Rain Gauge: Exploring the Design and Sustainability of 3D Printed Clay Physicalizations

Bridger Herman*
College of Science and Engineering

Jessica Rossi-Mastracci
College of Design

Heather Willy
College of Design

Molly Reichert
College of Design

Daniel F. Keefe
College of Science and Engineering

University of Minnesota

Figure 1: This work explores the design and sustainability of 3D printed clay physicalizations. *Rain Gauge* is a clay data physicalization depicting monthly precipitation data from 1944-2024. A. monthly precipitation encoded as line length; B. clay 3D printing process; C-E. progression as the *Rain Gauge* receives rainfall; F-G. lasting rainfall effects.

ABSTRACT

Data physicalizations are a time-tested practice for visualizing data, but the sustainability challenges of current physicalization practices have only recently been explored; for example, the usage of carbon-intensive, non-renewable materials like plastic and metal. This work explores clay physicalizations as an approach to these challenges. Using a three-stage process, we investigate the design and sustainability of clay 3D printed physicalizations: 1) exploring the properties and constraints of clay when extruded through a 3D printer, 2) testing a variety of data encodings that work within the constraints, and 3) introducing *Rain Gauge*, a clay physicalization exploring environment-driven unmaking on a climate dataset. Throughout our process, we investigate the material circularity of clay-based digital fabrication by reclaiming and reusing the clay stock in each stage. Finally, we reflect on the implications of ceramic 3D printing for data physicalization through the lenses of practicality and sustainability.

Index Terms: Data physicalization, sustainability.

1 INTRODUCTION

Humans have encoded data in physical form for millennia. Today, data physicalizations still provide advantages over digital data displays, such as more engagement and discussions about data [18], better memorability [9, 35], and even better analytical performance in some situations [17, 21, 10].

However, concerns have been raised about the sustainability of using physical objects in tangible computing and physicalization, where the physical objects may be created for one purpose then discarded [19]. Defining sustainability in physicalization is complicated, and there is no universally agreed-upon definition [30]. Generally, questions must be raised when considering the sustainability of a physicalization, such as *"What materials are used?"*, *"Where do the materials come from and how are they transported?"*, and *"What happens to the physicalization after its initial purpose has ended?"* The majority of recent physicalizations are made out of non-renewable materials like metal and plastic that don't naturally degrade over time, or produce harmful byproducts when degrading [13]. Against the backdrop of the perpetual plastic problem [25], managing the sustainability and life cycle of data physicalizations is more important than ever.

Conversely, ceramics practices have a long tradition of using natural materials for utility and aesthetics in architecture and art alike. Human Computer Interaction researchers have taken recent interest in ceramics [7] and biomaterials that function like ceramics [3] for their versatility and reusability. Yet, ceramics are still uncommon for encoding, analyzing, and presenting data.

We envision a future in which data physicalization practitioners are empowered to use the time-tested practices of ceramics, where the process of creating a physicalization connects one intimately with the data being visualized and its material properties and composition. Most clays are largely comprised of water, which enables unique opportunities to explore creative unmaking practices [34] for modifying data encodings using water (e.g., rainwater). Clay can also encode data in ways not possible with other materials; for example, self-adhesion enables the lines and loops in Figs. 1 and 4D, water absorption and bonding provide the "melting" effect in Fig. 1, and clay memory (alignment and charge of clay molecules [1]) allows clay working processes (e.g., kneading or wedging) to be visible even after a model dries. Generally, clay's natural ingredients (silica, alumina, water) enable efficient *circular material processes*; we can reuse previously created clay objects by breaking them down and adding water, thereby reducing the amount of new material needed for creating physicalizations. As such, we believe that clay is especially well-suited to physicalizing data, and this paper explores the design and sustainability of clay 3D printed physicalizations by investigating their properties and constraints and testing novel data encodings. We also explore environment-driven unmaking of a clay physicalization by exposing it to rainwater, and through our process, we prioritize a circular material process to minimize material waste.

---

*authors' emails: {herma582,jlrossi,will1070,mreicher,dfk}@umn.edu

2 BACKGROUND

The work in this paper builds on multiple areas: research on sustainability in data physicalization, circular material systems, and the time-tested practice of ceramics.

2.1 Sustainability in Physicalization and Prototyping

Sustainability concerns associated with data physicalization have only recently come to mainstream attention. There is no single definition that encompasses sustainability in physicalization; it can be affected by everything from the data source, for example the environmental impact of data centers, to the end-of-life disposal via recycling, reuse, or landfill. Morais et al. provide the Sustainable Physicalization Practices (SuPPra) framework for exploring sustainability throughout the entire physicalization design process, from initial explorations to their end of life [30]. The framework introduces a series of guiding questions for physicalization researchers and practitioners to ask during the various phases of a physicalization project. In this paper, we deploy questions from SuPPra to examine the sustainability physicalization practices using clay 3D printing; a copy of our final SuPPra matrix may be found in the supplemental materials.

Sustainability has not always been a concern for physicalization. Early physicalizations were made out of natural materials, for example clay tokens [32], stones [5], or wood [8, p.36]. Today, though, physicalizations are mainly fabricated with non-renewable materials like metal and plastic [13]. This presents a sustainability challenge, particularly with plastic 3D printed physicalizations because they can break down into microplastics over time and often aren't reusable or recyclable [26].

To answer the challenge, new practices and materials are emerging for data physicalization, and more broadly, tangible computing. Researchers in Sustainable Human Computer Interaction have turned to novel biomaterials such as fungi [26], household materials like flour [14], and food waste compost [3] to reduce waste in digital fabrication for tangible user interfaces. Others have looked to advance the sustainability of 3D printing practices in general; Le Duigou et al. investigated the use of wood composites to create shape-changing materials [27], while Fredricks et al. explored the use of algae in 3D printable composites [15]. In Architecture and Landscape Architecture, using natural, site-local materials is becoming more common (i.e., rammed earth construction [28]), and digital fabrication techniques have been applied to rammed earth construction as well (e.g., [31]). The work in this paper is inspired by these works' use of natural materials, material circularity, and reduction of material waste during the prototyping process.

2.2 Ceramics and Data Physicalization

Like data physicalizations, ceramics have a rich history for artistic and practical purposes: from architectural elements like roof tiles and terracotta façades, to hand-crafted pottery and sculpture, ceramics have been used for thousands of years. The current practice of ceramics is as broad and diverse as its history, with artists like Melissa Weiss creating household items from hand-harvested clay [37], and Jeremy R. Brooks who crochets using clay [6]. 3D printing with clay is a new trend among ceramicists, and artists like Piotr Wasinowski [36], Kate Blacklock [4], and Erin Lynn Smith [33] work with this medium to create forms that are impossible to produce with traditional ceramic techniques. Further, ceramics provide a straightforward circular material workflow to enable high reuse rates [22]; after initial material extraction, unfired ceramics can be easily reclaimed by combining them with water, and fired ceramics can be broken down and used as aggregate.

Despite the long-standing tradition of ceramics, the idea of depicting *data* using ceramics is fairly new. Some artists create ceramic objects to overlay data upon [29], and others use data as input to produce 3D printed ceramic forms; for example, Jonathan Keep's sound surfaces represent audio waveform data [23]. On a more personal note, Desjardins et al. have taken personal audio and vibration data and encoded them into cups [11] and data sculptures to decorate one's living space [12]. Our work utilizes lessons learned from these prior works, such as default printer settings and possible data encodings.

3 DESIGN PROCESS

Our design process follows the stages of the SuPPra framework [30]. From *Exploration*, to *Ideation and Creation*, to *Presentation*, and finally *End Of Life*, we leverage questions in the framework to guide our process and spark discussion regarding our materials, data, and processes. A copy of our SuPPra matrix may be seen in the supplemental materials.

3.1 Exploration

To begin, we examined the sustainability of 3D printed ceramics for data physicalization, determined procedures for reclaiming and reusing clay, and researched best practices for clay 3D printing. We leveraged team members' diverse skillsets ranging from Architecture and Landscape Architecture to Computer Science, including an artist who works with clay regularly.

3.1.1 Sustainability Plan

First, we established a series of guidelines for sustainably managing our finite clay resources. Since our process is largely investigative, our emphasis is on rapidly producing many prototypes, many of which may only be used to gain knowledge on the material, the printing process, and the available parameters. Clay is an ideal material for this iterative process because the material may be reclaimed at any stage until it is fired.

Our reclaim process is twofold. First, any print failures and wet clay discards are immediately added back to our clay stock, enabling us to mostly avoid material waste from print failure and 3D printing support structures. Second, with prints that finish as intended, we let them dry, document them, and reclaim the dried clay pieces using the technique described in Sec. 3.1.2. Firing the models in a kiln limits their reusability, but fired models can still be broken down and used as aggregate for recycled clays. We did not have access to a kiln, so every object described herein remains unfired, and thus fully reclaimable.

We also investigated the sustainability of the materials and data. We use a B-stock clay from our local clay supplier, which contains primarily water, crystalline silica, and aluminum oxide, common ingredients found in most clay recipes. Our supplier was not able to provide us with further sourcing information, so the additional environmental impacts of the clay production are unclear (e.g., extraction, transportation). The data used for the *Rain Gauge* physicalization are sourced from the U.S. National Oceanic and Atmospheric Administration (NOAA)'s public climate data repository[1]. At the time of writing, NOAA did not provide information on the sustainability practices of their data collection and storage.

3.1.2 Methods

To produce the prototypes and physicalizations shown in the paper, we use a Potterbot 10 Pro clay 3D printer. GCode toolpath files for the printer are created with custom Grasshopper scripts within the Rhinoceros 8.0 software. We prepare the clay following guidelines from our team's combined knowledge of ceramics and online guides provided by Jonathan Keep [24] and others. We print on top of a masonite board attached to the Potterbot's print bed. Multiple prepared boards allow us to continue printing by swapping out the board without touching the completed object. Before printing, we slightly moisten the masonite build surface to help the first layer better adhere to the build plate.

---

[1] `https://www.ncei.noaa.gov/cdo-web/search`

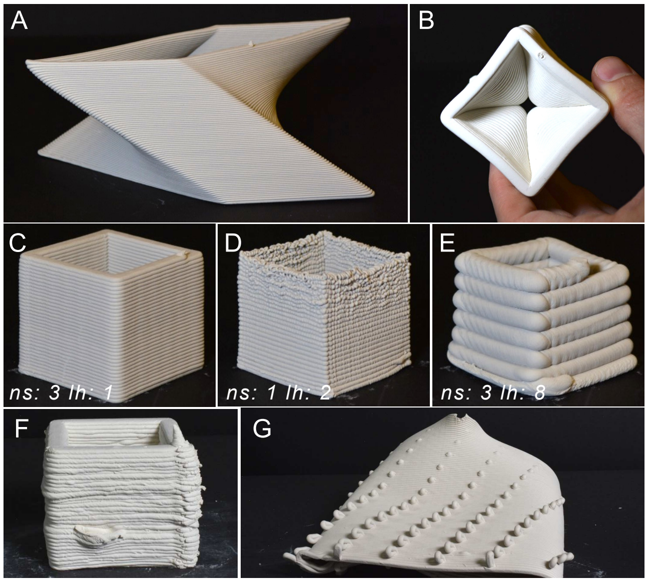

Figure 2: A series of clay test prints with varying geometries (A-B), nozzle sizes and layer heights (C-E; in mm), and failures (F-G).

3.2 Ideation and Creation

We follow a three-stage process for designing ceramic data physicalizations. We begin by exploring the properties and constraints of our 3D printer, we use knowledge from these parameter explorations to create novel data encodings, and finally we apply these encodings to real data in the *Rain Gauge* data physicalization. During each stage, we carefully manage the materials and reclaim them where possible for the next stage.

3.2.1 Stage I: Material Exploration

Fig. 2 shows a subset of prints created during our design process to better understand how clay behaves when 3D printed. We tested multiple geometries, layer heights, nozzle sizes, and extrusion rates to identify the relationships between these variables.

We had several key takeaways from Stage I. Most critically, we confirmed that our printer does not support changes to extrusion rate well (e.g., retractions), which is a known constraint for many clay 3D printers. This constraint guides the remainder of the prototypes and encodings we explore: *we build all printing toolpaths such that the printer is continuously extruding*. In particular, we noticed that the extruder takes a while to reach the correct extrusion rate; we handle this delay using a skirt around the model or a first-layer support structure off to the side. Our custom Grasshopper script outputs a single, continuous GCode toolpath to avoid any material stuttering due to the extrusion delay. With custom toolpaths, we found that previewing the GCode before printing was critical; Fig. 2G shows a print failure where a buggy toolpath caused the print nozzle to crash through the unfinished object.

As shown in the three cube prints in Fig. 2C-E, the nozzle size to layer height ratio is another noteworthy consideration. Similar to Jonathan Keep's experiments on the matter [24], we found that *nozzle size : layer height* ratios of 2:1, 3:1, and 5:1 worked particularly well. We also observed emergent behavior with some nozzle sizes and layer heights; particularly when the layer height is greater than the nozzle size. On the 1mm nozzle, we particularly note the "squiggles" that form as the thin model walls vibrate. In these experiments, we found that the extrusion rate is critical to controlling the character of the clay output; too much extrusion can crush lower layers (Fig. 2F), and too little can cause the print to stop.

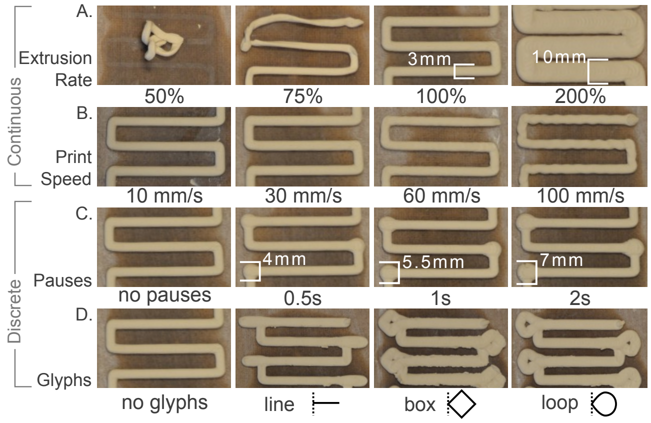

Figure 3: We explored four encodings: A. Extrusion Rate, B. Print Speed, C. Pauses, and D. Geometric Glyphs. All prints are with a 3mm nozzle.

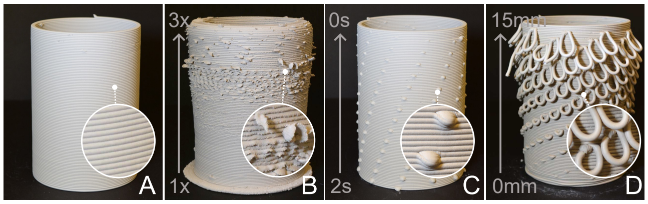

Figure 4: The most salient data encodings from the first-layer prints are applied to cylinders; A. No Encoding, B. Extrusion Rate, C. Pauses, and D. Loop Glyphs.

On the design and reproducibility of digital 3D objects, we found that sharp corners are difficult to reproduce (Fig. 2A-B), particularly with larger nozzle sizes and layer heights, which tend to create a "toothpaste" effect when extruding the clay. We also observe that overhangs are readily reproducible due to the larger nozzle size compared with standard plastic 3D printers. Finally, we note that the printer's travel path is sometimes evident in the final objects; for example, the clay "pulling" at the corners creating a rounded top, and a slight counterclockwise swirl/distortion seen in the center of Fig. 2B resulting from the counterclockwise toolpath direction.

3.2.2 Stage II: Encoding Ideation

Fig. 3 shows the options we explored to encode data using clay, given the material constraints found in Stage I. We tested four types of data encodings; two continuous (extrusion rate and print speed), and two discrete (pauses and geometric glyphs). All tests were performed with a 3mm nozzle and a 1mm layer height (3:1) on a single-layer "zigzag" object.

Fig. 3A shows our findings that extrusion rate corresponded well with line thickness, a common mapping in visualizations. Extrusion rates below 100% did not work well; in our setup the clay seemed to stop adhering to the build plate around 80%. High extrusion rates also tended to produce emergent behavior when the layer height was not also increased; for example, the ruffles shown near the top of Fig. 4B as the extrusion rate passes 200%.

Our findings here align with Jonathan Keep's earlier findings that speed surprisingly has a negligible effect on the print output [24]. Indeed, our tests show that the only noticeable artifact of high speeds is a slight wobbling along the line's travel due to the extruder tube's periodic motion at high speeds (100mm/s, Fig. 3B).

Beyond encoding data with continuous output, we also experimented with discrete mappings like pauses and glyphs (Fig. 3C-D).

Due to the extruder delay described in Sec. 3.2.1, pauses create circular "blobs" at specified locations. As seen in Fig. 4C, pauses in vertical geometry also displace the surrounding layers. Expanding on the pauses, we also explore geometric glyphs like lines, boxes, and loops whose lengths are defined by the input data. The results are especially interesting when applied to an object with height, as the glyphs are affected by gravity and the clay's adhesion in unexpected and emergent ways, as shown in Fig. 4D.

We build on the lessons learned from Stage II to create the *Rain Gauge* physicalization in Stage III. The clay from the first-layer prints shown in Fig. 3 were reclaimed immediately after the photos were taken and reused to create the cylinders shown in Fig. 4.

3.2.3 Stage III: *Rain Gauge*

Using our observations from Stages I and II, we produced a data physicalization entitled *Rain Gauge*, shown in Fig. 1. *Rain Gauge* is a cylindrical cup-like physicalization encodes two precipitation-related variables from the past 80 years (1944–2024), measured at NOAA's Minneapolis, MN, USA weather station. The printer's toolpath is based on a spiralized cylinder 10cm in diameter and 15cm tall, with 1.5mm space between each spiral layer (1.5mm layer height; 2:1 ratio). To start, monthly precipitation is encoded as the line length outwards from the cylinder; 0mm = $<$1mm precipitation (October 1951), 15mm = 454mm precipitation (July 1987). Each vertical column represents a month, and years have an alternating offset to minimize occlusions and material interference between years. Then, we apply an extrusion rate for each year (spiral layer) based on the number of days with more than 2.5cm of rain; 100% extrusion = 1 day, 200% = 13 days. We add 20 spiral layers of spacing with no data at the bottom, and the base is filled in with a spiral cap to be watertight (at least to start).

Fig. 1C-E shows our investigation of environment-driven unmaking on the climate data physicalization. As discussed earlier, dry unfired clay can be easily rehydrated, and we explored the selective rehydration of the *Rain Gauge* with rainwater. First, we allowed the physicalization to fully dry after printing. Then, we placed the *Rain Gauge* outside, and the physicalization received 0.8cm of rain over a half hour period. The *Rain Gauge* collected and absorbed the rainwater, re-saturating the dried clay and causing the dry parts to squish the wetter clay at the bottom. Rainfall also textured the upward-facing surfaces including the upper rim and the bottom. After the rain ended, the physicalization leaned towards the summer months with the spacer rows at the bottom almost entirely absorbed, and the bottom cap remained watery (Fig. 1G). Finally, we allowed the physicalization to dry again, leaving the rainwater's effects imprinted on the *Rain Gauge*.

Beyond the scope of this paper, all *Rain Gauge* prototypes except one were reclaimed; we intend to fire the remaining object and use it for demonstrations and in teaching visualization-related courses.

4 DISCUSSION AND LIMITATIONS

One thing we immediately noticed when starting this project is the process necessitated by clay as a material. With standard plastic 3D printers, a maker commonly builds a 3D model in CAD software, slices the model, and sends it to the printer, often not requiring more interaction with the material than loading a spool of filament. However, 3D printing with clay requires a more intimate process where the maker is directly affecting the materials used in the final physicalization, for example, by adding water to the clay and wedging it to remove air bubbles before loading the extruder tube. This style of "intimate making" is an emerging practice in the Human Computer Interaction research community, and has the potential to support more conscientious materials usage when prototyping [3].

Further differences from plastic 3D printers include the importance of the toolpath line and print speed. With the larger nozzle sizes and corresponding layer heights (e.g., 3mm / 1.5mm in clay vs. 0.4mm / 0.15mm in plastic), modifying the toolpath line is a crucial technique for designing 3D printed clay objects. The larger nozzles and resulting thicker material path also enable fast prints; at a print speed of 30 mm/s, the slowest model to print was *Rain Gauge* (1̃0min), and the 5cm cubes shown in Fig. 2C-E were even faster (3̃0sec - 5min, depending on layer height).

The clay form factor also enables designs and data encodings for physicalization that are not possible to produce with other materials. By experimenting with printing parameters like layer height, clay enables makers to create specific textures and effects using emergent behavior between the extruder and the model, as seen in Fig. 2D. Beyond its material properties and geometric affordances, clay also gives a rich set of opportunities for exploring the consequential aspects of physicalization [20], such as the effects of the surrounding environment and people, as well as post-production modification via creative unmaking (e.g., breaking or melting) [34]. Clay physicalizations may also be fired in a kiln, providing further options for encoding data with glossiness, translucency, not to mention color (variable glazing), and even shape-changing when fired [2]. Despite our lack of access to a kiln during the early stages of the project described in this paper, we are excited to explore firing clay physicalizations in the future.

In our process, we also uncovered some limitations of clay 3D printing. First, clay is less predictable to work with than plastic; there may be air bubbles or inconsistencies in the clay that affect the final physicalization (e.g., Fig. 2F), and shrinkage is a major consideration when creating pieces with specific measurements. Additionally, every clay body has different properties (water content, plasticity, self-adhesion). These variabilities require working much more closely with the material and allow physicalization practitioners to explore time-tested ceramic practices. Working with clay in this manner also requires a dedicated shop space and the time spent cleaning; during this process at least one hour per week was dedicated to cleaning the shop floors, Potterbot, and equipment.

A key goal of the project was to enable a circular material process for ceramic 3D printed physicalizations to reduce wasted material during the design process; however, we still relied on an initial purchase of new material from a clay supplier. Clay is a better alternative than plastic from an environmental and human health standpoint because it easily breaks down into its respective natural components, but avoiding new material in the first place would likely be the best choice. Biodegradable and compostable fabrication alternatives [26, 3] show promise for fully circular material streams in digital fabrication, but it is still unclear the degree to which they can be used by standard or paste-based 3D printers.

5 CONCLUSIONS

In summary, this work explored the design and sustainability of clay 3D printed data physicalizations. We methodically investigated the clay material and constraints of the printing process, we tested novel data encodings with clay, and we explored environment-driven unmaking of the *Rain Gauge* climate data physicalization. Given the early results shown in this paper, 3D printed clay physicalizations seem promising both from a material circularity standpoint *and* for the unique design opportunities that clay affords. Beyond the design opportunities explored in this paper, we are excited to encode data by varying the extrusion materials dynamically, exploring custom extrusion nozzles, varying the line toolpath (e.g., variable weaving [16]), applying glazes, and firing the final physicalizations. All in all, we believe that clay is well-suited to creating data physicalizations, and the future potential of 3D printed clay physicalizations clearly calls for further study.

SUPPLEMENTAL MATERIALS

Supplemental materials may be found at `https://osf.io/2khc8/`, including the final SuPPra matrix, Grasshopper definitions for creating custom GCode toolpaths, *Rain Gauge* models and data, and data processing scripts.

ACKNOWLEDGMENTS

The authors wish to thank Molly Sanford and Justin Kindelspire for their assistance in all things shop-related, and Adam Marcus for the Potterbot and Grasshopper tips. This work was supported in part by a Digital Design Center Computational Creativity grant from the University of Minnesota.

REFERENCES

[1] T. Anderson. Techno File: Clay Memory. https://ceramicartsnetwork.org/ceramics-monthly/ceramics-monthly-article/Techno-File-Clay-Memory, Sept. 2019. 1

[2] F. Bell, E. Mcclure, C. Friedman-Gerlicz, R. Ta, and L. Buechley. Shape-Changing Clay-Dough: Taking a Material-Oriented Approach to 3D Printing Ceramic Forms. In *Proc. Conf. Hum. Fact. Comput. Sys. (CHI)*, CHI '24, pp. 1–19. Association for Computing Machinery, New York, NY, USA, May 2024. doi: 10.1145/3613904.3642246 4

[3] F. Bell, N. Ofer, and M. Alistar. ReClaym our Compost: Biodegradable Clay for Intimate Making. In *Proc. Conf. Hum. Fact. Comput. Sys. (CHI)*, pp. 1–15. ACM, New Orleans LA USA, Apr. 2022. doi: 10.1145/3491102.3517711 1, 2, 4

[4] K. Blacklock. 3D Printed Ceramics. https://www.kateblacklock.com/3d-printed-ceramics, 2023. 2

[5] A. L. Boegehold. Toward a Study of Athenian Voting Procedure. *Hesperia*, 32(4):366, Oct. 1963. doi: 10.2307/147360 2

[6] J. R. Brooks. Jeremy R. Brooks. https://klai-body.com/home.html. 2

[7] L. Buechley, J. Gould, and F. Bell. CeraMetal: A New Approach to Low-Cost Metal 3D Printing with Bronze Clay. In *Proc. Conf. Hum. Fact. Comput. Sys. (CHI)*, pp. 1–16. ACM, Honolulu HI USA, May 2024. doi: 10.1145/3613904.3642155 1

[8] B. Buxton. *Sketching User Experiences: Getting the Design Right and the Right Design*. Morgan Kaufmann, 2010. 2

[9] A. Cockburn and B. McKenzie. Evaluating the Effectiveness of Spatial Memory in 2D and 3D Physical and Virtual Environments. In *Proc. Conf. Hum. Fact. Comput. Sys. (CHI)*, p. 8. Association for Computing Machinery, 2002. doi: 10.1145/503376.503413 1

[10] K. Danyluk, T. Ulusoy, W. Wei, and W. Willett. Touch and Beyond: Comparing Physical and Virtual Reality Visualizations. *IEEE Trans. Visual. and Comput. Graph.*, 28(4):1930–1940, 2020. doi: 10.1109/TVCG.2020.3023336 1

[11] A. Desjardins and T. Tihanyi. ListeningCups: A Case of Data Tactility and Data Stories. In *Proc. Des. Inter. Sys. Conf. (DIS)*, pp. 147–160. ACM, San Diego CA USA, June 2019. doi: 10.1145/3322276.3323694 2

[12] A. Desjardins, T. Tihanyi, F. El Shabazz-Thompson, B. Craft, and J. Saimo. The Inner Ear: Capturing and Physicalizing Home Vibrations. In *Proc. Des. Inter. Sys. Conf. (DIS)*, pp. 594–607. ACM, Pittsburgh PA USA, July 2023. doi: 10.1145/3563657.3596070 2

[13] Ž. Dumičić, K. Thoring, H. W. Klöckner, and G. Joost. Design Elements in Data Physicalization: A Systematic Literature Review. In *Proc. Design Research Society*, June 2022. doi: 10.21606/drs.2022.660 1, 2

[14] J. Faludi, C. M. Van Sice, Y. Shi, J. Bower, and O. M. Brooks. Novel Materials can Radically Improve Whole-System Environmental Impacts of Additive Manufacturing. *Journal of Cleaner Production*, 212:1580–1590, Mar. 2019. doi: 10.1016/j.jclepro.2018.12.017 2

[15] J. L. Fredricks, H. Iyer, R. McDonald, J. Hsu, A. M. Jimenez, and E. Roumeli. Spirulina-Based Composites for 3D-Printing. *Journal of Polymer Science*, 59(22):2878–2894, 2021. 2

[16] C. Friedman-Gerlicz, D. Gelosi, F. Bell, and L. Buechley. WeaveSlicer: Expanding the Range of Printable Geometries in Clay. In *Proc. Conf. Hum. Fact. Comput. Sys. (CHI)*, pp. 1–16. ACM, Honolulu HI USA, May 2024. doi: 10.1145/3613904.3642622 4

[17] B. Herman, C. D. Jackson, and D. F. Keefe. Touching The Ground: Evaluating the Effectiveness of Data Physicalizations for Spatial Data Analysis Tasks, 2024. (IEEE VIS; In Press). 1

[18] T. Hogan and E. Hornecker. How Does Representation Modality Affect User-Experience of Data Artifacts? In *Haptic and Audio Interact. Design*, vol. 7468, pp. 141–151. Springer Berlin Heidelberg, Berlin, 2012. doi: 10.1007/978-3-642-32796-4_15 1

[19] L. E. Holmquist. Bits are Cheap, Atoms are Expensive: Critiquing the Turn Towards Tangibility in HCI. In *Extended Abstracts Conf. Hum. Fact. Comput. Sys. (CHI)*, pp. 1–8. ACM, Hamburg, Apr. 2023. doi: 10.1145/3544549.3582744 1

[20] E. Hornecker, T. Hogan, U. Hinrichs, and R. Van Koningsbruggen. A Design Vocabulary for Data Physicalization. *ACM Trans. Comput.-Hum. Inter.*, 31(1):3617366, Aug. 2023. doi: 10.1145/3617366 4

[21] Y. Jansen, P. Dragicevic, and J.-D. Fekete. Evaluating the Efficiency of Physical Visualizations. In *Proc. Conf. Hum. Fact. Comput. Sys. (CHI)*, pp. 2593–2602. ACM, Paris, Apr. 2013. doi: 10.1145/2470654.2481359 1

[22] L. Jones and R. Urbano Gutiérrez. Circular ceramics: Mapping UK mineral waste. *Resources, Conservation and Recycling*, 190:106830, Mar. 2023. doi: 10.1016/j.resconrec.2022.106830 2

[23] J. Keep. Jonathan Keep. Digital Pots. http://www.keep-art.co.uk/digitial_sound.html, 2016. 2

[24] J. Keep. A Guide to Clay 3D Printing, 2020. 2, 3

[25] L. Klauss, S. Morét, and M. Stefaner. Perpetual Plastic — Beach debris reveals the fate of all plastic ever made. https://perpetual-plastic.net/, 2020. 1

[26] E. S. Lazaro Vasquez, H.-C. Wang, and K. Vega. Introducing the Sustainable Prototyping Life Cycle for Digital Fabrication to Designers. In *Proc. Des. Inter. Sys. Conf. (DIS)*, pp. 1301–1312. ACM, Eindhoven Netherlands, July 2020. doi: 10.1145/3357236.3395510 2, 4

[27] A. Le Duigou, D. Correa, M. Ueda, R. Matsuzaki, and M. Castro. A Review of 3D and 4D Printing of Natural Fibre Biocomposites. *Materials & Design*, 194:108911, Sept. 2020. doi: 10.1016/j.matdes.2020.108911 2

[28] V. Maniatidis and P. Walker. A Review of Rammed Earth Construction. *Developing Rammed Earth for UK Housing*, 12, 2003. 2

[29] C. Martinez. Developing a Creative Practice with Ceramic Data Physicalizations. https://dhandlib.org/2024/04/29/developing-a-creative-practice-with-ceramic-data-physicalizations/, Apr. 2024. 2

[30] L. Morais, G. Panagiotidou, S. Hayes, T. Losev, R. Noonan, and U. Hinrichs. From Exploration to End of Life: Unpacking Sustainability in Physicalization Practices. In *Proc. Conf. Hum. Fact. Comput. Sys. (CHI)*, pp. 1–17. ACM, Honolulu, May 2024. doi: 10.1145/3613904.3642248 1, 2

[31] R. Rael and V. San Fratello. Casa Covida. https://www.rael-sanfratello.com/made/casa-covida, 2020. 2

[32] D. Schmandt-Besserat. Tokens: The cognitive significance. *Documenta Praehistorica*, 26:21–27, 1999. 2

[33] E. L. Smith. Erin Lynn Smith Studio. https://erinlynnsmith.studio/. 2

[34] K. W. Song and E. Paulos. Unmaking: Enabling and Celebrating the Creative Material of Failure, Destruction, Decay, and Deformation. In *Proc. Conf. Hum. Fact. Comput. Sys. (CHI)*, pp. 1–12. ACM, Yokohama Japan, May 2021. doi: 10.1145/3411764.3445529 1, 4

[35] S. Stusak, J. Schwarz, and A. Butz. Evaluating the Memorability of Physical Visualizations. In *Proc. Conf. Hum. Fact. Comput. Sys. (CHI)*, pp. 3247–3250. ACM, Seoul Republic of Korea, Apr. 2015. doi: 10.1145/2702123.2702248 1

[36] P. Waśniowski. Piotr Waśniowski's Ceramic 3D Printing. https://www.instagram.com/piotr_wasniowski/. 2

[37] M. Weiss. Melissa Weiss Pottery. https://www.melissaweisspottery.com. 2