below:

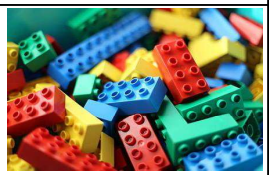
Materials	Pictures	Control over Shape	Control over Size	Types of Physical Actions
LEGO Bricks		**Rigid shape;**	**Rigid size;**	**Stacking;** **Patterning;**
PlayDoh / Modeling Clays		**Flexible shape;**	**Flexible Size;**	**Stacking;** **Patterning;** **Braiding;** **Rollable;** **Hanging;**

Figure A.27: List of Sample Materials - Page 1

Wooden Blocks		Rigid shape;	Rigid size;	Stacking; Patterning;
Pipe Cleaners		Flexible shape;	Rigid Size; Flexible Size (possible);	Patterning; Rollable; Pinning; Tying; Hanging;
Popsicles Sticks		Rigid shape;	Rigid size;	Patterning;
Beads		Rigid shape;	Rigid size;	Patterning; Stacking;

Figure A.28: List of Sample Materials - Page 2

Sticky Notes		Flexible shape;	Rigid size;	Pinning; Sticking; Patterning;
Board Pins / Push Pins		Rigid shape;	Rigid size;	Pinning; Tying; Hanging;
Wool / Yarn Or Sewing Thread	 	Flexible shape;	Flexible Size;	Patterning; Sewing; Rollable; Pinning; Weaving; Tying; Hanging; Pinning;

Figure A.29: List of Sample Materials - Page 3

Stones / Pebbles		**Rigid shape;**	**Rigid size;**	**Patterning;** **Stacking;**

Example of Tripod stand:

Tripod Stand (mobile phone not included)	

Figure A.30: List of Sample Materials - Page 4

Co-Visualization Research Template

Documentation Template

Group Number: _____

Figure A.31: Diary Template - Page 1

Planning, Recording &
Documentation

[approx. 2-3 hrs.]

Figure A.32: Diary Template - Page 2

Planning, Recording & Documentation

After going through the Study Handout,

1. **Please write down the one activity that you have selected to take part in together:**

[**NOTE:** Please select one task/activity that will ensure sufficient data collection. Remember that you need to collect data several times (i.e., something that lasts for a reasonable amount of time and with multiple instances of data collection)]

Figure A.33: Diary Template - Page 3

Planning, Recording & Documentation

2. What was the type of activity? (e.g., indoor, outdoor etc.)

3. How many hours did you spend on the selected activity?

Figure A.34: Diary Template - Page 4

Planning, Recording & Documentation

4. How and why did you select the activity (e.g., through discussion, it's one of your favourite activities, happens often, etc.)? Please explain the process elaborately.

Figure A.35: Diary Template - Page 5

Planning, Recording & Documentation

5. How did you collect the data? That is, what type of data did you collect together? What tool(s) did you use to record and/or store the data? Please include picture(s) or screenshots that illustrates how you collected the data. [NOTE: Please create a duplicate of this page if you require more space.]

Figure A.36: Diary Template - Page 6

Mapping, Construction & Documentation

[approx. 2-3 hrs.]

Figure A.37: Diary Template - Page 7

Mapping, Construction & Documentation

1. **Please list the material(s) that you are using for your visualization:**

[**NOTE:** The material you need can be gathered, recycled, or bought, which will be reimbursed up to **$75, including the tripod (if you do not have one)**. You will be compensated upon submission of purchase receipt. Refer to the List of sample materials for suggestions on the types of materials you can use.]

Figure A.38: Diary Template - Page 8

Mapping, Construction & Documentation

2. Capture 1-2 picture(s) of the materials that you selected for constructing the visualization. Upload the picture(s) here:

[NOTE: Please create a duplicate of this page if you require more space.]

Figure A.39: Diary Template - Page 9

Mapping, Construction & Documentation

3. What mapping have you decided on? That is, how does the material(s) that you selected represent the different aspects of your data? Did you consider any alternative option(s)? If so, what?

Figure A.40: Diary Template - Page 10

Mapping, Construction & Documentation

4. Explain how you decided what visualization to construct and how you intend to collaborate while building it.

Figure A.41: Diary Template - Page 11

Mapping, Construction & Documentation

5. Record the entire session of collaboratively constructing the visualization in a video and make sure the audio is included as well. Upload the video(s) here:

[NOTE: In case you speak more than one language at home, please either do the exercise in English or provide a translation in English during the session. Please create a duplicate of this page if you require more space.]

Figure A.42: Diary Template - Page 12

Mapping, Construction & Documentation

6. Provide multiple pictures and a detailed video with voiceover that describes the different aspects of your visualization. Upload the pictures and video here:

[NOTE: In case you speak more than one language at home, please either do the exercise in English or provide a translation in English during the session. Please create a duplicate of this page if you require more space.]

Figure A.43: Diary Template - Page 13

Mapping, Construction & Documentation

7. Did you make any changes to the material list you initially planned to use? If so, which new material(s) did you use and why?

Figure A.44: Diary Template - Page 14

Post-study Interview

[approx. 1 hr.]

Figure A.45: Diary Template - Page 15

Post-study Interview

When you have completed the construction activity, please send us an email at dibyaprokash@uvic.ca so that we can arrange a post-activity interview session with you over Zoom.

At this time, **please also share with us the data you used for the visualization. This data can be shared with us in any format that is easy for you.** For example, in the form of a picture or you can share an excel sheet. You can either paste a link to your data file here or you can send it to us as an email attachment.

Figure A.46: Diary Template - Page 16