ListeningCups: A Case of Data Tactility and Data Stories

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ABSTRACT

In this pictorial, we present the ListeningCups: a set of 3D printed porcelain cups embedded with datasets of everyday ambient sounds. During a one-week pilot project, a ceramic artist and an interaction design researcher collaborated to explore meaning making around everyday data (sound in our case). We developed a workflow to capture data, prepare datasets, transcribe data from decibels to G-code, and create a set of 3D printed porcelain cups which represent this data in a textural and tactile form. We discuss how our work also included aesthetic investigative practices as well as data accidents. We conclude by contributing two concepts—data tactility and data stories—that can serve as starting points for designers, artists, or researchers interested in the intersection of materiality, data, fabrication, and ceramics.

Authors Keywords

Digital ceramics; Data tactility; Data physicalization; Data stories; Internet of Things; Craft; Digital Fabrication; Ceramic 3D printing; Domestic objects.

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INTRODUCTION

With connectivity, sensors, and actuators, the Internet of Things (IoT) promises simplified, streamlined, productive, and efficient everyday support. Connected door locks, light bulbs, cameras, and thermostats are often presented through their functionality: automated, hands off and even magical ways to control mundane tasks and maintenance around the home. With a growing number of IoT devices [2, 9, 18], the amount of data collected, aggregated, and analyzed is also growing exponentially.

Yet, this data is often left in the background, ignored, or inaccessible to the everyday user—the people who themselves are at the center of this data. In this pictorial, we ask: How can users of IoT engage with this data in a way where it becomes meaningful to them? How might one make sense of their data? How is meaning created from IoT data? In other words, in addition to benefiting from the functionality of IoT devices, how might people also gain value from seeing, touching, feeling the data itself? In this pictorial, we make two proposals based on our work with the data driven 3D printed ListeningCups: data tactility and data stories.

Data Tactility: By giving a physical shape to the data collected over time in the form of a familiar and highly tactile functional object, we hope to spur imagination, memory, and reflection. Bringing back this tactile data to environments of daily life—from which the data was collected in the first place—allows the user to live with the new material object and the data itself. Textures and material qualities of the artifact are revealed, may be contemplated, and reflected upon through a direct experience of touch. The experience, through many different modalities, has the potential to create a space to engage with data differently, through curiosity, emotion, and investigative practices.

Data Stories: Tactile data artifacts hold many narrative layers [16, 20, 27], including stories of data collection, data transcription, material fabrication, and everyday use. While the designer’s, maker’s, or craftsperson’s technical and aesthetic biases as well as the physical manipulation of the materials during the hands-on process will change many aspects of how the data is encountered in physical from, it is ultimately up to users to give life to those stories, for themselves, or for others.

The concepts of data tactility and data stories are the result of a collaborative research pilot project between an interaction design researcher (Desjardins) and a ceramic artist (Tihanyi). Together, we created The ListeningCups: a set of 3D printed porcelain cups whose textures (a series of small bumps) represent snippets of sound recorded in various spaces. During a week-long residency at Slip Rabbit Studio, a digital ceramics lab, we developed a workflow for capturing ambient sound data, transcribing the volume levels (decibels) into machine code information (G-code), which then produced a texture on a Potterbot7 ceramic 3D printer. To promote functionality, we finished the porcelain pieces with glaze and fired them to vitreous temperature of 2160 degrees F. We chose digital ceramics to investigate our research question because this area is already at the intersection between the digital and material worlds, similarly to IoT devices. Moreover, ceramics has a rich tradition and history enmeshed in common everyday environments, particularly in the home.

In this pictorial, we present an account of our process, the ListeningCups, and a self-reflection on our experience throughout our process. We conclude by articulating two main lessons from our work that could be generative and inspirational for other designers, artists, data scientists, and researchers in the DIS community: the value of data tactility and the importance of data stories.

RELATED WORKS AND PRECEDENTS

Our work builds on and expands works in the areas of data physicalization and 3D printed ceramics.

Data physicalization

Akin to data visualization, data physicalization aims at transforming data sets into physical data-driven objects, in order to support exploration, understandings, and communication. Jansen et al. define data physicalizations as “*a physical artifact whose geometry or material properties encode data*” [14:3228]. Relatedly, data sculptures are referred to as “*a highly data-oriented physical form, possessing both artistic and functional qualities, to augment an audience’s understanding of the underlying data and issues.*” [33:346].

In the past decade or so, researchers in this field have explored the complexities of how data is collected, chosen, and prepared for physicalization [12]. Wang et al. [29] raise questions regarding levels of abstractness and fidelity of data representations, as well as how to find the appropriate mapping between the data and the representation. While many works focus on the ways physicalizations are constructed (e.g. see [11, 12, 23, 24]), Lupton [17] offers an important account of how perceptible data materialization can lead to a better incorporation of data in everyday life. She states: “*I argue that these forms of data materialisation* [those that invite touching and handling] *are potentially integral to new modes of understanding and incorporating personal data into everyday life, living with and alongside these data.*” [17:1600]. Along similar lines, Willett et al. [32] champion data physicalizations that are embedded and situated in everyday life as a way to bring physicalizations closer to their data referents, or in other words to where data was or is collected. Building on these works, we argue that data tactility supports continuous engagements with data as people live alongside materialized artefacts. Also of inspiration to our work is the idea that data physicalization can become a participatory act, one where people might choose what data to track and how to represent it in their own lives (e.g. [19, 25, 26]).

Partially due to our background and previous projects in pottery/ceramics, we extend this corpus of literature by emphasizing the maker’s and the user’s interaction with the data through the haptic modality. While materialization and physicalization focus on 3-dimensional and spatial qualities of the representation, our research is contextualized in a broader artistic practice focused on the sense of touch.

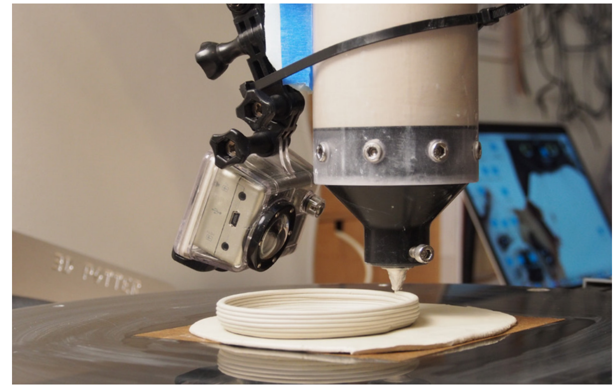
3D printing ceramics

Ceramic history is strongly connected to the history of household personal and domestic objects: food serving and cooking pots, washbasins, storage vessels and receptacles, traditionally made by hand, on the potter’s wheel or by pressing or pouring liquid clay into a plaster mold. 3D printing references and simultaneously updates many historical precedents and modes of production.

Ceramic paste extrusion printing is a relatively recent but rapidly developing area that is currently finding its way into both art and design practice. Beginning in 2009 [30], through research initiatives concerning hardware and software possibilities by designers Dries Verbruggen and Claire Varnier at Studio Unfold, in Antwerp, Belgium [31], and Olivier van Herpt [10] at the Design Academy Eindhoven in 2012-13, the utilization of the deposition modeling (FDM) process with high-plasticity ceramic materials took off. Parallel investigations by ceramic artists like Jonathan Keep [15] of UK (around 2012), as well as various artists hosted for a residency at the FabLab of the European Ceramic Workcentre [8], in the Netherlands, lead to exploring the specific language of clay, refocusing the dialogue on the iterative nature of the digital ceramic process and the aesthetics of imperfection created by code blips, technical and material variations.

Clay’s natural plasticity and workability are dependent on many factors, including the kinds of ceramic ingredients used, their methods of preparation, as well as environmental aspects, like air temperature and moisture. Working with ceramics is time-sensitive and material-sensitive, which, combined with a craftsperson’s touch, the nature of the specific tools used, and clay’s own ability to morph throughout the process, results in a certain level of unpredictability and a degree of variability to the finished object. In addition, the digitally aided workflow creates limitless entry points for creating and hacking a design, be those on the level of the design software, code, machine properties and settings or focused on the ceramic materials themselves.

Artists and designers in the DIS community and beyond have collaborated on using data [21], sound and clay [22] algorithm [15], 3D modeling [28], and direct alteration of the material such as the glaze [6] in combination with the ceramic process. In addition to being inspired by these precedents, our workflow was informed by empirical evidence on specific interactions between material, code and tool, which were accumulated through Tihanyi’s ceramics practice and her experimentations with the Potterbot7 printer at Slip Rabbit Studio.

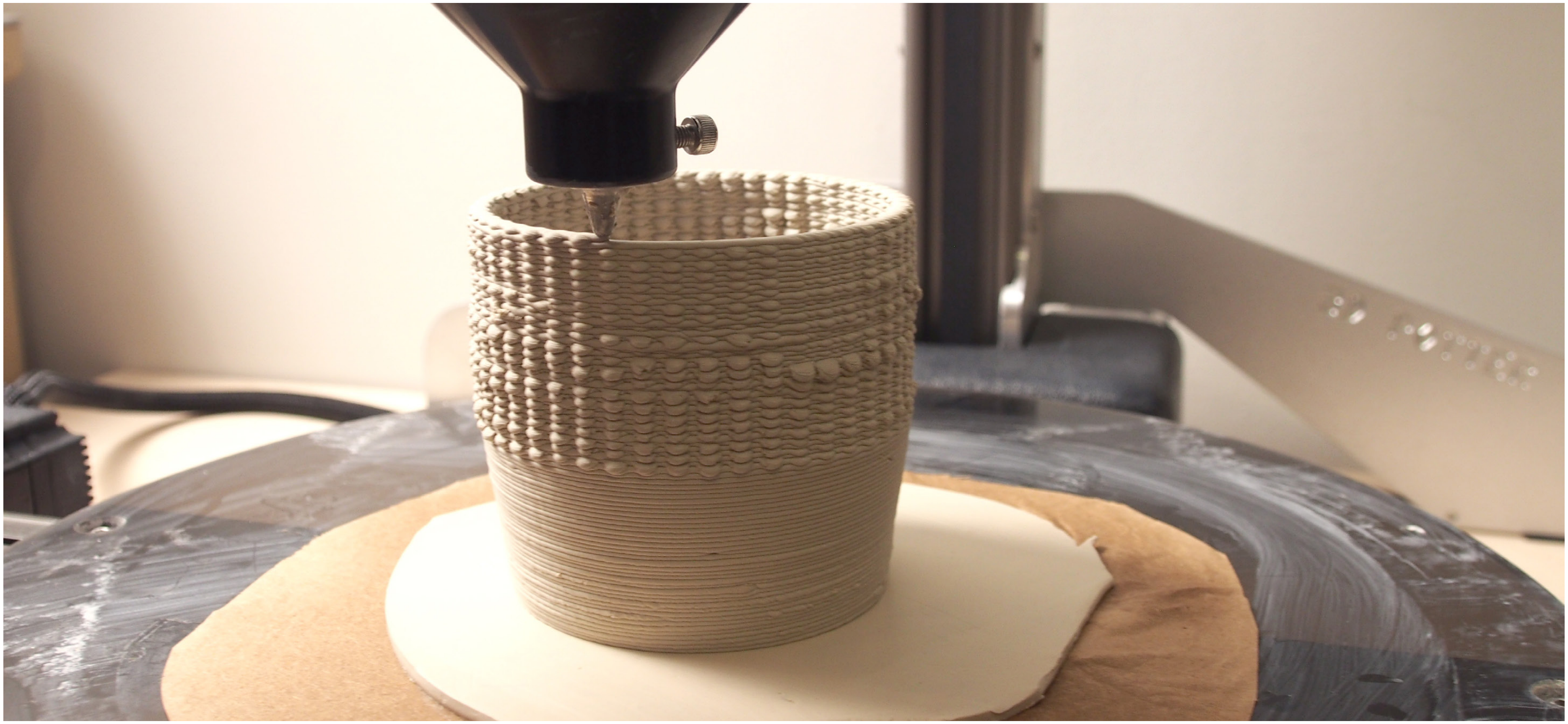


OUR APPROACH

During this pilot project, we developed a ceramic artist/interaction design researcher collaboration. Desjardins (the interaction design researcher) was interested in the process of transcribing the data and its implication for IoT. This interest stemmed from her past research in developing personal, contingent, situated, and bespoke concepts for domestic IoT [4]. The inherent physicality of IoT was often in strong contrast to the invisibility of the data, provoking Desjardins’s imagination. Tihanyi (the ceramic artist and director of Slip Rabbit Studio) has been working with physicalization of mathematical matrices through ceramic 3D printing. Tihanyi has also been working on developing a framework for engaging individuals with disability, which would require user input to be captured specifically with the goal of creating 3-dimensional forms and textures.

During an intensive one-week residency, we developed a workflow for 3D printing cups. During the week, we iterated on the process repeatedly, engaged in troubleshooting, and reflected on our process.

We documented our process and outcomes through photographs, videos, files for storing the original data, files of the processed data and files of G-code for printing, notebooks, and post-mortem reflections and discussion notes. We used this documentation to support our reflection and analysis of the process.

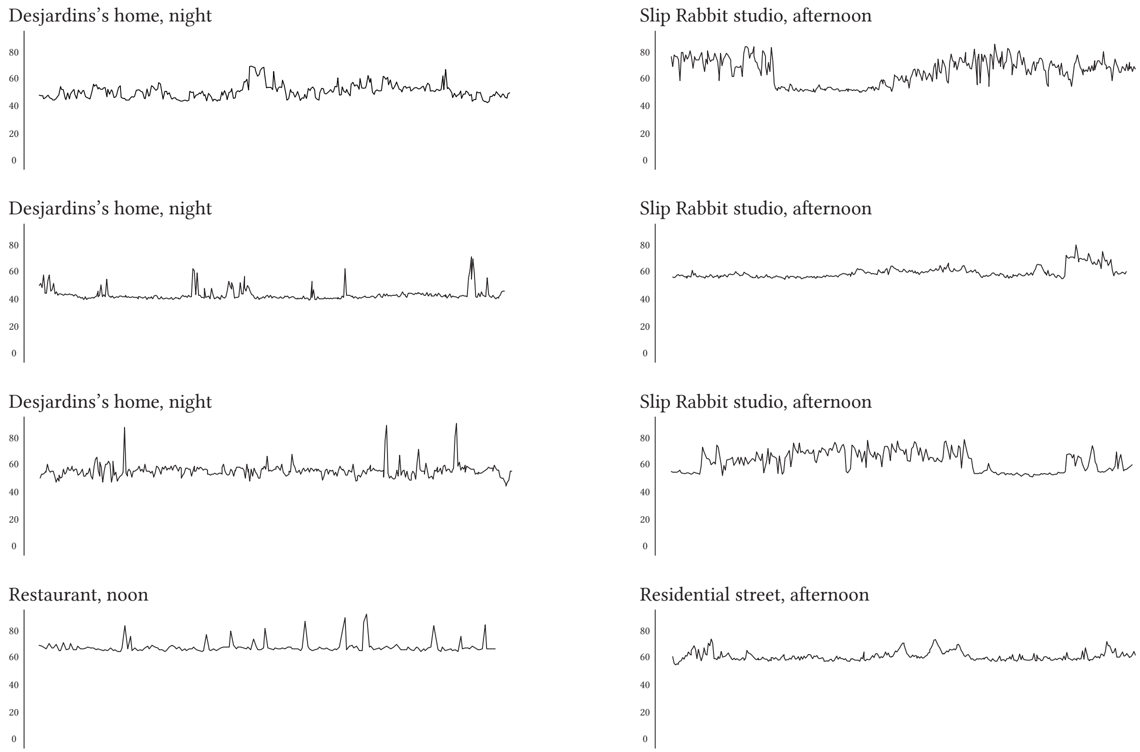


THE LISTENINGCUPS

As a result of our process, we created a series of 3D printed porcelain cups. The texture on the cups is a representation of short snippets of decibel levels in sounds recorded in various everyday places: Desjardins’s home, a restaurant, Slip Rabbit Studio, and a residential street.

A special property of clay is to respond to the shape, movement and behavior of the tool. For this reason, here we focused on utilizing the specific nature of the digital tool, a Potterbot7 ceramic printer, which relies on continuous extrusion and has no retraction. The texture on the cups is produced by a very novel technique in 3D printing: by pausing the printer’s XY axes movement. When pausing the printing bed of this Cartesian printer, the nozzle stays in the same position while more soft porcelain is being extruded, causing excess material to deposit and thus a small bump to form both on the inside and outside of the vessel’s wall. The length of each pause was determined by the associated data point’s decibel range. After several experiments, we created a texture library and concluded which lengths of duration (between 0 and 4000 milliseconds) were the most effective at exhibiting texture—and hence data—differences. While all the cups are built from the same raw data set, the variation in texture and appearance is based on different mappings of data to pauses. Additional variations were created by changing material conditions of the clay, for example, air humidity and temperature, the conditions of handling during the pottery process (wedging, reclaiming) as well as different nozzles, printing speeds, and pressures.

We used a free app called ‘Decibel X’ to capture decibel levels.



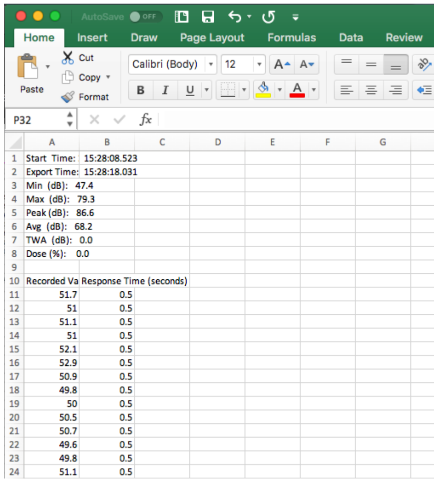
CAPTURING THE DATA

When we started the project, our intention was to experiment with data, tactility and IoT. In the first days of the project, we explored a variety of data that we could potentially use. Part of this process led us to reconsider the mobile phone as a pre-packaged sensor kit (similarly to how Chatting et al. [3] also use a phone’s sensors as a platform for prototyping). Through various accessible mobile apps, it is possible to see the data captured in real time by a variety of sensors and to record this data.

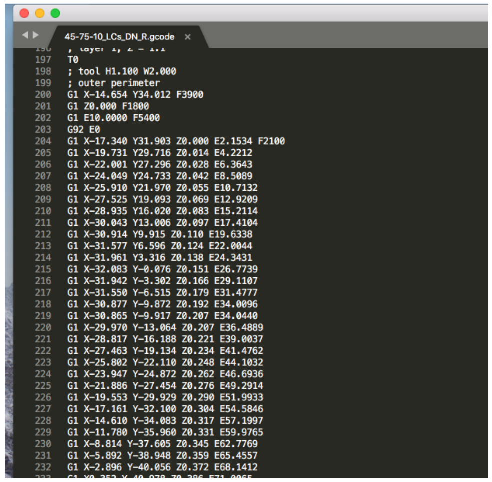
We chose to represent sound data in this project because it is a modality that is rarely explored in general everyday use of IoT devices (see exception [26]), although it may have implications for personal health, comfort, and safety in high-noise exposure environments. Temperature, motion, lights, etc. are often part of connected devices’ systems, however, ambient sound is often left unexplored. More importantly, we felt that sound could serve as a strong indicator of an environment that a user might be a part of. We were curious about trends of sound levels over time and how much sound changed over the course of a day. For the purpose of the design residency, we decided to record short clips of ambient audio data that could represent different audio spaces and times. Desjardins used a mobile app to record data in 8 short clips of 3 minutes each (the duration was determined by the app). We deliberately chose tools, which would be free-of-charge and commonly available to participants in a later, expanded iteration of this project.

We chose these four locations because they had the possibility to represent the everyday and mundane sounds we encounter on a daily basis in Seattle, USA. We aimed at collecting samples that would offer a diversity in their time of the day, but also the sound scapes they would represent. With an interest in investigating personal IoT data, Desjardins was curious to support an inquiry into her everyday sounds.

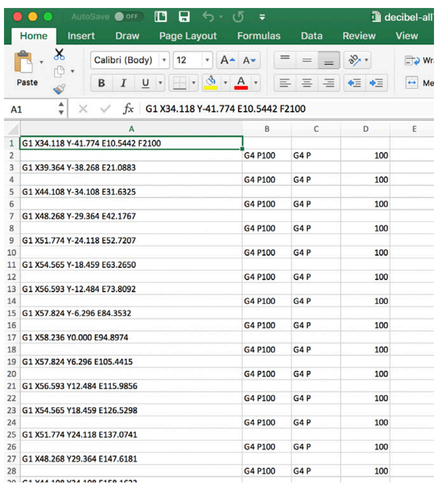
After slicing in each cup form, we determined that the number of surface points (vertices) available was between 2500-3000, and we used a sampling rate in the app to match this. For testing purposes, we felt that this was sufficient. While these clips are very short, they were taken throughout a 24 hours period, aiming at representing many parts of a day. In future works, we can imagine much longer data capture periods, leading to reflections from users that could be much more temporally engaged. However, for the purpose of developing a workflow and imagining how data might be rendered tactile, we were satisfied with this data set.



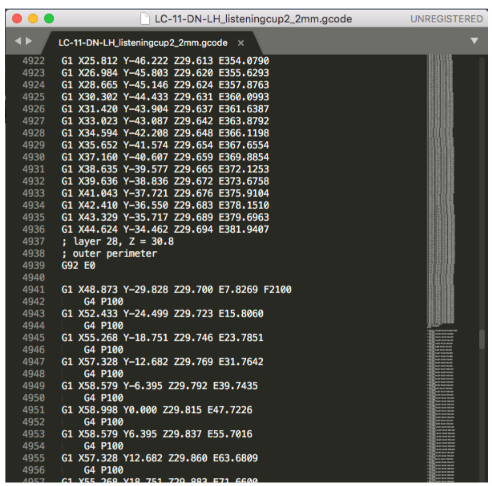
To add the pauses based on the decibel data into G-code, first, (1) we imported the data collected into an excel sheet.



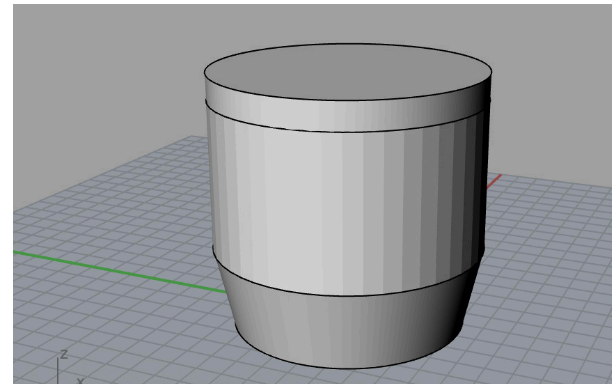
(2) We generated the G-code for the basic shape of the cup.



(3) We copied the lines where we wanted the added data texture in excel. Between each G-code line, we inserted a ‘G4 P’ command, dictating the length of the pause at each point.



(4) We copied the excel cells as lines back in a text editor (Sublime).

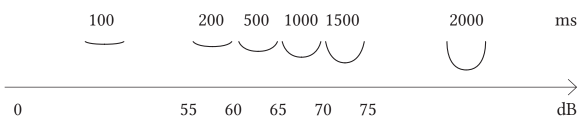


In order to assign data to every point of the G-code, we also had to consider the number of vertices (XY coordinates) within each layer. After some experimentation we decided to use a 48 sided polygon instead of a circle, to create a more controlled set of points that was independent from scale or shape. After exporting the STL from Rhino5, we used Simplify3D as a slicer to generate a G-code.

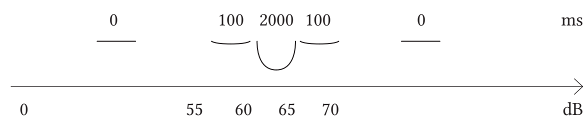
PREPARING DATA SETS

Excel was one of our main tools to edit the G-code for the 3D printer. The structure offered by the cell, row and line framework (as exemplified by Dourish [7]) was sufficient to import, combine, and export sets of data, both decibel values and G-code. After developing our workflow, we noticed the simplicity and ease at which our files were flowing between Rhino5 (creating the shape of the cup), Simplify3D (creating G-code commands), Sublime (reading G-code commands), and Excel (associating data point values to pause lengths and including those pauses into the G-code), allowing us to by-pass creating G-code directly in Grasshopper or in Python. The simplicity of the process allowed for transparency and control, something we strove for in this exploratory phase of the project. In addition, our goal was to move relatively fast, so relying on our existing skillsets rather than learning new software was important.

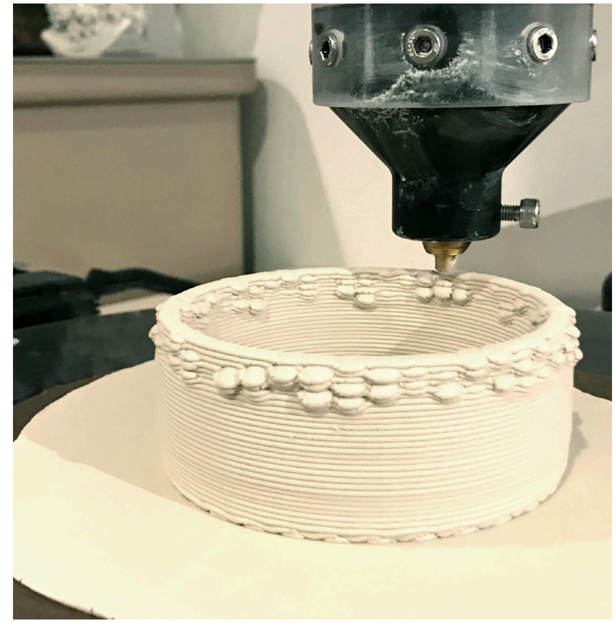
Moreover, to gain more control on the number of points per line, we chose 48 points. 48 points was poetic and meaningful: we could easily connect 48 points to a 24 hour timeline if wanted.



We experimented with two scales for the transcriptions. (1) The first scale was gradual: a soft sound would be represented by a small bump and a louder sound would be a larger bump. Pauses between 100 to 2000 milliseconds were assigned on a linear scale.



(2) The second scale highlighted human conversations (usually around 60 to 65 dB). We assigned sounds in the range of 60 to 65 dB a larger bump (2000 milliseconds). Anything around 55-60 dB or 65-70 dB was a small bump (100 milliseconds) and anything else was assigned no pause.



Interestingly, everytime the 3D printer paused to represent a sound, it became silent since the motors stopped moving in the XY axis. We were amused and in awe of this inversed soundscape produced by our transcription method.

In addition to experimenting with scales, we also played with how we ordered the data.

In the cups above, the cup represents a whole day, where the bottom of the cup is the morning, and the top of the cup is the end of the day.

However, we also moved data points around to showcase all the evening data on one side of the cup. Here, we see a clear demarcation between night data and day data.

CHOOSING THE RIGHT TRANSCRIPTION

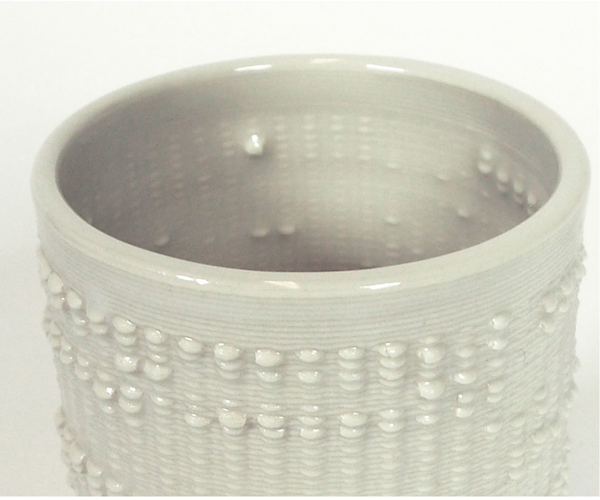
Once we had captured the data, we tried a variety of approaches to transcribe decibels into G-code pauses for the printer.

While cups created with both scales were based on the same raw data, the resulting cups looked and felt different, but also supported dramatically different types of data stories. One had stories about the sensor and a gradual scale (a small bump was a soft sound; a big bump was a loud sound), the other was about humans in the space (big bumps highlighting the human conversation range). Of course, there is no way of knowing if sounds at 60-65 dB were in fact human conversations, but it opens an imaginary space around what stories are behind the various ambient sounds in a space.

Early experimentations to see the impact of a bump amongst many lines (cup on the right) and the effect of repeating bumps at every line or every other line (cup on the left).

The longer the pauses, the more pronounced were the bumps. From left to right, we see how long pauses generate a coarse aggressive texture while shorter pauses yield a more delicate texture, almost reminescent of weaving.

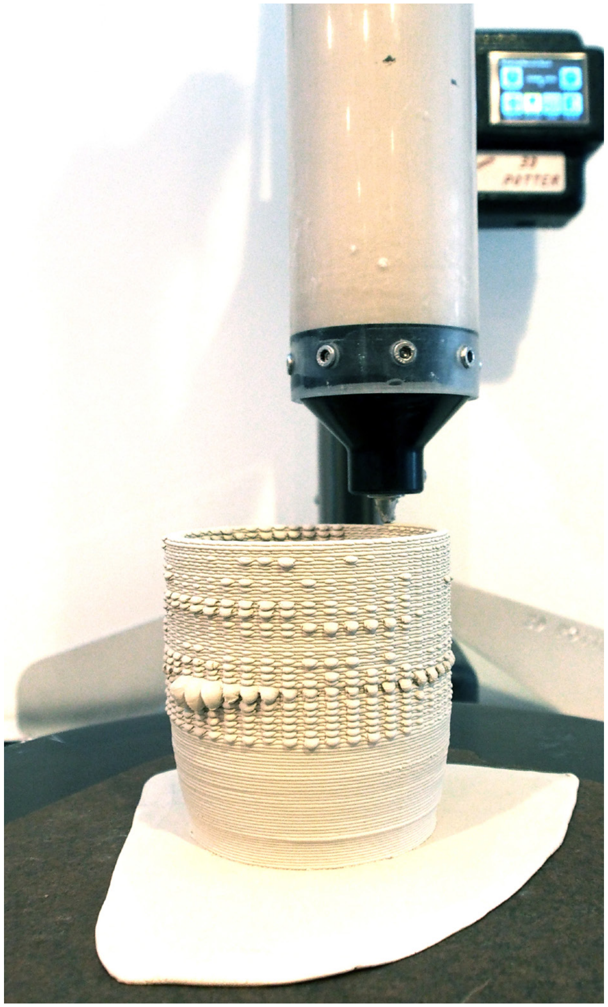
The size of the nozzle influenced the baseline thickness of the extruded clay. The left cup was created with a nozzle of 3.5 mm (and a layer height of 1.5mm) while the right cup was created with a nozzle of 2mm (and a layer height of 1.1 mm).



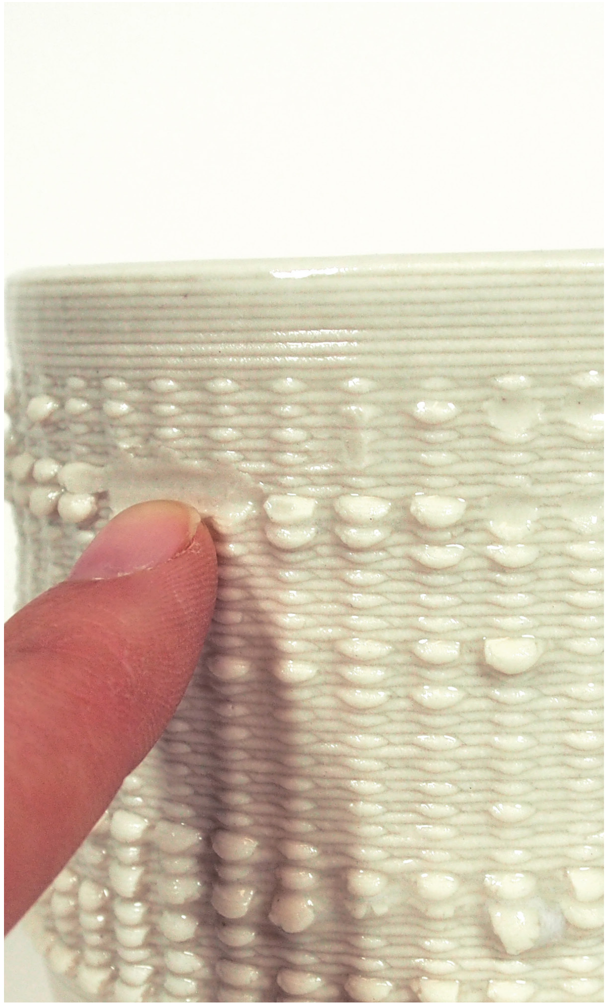
The glazing inside the cup is thicker, partially covering the texture (for functionality and hygiene), than the one outside the cup, which shows accentuated texture (to create more tactile information for the hand of the user).

AESTHETIC CALIBRATION

While the meaning of the transcriptions could be adjusted by the ordering of the data points or the scales used, we also extensively experimented with different nozzle sizes, clay pressure in the extruding tube, and printing speed in order to create and evaluate various aesthetic outcomes. We were ‘playing’ with the machine, both to reach visual and tactile results appealing to our tastes, and also with the user’s experience in mind, while conveying information about the sound data. This close relationship with the machine was possible because Tihanyi already had an excellent understanding and anticipating of what the printer could do, including the innovative use of the dwell command for the production of texture. This allowed for a three-way collaboration between the machine, Tihanyi, and Desjardins.



In one of our prints, a piece of debris in the clay was caught in the nozzle. The printer continued along its path, with not much clay oozing out, until Tihanyi successfully removed the piece of debris by hand. As soon as she removed the debris, the built up pressure in the extrusion tube pushed out a lot of soft clay, very fast. This created this sequence of six very big bumps in the cup.



In another instance, after a long day in the studio, Desjardins moved a freshly printed cup to the drying rack and accidentally hit another cup with it. The clay was still very soft and the impact 'smooshed' a few of the bumps.

In some of our early prints, we realized that a pause was always longer at the origin point of the layer, creating additional build-up and thus, a visible seam. This effect was a result of the slicer algorithm, which created each layer with a discrete height. Changing to an incremental increase of the Z height from coordinate point to coordinate point remedied the situation.

DATA ACCIDENTS

While the 3D printer definitely brings some predictability to the making process, the plasticity of the clay and the human manipulation involved often result in accidents and surprises in the printed cups, rendering each unique.

Those accidents change the texture on the cups, and by definition, might also change the perceived meaning of the data embedded in the cups. The way we tell stories about the data is then also influenced by the irregularities in the making process. For instance, one might imagine a very loud sound happening on the cup in the left image. Or one might also imagine a noise canceling device on the cup in the middle photo. Or that regularly, at every day, at the same exact time, a louder noise happens on the cups in the photo above.

Image credit: Rollofall

HINTS TOWARDS USE

Since the pilot was completed (September 2018), we have been living with the cups. They have been in our homes, our studios, and our offices. Two observations stand out. First the tactility of the bumps presents itself differently depending on the activity. Pouring hot beverage might entice us to choose the cup with the "noisiest" surface texture: the extra space sparing our hands from being scalded. The accidental sharpness of some of the extrusions wakes up the senses during long hours spent on a task. Moving the hand up and down the sides of the cup mirrors one's emotional state during a meandering conversation. Washing the cups, for instance, accentuates the texture based on how the water ripples and moves on the surface of the cup. While washing by hand is an activity that is relatively fast, it still offers a moment for reflection: What sound provoked that bump? Why is this part feeling more smooth, why were we so quiet?

Our second observation is about the ways we, both Tihanyi and Desjardins, have been talking about the cups to our colleagues, students, friends, family members, and studio visitors. As we explain that the bumps are created to represent ambient sound data, our interlocutors start to imagine, speculate, ask questions. In those moments, we wonder how much more detail we need to tell them. How much of the factual data do we need to talk about? How much can we let them imagine the data that is behind these cups is a balance we are discovering?

DISCUSSION

In this pictorial, we have presented the ListeningCups: 3D printed porcelain cups that embody and represent, through small bumps, ambient sound data. As we reflect on the process of transcribing ambient sound data to tactile cups, we wish to highlight how data tactility and data stories may play a central role in unraveling meaning from IoT data.

Data tactility: In process, anticipated, and lived

The meaning of our dataset takes shape in the ways we worked with the machine [5]. Experimenting with different nozzles, layer heights, clay humidity, and pause lengths, turned out to be an integral part to our creative and craft *process*. The meaning embedded in the tactility of the cups was not only a result of the abstract data transcription from the excel sheets to the G-code through the 3D printer; in that sense, data tactility is contingent on the material, tools, and processes of making.

Interestingly, while our focus was on tactile representations, a part of our work relied on *anticipated* tactility. As the printer deposited soft clay, we could not yet touch the clay (we would have deformed it), but we could imagine tactile feelings by visually observing the size or regularity of the bumps. It is stipulated that the neural network for haptic exploration is likely to use some of the same pathways in the brain as visual processing [13]. Both systems can be primed—resulting in a stronger activation—with information from the other modality [13]. After a few days of drying, we trimmed the bottoms, allowing for one of the first times a contact between our hands and the printed clay. As the clay dried further, as it was bisque fired, and then glazed before its final firing, we ‘felt’ the data in many forms. While Tihanyi could rely on her past experience with 3D printed clay to anticipate tactile experiences, Desjardins had to imagine tactility through the eyes of first-time discovery.

Finally, data tactility becomes *lived-with* once the cups are finalized with their glaze. The data, now embedded in these everyday objects, might trigger memories, emotional thoughts, and emphasize reflection when fingers cross a specific bump or a smoother area. The human haptic system explores objects in a piecemeal fashion. Jumping from area to area, it samples bits of information about hardness, temperature, sharpness, granularity, etc. in an active and nonlinear way, seeking out exactly the bit that it needs to create a meaningful and memorable interpretation. Tactility—as opposed to structure, which is primarily determined by the digital workflow and the mechanics of the machine—is a consequence of the material, and thus can only be accessed in an unmediated and intensely direct and personal way, “non-analytically, receptively” [1] in everyday interactions.

While data physicalization often proposes that data be made tactile as an opening for reflection and analysis, our conceptualization of data tactility offers a way to investigate what different forms and moments of tactile engagement with data might happen before it is lived with. We encourage the DIS community to consider data tactility throughout the entire lifespan of data artifacts, from data capture, to fabrication and everyday use.

Data stories: Subjectivity and fiction

Once glazed, the cups are open for interpretation, as we have described in the section ‘Hints towards use’. These future interpretations will be responding to the captured interpretations and subjectivity that are already embedded in the cups themselves. In fact, underlying the account of our process in this pictorial lies a narrative revealing data’s susceptibility to subjectivity. The process of data transcription—capturing, organizing, mapping and materializing the data—was filled with decisions we, as designer and artist, made. Those decisions were influenced by multiple factors including our intention, our aesthetic taste, our perception of how potential users would use the cups, our past experiences, and our research questions. This susceptibility to subjectivity offers a contrasting point to common assumptions that data is perfect, clean, and clear.

To further explore this tension, on the last day of the residency, Desjardins purposefully changed some data points by hand in the G-code, creating ‘fictional ‘data, with the potential of supporting fictional data stories. Invented data, falsified data or accidental data (as we presented above) remind us that, through tactility, data is also rendered a malleable material, opening possibilities for imagination and interpretation. Missing bumps might represent sounds one wanted to forget or erase from the record. Fabricated bumps might reveal rhythms one aspires to reproduce in their own space. While data stories from IoT devices are expected to be ‘right’ or ‘real’, our work with the ListeningCups shows that the focus can shift to the ways people might recount these stories, or the ways they might imagine past events (real or not). The variety of cups created from the one dataset Desjardins collected also invites our imagination to run wild: every person will likely to tell a different story with their data set.

Our work contributes a starting point to discuss how data stories are crafted through subjectivity in the making process and in the imaginative ways people engage with the data physicalizations. We invite designers, artists, and researchers to consider bespoke and unique approaches when experimenting with IoT (or other) datasets to support individual and situated data stories.

FUTURE INVESTIGATIONS

As design researchers, designers, and artists continue to explore the intersection between clay and everyday data, we wish to highlight two additional considerations. Firstly, IoT data is closely related to people’s personal everyday lives. Our slow and fine process for adjusting the bumps to the proposed transcription was filled with subjective choices based on Tihanyi and Desjardins’s preferences, disciplinary context, and values (e.g. deciding what should ‘count’ as a larger bump). When imagining data objects for others, based on their own data, we encourage design researchers to reflect on these questions: How much input can the user have in choosing their transcription? How might users collect their own data? Secondly, it seems to be a natural next step to pursue working with groups whose sense of touch is differently attuned, such as craftspeople, artisan bakers, individuals of low or no vision or those whose work is primarily relegated to the tactile modality. Partnering with individuals from such groups would allow further explorations of data collection over longer periods of time, as well as data transcription and aesthetic investigations.

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REFERENCES

[1] Anni Albers. 1965. On Weaving. First edition. Wesleyan University Press, Middletown, Connecticut.

[2] Luigi Atzori, Antonio Iera, and Giacomo Morabito. 2010. The Internet of Things: A survey. Computer Networks 54, 15: 2787–2805. https://doi.org/10.1016/j.comnet.2010.05.010

[3] David Chatting, David S. Kirk, Abigail C. Durrant, Chris Elsden, Paulina Yurman, and Jo-Anne Bichard. 2017. Making Ritual Machines: The Mobile Phone As a Networked Material for Research Products. In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI ’17), 435–447. https://doi.org/10.1145/3025453.3025630

[4] Audrey Desjardins, Jeremy E. Viny, Cayla Key, and Nouela Johnston. 2019. Alternative Avenues for IoT: Designing with Non-Stereotypical Homes. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI ’19). https://doi.org/10.1145/3290605.3300581

[5] Laura Devendorf and Kimiko Ryokai. 2015. Being the Machine: Reconfiguring Agency and Control in Hybrid Fabrication. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI ’15), 2477–2486. https://doi.org/10.1145/2702123.2702547

[6] Nir Dick, Naama Glauber, Adi Yehezkeli, Moran Mizrahi, Shani Reches, Maiayn Ben-Yona, Anna Carmi, and Amit Zoran. 2018. Design with Minimal Intervention: Drawing with Light and Cracks. In Proceedings of the 2018 Designing Interactive Systems Conference (DIS ’18), 1107–1120. https://doi.org/10.1145/3196709.3196814

[7] Paul Dourish. 2017. The Stuff of Bits: An Essay on the Materialities of Information. MIT Press.

[8] Fablab. fablab | EKWC. Retrieved January 16, 2019 from https://sundaymorning.ekwc.nl/en/fablab-4/

[9] Ester Fritsch, Irina Shklovski, and Rachel Douglas-Jones. 2018. Calling for a Revolution: An Analysis of IoT Manifestos. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI ’18), 302:1–302:13. https://doi.org/10.1145/3173574.3173876

[10] Olivier van Herpt. 3D Printing Ceramics - Olivier van Herpt. Retrieved January 16, 2019 from http://oliviervanherpt.com/3d-printing-ceramics/

[11] 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 (TEI ’16), 753–756. https://doi.org/10.1145/2839462.2854112

[12] Samuel Huron, Pauline Gourlet, Uta Hinrichs, Trevor Hogan, and Yvonne Jansen. 2017. Let’s Get Physical: Promoting Data Physicalization in Workshop Formats. In Proceedings of the 2017 Conference on Designing Interactive Systems (DIS ’17), 1409–1422. https://doi.org/10.1145/3064663.3064798

[13] Thomas W. James, G. Keith Humphrey, Joseph S. Gati, Philip Servos, Ravi S. Menon, and Melvyn A. Goodale. 2002. Haptic study of three-dimensional objects activates extrastriate visual areas. Neuropsychologia 40, 10: 1706–1714. https://doi.org/10.1016/S0028-3932(02)00017-9

[14] Yvonne Jansen, Pierre Dragicevic, Petra Isenberg, Jason Alexander, Abhijit Karnik, Johan Kildal, Sriram Subramanian, and Kasper Hornbaek. 2015. Opportunities and Challenges for Data Physicalization. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI ’15), 3227–3236. https://doi.org/10.1145/2702123.2702180

[15] Jonathan Keep. Jonathan Keep, digital 3D ceramic printing journal 2012 - 11. Retrieved January 16, 2019 from http://www.keep-art.co.uk/journal_2.html

[16] Giorgia Lupi, Stefanie Posavec, and Maria Popova. 2016. Dear Data. Princeton Architectural Press, New York.

[17] Deborah Lupton. 2017. Feeling your data: Touch and making sense of personal digital data. New Media & Society 19, 10: 1599–1614. https://doi.org/10.1177/1461444817717515

[18] Daniele Miorandi, Sabrina Sicari, Francesco De Pellegrini, and Imrich Chlamtac. 2012. Internet of things: Vision, applications and research challenges. Ad Hoc Networks 10, 7: 1497–1516. https://doi.org/10.1016/j.adhoc.2012.02.016

[19] Bettina Nissen and John Bowers. 2015. Data-Things: Digital Fabrication Situated Within Participatory Data Translation Activities. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI ’15), 2467–2476. https://doi.org/10.1145/2702123.2702245

[20] María Teresa Rodríguez, Sérgio Nunes, and Tiago Devezas. 2015. Telling Stories with Data Visualization. In Proceedings of the 2015 Workshop on

Narrative & Hypertext (NHT ’15), 7–11. https://doi.org/10.1145/2804565.2804567

[21] Daniela K. Rosner, Miwa Ikemiya, and Tim Regan. 2015. Resisting Alignment: Code and Clay. In Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction (TEI ’15), 181–188. https://doi.org/10.1145/2677199.2680587

[22] Hidekazu Saegusa, Thomas Tran, and Daniela K. Rosner. 2016. Mimetic Machines: Collaborative Interventions in Digital Fabrication with Arc. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI ’16), 6008–6013. https://doi.org/10.1145/2858036.2858475

[23] S. Stusak, A. Tabard, F. Sauka, R. A. Khot, and A. Butz. 2014. Activity Sculptures: Exploring the Impact of Physical Visualizations on Running Activity. IEEE Transactions on Visualization and Computer Graphics 20, 12: 2201–2210. https://doi.org/10.1109/TVCG.2014.2352953

[24] 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 32nd annual ACM conference on Human factors in computing systems - CHI ’14, 3845–3854. https://doi.org/10.1145/2556288.2557310

[25] 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 (CHI ’18), 154:1–154:13. https://doi.org/10.1145/3173574.3173728

[26] Cesar Torres and Eric Paulos. 2015. MetaMorphe: Designing Expressive 3D Models for Digital Fabrication. In Proceedings of the 2015 ACM SIGCHI Conference on Creativity and Cognition (C&C ’15), 73–82. https://doi.org/10.1145/2757226.2757235

[27] Janet Vertesi, Jofish Kaye, Samantha N. Jarosewski, Vera D. Khovanskaya, and Jenna Song. 2016. Data Narratives: Uncovering Tensions in Personal Data Management. In Proceedings of the 19th ACM Conference on Computer-Supported Cooperative Work & Social Computing (CSCW ’16), 478–490. https://doi.org/10.1145/2818048.2820017

[28] Ron Wakkary, Henry Lin, Shannon Mortimer, Lauren Low, Audrey Desjardins, Keith Doyle, and Philip Robbins. 2016. Productive Frictions: Moving from Digital to Material Prototyping and Low-Volume Production for Design Research. In Proceedings of the 2016 ACM Conference on Designing Interactive Systems, 1258–1269. https://doi.org/10.1145/2901790.2901880

[29] 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 (CHI EA ’16), 409–422. https://doi.org/10.1145/2851581.2892570

[30] C. Warnier, D. Verbruggen/Unfold, S. Ehmann, and R. Klanten (eds.). 2014. Printing Things: Visions and Essentials for 3D Printing. Gestalten, Berlin.

[31] Claire Warnier and Dries Verbruggen. Ceramic 3d Printing. Unfold Design Studio. Retrieved January 16, 2019 from http://unfold.be/pages/ceramic-3d-printing

[32] W. Willett, Y. Jansen, and P. Dragicevic. 2017. Embedded Data Representations. IEEE Transactions on Visualization and Computer Graphics 23, 1: 461–470. https://doi.org/10.1109/TVCG.2016.2598608

[33] 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 (DIMEA ’08), 343–350. https://doi.org/10.1145/1413634.1413696