Knitting Interactive Spaces: Fabricating Data Physicalizations of Local Community Visitors with Circular Knitting Machines

Lee Jones
lee.jones@queensu.ca
iStudio, Queen's University
Kingston, Ontario, Canada

Greta Grip
greta.grip@gmail.com
Independent Artist
Ottawa, Ontario, Canada

Boris Kourtoukov
boris@kourtoukov.com
Independent Artist
Oslo, Norway

Varvara Guljajeva
varvarag@ust.hk
Computational Media and Arts, Hong Kong University of Science and Technology (Guangzhou)
Guangzhou, Guangdong, China

Mar Canet Sola
mar.canet@tlu.ee
Baltic Film, Media and Arts School, Tallinn University
Tallinn, Estonia

Sara Nabil
sara.nabil@queensu.ca
iStudio, Queen's University
Kingston, Ontario, Canada

Figure 1: *The Life of a Building* (2021-2022), commissioned by the Ottawa Art Gallery, knit visitor data at the gallery during the pandemic recovery year from July 2021-2022. An ultrasonic sensor placed at the front entrance detected when individuals walked into the gallery and in response instructed a circular knitting machine to knit a row of stitches. The colour of yarn (changed each month) physicalized visitor data and "piled up" over the year.

ABSTRACT

Innovations in digital fabrication technologies are increasingly enabling artists and designers to create data physicalizations in real time. In this paper, we discuss how we adapted a circular knitting machine to physicalize visitors at a local art gallery during the pandemic recovery year. To evaluate this year-long installation, we conducted design critiques with 15 individuals including those who worked in the building and lived alongside it for a year, as well as subject matter experts. We then iteratively worked with 11 of those individuals to gain insights for re-deploying the visualization for interpretation. Overall, this paper contributes long-term reflections and recommendations for using digital fabrication for real-time data physicalizations.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; **Visualization**.

KEYWORDS

machine knitting, data physicalization, textile fabrication, computational fabrication, digital fabrication, personal fabrication

ACM Reference Format:
Lee Jones, Greta Grip, Boris Kourtoukov, Varvara Guljajeva, Mar Canet Sola, and Sara Nabil. 2024. Knitting Interactive Spaces: Fabricating Data Physicalizations of Local Community Visitors with Circular Knitting Machines. In *Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '24), February 11–14, 2024, Cork, Ireland*. ACM, New York, NY, USA, 14 pages. https://doi.org/10.1145/3623509.3633359

1 INTRODUCTION

Digital fabrication technologies are increasingly enabling designers to incorporate data sources in the design of physical, tangible objects. In this paper, we explore how textile fabrication machines can be used to create real-time data physicalizations, as well as the constraints these physicalizations experience during long-term deployments. We discuss the making and evaluation of an aesthetic

TEI '24, February 11–14, 2024, Cork, Ireland

ACM ISBN 979-8-4007-0402-4/24/02.
https://doi.org/10.1145/3623509.3633359

data physicalization called *The Life of a Building* (2021-2022) [48], commissioned by the Ottawa Art Gallery, which aimed to visualize visitor data during the pandemic recovery year (see Figure 1). This installation used a circular knitting machine, the *Circular Knitic* [29], connected to motion sensors in the gallery. When an individual entered the gallery, this caused a row to be knit on the physicalization. By changing the colour of the yarn each month, the result is a long, colourful, knit tube that visualizes the fluctuations, the waves and shutdowns, during the year.

1.1 Motivation

This installation was motivated by the pandemic context with a desire to document the pandemic recovery year. The COVID-19 pandemic caused disruptions in many industries, including creative and cultural industries and institutions [51]. UNESCO reported that 90% of museums and cultural institutions had to close their physical spaces during lockdowns, resulting in the cancellation or delay of events and exhibitions [89]. As a result, many museums explored alternatives such as moving activities outside [50], and shifts to digital-first strategies [52, 70]. When physical spaces could re-open, physical distancing restrictions often limited the amount of visitors that could attend, or felt comfortable doing so, and resulted in lower attendance rates (a key metric for many of these institutions) [70].

To celebrate the re-opening of the Ottawa Art Gallery after provincial pandemic closures, the gallery commissioned the first and second authors to visualize visitor data to better understand the changes happening within the physical building [8]. To do so, we used textile fabrication to visualize that data in real time, while also allowing hybrid participation to highlight the ways that the digital and hybrid events during the pandemic made art events more inclusive and expanded the gallery community to those that lived outside of the city. The installation *The Life of a Building* was launched in July 2021 when the gallery re-opened with the goal of visualizing visitors during the pandemic recovery period and ended one year later at the end of July 2022.

1.2 Research questions

As design researchers, we approached this project with two roles: commissioned artists engaged in critical design, but also as HCI researchers with an inquiry-based practice. Although knitting machines have been used in previous work [35, 49, 55], longitudinal studies reflecting on the public reception of such data physicalizations (beyond a brief encounter or lab study) is underexplored. Textiles, and especially knitting as a fabrication method, can be fabricated continuously, which provides unique opportunities when it comes to data physicalizations with ***real-time*** data capture where the physicalization results (and how much material will need be fabricated throughout the deployment) are unpredictable. Thus, we seized this opportunity to address two design research questions:

- **RQ1**: What are the constraints and challenges that will arise while physicalizing real-time data with textile fabrication?
- **RQ2**: How do people experience data represented through a textile medium over a period of 1 year?

1.3 Contribution

In this paper, we provide insights on developing textile data physicalizations based on reflections on the year-long installation. To do so, we conducted design critiques with 15 participants at the end of the installation year to understand the impact that the work had for those working within the building, as well as the benefits and limitations of visualizing data in real-time using textile computational fabrication. We followed this with a group discussion with 11 of them to unfold key insights for redeploying the work for interpretation. Hence, this paper has two main contributions including:

(1) **Reflections on long-term usage**: We discuss the impact the installation had for individuals working in the building, and their salient reflections on living alongside the installation.
(2) **Iterations on the installation for re-deployment**: We discuss the re-deployment of the data physicalization for interpretation.

2 RELATED WORK

This project is grounded in the literature of data physicalizations, aesthetic data sculptures, and visualizing data in context.

2.1 Data physicalizations

One of the most cited and accepted definitions of a data physicalization is *"a physical artifact whose geometry or material properties encode data"* [46]. Digital fabrication, which is the ability to fabricate tangible objects from digital patterns [26], has made it more feasible and accessible to take digital data sources and incorporate or transform them into physical objects [37, 46]. The unique opportunity with data physicalizations is that they leverage our physical skills, embodied cognition, and understanding of how we move through the world [46]. For example, in previous work comparing 2D and 3D visualizations, individuals remembered examples from the data better in 3D [45, 85]. Physicalizations can also leverage skills such as our understanding of space, and the ability to leverage non-visual senses such as those of touch, taste [56, 91], or smell [5].

Data physicalizations have unique constraints when compared to data visualizations. They must deal with physical constraints such gravity, structural stability, and the fact that they take up physical space [3, 46, 87]. In the context of digital fabrication, designers need to ensure that materials won't run out during the process of fabrication [46], and often have a lack of control over the environment that the data physicalization is placed within [90]. For data physicalizations that use digital fabrication, many of the difficulties and challenges come from the "rendering" process, which will vary depending on the material and medium of fabrication [20].

Most data physicalization research within HCI focuses on novel devices with updatable physical displays. There are several common ways that these displays provide updates, such as linear actuators or pin-based displays for creating shape-changing surfaces [22, 23, 61, 68, 80]. Another common approach is assemblies, which are small parts or tangible bits where individual objects act as a swarm to create a data physicalization [57, 86] or can be used as a kit of parts to create one [41]. Other well-known approaches include string-based visualizations [21], shape-changing objects [15, 69], or the use of non-screen tangible lighting [79, 84].

2.2 Data sculptures

Another research direction is the exploration of aesthetic data physicalizations or "data sculptures" [94], which have both functional and expressive purposes. Their aesthetic characteristics can support an ambient presence where the object, rather than looking like a "device", looks like something that would belong in someone's home [38, 66, 67, 80]. Here the focus is on the materiality of data physicalizations, often leveraging hybrid craft digital fabrication processes [43, 97]. Craft practitioners, designers, and researchers can either develop a new skillset, such as that of 3D printing clay [16], or can use augmented digital tools to support them in the hand-crafting process [72]. Aesthetic data physicalizations have been used for a diversity of purposes, such as to celebrate positive memories [78] or commemorate and document personal challenges [17, 18]. Expressive and crafted data physicalizations are increasingly being researched as a way to make data recording and physicalization accessible to novices [1, 36, 88, 90, 93].

2.3 Data in context

The recent concept of physecology [83] expands the study of data physicalizations beyond the object to also include the physical context and environment. As highlighted by Sauve et al. [83], there is limited work on data physicalizations that explore visualizing the data of physically co-located communities [6, 25, 47, 53, 58, 60, 77]. Researchers have discussed the concept of "situatedness" with data physicalizations [3, 12], where the data is presented for interpretation in the location or environment that the data relates to. The goal with situatedness is to connect people with the places and spaces they inhabit to encourage reflection and greater understanding [12]. Researchers have also explored adding qualitative context to quantitative data physicalizations to help individuals further reflect and interpret the data [40].

2.4 Textile data physicalizations

In this paper, we further explore an aesthetic data physicalization using a textile digital fabrication machine. To date, there has been some work in data physicalizations using textiles, but the focus is often presenting data after collection, rather than physicalizing real-time data. Designers have visualized bio data [31–33, 49], personal libraries [35], economic data [54], and satellite data [76]. Individuals can also hand-craft their own data to be interpreted by others [24]. For example, there are several knitting projects like *Stitching the Curve* [63], and *The Tempestry Project* [4, 75], where individuals have hand-knit data to bring attention to contemporary issues. In contrast, our design uses digital fabrication, and explores how fabrication can happen automatically, in order to present unpredictable live data.

Previous research in this area has explored how knit structures and patterns can in themselves be "stateful" [64], with for example patterns for pushable bubbles, or pullable loops, and enable individuals to document their data in expressive real-time ways through tangible manipulation. Digital fabrication machines can also be adapted to incorporate live-data, such as previous work on exploring undetermination with digital looms [2], or changing the colour of yarn during fabrication [32]. Textile digital physicalizations, due to the ways that textiles can be continuously rolled or piled up, can be almost endless rather than being constrained by space [62] (in comparison to the constrained space of a 3D printer or laser cutter bed). This is a process we explore further in this current work.

3 THE LIFE OF A BUILDING

In this section, we describe the setup and implementation of an installation that aimed to visualize and physicalize the community of a local gallery by creating rows of stitches as individuals entered the physical space (Figure 2) or interacted online (Figure 3).

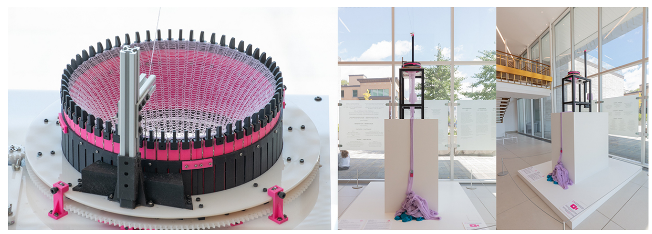

Figure 2: Our project installation on display during the second month (August 2021). The knitting machine can be seen from below as well as from above as individuals go up the stairs and approach through the atrium balcony. Images courtesy of Justin Wonnacott.

3.1 Physicalizing the community with textiles

The main goal of this installation was to physicalize the community of the Ottawa Art Gallery through a textile medium. During the pandemic, textile crafts became a source of comfort for many individuals, and in this installation we wanted to knit together the community as it came out of the pandemic shut downs.

During the gallery re-opening, and due to local physical distancing guidelines, individuals who went to the gallery would often not see anyone else in the space during their visit. This was due to limitations on the number of visitors allowed to register to visit for any given hour. In response, the artwork aimed to physicalize and record each visitor entering the space. Although visitors might not see others during their visit, they could see the community returning through the data physicalization and rows of stitches.

3.2 In-person interaction

We created a bright pink box at the gallery entrance that contained an ultrasonic sensor connected to a Particle Wi-Fi microcontroller [42]. When an individual entered the building, the sensor would recognize when an individual passed through the lobby entrance and then would send that information to the microcontroller's cloud data storage, activating the knitting machine to create a row of stitches.

The ultrasonic sensor resembled a pair of eyes and so we painted the sensor box with a matching smile. Together, these features aimed to provide visitors with an awareness that this box was monitoring them. Next, they would see wayfinding signage with an icon of a pink yarn cone (matching the sensor box), leading them up the stairs, and through the gallery to the knitting machine on the other side. In this way the installation aimed to bring individuals through the space by having the sensor at the entrance and then signage guiding them to the machine on the other side of the building.

To knit the community, we adapted the *Circular Knitic* (2014) [29, 30], an open hardware circular knitting machine created by the artistic duo Varvara & Mar (Varvara Guljajeva and Mar Canet Sola). In the spirit of maker culture, the duo released the files for reproducing the machine using digital fabrication machines (such as 3D printers and laser cutters). Using the files provided on GitHub [29], we were able to get the machine created by a local prototyping studio. We then customized the machine to use the Particle Wi-Fi microcontroller [42] so that we could transmit sensor data to it wirelessly. We chose a circular knitting machine for this installation, rather than a flatbed machine, due to the ability to make a continuous record in the round.

The knitting machine was placed on a plinth with a weight attached to the knit tube that would pull the yarn down enabling it to continue to make new rows of stitching. Due to the architecture of the building, visitors could also go up the stairs to see the work from above. In this way, visitors could see the textile fabrication process from multiple angles (Figure 2). To interpret the artwork, there was a text panel placed beside the installation (Appendix A).

3.3 Online interaction

Alongside measuring individuals entering the physical space, the gallery wanted to highlight some of the insights from their pandemic programming, and how virtual events expanded the Ottawa Art Gallery community to beyond its physical location. For example, the gallery did many virtual artist talks, tours, and workshops. As a result, we developed a hybrid installation where individuals could also virtually add stitches to the physical record.

On the the Ottawa Art Gallery's website, we created a microsite (Figure 3) where people could click a button (during gallery opening hours), and then watch the knitting machine stitch their row through the Youtube live stream (Figure 4). The livestream was created with an overhead webcam connected to a Mac Mini device running OBS (Open Broadcaster Software) [74], an open-source live streaming solution.

4 RESEARCH APPROACH AND METHODS

In this project, we adopted a Research through Design (RtD) approach that viewed the produced knit data as a provocative artefact for research inquiry as opposed to an end-product. The project life cycle iterated between fabrication, visualization, and physicalization on one end, and collaborative exploration, evaluation, and reflection on the other end. Those two intertwined strands started from our research questions, implementation and deployment, all the way to the evaluation through an expert user study followed by the re-installation based on user feedback and design critique. At the end of the year-long design research project, we gathered user feedback in a two-part study: 1) design critiques for reflections and recommendations; and 2) a group discussion for re-deploying the physicalization, see Figure 5.

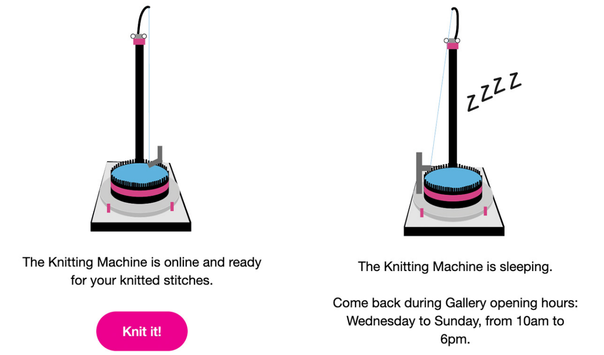

Figure 3: During gallery opening hours, virtual users could click a button on the Ottawa Art Gallery's website to create a row of stitches and then watch the machine knit those stitches in the live stream.

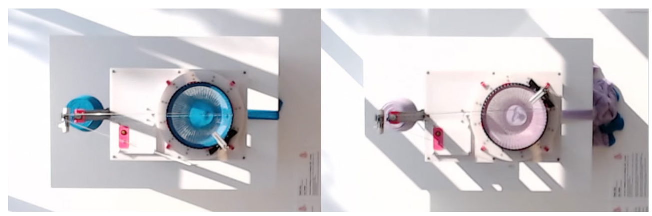

Figure 4: View of the artwork through the online live stream.

4.1 Research through Design

As design researchers, the Research through Design (RtD) [95, 96] approach supports our creative inquiry and empowers us with thinking about research through designing and reflecting on our evolving data physicalization artefact. The goal is not an end-product or "design", but the "designing" and fabricating the artefact in the real-time, bringing otherwise invisible collected data about our presence into existence. In addition, we relied on a collaborative design exploration across stakeholders [7]. This approach fueled our iterative process that flowed organically as we learned from each step how to better represent, visualize, and physicalize the data in a *soft, malleable, and textile* form.

4.2 Part 1: Design critiques

The aim of design critiques was to understand how participants experienced the physicalization, and to gather suggestions for future iterations. In previous work, design critiques have been proposed for evaluating aesthetic ambient displays [65], studio-based making [73], RtD artefacts [13], and especially for works created in a visual arts context [34].

4.2.1 Participants. The first part of our study (Part 1) was conducted with gallery employees and external experts with the dual goal of understanding the long-term experience of the installation as well as gathering recommendations on how to improve the installation for future iterations. We recruited 15 individuals (P1~P15) for design critiques. Participants 1~11 all worked at the gallery and were able to reflect on what it was like to have the installation at

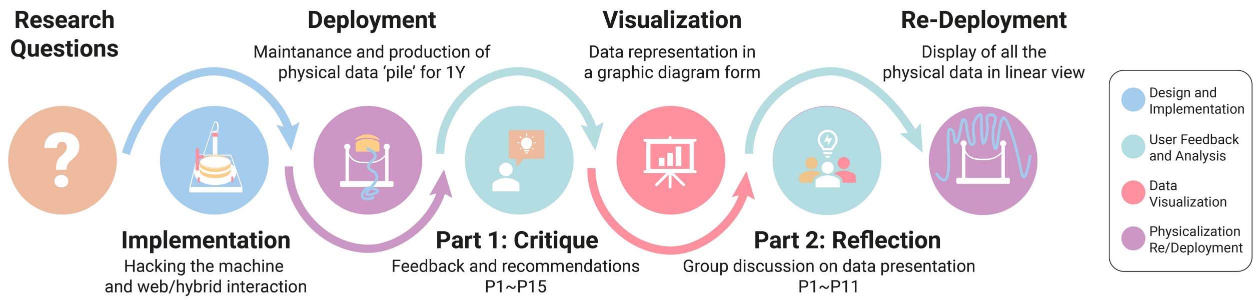

Figure 5: Our design process showing the project's life cycle starting from research questions, implementation, and deployment, to evaluation, and the re-installation based on user feedback.

their workplace for a period of 1 year. Participants 12~15 did not work at the gallery but had expertise in useful areas for evaluating and discussing the installation: one participant leads an information visualization research team, one is a researcher in exhibition design, one is a professor in theatre set design, and one is an arts educator. All participants were regular museum visitors (pre-pandemic). All participants were local residents of the same city where the installation took place. The goal in having this mix of participants was to both gather critiques on the long-term impressions of living alongside the artwork for a year, while also gathering first impressions from the visitor perspective.

4.2.2 Procedure. These sessions were conducted virtually due to COVID-19 restrictions. The gallery placed a bench beside the artwork, and participants were asked to go to the art gallery, locate the artwork, and then join a Zoom call [14] through their phones. We used Zoom so that participants could show us what they were looking at if needed, as well as for transcription purposes.

For our expert participants who were seeing the work for the first time (P12~P15), once they joined the Zoom call [14] they were first asked about their interpretation of the work based on what they saw and the textual panel. This included how they located the artwork, their initial impressions on what was happening, what caused a row of stitches to be created, and how they interpreted the pile of knitting at the bottom of the plinth. After their initial impressions, we then described what caused a row of stitches to be created (someone entering the gallery or clicking a button online) and the changing of the yarn colour each month, starting in July 2021 and ending at the end of July 2022. For all participants (experts and individuals who lived with the physicalization for a year) we then asked them, knowing the setup, on their impressions of the year based on the knit data (most visitors, least visitors, etc.). For participants who had lived with the artwork over the entire year (P1~P11), we then asked them about what that experience was like. Then we did a design critique where we discussed their recommendations for the next iteration.

4.3 Part 2: Visualization and reflection

Based on the qualitative data collected in Part 1, we engaged in several attempts to visualize the sensor data in meaningful ways to facilitate interpretation and critical reflection.

We physically measured each of the knit "months" and created a data spreadsheet of the "length" of each month, representing the interaction frequency throughout the year. First, we did a straightforward bar graph that shows how "long" each month was knit, representing the number of interactions per month. Even by adding respective yarn colour and transposing into horizontal bars, we realized that this is a mute representation of the data that doesn't reflect the longitudinal, textural, and aesthetic qualities of the data visualized.

Finally, our visual design evolved into an annotated illustration of yarn balls (as legend) and a long knit tube (similar to the actual knit artefact) divided into colour-coded sections (in a "knit" pattern) and "lengths" mapping the physical measured length of each month (Figure 6). Although as a graph this might seem to some as less "scientific" (as with many other design research approaches), it proved to be a better way to represent and reflect on the data in subsequent correspondence with stakeholders in Part 2.

With this aesthetic data visualization, we conducted a follow up session with the subsection of participants who worked at the art gallery (P1~P11)). We used this population so they could reflect on what occurred in the previous year using the linear visualization and could annotate their own memories onto it.

We conducted the group meeting through Zoom [14]. Before this meeting, we placed the visualization (Figure 6) on an online whiteboard (Miro). We then went through and as a group added virtual sticky notes to the visualization based on what individuals experienced throughout the year. We then asked the group questions about what it was like to use the visualization to reflect on the year it visualized, and the benefits and limitations of seeing the data in this way.

4.4 Analysis

We used automatic verbatim transcriptions [14] for analysis. These automatic transcriptions were verified and edited by the first author by comparing them to the video recording. We then performed reflexive thematic analysis as described by Braun et al. [9–11] that aims to generate analysis by leveraging the lens or perspective of the researchers; in our case, the lens focused on understanding the constraints of textile data physicalizations. This was an iterative process where codes were developed over several stages. First, we imported the transcripts into MaxQDA [27] for analysis, a software

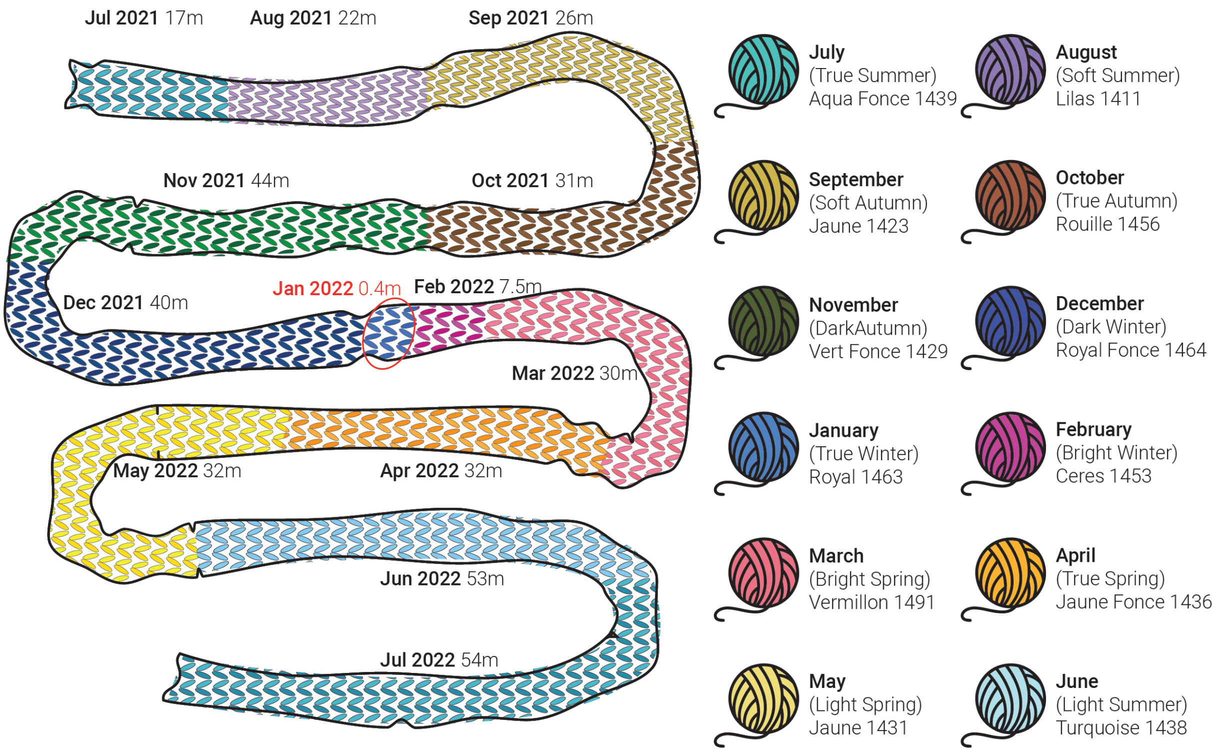

Figure 6: The illustrative summary of the data that was used for discussing the results and how the artwork would be re-deployed for interpretation. The illustration demonstrates when gallery visitation increased, and when it decreased during closures (such as the closures during January and February 2022).

that enables easy iteration, note taking, and collaboration for qualitative research. This first involved familiarization with the data by reading the transcripts over several times and taking notes, and then an initial coding of the complete dataset with line-by-line data-derived codes for each quote that emulated the language our participants used. With this initial list of codes, we then grouped them into central organizing concepts to create narrative themes around the user experience of the textile data physicalization. These themes and subthemes were reviewed to create a thematic map with sentence summaries of each theme and subtheme. This thematic map was then used to develop final themes on recommendations for future iterations of the artwork with quotes and data extracts to further demonstrate our findings.

4.5 Redeployment: Public data presentation

As a final step in the life cycle of this project we brought the physicalization back to the community and deployed it again for interpretation with insights from our study findings. In May 2023, the textile data physicalization was hung again in the main atrium of the gallery as a physical and tangible manifestation of the invisible interactions with(in) the building.

5 FINDINGS

Our participants discussed the textile data physicalization in relation to five themes including: the ability to create an ambient awareness of visitors, demonstrating the fabrication process of physicalizing data, issues with the cause-and-effect relationship, the importance of context for data physicalizations, and a separate step needed for data presentation.

5.1 Soft and slow ambient awareness of visitors

The knit physicalization provided an ambient awareness of visitors to the space both through the intended textile physicalization as well as through the resulting sounds of fabrication as the motor swirled and the machine stitched new rows.

5.1.1 Soft data is comforting. Our participants discussed the benefits of textile data physicalizations being soft *"material expressions of data"* (P14) that provided *"a different way of looking at it"* (P12). The use of a knit medium was described as providing comfort to viewers by being *"bright and cheerful and soft, in an otherwise stressful time in our lives"* (P3). The pile of stitches invoked playful feelings – *"the lump is really awesome [. . .] you just want to like, jump into it, which is very comforting"* (P2). Even though individuals could not touch the work, textile knits were described as familiar. As P9 states: *"It's certainly a much more human and gentle way to present the data. [It's] what we wrap our bodies in. Textiles are familiar to all of us"* (P9). The textile visualization also helped to make the data more tangible and concrete: *"we usually think of data as being very cold and disconnected from us whereas this felt immediate. It felt like we embodied those rings of beautiful colour. I like that idea that it's* *something soft and immediate and that we could connect to it, and could understand that it was us that impacted it as opposed to some of the nebulousness that makes up data in our world* (P8)." Though participants couldn't touch the data, they described how seeing the textile physicalization still brought out those tactile associations of soft and comforting.

5.1.2 Recognizing the sounds of fabrication. A more ambient aspect of the artwork was the sound the machine made as it knit stitches and fabricated rows in response to people entering the building. *"There's the sound, but the sound is more of a background sound until you realize that it goes on and off"* (P12). Over time, individuals who worked in the building started to recognize the sound as part of the ritual of entering the building. *"Going up the stairs I'd hear it [the machine] going [. . .] and I'd be very conscious of making that noise every time I came in[to the building]"* (P2). Because the machine was on the other side of the building, it also made employees aware of when people were entering and to anticipate their arrival: *"I would open up the shop every morning. I would hear the machine start going and then I would know, I would kind of anticipate, visitors coming upstairs. So, it became like a way of knowing that people were there* (P11)." Though the sound of fabrication was not an intended part of the physicalization, our participants discussed how it created an awareness of individuals moving through the space.

5.1.3 Value of returning to it throughout the year. Our participants described the installation as *"a slow piece of art"* (P12) that gave them an ambient awareness of visitors throughout the year. Due to pandemic and physical distancing restrictions there were often very few individuals in the gallery at any given time, and individuals came alone or in smaller groups than pre-pandemic. The installation acted as a visual reassurance that though individuals came alone, they could still see the other visitors through the installation. For individuals who worked in the building daily they felt the *"impact of the actual knitted output that [they] would see every day"* (P11) and seeing *"the length of the sock just get longer"* (P3). Individuals who checked in on it throughout the day, such as gallery security, enjoyed seeing the changes. As P11 discussed: *"It was really cool to see that the security team was really interested in it. I don't think I've ever gotten so much feedback from the security team about an artwork as I did from this one."*

Though the physical distancing environment in the gallery gave the impression of the gallery being empty – the installation enabled individuals to see the collective of gallery visitors. *"Sometimes it seemed like there weren't visitors, but I would kind of check [the installation], I was using it as a visual log, and we were like: 'Okay, people came this month'"* (P9). Gallery employees also worked from home to a greater extent, and enjoyed seeing the updates to the visualization every time they came in and to see what happened while they were away. As P3 states: *"Because we were all working at home most of the time, we didn't really have a sense of the activity in the building. It was nice to come and see there were a lot of visitors. We can see all the stitches."* The fluctuations in the knit record also gave employees an impression of how events happening in the city were impacting gallery visitation. As P9 discussed: *"I like the idea of artwork that changes [...] it's different depending on what's happening around it. I was thinking a lot about the pandemic and the constant closures and the uncertainties and watching these bands of colour and the widths. It's an interesting approach to have something that isn't stable, and it's continuing to become".*

5.2 Showing the fabrication process

Having a data physicalization that was fabricated in real time brought attention to the fabrication process itself.

5.2.1 Data physicalizations can help with understanding fabrication. By using textile fabrication to create the data physicalization in real time, viewers were able to watch the fabrication process of the machine creating rows of stitches. They were more interested in watching the machine fabricate and physicalize data, rather than the data itself, i.e. the result. As P3 summarizes: *"The benefit came from walking by, and seeing it actively stitching, not so much seeing the pile. Seeing it moving made the building feel very alive".* This focus on the fabrication process, rather than the data being physicalized, came from constraints within the fabrication process of knitting (i.e. the reliance on gravity and weights to create a new row). As P13 discussed the knit visualization: *"It's coming down and creating a natural piling up [. . .] the natural pile of gravity".* Our participants discussed their attention being drawn to the fabrication process and spending time watching it to see how the machine worked: *"I can see the mechanism for making the loop [stitch], I can see the string slowly going up, you know around and up the mechanism, I get a sense that the weight is there to keep it pulling down"* (P14). For our participants the act of fabricating and recording the data gave them a sense of the real-time activity in the space, rather than the history of what had come before in the knit record.

5.2.2 Enable viewers to see the fabrication process in detail. The architecture of the space also enabled this focus. By having the artwork on the stairwell, it meant that individuals could look at the work from below or could climb the stairs to see the machine from the top. Participants mentioned wanting to get even closer to the machine to be able to watch the mechanisms and recommended further highlighting the fabrication process by enabling participants to get a closer and more detailed view of the machine stitching. As P15 summarizes: *"It was hard to see from that distance. To improve it [I recommend] having a closer view of the actual looping over. I wasn't really satisfied with seeing that process [from afar]."* This demonstrates how the scale of the installation impeded participants from getting close and examining the fabrication process.

5.3 Distance creates confusion

Though our installation aimed to capture and encourage movement through the space by having the sensor and knitting machine on opposite ends of the building, participants highlighted the way that this distance made it harder to understand the interaction.

5.3.1 Confusion over cause and effect. All participants seeing the work for the first time discussed barriers to understanding what the data physicalization was visualizing. Due to the colour variations, they understood that it was visualizing data (as P14 states *"I have a sense of a sort of partial set of data on the ground"*), but what it was visualizing wasn't immediately clear. As P12 summaries, *"At first it wasn't clear, [and then] you read the interpretive panel and it suggests that your interaction has some influence on it. So, then I extrapolated that there must be some movement sensor".* This feeling of uncertainty, and that they had to "*guess*" what it was measuring, was shared across all of our first-time interviewees. As P13 states: *"It seems like it's movement within the space so I'm guessing it's as people enter?"* Individuals relied on the interpretive panel to infer what the interaction was and felt that the textual description was not specific enough. As P12 summarized: *"It wasn't clear why it's turning on and off, like it wasn't clear because it says it's an interaction, but it doesn't really tell you what the interaction is."* P15 echoed this sentiment: *"I know that it is activity at the gallery, but at what point that was being measured wasn't really clear."*

Part of the confusion was understanding the cause and effect. What was being measured specifically (i.e. where and what the sensor was), as well as the impact of that measurement on the knit record. *"What's an individual? Is an individual one little loop [i.e. a stitch]? Is it the entire group going around [i.e. a row]? When I look at it I don't get a sense of scale"* (P14).

To fix this, our participants recommended including more transparency about how the data is collected and the scale of each interaction. As P14 summarizes: *"There is a real lack of transparency for the data collection process. You need to make those things more explicit for your audience. You need to craft a story as to what you want me to look at [...] make it as clear as possible"*. Solutions included mentioning where the sensor was placed in the description; drawing more attention to, and explaining, the movement sensor at the entrance of the building; and being explicit that each person measured was a row of stitches.

5.3.2 Encourage active rather than passive engagement. To get from the sensor at the front entrance to the knitting machine required individuals to notice and follow the wayfinding signage up a flight of stairs and down a hallway. Our participants recognized the wayfinding signage on the floor to the machine, (*"At the front door, we saw clearly on the steps the instructions to follow the icon, so it was no problem at all"* (P15)), but often missed the bright pink sensor box at the gallery entrance (*"I didn't notice it"* (P3)). As P2 summarizes, *"Because the sensor was at one entrance and the artwork was at the other [...] I kind of forgot about the sensor"*. Our participants recommended making the interaction more active by having individuals perform an action (such as opening a labeled door) as they walked into the building rather than passively measuring them with a motion sensor. By forcing more active participation, individuals would become more aware of what the machine is measuring and the cause-and-effect relationship. This was emphasized by positive comments on the direct interaction through the button on the gallery's website: *"So what the kids like to do, just because it was like the direct interaction, was to go on my phone on the website and trigger the machine and see it instantly knit from my phone. That direct interaction was great"* (P10). Overall, our participants recommended giving visitors a more active role in order to make the cause-effect connection stronger.

5.4 Providing context

Our participants discussed the challenges with contextualizing the textile data physicalization.

5.4.1 Importance of interpretive panel and being told how to 'read' the visualization. Our participants seeing the work for the first time needed the interpretative panel to understand what they were looking at – *"[I] only get that by reading the panel"* (P13). Viewers wanted more *"direction [...] on how to make sense of the data"* (P14). They discussed the importance of data storytelling and telling viewers how to interpret the work or what specifically to look for. As P14 summarizes: *"there's so much potential, there are so many stories here, but I want [you] to lead [me] through the story you are trying to tell"*. Another approach could be adding leading questions of what to look for. *"If you get just a little hint, it doesn't give you the answer, but it helps you look at it from a different perspective that you might not have had"* (P15). By providing this context individuals can then use the data and *"mobilize it"* (P14). As it was, the live installation featured the collection of data, but didn't provide viewers with a way of interpreting and making sense of the result.

5.4.2 What does each colour reference? As mentioned earlier, the rings of colour signaled to visitors that they were looking at a visualization (*"I knew that each measured a set amount of time"* (P12)), but they required more information on what each colour referenced. Immediately, they wanted to correlate the colours to a time of the year – *"you're looking to see this summer month, or a winter month"* (P15). Initially we chose a rainbow of colours to celebrate the re-opening of the gallery, but our viewers wanted the colours to be more literal and tied to the period of the year. Even after being told the colour of the starting month, and the colour of the last month (the same shade of blue for July 2021 and July 2022), individuals had a difficult time making connections between colour and month. For example, when asked about the fluctuations throughout the year, they would say there was a lot of one colour or less of another colour, rather than saying the month or time-period. They were able to interpret that areas with more of a single colour were when pandemic restrictions were lifted but were not able to connect the colours to their respective month.

5.4.3 What was going on at the time? To make sense of the data, participants wanted more context – *"I kept wanting to see it in relation to other data"* (P10). For example, P14 suggested *"diagramming things that were happening with the Ottawa Art Gallery and within Ottawa in terms of COVID and other sorts of things"*. Our participants suggested adding ways to annotate the knit data with markers or pins to be able to overlay a timeline on the knit physicalization. The visualization could also be annotated by the individuals creating the data with their movements to highlight that *"every point of data is someone's personal experience"* (P14).

5.5 Data fabrication versus presentation

Our participants discussed how, with the focus on the knitting fabrication process and the pile of knit data, the installation showed the process of data collection, rather than data presentation. As P14 summarizes, *"in many ways this installation is not about me and it's not about my understanding. This data is really the process of collection, and then there's also [a separate process for] data visualization for presentation purposes"*. Our participants discussed how data presentation would require the knit data physicalization to be shown in a different way.

5.5.1 The pile of knit data covers months. The main reason why individuals could not use the knit visualization to understand and interpret the data was because the fabrication process created a pile of data which hid previous months – *"[it] is so jumbled up and just sort of piled on top of one another"* (P14). At first the data created a mountain shape, with each month on top of the other, and where months could be compared, but by May the pile had fallen over. As P2 summarizes the change, *"As the month went on, I found it difficult to get anything from that data when it fully slumped over. I couldn't even see all the colours anymore"*. This negatively impacted the ability to read the visualization in a linear way – *"the way it's laid out it seems to be spilled over to the side, so it doesn't seem linear"*. There were also two months (January and February) where shut downs occurred and resulted in very small amounts of knit rows that were completely covered by the knit months that followed them. As P15 describes, *"I was looking for 12 [months] so there needs to be two more colours [hidden] here"*.

5.5.2 Viewers want to explore and compare. Along with the excitement around the data collection process, participants also wanted the data presented in a way that it could be understood. As P11 summarizes *"I think people are excited, not only in participating in the moment, but kind of knowing the whole story"*. To do so, our participants expressed a desire to touch the knit pile and to stretch it out and see it as the linear tube of knitting. As P3 discussed, *"I really want to see it all stretched out to really get a sense of how long it is, because it's hard to tell when it's all bundled up in a pile"*. The art gallery context prevented them from doing so, *"there's the suggestion that I shouldn't be touching this since this has been marked off"* (P14). To support the ability to explore and understand the visualization, our participants recommended displaying it in a linear way by, for example, *"displaying it longitudinally around room"* (P15) or to have it *"go up and loop over or to somehow activate [the area] above"* (P9).

5.5.3 Annotate data in real-time. Participants enjoyed seeing each other's comments on the data during the group reflection and said it helped them make sense of what they were seeing. As P2 states, *"I like seeing all our comments on it, because the comments do relate to the sensor links, and the comments actually make sense"*. Individuals expressed some difficulty adding annotations to the data afterwards, i.e. after the year was completed. They expressed feeling like that time period was *"a blur"* (P10). Instead, they recommended being able to add annotations to the data in the moment. As P2 summarized, *"For future iterations, having a feedback session about that month while it's happening, [. . .] while in the process of it happening, would be useful"*. For example, being able to pull out the data linearly and reflecting as a group – *"I like that whole idea of being able to all be together in a room touching the sock and like connecting that way. I think that would be incredible"* (P4). They also recommended annotating the visualization in a tangible way directly on the knit record. As P3 discussed, *"I think it would be cool as well if we had like a little tag, with all the openings of 2021 on it or real time major events of the gallery, and then they're like physically on the sock"*.

6 RE-DEPLOYMENT

After running our study, and a year after the initial deployment ended, *The Life of a Building* was re-deployed at the Ottawa Art Gallery in the same location where it was initially displayed at

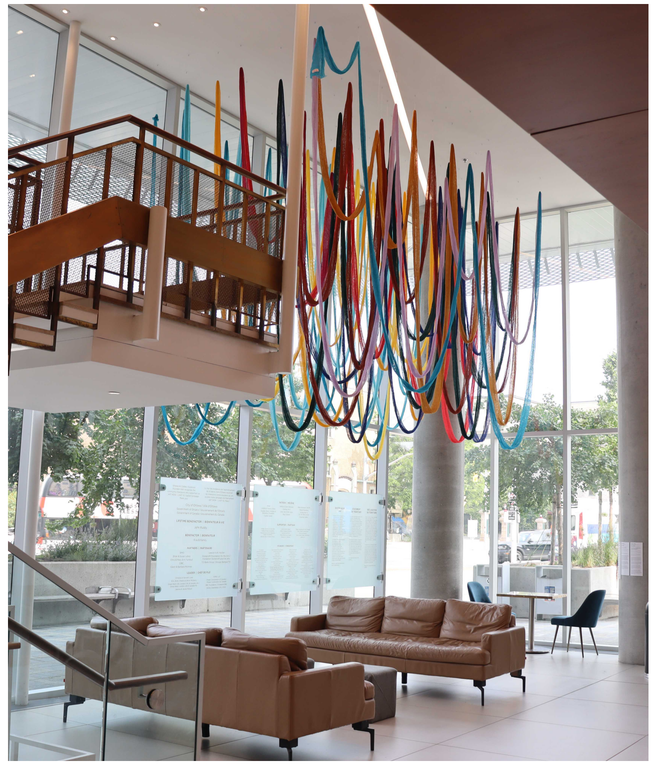

Figure 7: The data physicalization was re-deployed above couches so individuals could spend time looking and reflecting on it from below.

the beginning of May 2023. The goal of this re-deployment was to iterate on how the data was shown based on the findings from our user study, and to create a space for reflecting on the year.

In our interviews, our participants discussed how the installation emphasized data collection, instead of data presentation, so in this re-deployment we aimed to create a space for data presentation and for visitors to reflect and make sense of the data (see Figure 7, Figure 8, and Figure 9). We once again used the atrium space, thus presenting the data in a way that it could be viewed from multiple angles while still presented in a linear fashion. The data was hung from the ceiling in a way that individuals could see the data spread out without having to touch it. When sitting on the couches they could view the data from below (see Figure 9). From the stairwell, they could view the data up close at eye-level.

A tangible legend listed the month corresponding to each yarn used and the length of each knit month. Beside each one legend item, we provided a sample of the yarn so individuals could more tangibly see and feel it. The legend aimed to enable individuals to make quick comparisons between months.

7 DISCUSSION

Though in this work we evaluated the constraints of a ***textile*** data physicalization, we came up against many of the challenges that other data physicalization researchers have experienced with other

Figure 8: When walking down the staircase the data physicalization can be viewed from another angle. On the far right is the blue from July 2021, on the far left is the blue from July 2022.

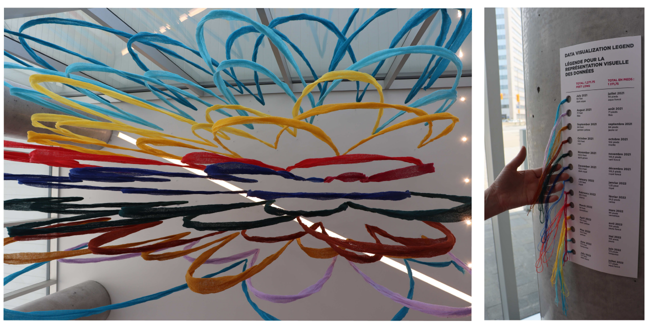

Figure 9: The view of the physicalization when sitting on the couches and looking up. A tangible legend was placed on the pillar beside the couches.

materials. Issues included data occlusion, scale, causation, and contextualization.

7.1 Data occlusion

Data physicalizations, due to the way that they exist in physical space, can create occlusions that obscure the data depending on a viewer's orientation and perspective when viewing the physicalization [81]. For example, the way that objects that are closer to you appear larger and can obscure objects farther away. In our current project, our participants discussed how the fabrication process itself created occlusion through the way that the physicalization piled months on top of one another. The process of live digital fabrication of data is challenging due to the physical processes of "rendering" data [20]. As found in previous work, live digital physicalizations deal with constraints of gravity, structural stability, physical space [3, 46, 87], and the lack of control of the environment [90]. To correct for the way the fabrication process and gravitational forces created data occlusions, we needed separate stages: one where the data was collected and fabricated, and another where it was presented for interpretation. In this way our project highlights how physicalizations can have a similar pipeline to traditional visualizations where data representation is a separate step from data presentation for public interpretation [39, 44]. This project, with the knit pile of data, highlights the way that gravitation forces can create occlusion with fabricated data physicalizations, where more recent data can hide or obscure older data.

7.2 Scale

Previous work has discussed the impact of scale on how we interpret data physicalizations: smaller physicalizations make it easier to explore and inspect the data [59]. Our findings further support this. In our case the length of the knit data produced each month made it difficult to inspect and compare months, and we required illustrations of it with measurements (i.e. our sketched illustrative summary) in order to discuss it with the Ottawa Art Gallery team before re-deployment. Whereas previous work found that large scale data physicalizations are easier to discuss [59], the large scale of our knit tube meant that it had to be spread out and presented farther way (i.e. on the ceiling and viewed from afar) so that individuals could see the physicalization (and the differences between months) in a comparable way. In contrast, a smaller scale physicalization could have been created by designing the system to fabricate less material (i.e. stitching a stitch rather than stitching a row per person), or by using a smaller knitting machine (i.e. one with fewer needles). The resulting data would have had the same textile appeal, but with less material would have likely been more easy to inspect, compare, and interpret without illustrative summaries.

7.3 Cause and effect

The installation used passive interactions (individuals entering the building), but our participants wanted cause and effect to be linked more strongly. This relates to the physecology concept of *"spatial input–output coupling"* [83] where individuals can clearly see the cause and effect. Our participants often missed the bright pink box at the door, or did not connect it with the knitting machine. Wayfinding signage led them to the machine. Individuals expected the interaction to be more closely linked, for example, to have the sensor spatially near or next to the machine, and suggested that having more active forms of interaction would help to link the cause with effect. Future work should make it clear what causes the physicalization to be created. As is, the sensor and knitting machine created what Guljajeva calls a "post-participation" form of interaction where individuals were not aware of their participation until they saw the knit record [28].

7.4 Context

Though "data sculptures" [94] often focus on aesthetics and materiality, our participants highlighted how data sculptures also need to be usable so that participants can make sense of them. Though individuals who worked in the building understood the project and found it meaningful, we also wanted the installation to be accessible to the broader community (i.e. visitors to the art gallery). Throughout HCI research on data physicalizations, researchers struggle with evaluating the "task" of data physicalizations – how should we evaluate their usability [19, 46]? Because the installation was meant to be accessible, future iterations must prioritize being "readable". In contrast, other data physicalizations are only meant for habitual communities (such as co-workers rather than visitors), and therefore might not need recognizable legends and obvious directions, and can rely on icons or knowledge on how the physicalization works [79]. In our study, participants required more legend items from the text panel such as: how much knitting is created per person, what is the timescale of each colour, what does each colour mean. In our case participants wanted to know that each person created a row, and that the colours represented months of time, and that, for example, July was represented with a specific shade of blue. This furthers previous research that discussed the importance of making "situatedness" more obvious with data physicalizations so that individuals can understand the relation and connection to the space [3, 12].

Our participants wanted more context to direct them on how to interpret the data with data storytelling. They provided a few recommendations including: asking leading questions for what to look for, or overlaying another source of data about what was going on at the time. Previous work has recommended adding qualitative context to quantitative data physicalizations to help individuals further reflect and interpret the data [40]. Our participants similarly recommended tangibly adding "tags" to the data in real time, due to how difficult it can be to reflect on time periods after the fact. Our project findings highlight the importance of capturing this information in real time during the data gathering period, and further supports previous work on constructing data physicalizations, where researchers found that participants often intertwine labelling with making practices [82]. In future work, we will aim to explore how to provide this context to tangible textile visualizations during the fabrication process.

8 REFLECTIONS ON DATA LOSS

For this project, the knitting machine "filtered" the data. For example, there were a few times where the machine jammed and data was lost for that day, or where individuals hanging around the ultrasonic sensor or passing by it together would skew the count of individuals in the knit record. Despite these "data accidents" [16] our resulting physicalization still shows the flow of individuals through the space during an unpredictable year. For example, you can see the increase in stitches as the community increasingly felt safe returning to public spaces, as well as the decrease in stitches during gallery closures (such as the provincial shut down in January 2022 in response to the Omicron variant [71], and the downtown closures in the area surrounding the Convoy in February 2022 [92]).

Besides data accidents during the fabrication process, there's also the potential data loss as the data physicalization ages. For example, when we brought the physicalization out again for redeployment we noticed a few areas where the colour of the yarn faded due its location in the window during the fabrication process. As artists we enjoy how these changes in the material reveal traces of the physicalization's journey, but it also highlights how crafted data physicalizations are affected by their environment and can experience data loss due to material aging.

9 CONCLUSION

Data physicalizations that are fabricated in real time come up against physical constraints. In this paper, we explored the ability to use textile digital fabrication to visualize visitor data at the Ottawa Art Gallery. To evaluate and gather insights from this year-long installation, we conducted design critiques with 15 individuals who either lived alongside the installation for a year, or were subject experts. Furthermore, we conducted a follow-up group discussion for reflecting on the visualization and physicalization of the collected data, to design the next iteration of the visualization. Our findings highlight difficulties with presenting data to be interpreted when it is gathered in real-time (emphasizing previous work on the physical constraints of data physicalizations), the downside of passive interactions for developing strong *"spatial input–output coupling"* [83], the need for legends and intuitive colour schemes in data physicalizations, and the need to contextualize data physicalizations with what was going on at the time. Overall, this paper contributes reflections from the year-long deployment, and design recommendations for future work in real-time digital fabrication of data physicalizations.

ACKNOWLEDGMENTS

We would like to thank the Ottawa Art Gallery for commissioning this work and for curators Rebecca Basciano and Catherine Sinclair, and the entire Ottawa Art Gallery team for bringing this project to life. We would like to thank our participants for generously contributing their time and expertise to this research, as well as our reviewers for their insights that helped improve this work. We would like to thank the team at Bayview Yards Prototyping Studio in Ottawa, Canada for producing the machine during the tumultuous time of the pandemic. This project was funded by Canada's Social Studies and Humanities Research Council (SSHRC) through the New Frontiers Research Funds (NFRF) grant: Exploration stream #NFRFE-2020-1271. Mar Canet Sola is funded through the EU Horizon 2020 research and innovation program (Grant No.810961).

REFERENCES

[1] Parastoo Abtahi, Victoria Ding, Anna C. Yang, Tommy Bruzzese, Alyssa B. Romanos, Elizabeth L. Murnane, Sean Follmer, and James A. Landay. 2020. Understanding Physical Practices and the Role of Technology in Manual Self-Tracking. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 4, 4, Article 115 (dec 2020), 24 pages. https://doi.org/10.1145/3432236

[2] Lea Albaugh, Scott E. Hudson, Lining Yao, and Laura Devendorf. 2020. Investigating Underdetermination Through Interactive Computational Handweaving. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference* (Eindhoven, Netherlands) *(DIS '20)*. Association for Computing Machinery, New York, NY, USA, 1033–1046. https://doi.org/10.1145/3357236.3395538

[3] S. Sandra Bae, Clement Zheng, Mary Etta West, Ellen Yi-Luen Do, Samuel Huron, and Danielle Albers Szafir. 2022. Making Data Tangible: A Cross-Disciplinary Design Space for Data Physicalization. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 81, 18 pages. https://doi.org/10.1145/3491102.3501939

[4] Fionna Barber and Jools Gilson. 2023. Stormy Weather: Textile Art, Water and Climate Emergency. *TEXTILE* 0, 0 (2023), 1–13. https://doi.org/10.1080/14759756.2023.2239568 arXiv:https://doi.org/10.1080/14759756.2023.2239568

[5] Andrea Batch, Biswaksen Patnaik, Moses Akazue, and Niklas Elmqvist. 2020. Scents and Sensibility: Evaluating Information Olfactation. In *Proceedings of the*

2020 CHI Conference on Human Factors in Computing Systems (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376733

[6] Jon Bird and Yvonne Rogers. 2010. The pulse of tidy street: Measuring and publicly displaying domestic electricity consumption. In *workshop on energy awareness and conservation through pervasive applications (Pervasive 2010)*.

[7] Laurens Boer and Jared Donovan. 2012. Provotypes for Participatory Innovation. In *Proceedings of the Designing Interactive Systems Conference* (Newcastle Upon Tyne, United Kingdom) *(DIS '12)*. Association for Computing Machinery, New York, NY, USA, 388–397. https://doi.org/10.1145/2317956.2318014

[8] Stewart Brand. 1995. *How buildings learn: What happens after they're built.* Penguin.

[9] Virginia Braun and Victoria Clarke. 2013. *Successful qualitative research: A practical guide for beginners.* sage.

[10] Virginia Braun and Victoria Clarke. 2021. *Thematic Analysis: A Practical Guide.* sage.

[11] Virginia Braun, Victoria Clarke, Nikki Hayfield, and Gareth Terry. 2019. *Thematic Analysis.* Springer Singapore, Singapore, 843–860. https://doi.org/10.1007/978-981-10-5251-4_103

[12] Nathalie Bressa, Henrik Korsgaard, Aurélien Tabard, Steven Houben, and Jo Vermeulen. 2022. What's the Situation with Situated Visualization? A Survey and Perspectives on Situatedness. *IEEE Transactions on Visualization and Computer Graphics* 28, 1 (2022), 107–117. https://doi.org/10.1109/TVCG.2021.3114835

[13] David Chatting, David S. Kirk, Paulina Yurman, and Jo-Anne Bichard. 2015. Designing for Family Phatic Communication: A Design Critique Approach. In *Proceedings of the 2015 British HCI Conference* (Lincoln, Lincolnshire, United Kingdom) *(British HCI '15)*. Association for Computing Machinery, New York, NY, USA, 175–183. https://doi.org/10.1145/2783446.2783566

[14] Zoom Communications. 2022. *Zoom.* Retrieved June, 2022 from zoom.us

[15] Maxime Daniel, Guillaume Rivière, and Nadine Couture. 2019. CairnFORM: A Shape-Changing Ring Chart Notifying Renewable Energy Availability in Peripheral Locations. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Tempe, Arizona, USA) *(TEI '19)*. Association for Computing Machinery, New York, NY, USA, 275–286. https://doi.org/10.1145/3294109.3295634

[16] Audrey Desjardins and Timea Tihanyi. 2019. ListeningCups: A Case of Data Tactility and Data Stories. In *Proceedings of the 2019 on Designing Interactive Systems Conference* (San Diego, CA, USA) *(DIS '19)*. Association for Computing Machinery, New York, NY, USA, 147–160. https://doi.org/10.1145/3322276.3323694

[17] Laura Devendorf, Kristina Andersen, and Aisling Kelliher. 2020. The Fundamental Uncertainties of Mothering: Finding Ways to Honor Endurance, Struggle, and Contradiction. *ACM Trans. Comput.-Hum. Interact.* 27, 4, Article 26 (sep 2020), 24 pages. https://doi.org/10.1145/3397177

[18] Laura Devendorf, Kristina Andersen, and Aisling Kelliher. 2020. Making Design Memoirs: Understanding and Honoring Difficult Experiences. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376345

[19] Evanthia Dimara and Charles Perin. 2020. What is Interaction for Data Visualization? *IEEE Transactions on Visualization and Computer Graphics* 26, 1 (2020), 119–129. https://doi.org/10.1109/TVCG.2019.2934283

[20] Hessam Djavaherpour, Faramarz Samavati, Ali Mahdavi-Amiri, Fatemeh Yazdanbakhsh, Samuel Huron, Richard Levy, Yvonne Jansen, and Lora Oehlberg. 2021. Data to physicalization: A survey of the physical rendering process. In *Computer Graphics Forum*, Vol. 40. Wiley Online Library, 569–598.

[21] Severin Engert, Konstantin Klamka, Andreas Peetz, and Raimund Dachselt. 2022. STRAIDE: A Research Platform for Shape-Changing Spatial Displays Based on Actuated Strings. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 263, 16 pages. https://doi.org/10.1145/3491102.3517462

[22] Aluna Everitt, Faisal Taher, and Jason Alexander. 2016. ShapeCanvas: An Exploration of Shape-Changing Content Generation by Members of the Public. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 2778–2782. https://doi.org/10.1145/2858036.2858316

[23] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. InFORM: Dynamic Physical Affordances and Constraints through Shape and Object Actuation. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology* (St. Andrews, Scotland, United Kingdom) *(UIST '13)*. Association for Computing Machinery, New York, NY, USA, 417–426. https://doi.org/10.1145/2501988.2502032

[24] Mikhaila Friske, Jordan Wirfs-Brock, and Laura Devendorf. 2020. Entangling the Roles of Maker and Interpreter in Interpersonal Data Narratives: Explorations in Yarn and Sound. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference* (Eindhoven, Netherlands) *(DIS '20)*. Association for Computing Machinery, New York, NY, USA, 297–310. https://doi.org/10.1145/3357236.3395442

[25] Sarah Gallacher, Jenny O'Connor, Jon Bird, Yvonne Rogers, Licia Capra, Daniel Harrison, and Paul Marshall. 2015. Mood Squeezer: Lightening up the Workplace through Playful and Lightweight Interactions. In *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing* (Vancouver, BC, Canada) *(CSCW '15)*. Association for Computing Machinery, New York, NY, USA, 891–902. https://doi.org/10.1145/2675133.2675170

[26] Neil Gershenfeld. 2012. How to make almost anything: The digital fabrication revolution. *Foreign Aff.* 91 (2012), 43.

[27] VERBI GmbH. 2022. *MAXQDA.* Retrieved June, 2022 from maxqda.com

[28] Varvara Guljajeva. 2018. *From interaction to post-participation: the disappearing role of the active participant (Interaktsioonist osalusjärgsuseni: aktiivse osaleja kaduv roll.* PhD thesis. Estonian Academy of Arts. Available at https://eka.entu.ee/shared/429088/GsqzlotFPrFi1tdtAmVX1Wo8cxFWi4iQjntDJcO4n0mE5NAx8K8pef9V3AC9k3lB.

[29] Varvara Guljajeva and Mar Canet Sola. 2014. *Circular Knitic.* https://doi.org/10.5281/zenodo.6124168

[30] Varvara Guljajeva and Mar Canet Sola. 2014. Circular Knitic. https://var-mar.info/circular-knitic/

[31] Varvara Guljajeva and Mar Canet Sola. 2020. NeuroKnitting Beethoven. https://var-mar.info/neuroknitting-beethoven/

[32] Varvara Guljajeva, Mar Canet Sola, and Iurii Kuzmin. 2023. Telematic performance enforced by the pandemic: neuroknitting beethoven. *International Journal of Performance Arts and Digital Media* 0, 0 (2023), 1–19. https://doi.org/10.1080/14794713.2023.2270790 arXiv:https://doi.org/10.1080/14794713.2023.2270790

[33] Varvara Guljajeva, Mar Canet Sola, and Sebastian Mealla Cincuegrani. 2012. NeuroKnitting. https://var-mar.info/neuroknitting/.

[34] William R. Hazlewood, Erik Stolterman, and Kay Connelly. 2011. Issues in Evaluating Ambient Displays in the Wild: Two Case Studies. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI '11)*. Association for Computing Machinery, New York, NY, USA, 877–886. https://doi.org/10.1145/1978942.1979071

[35] Annika Hinze, Nicholas Vanderschantz, Nicole Sijnja, Bill Rogers, and Sally Jo Cunningham. 2022. Physical Metadata Visualisation: The Knitted Personal Library. In *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Daejeon, Republic of Korea) *(TEI '22)*. Association for Computing Machinery, New York, NY, USA, Article 78, 7 pages. https://doi.org/10.1145/3490149.3505582

[36] Trevor Hogan, Uta Hinrichs, Yvonne Jansen, Samuel Huron, Pauline Gourlet, Eva Hornecker, and Bettina Nissen. 2017. Pedagogy & Physicalization: Designing Learning Activities around Physical Data Representations. In *Proceedings of the 2017 ACM Conference Companion Publication on Designing Interactive Systems* (Edinburgh, United Kingdom) *(DIS '17 Companion)*. Association for Computing Machinery, New York, NY, USA, 345–347. https://doi.org/10.1145/3064857.3064859

[37] Trevor Hogan, Eva Hornecker, Simon Stusak, Yvonne Jansen, Jason Alexander, Andrew Vande Moere, Uta Hinrichs, and Kieran Nolan. 2016. Tangible Data, Explorations in Data Physicalization. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction* (Eindhoven, Netherlands) *(TEI '16)*. Association for Computing Machinery, New York, NY, USA, 753–756. https://doi.org/10.1145/2839462.2854112

[38] Sarah Homewood, Harvey Bewley, and Laurens Boer. 2019. Ovum: Designing for Fertility Tracking as a Shared and Domestic Experience. In *Proceedings of the 2019 on Designing Interactive Systems Conference* (San Diego, CA, USA) *(DIS '19)*. Association for Computing Machinery, New York, NY, USA, 553–565. https://doi.org/10.1145/3322276.3323692

[39] Eva Hornecker, Trevor Hogan, Uta Hinrichs, and Rosa van Koningsbruggen. 2023. A Design Vocabulary for Data Physicalization. *ACM Trans. Comput.-Hum. Interact.* (aug 2023). https://doi.org/10.1145/3617366 Just Accepted.

[40] Steven Houben, Ben Bengler, Daniel Gavrilov, Sarah Gallacher, Valentina Nisi, Nuno Jardim Nunes, Licia Capra, and Yvonne Rogers. 2019. Roam-IO: Engaging with People Tracking Data through an Interactive Physical Data Installation. In *Proceedings of the 2019 on Designing Interactive Systems Conference* (San Diego, CA, USA) *(DIS '19)*. Association for Computing Machinery, New York, NY, USA, 1157–1169. https://doi.org/10.1145/3322276.3322303

[41] Steven Houben, Connie Golsteijn, Sarah Gallacher, Rose Johnson, Saskia Bakker, Nicolai Marquardt, Licia Capra, and Yvonne Rogers. 2016. Physikit: Data Engagement Through Physical Ambient Visualizations in the Home. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 1608–1619. https://doi.org/10.1145/2858036.2858059

[42] Particle Industries Inc. 2022. Particle Devices. https://www.particle.io/

[43] Jennifer Jacobs, David Mellis, Amit Zoran, Cesar Torres, Joel Brandt, and Theresa Jean Tanenbaum. 2016. Digital Craftsmanship: HCI Takes on Technology as an Expressive Medium. In *Proceedings of the 2016 ACM Conference Companion Publication on Designing Interactive Systems* (Brisbane, QLD, Australia) *(DIS '16 Companion)*. Association for Computing Machinery, New York, NY, USA, 57–60. https://doi.org/10.1145/2908805.2913018

[44] Yvonne Jansen and Pierre Dragicevic. 2013. An Interaction Model for Visualizations Beyond The Desktop. *IEEE Transactions on Visualization and Computer*

Graphics 19, 12 (2013), 2396–2405. https://doi.org/10.1109/TVCG.2013.134

[45] Yvonne Jansen, Pierre Dragicevic, and Jean-Daniel Fekete. 2013. Evaluating the Efficiency of Physical Visualizations. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Paris, France) *(CHI '13)*. Association for Computing Machinery, New York, NY, USA, 2593–2602. https://doi.org/10.1145/2470654.2481359

[46] Yvonne Jansen, Pierre Dragicevic, Petra Isenberg, Jason Alexander, Abhijit Karnik, Johan Kildal, Sriram Subramanian, and Kasper Hornbæk. 2015. Opportunities and Challenges for Data Physicalization. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 3227–3236. https://doi.org/10.1145/2702123.2702180

[47] Charlene Jennett, Ioanna Iacovides, Anna L. Cox, Anastasia Vikhanova, Emily Weigold, Layla Mostaghimi, Geraint Jones, James Jenkins, Sarah Gallacher, and Yvonne Rogers. 2016. Squeezy Green Balls: Promoting Environmental Awareness through Playful Interactions. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play* (Austin, Texas, USA) *(CHI PLAY '16)*. Association for Computing Machinery, New York, NY, USA, 389–400. https://doi.org/10.1145/2967934.2968102

[48] Lee Jones, Greta Grip, and Boris Kourtoukov. 2022. The Life of a Building: Machine Knitting a Year of Visitor Data and Online Community Participation During a Pandemic. In *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Daejeon, Republic of Korea) *(TEI '22)*. Association for Computing Machinery, New York, NY, USA, Article 80, 5 pages. https://doi.org/10.1145/3490149.3507783

[49] Lee Jones, Greta Grip, and Sara Nabil. 2023. Wear Your Heart on Your Sleeve: Using Digital Knitting Machines to Craft Wearable Biodata Portraits. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference* (Pittsburgh, PA, USA) *(DIS '23)*. Association for Computing Machinery, New York, NY, USA, 547–563. https://doi.org/10.1145/3563657.3596007

[50] Lee Jones, Alaa Nousir, Tom Everrett, and Sara Nabil. 2023. Tangible, Public, and Miniature Creative Exchanges: What HCI and Design Researchers Can Learn From the Free Little Art Gallery Movement. In *Proceedings of the 15th Conference on Creativity and Cognition* (Virtual Event, USA) *(C&C '23)*. Association for Computing Machinery, New York, NY, USA, 413–428. https://doi.org/10.1145/3591196.3593433

[51] Olena Khlystova, Yelena Kalyuzhnova, and Maksim Belitski. 2022. The impact of the COVID-19 pandemic on the creative industries: A literature review and future research agenda. *Journal of Business Research* 139 (2022), 1192–1210. https://doi.org/10.1016/j.jbusres.2021.09.062

[52] Ellie King, M Paul Smith, Paul F Wilson, and Mark A Williams. 2021. Digital responses of UK museum exhibitions to the COVID-19 crisis, March–June 2020. *Curator: The Museum Journal* 64, 3 (2021), 487–504.

[53] Lisa Koeman, Vaiva Kalnikaité, and Yvonne Rogers. 2015. "Everyone Is Talking about It!": A Distributed Approach to Urban Voting Technology and Visualisations. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 3127–3136. https://doi.org/10.1145/2702123.2702263

[54] Marinos Koutsomichalis, Afroditi Psarra, and Maria Varela. 2014. Oiko-Nomic Threads. In *Proceedings of the 2014 ACM International Symposium on Wearable Computers: Adjunct Program* (Seattle, Washington) *(ISWC '14 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 59–64. https://doi.org/10.1145/2641248.2641281

[55] Ebru Kurbak and Mahir M. Yavuz. 2009. News Knitter. In *ACM SIGGRAPH 2009 Art Gallery* (New Orleans, Louisiana) *(SIGGRAPH '09)*. Association for Computing Machinery, New York, NY, USA, Article 29, 1 pages. https://doi.org/10.1145/1667265.1667298

[56] Carine Lallemand and Maud Oomen. 2022. The Candy Workshop: Supporting Rich Sensory Modalities in Constructive Data Physicalization. In *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI EA '22)*. Association for Computing Machinery, New York, NY, USA, Article 404, 7 pages. https://doi.org/10.1145/3491101.3519648

[57] Mathieu Le Goc, Lawrence H. Kim, Ali Parsaei, Jean-Daniel Fekete, Pierre Dragicevic, and Sean Follmer. 2016. Zooids: Building Blocks for Swarm User Interfaces. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16)*. Association for Computing Machinery, New York, NY, USA, 97–109. https://doi.org/10.1145/2984511.2984547

[58] Siân E Lindley, Anja Thieme, Alex S Taylor, Vasilis Vlachokyriakos, Tim Regan, and David Sweeney. 2017. Surfacing small worlds through data-in-place. *Computer Supported Cooperative Work (CSCW)* 26, 1 (2017), 135–163.

[59] Irene López García and Eva Hornecker. 2021. Scaling Data Physicalization – How Does Size Influence Experience?. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Salzburg, Austria) *(TEI '21)*. Association for Computing Machinery, New York, NY, USA, Article 8, 14 pages. https://doi.org/10.1145/3430524.3440627

[60] Eleni Margariti, Vasilis Vlachokyriakos, and David Kirk. 2023. Understanding Occupants' Experiences in Quantified Buildings: Results from a Series of Exploratory Studies.. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 640, 15 pages. https://doi.org/10.1145/3544548.3581256

[61] Daphne Menheere, Evianne van Hartingsveldt, Mads Birkebæk, Steven Vos, and Carine Lallemand. 2021. Laina: Dynamic Data Physicalization for Slow Exercising Feedback. In *Proceedings of the 2021 ACM Designing Interactive Systems Conference* (Virtual Event, USA) *(DIS '21)*. Association for Computing Machinery, New York, NY, USA, 1015–1030. https://doi.org/10.1145/3461778.3462041

[62] Issey Miyake and Fujiwara Dai. 1997. Issey Miyake, Fujiwara Dai. A-poc queen textile. 1997: Moma. In *The Museum of Modern Art*. Association for Computing Machinery. https://www.moma.org/collection/works/100361

[63] Abigail Moreshead and Anastasia Salter. 2023. Knitting the in_visible: data-driven craftivism as feminist resistance. *Journal of Gender Studies* 0, 0 (2023), 1–12. https://doi.org/10.1080/09589236.2023.2258068 arXiv:https://doi.org/10.1080/09589236.2023.2258068

[64] Annika Muehlbradt, Gregory Whiting, Shaun Kane, and Laura Devendorf. 2022. Knitting Access: Exploring Stateful Textiles with People with Disabilities. In *Designing Interactive Systems Conference* (Virtual Event, Australia) *(DIS '22)*. Association for Computing Machinery, New York, NY, USA, 1058–1070. https://doi.org/10.1145/3532106.3533551

[65] Sara Nabil, Aluna Everitt, Miriam Sturdee, Jason Alexander, Simon Bowen, Peter Wright, and David Kirk. 2018. ActuEating: Designing, Studying and Exploring Actuating Decorative Artefacts. In *Proceedings of the 2018 Designing Interactive Systems Conference* (Hong Kong, China) *(DIS '18)*. Association for Computing Machinery, New York, NY, USA, 327–339. https://doi.org/10.1145/3196709.3196761

[66] Sara Nabil and David Kirk. 2021. Decoraction: A Catalogue for Interactive Home Decor of the Nearest-Future. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Salzburg, Austria) *(TEI '21)*. Association for Computing Machinery, New York, NY, USA, Article 98, 13 pages. https://doi.org/10.1145/3430524.3446074

[67] Sara Nabil, David S. Kirk, Thomas Plötz, Julie Trueman, David Chatting, Dmitry Dereshev, and Patrick Olivier. 2017. Interioractive: Smart Materials in the Hands of Designers and Architects for Designing Interactive Interiors. In *Proceedings of the 2017 Conference on Designing Interactive Systems* (Edinburgh, United Kingdom) *(DIS '17)*. Association for Computing Machinery, New York, NY, USA, 379–390. https://doi.org/10.1145/3064663.3064745

[68] Ken Nakagaki, Daniel Fitzgerald, Zhiyao (John) Ma, Luke Vink, Daniel Levine, and Hiroshi Ishii. 2019. InFORCE: Bi-Directional 'Force' Shape Display for Haptic Interaction. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Tempe, Arizona, USA) *(TEI '19)*. Association for Computing Machinery, New York, NY, USA, 615–623. https://doi.org/10.1145/3294109.3295621

[69] Ken Nakagaki, Sean Follmer, and Hiroshi Ishii. 2015. LineFORM: Actuated Curve Interfaces for Display, Interaction, and Constraint. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* (Charlotte, NC, USA) *(UIST '15)*. Association for Computing Machinery, New York, NY, USA, 333–339. https://doi.org/10.1145/2807442.2807452

[70] Lukas Noehrer, Abigail Gilmore, Caroline Jay, and Yo Yehudi. 2021. The impact of COVID-19 on digital data practices in museums and art galleries in the UK and the US. *Humanities and Social Sciences Communications* 8, 1 (2021), 1–10. https://doi.org/10.1057/s41599-021-00921-8

[71] Office of the Premier. January 03, 2022. Ontario Temporarily Moving to Modified Step Two of the Roadmap to Reopen. https://news.ontario.ca/en/release/1001394/ontario-temporarily-moving-to-modified-step-two-of-the-roadmap-to-reopen

[72] Huaishu Peng, Jimmy Briggs, Cheng-Yao Wang, Kevin Guo, Joseph Kider, Stefanie Mueller, Patrick Baudisch, and François Guimbretière. 2018. RoMA: Interactive Fabrication with Augmented Reality and a Robotic 3D Printer. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3174153

[73] Alan Poole, Robb Mitchell, Katrin Wolf, and Rahimullah Sarban. 2016. Bodily Sketching With Sensable Stretchables. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction* (Eindhoven, Netherlands) *(TEI '16)*. Association for Computing Machinery, New York, NY, USA, 770–773. https://doi.org/10.1145/2839462.2854122

[74] OBS Project. 2022. OBS - Open Broadcast Software. https://obsproject.com/

[75] The Tempestry Project. 2023. The Tempestry Project. https://www.tempestryproject.com/

[76] Afroditi Psarra and Audrey Briot. 2019. Listening Space: Satellite Ikats. In *Proceedings of the 23rd International Symposium on Wearable Computers* (London, United Kingdom) *(ISWC '19)*. Association for Computing Machinery, New York, NY, USA, 318–321. https://doi.org/10.1145/3341163.3346932

[77] Yvonne Rogers, William R. Hazlewood, Paul Marshall, Nick Dalton, and Susanna Hertrich. 2010. Ambient Influence: Can Twinkly Lights Lure and Abstract

Representations Trigger Behavioral Change?. In *Proceedings of the 12th ACM International Conference on Ubiquitous Computing* (Copenhagen, Denmark) *(UbiComp '10)*. Association for Computing Machinery, New York, NY, USA, 261–270. https://doi.org/10.1145/1864349.1864372

[78] Kimiko Ryokai, Elena Durán López, Noura Howell, Jon Gillick, and David Bamman. 2018. Capturing, Representing, and Interacting with Laughter. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3173932

[79] Kim Sauvé, Saskia Bakker, and Steven Houben. 2020. Econundrum: Visualizing the Climate Impact of Dietary Choice through a Shared Data Sculpture. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference* (Eindhoven, Netherlands) *(DIS '20)*. Association for Computing Machinery, New York, NY, USA, 1287–1300. https://doi.org/10.1145/3357236.3395509

[80] Kim Sauvé, Saskia Bakker, Nicolai Marquardt, and Steven Houben. 2020. LOOP: Exploring Physicalization of Activity Tracking Data. In *Proceedings of the 11th Nordic Conference on Human-Computer Interaction: Shaping Experiences, Shaping Society* (Tallinn, Estonia) *(NordiCHI '20)*. Association for Computing Machinery, New York, NY, USA, Article 52, 12 pages. https://doi.org/10.1145/3419249.3420109

[81] Kim Sauvé, Dominic Potts, Jason Alexander, and Steven Houben. 2020. A Change of Perspective: How User Orientation Influences the Perception of Physicalizations. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376312

[82] Kim Sauvé, Argenis Ramirez Gomez, and Steven Houben. 2022. Put a Label On It! Approaches for Constructing and Contextualizing Bar Chart Physicalizations. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 82, 15 pages. https://doi.org/10.1145/3491102.3501952

[83] Kim Sauvé, Miriam Sturdee, and Steven Houben. 2022. Physecology: A Conceptual Framework to Describe Data Physicalizations in Their Real-World Context. *ACM Trans. Comput.-Hum. Interact.* 29, 3, Article 27 (jan 2022), 33 pages. https://doi.org/10.1145/3505590

[84] Samarth Singhal, Carman Neustaedter, William Odom, Lyn Bartram, and Yasamin Heshmat. 2018. Time-Turner: Designing for Reflection and Remembrance of Moments in the Home. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3173574.3173753

[85] Simon Stusak, Jeannette Schwarz, and Andreas Butz. 2015. Evaluating the Memorability of Physical Visualizations. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 3247–3250. https://doi.org/10.1145/2702123.2702248

[86] Ryo Suzuki, Clement Zheng, Yasuaki Kakehi, Tom Yeh, Ellen Yi-Luen Do, Mark D. Gross, and Daniel Leithinger. 2019. ShapeBots: Shape-Changing Swarm Robots. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 493–505. https://doi.org/10.1145/3332165.3347911

[87] Saiganesh Swaminathan, Conglei Shi, Yvonne Jansen, Pierre Dragicevic, Lora A. Oehlberg, and Jean-Daniel Fekete. 2014. Supporting the Design and Fabrication of Physical Visualizations. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Toronto, Ontario, Canada) *(CHI '14)*. Association for Computing Machinery, New York, NY, USA, 3845–3854. https://doi.org/10.1145/2556288.2557310

[88] Alice Thudt, Uta Hinrichs, Samuel Huron, and Sheelagh Carpendale. 2018. Self-Reflection and Personal Physicalization Construction. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3173728

[89] UNESCO. 2020. Museums around the world in the face of COVID-19. (2020). https://unesdoc.unesco.org/ark:/48223/pf0000373530

[90] Rosa van Koningsbruggen, Hannes Waldschütz, and Eva Hornecker. 2022. What is Data? - Exploring the Meaning of Data in Data Physicalisation Teaching. In *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Daejeon, Republic of Korea) *(TEI '22)*. Association for Computing Machinery, New York, NY, USA, Article 13, 21 pages. https://doi.org/10.1145/3490149.3501319

[91] Yun Wang, Xiaojuan Ma, Qiong Luo, and Huamin Qu. 2016. Data Edibilization: Representing Data with Food. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI EA '16)*. Association for Computing Machinery, New York, NY, USA, 409–422. https://doi.org/10.1145/2851581.2892570

[92] Wikipedia. 2023. Timeline of the Canada Convoy Protest. https://en.wikipedia.org/wiki/Timeline_of_the_Canada_convoy_protest

[93] Tiffany Wun, Lora Oehlberg, Miriam Sturdee, and Sheelagh Carpendale. 2019. You Say Potato, I Say Po-Data: Physical Template Tools for Authoring Visualizations. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Tempe, Arizona, USA) *(TEI '19)*. Association for Computing Machinery, New York, NY, USA, 297–306. https://doi.org/10.1145/3294109.3295627

[94] Jack Zhao and Andrew Vande Moere. 2008. Embodiment in Data Sculpture: A Model of the Physical Visualization of Information. In *Proceedings of the 3rd International Conference on Digital Interactive Media in Entertainment and Arts* (Athens, Greece) *(DIMEA '08)*. Association for Computing Machinery, New York, NY, USA, 343–350. https://doi.org/10.1145/1413634.1413696

[95] John Zimmerman, Jodi Forlizzi, and Shelley Evenson. 2007. Research through Design as a Method for Interaction Design Research in HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '07)*. Association for Computing Machinery, New York, NY, USA, 493–502. https://doi.org/10.1145/1240624.1240704

[96] John Zimmerman, Erik Stolterman, and Jodi Forlizzi. 2010. An Analysis and Critique of Research through Design: Towards a Formalization of a Research Approach. In *Proceedings of the 8th ACM Conference on Designing Interactive Systems* (Aarhus, Denmark) *(DIS '10)*. Association for Computing Machinery, New York, NY, USA, 310–319. https://doi.org/10.1145/1858171.1858228

[97] Amit Zoran. 2015. Hybrid Craft: Showcase of Physical and Digital Integration of Design and Craft Skills. In *ACM SIGGRAPH Art Gallery* (Los Angeles, California) *(SIGGRAPH '15)*. Association for Computing Machinery, New York, NY, USA, 384–398. https://doi.org/10.1145/2810185.2810187

A TEXT PANEL

To interpret the artwork, there was a text panel placed beside the installation. The description stated:

"Can we convert you into a knitted row? Gathering data from the Ottawa Art Gallery visitor interactions —on our website and onsite in the building itself— this machine is knitting a tactile visualization of ongoing visitor statistics.

Linked to digital platforms and sensors in the Gallery, the machine responds to visitors with a knitted full circular row. Growing longer, and piling up as each interaction is documented, the knitted creation will be a record of the Ottawa Art Gallery's activity over the course of one year.

Ottawa-based artists Greta Grip and Lee Jones are interested in the relationships between textiles and information technology. Here, data is filtered into something supple.

We live in a world in which data mining is a hidden practice, and the digital traces we leave behind are collected and used without our knowledge. By contrast, this machine is transparent in its conversion of selected data into something tactile: a graphic spectrum of colour, and the tangible result of our collective interaction, growing before our eyes."