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Which Interaction? Mapping Feedback and Feedforward in Data Physicalization(s)

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Which Interaction?
Mapping Feedback and Feedforward in Data Physicalization(s)

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Abstract

Data Physicalization (DP) encodes data into physical artifacts to enhance interaction, understanding, and engagement. This paper explores the relationship between data encoding, user interaction, and design principles in DP, with a focus on feedback and feedforward mechanisms. Through a scoping review and an annotated portfolio of 36 case studies, DP is categorized into three types: static, constructive, and dynamic. Each type influences how users experience and interact with the data. A practical activity with 96 master's students mapped 20 case studies onto a feedback-feedforward matrix, revealing insights into how artifact design, data encoding, and user engagement relate. The findings show that constructive DPs enable immediate feedback through user-driven physicalization, while dynamic DPs often present hidden or ambiguous feedforward due to their complexity and real-time adaptability. Static DPs, though less interactive, rely on perceived affordances to convey data meaning over time. This research refines a feedback-feedforward matrix for DP artifacts, offering a structured approach for analyzing user interactions of physicalizations. It also highlights the role of temporality, showing how interaction timing shapes feedback and feedforward dynamics. The study suggests that focusing on user interaction, temporality, and embodiment can expand DP's design possibilities. Further research is needed to address limitations, including the scalability of the methodology and the applicability of feedback and feedforward across different DP types.

Data Physicalization; Feedback; Feedforward; Annotated Portfolio

Data is pervasive in the information society, shaping political stances, influencing collective decisions, and often functioning as a form of currency. A body of literature within Information Studies and Science and Technology Studies (STS) is proposing several concepts to describe how aspects of the world are being quantified into data.

An example is datafication, a contemporary process which exploits digital technologies directed at recording aspects of human lives and bodies, and rendering them into digitized information (van Dijck, 2014). Deborah Lupton talks about data-selves, referring to the digital representations of people that emerge from the data collected about them. These data assemblages are integrated into social life, identity, and self-perception, effectively becoming extensions of ourselves both in digital and social contexts. The tendency to measure, track and quantify aspects of human lives resonates in bottom-up practices and communities, such as the Quantified Self movement, which pushes people to experiment with their own tracked data to gain better understanding of their bodies and vital signs. This growing trend of monitoring personal traits has far-reaching effects, since data is often perceived as something abstract, 'given' to us completely out of context (Lee-Smith et al., 2023).

In this regard, Human-Data Interaction (HDI) investigates systems that facilitate humans' interpretation and engagement with data (Mortier et al., 2014). HDI opens innovative spaces for developing practices that can manage and interpret data to make it usable and knowable (Lupton, 2018), based on interactive and sensorial artifacts imbued with it. Human-Computer Interaction and Design have proved to support the HDI space. A notable example, closely related to several research areas within and around HCI is Data Physicalization (DP), defined as a physical artifact that encodes data to geometry or material properties (Jansen et al., 2015).

This present study is situated within doctoral research in design titled "Probing Data Physicalization for contextual meaningful interactions". The paper overviews DP and related emerging research areas and analyzes real case studies of physical artifacts encoding/physicalizing data through an annotated portfolio methodology (Gaver & Bowers, 2012). Building from initial insights, it will present the results of an activity carried out with master's students from the School of Design of Politecnico di Milano (Digital and Interaction Design) consisted of mapping the case studies into a feedback and feedforward matrix. The aim was to test and validate the initial insights of a correlation between the DP type and the consequent feedback (physicalization of data) and feedforward (user interaction).

The main findings showed that feedback and feedforward change significantly according to the type of DP, if static, constructive or dynamic. The discussion will be twofold: on one hand, it will focus on the ambiguity of feedback and feedforward in the analyzed case studies; on the other hand, on the importance of a though user interaction to expand the design spaces of DP. Ultimately authors reason on the aspect of temporality when designing the feedback and feedforward, particularly of dynamic DP. Authors will conclude by highlighting current limitations and the next planned activities.

Theoretical background

A foundational work worth mentioning when approaching DP is the one of Tangible User Interfaces developed and the end of 1990s at MIT Media Lab guided by Hiroshii Ishii. Tangible Interaction Design amplifies the TUIs discourse of simply “giving physical form to digital information” and its subsequent physical control (Ishii & Ullmer, 1997). Hornecker and Buur (2006) propose to focus on designing the interaction itself (instead of the interface) by exploiting the richness of bodily movements. In summary, the interactive system should manifest a tangible, physical embodiment of data and allow bodily interactions while being embedded in real spaces and contexts.

Data Physicalization

As previously mentioned, Data Physicalization (DP) is a physical artifact which geometry or material property encode data (Jansen et al., 2015). The most closely connected area of DP is Data Visualization (Dragicevic et al., 2021), which goal is to study “the use of computer supported, interactive, visual representations of abstract data to amplify cognition” (Card, 2009). In other words, Data Viz translates data into compelling graphics, reducing complexity and making information more accessible.

In an emphatic way, DP brings the interaction with data on a tangible and haptic scale. Most studies reviewed reference the definition provided by Jansen et al. (2015). Prior to this, Zhao and Vande Moere (2008) had already formalized a concept for "objects that physicalize data". Drawing on the field of information visualization, the researchers described Data Sculptures as physical artifacts rooted in data, intended to enhance the audience's comprehension of datasets. Data sculptures can be significantly impactful in raising awareness about environmental issues and climate change, for instance, within educational settings, as they translate numerical data from digital displays into tangible objects that serve as metaphors for the underlying data (Vande Moere & Patel, 2010).

Seemingly, DP could encode data in the shape as well as in the material or artifact’s behavior (Hogan & Hornecker, 2013). Scholars are actively proposing closely related definitions and concepts. While some overlap to Jansen’s one, many highlight one or another feature. For instance, Signer et al. (2018) propose a cohesive framework to develop dynamic DP which change dynamically to new data inputs. Scholars highlight their potential to make data more intuitive and engaging, especially in contexts where real-time data is crucial, such as environmental monitoring and public data displays.

Willett et al. (2016) reflect on the relationship between the data referents (meaning the entities to which data correspond) and their visual or physical representations. Their concept of embedded DP spots the importance of situational data representation which are spatially and temporally close to the represented phenomena. Related to this yet advancing it further, the related concept of Autographic Visualization (Offenhuber, 2020) is defined as “a set of techniques for revealing material phenomena as visible traces”. In this type of representation, data manifest itself into a tangible artifact or material.

An interesting take on DP is provided by Narrative Physicalization (Karyda et al., 2020) intended as everyday objects redesigned to support self-reflection and engagement with personal data.

A work by Burzio and Ferraro (2023) gathered relevant definitions to clarify whether scholars uniformly adhere to the Jansen's definition or, instead, propose an extension or an entirely new interpretation. Authors systematized the definitions according to the ways data are represented and what actions they enable from users. Data can be: i) rendered into physical shapes (data sculptures) or through materials (data manifestation, autographic visualization); ii) encoded in forms and materials (data materialization and data objects); iii) embodied through iterative interactions (narrative physicalization, data agents). Such data representations enable observation, contemplation, use, reflection and affection from users' perspectives.

Scholars propose different views on what constitute data. Data viz and Information Visualization often apply a positivistic approach to data, while design takes on a constructive approach (Bae et al., 2022). Offenhuber (2019) approaches data as something inherently contextual, material, and intertwined with its mode of representation (data inscribing itself, leaving material traces). Grounding from Barad's agential realism, Sanches et al. (2022) interpret data as a co-constituted phenomenon emerging through entangled processes of observation, interpretation, and materialization.

There is a significant momentum in this research area. While the potential of tangible representation of data for learning, decision-making, participation, and contextual sensemaking is widely recognized, is less understood how they manage to do that. A recent work by Daneshzand et al. (2025) highlights this limitation, exploring the use of data physicalization in design processes using technology probe "KiriPhys".

DP (intended as outputs) vary in forms and interactions alike. Researchers highlight difficulties in evaluating DP due to the need for tailored frameworks, difficulty in assessing cognitive impact and engagement, accessibility concerns, and context-sensitive outcomes (Jansen et al., 2013; Jansen et al., 2015).

Feedback and feedforward in Interaction Design (IxD)

The difficulties in evaluating the efficacy of DP are noted. Here, authors propose a way to extract insights about the user interaction by looking at feedback and feedforward of DP outputs. This process might become part of a larger, structured framework useful for evaluating the efficacy and engagement of users when interacting with any physical representation of data.

Lying in the context of usability, the notions of feedback and perceived affordance (changed to signifiers on a later edition of the book) have become foundational concepts for interaction design since Donald Norman's book "The Design of Everyday Things". Later, Djajadiningrat et al. (2002) introduced to the HCI community the notion of feedforward, meaning the communication of the purpose of an action, arguing that this concept might be more appropriate for electronic products rather than the affordance one. In their work the authors define a system as successfully designed if it has a present feedforward and inherent feedback, meaning the correct coupling between action performed and feedback received.

Building on that, Vermeulen et al. (2013) propose feedforward as a possible solution for the cognitive gap between a user's intention and the system's response (Norman's "Gulf of Execution"). In their work, they propose a schema to understand the relationship between perceived affordances, feedforward, and feedback, before and after the action. While perceived affordances reveal the physical affordance, telling users that there is a physical action available and how to perform it, feedforward reveals the functional affordance, which tells users "what will happen when they perform that action" (Vermeulen et al., 2013). The authors warn that even if designed, feedforward might still appear as hidden (the user does not know what will happen) or false (the user thinks something different will happen).

Feedback and feedforward are well-established concepts within design. Nonetheless, successfully integrate such aspects into an emerging area such as DP might be a tricky challenge. To this date the only study which reflects on feedforward specifically in relation to physicalizations is the one of Daneshzand et al. (2025), which highlights the designer's forward-thinking when making design choices, considering the physical aspects of the results. In the next sections we will delve deeper into the attempt of mapping DP case studies into a feedback-feedforward matrix.

Methodology

This paper's methodology includes a scoping review within the emerging area of Data Physicalization. The sources are both academic works as well as practical, real-world case studies of artifacts that physicalize data in some ways. Such cases have been elaborated using the method of annotated portfolio (Gaver & Bowers, 2012). An annotated portfolio could be a collection of designed artifacts into a portfolio, bringing together individual artifacts as a systematic body of work. As reported from Gaver and Bowers, "artifacts are illuminated by annotations. Annotations are illustrated by artifacts".

The results deriving from theoretical and academic works have been explained in the previous section. The following ones will focus on the methodology and the results of an empirical activity with practical case studies as protagonists. As previously mentioned, the activity was conducted with master's students in Digital and Interaction Design at Politecnico di Milano (School of Design).

An annotated portfolio

After conducting a theory-based scoping review of the literature, the authors felt it was necessary to explore examples of DP in the real world. As mentioned above, an annotated portfolio can be a collection of practical, real-world cases to give insights on how a specific type of artifact might look like. The case studies' sources were both academic and grey literature. Academic literature included cases presented in conferences (such as papers or pictorials), while grey literature included design-oriented platforms and exhibitions.

Case studies collection

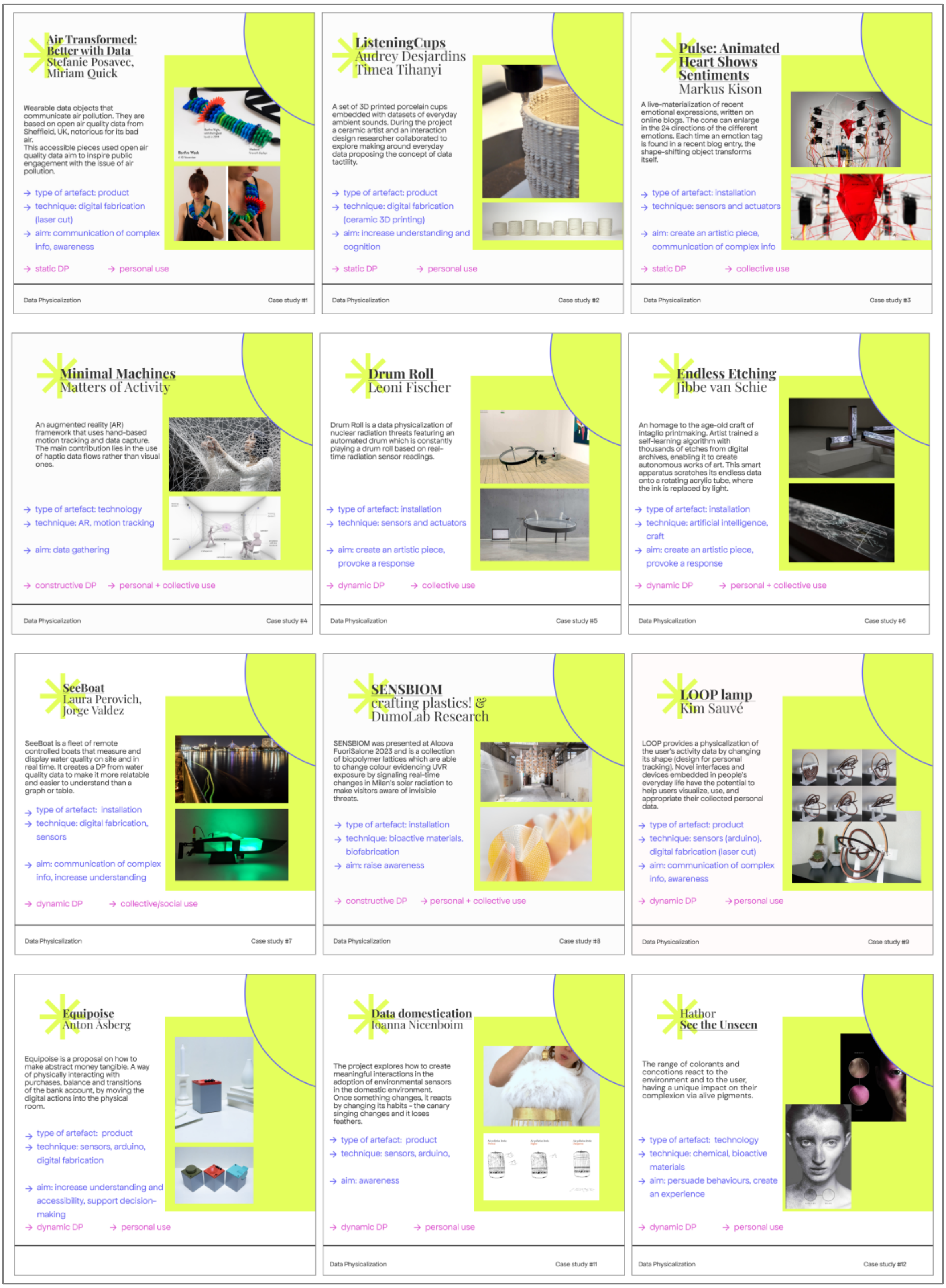
The case studies were gathered in a Figma board and summarized into visual cards. Initially each card included the following annotations: i) artifact's title and author(s); ii) pictures; iii) typology of product; iv) technique used; v) aim of DP.

While collecting cases, authors acquired insights on the different "anatomies" of DP and annotated the way they interact with data itself, for instance, whether the dataset evolves over time or not. Ultimately, authors clustered them into static, constructive, and dynamic DP, having found the definitions in literature. Static DP do not update or change in response to new data inputs. Constructive DP emphasizes the construction, manipulation, and assembly of physical artifacts that represent data (Wijers et al., 2024) while dynamic DP update based on a new datasets' input (Signer et al., 2018). Moreover, authors annotated if the DP is intended for personal or collective use.

After careful reflection, the authors excluded a few cases of tracking devices which are monitoring and displaying certain data. Moreover, they excluded cases of data edibilization, defined as the encoding of data through edible materials (Wang et al., 2016), and data sonification, defined as the encoding of data through sound (Kaper et al., 1999). Those artifacts did not respond to Jansen's definition (2015) of "physical object whose geometry or material properties encode data".

The annotated portfolio included a total of 36 case studies. Each case study has been represented in a visual card. Figure 1 shows a selection of 20 case studies that were examined during the activity with the students.

In this work, authors are not presenting insights about the techniques/methods used for physicalizing data nor the aims of the DP. Those will be approached in a separate study.



Moholy-Nagy University of Art and Design, Budapest

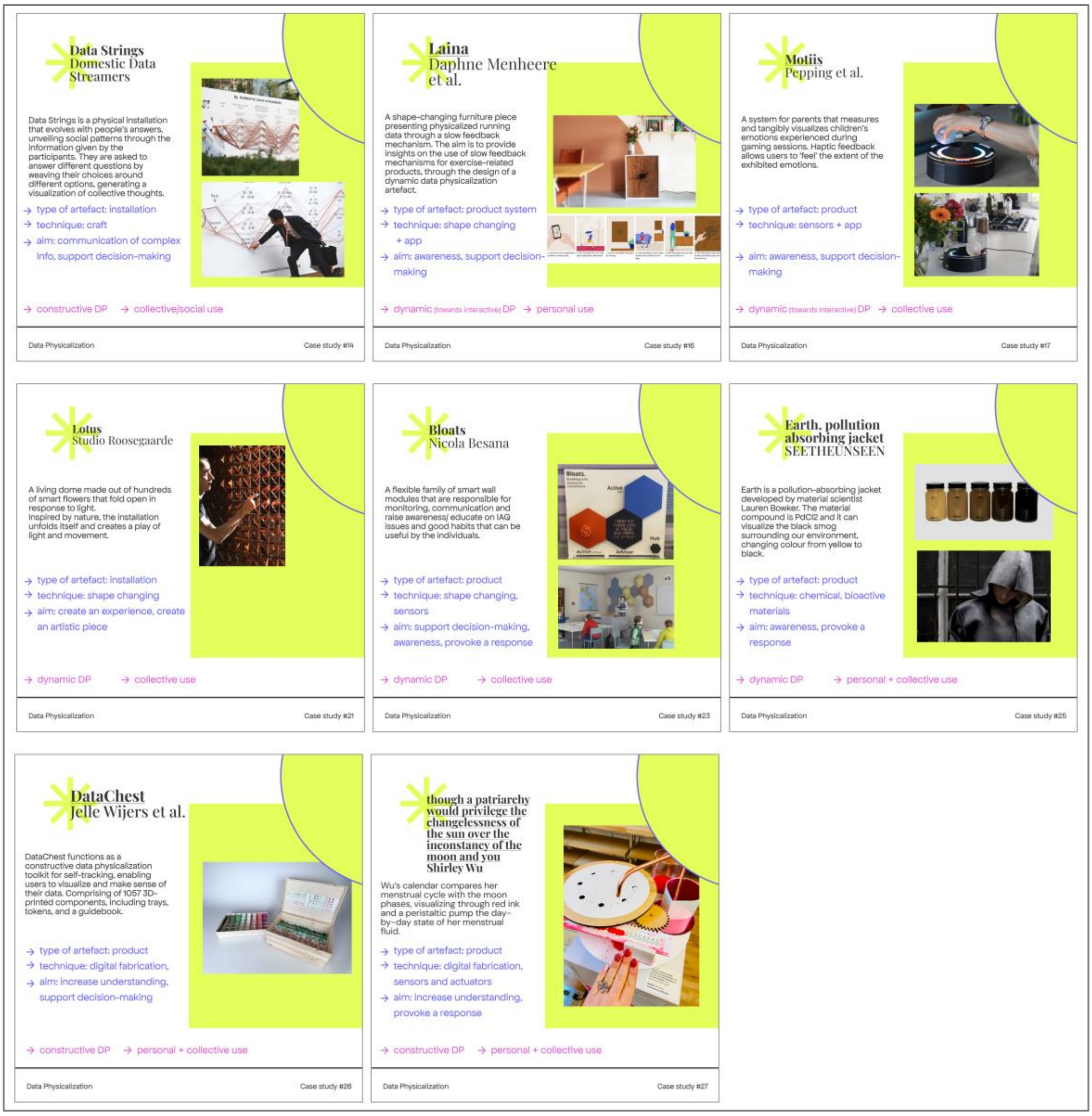


Figure 1: Cards of the 20 case studies used in the activity with the students. The numbering follows the sequence in which they were found and added in the Figma board.

A first analysis of the portfolio

Examples of the DPs are sound datasets encoded in ceramic cups (Desjardins & Tihanyi, 2019); a slow feedback mechanism to monitor sport performances (Menheere et al., 2021); data strings constructed by the public (Domestic Data Streamers, 2013); and a dynamic menstrual cycle calendar (Shirley Wu, 2023).

The first analysis was performed by authors by mapping the case studies over two progression lines, the first one defining the data encoding level into the artifact (present/absent), a second one on the interaction with users (present/absent). This step provided very first intuitions on the correlation between the data encoding level and the presence/absence of user interaction. From that moment on, authors started referring to the notions of feedback and feedforward when approaching the human-data interaction in DP(s).

Activity with the students

To give strength to the first analysis' intuitions, authors designed and conducted an activity with master's students to annotate feedback and feedforward of a selection of 20 case studies from the annotated portfolio (Fig.1). This selection's aim was to include diverse DPs, in terms of type of product, technique, aim, and so on.

The activity began with a theoretical lecture introducing key concepts related to data physicalization, including data materialization, data manifestation, and data object, along with foundational design principles. To minimize potential bias, the authors deliberately withheld their initial insights from the students. Following the lecture, a total of 96 students divided into 16 groups collaboratively mapped the case studies on a feedback and feedforward matrix through the supporting tool of a shared Figma board.

The session concluded with an hour-long group discussion, during which students reflected on and debated the placement of specific case studies. These reflections provided additional depth to the analysis and are further detailed in the Results section.

Results

Overall, the map confirmed the initial intuition that the way data is encoded in the artifact not only significantly affects the shape of the DP but also impacts user interaction.

Feedback

The feedback placement of the static DPs (Air Transformed, ListeningCups) was controversial and a topic of discussion. For some students they have absent feedback since they do not change geometry or material properties over time. Others argued that the feedback is present just dilated over time, from the creation of the artifact to its dismissal.

If static DP(s) have controversial feedback, dynamic DP(s) are halfway between absent and present. Particularly on this last point, students argued that in dynamic DP the feedback (even if present) is not of immediate comprehension. Laina, for instance, physicalizes running data through a slow feedback mechanism; nonetheless, the pin arrangement on the board does not give a clear idea of a value: did I do well or not?

Most students argued that the clearest feedbacks from the dynamic DPs are the ones showing a simpler data type and variation using color change. For instance, Sensbiom is an installation able to change color from orange to red, evidencing UVR exposure by signaling real-time changes.

Constructive DPs are the ones considered to have the most present feedback of all case studies. This is since the physicalization is constructed by the user or the public in a shared effort, changing over time.

Feedforward

The feedforward, intended as what will happen when a user performs an action on the object, seems perceptible for the static DPs. In fact, they are everyday artifacts (a necklace and cups), so the user expects to use them as any other resembling object.

Similarly, it seems perceptible for constructive DP. For instance, the DataChest case is a constructive DP toolkit for self-tracking, enabling users to visualize and make sense of their data using tokens of different sizes and shapes. Students agreed on the fact that the result of the action might be exactly what the user expects, since they know beforehand what kind of physicalization they intend to construct.

Dynamic DP instead tend to have hidden feedforward. This aspect unfolds in two stances. In the first, the user does not have the possibility to interact with the artifact. Examples in this sense are Sensbiom (UVR exposure, see above) or See Boat, which are remote-controlled boats that measure and display water quality on-site and in real-time. In both cases, the user is an observer, and they might respond to the communicated data in their everyday life, through behavioral change, for instance, protecting themselves more carefully from UVR.

In the second stance, the user might interact with the artifact, but it is not clear how and what they can expect to happen. For instance, Motiis is a system that tangibly visualizes children's emotions experienced during gaming sessions. Parents can haptically interact with it to feel the data, nonetheless the effects of their actions are not clear: will the artifact suggest ways for the parents to open conversations with their children? Will it record the different emotions?

Students agree that the dynamic DP with the most perceptible feedforward is the case of Bloats, a flexible family of smart wall modules that monitor and communicate the indoor air quality (IAQ) of school classrooms. Each module has a specific call to action that clarifies to teachers and students how to behave while educating them to pay better attention to IAQ issues.

Final elaboration of the matrix

The initial insights paired with the class activity (the 16 matrixes and the discussion in class) informed authors in the re-elaboration of a final feedback and feedforward matrix, shown in Figure 2.

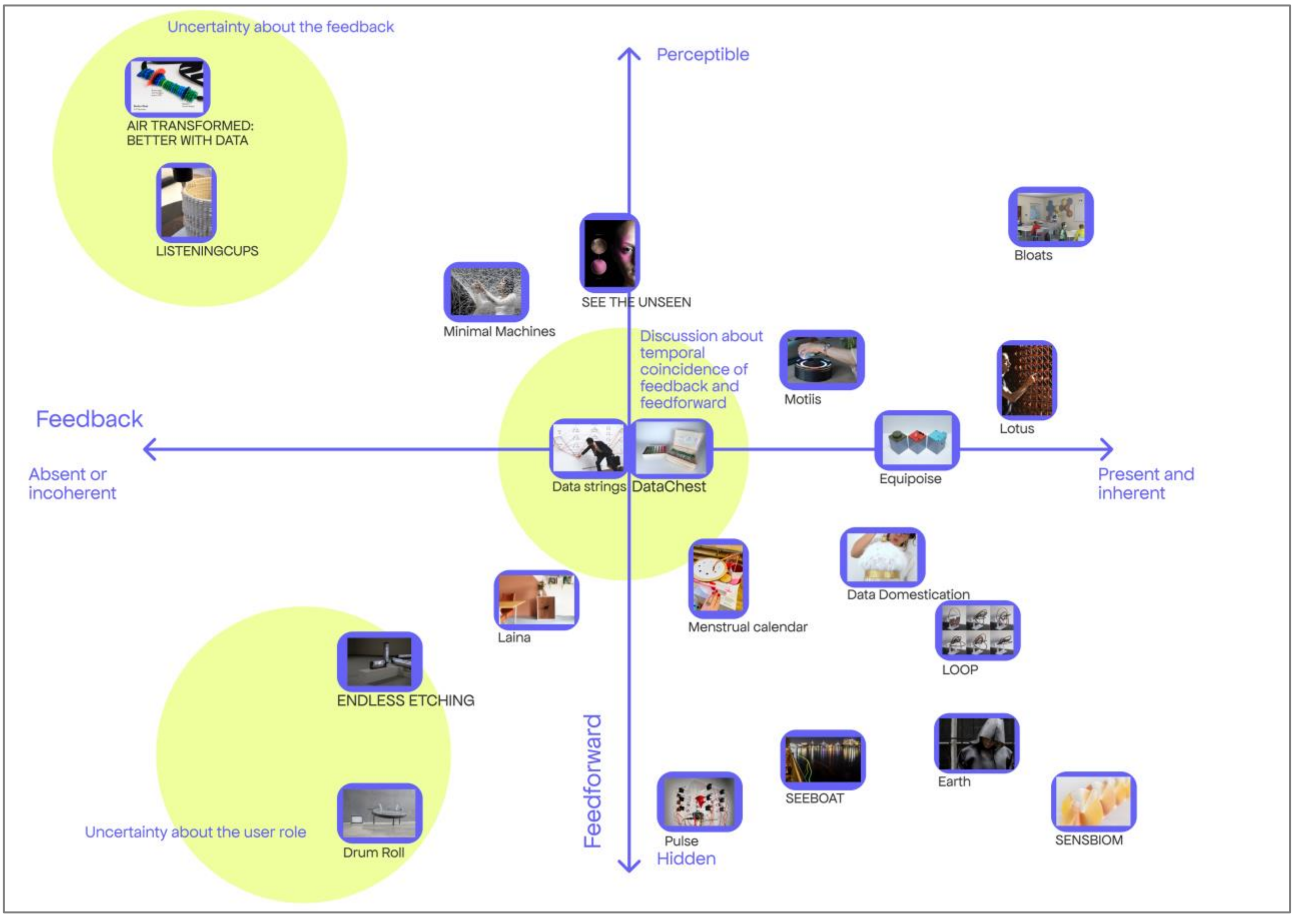


Figure 2: Final matrix re-elaborated following the class activity, with highlighted the areas where the uncertainty and discussion points were largest.

Static DP might benefit better from the notion of perceived affordances instead of feedforward, since the latter refers mostly to electronic/smart devices (Djajadiningrat et al., 2002). According to literature, perceived affordances reveal the physical affordance, telling users that there is a physical action available and how to perform it. This result might frame the efficacy to the feedback and feedforward matrix only to dynamic and constructive DP.

After careful reflection, authors placed the constructive DPs in the middle of the matrix, since the suggestion of an action and the resulting action almost overlap. The design of Data Strings, for instance, suggests the public physically move the strings to create a visualization. The physical visualization is then immediately created, erasing the temporal gap usually occurring between the suggestion of an action and the result of a performed action.

The two main results of this paper, the annotated portfolio and the resulting feedback and feedforward matrix, trigger several points that will be outlined in the Discussion section.

Discussion

Designing physicalizations

The portfolio outlines that the focus is targeted either to the aim of the physicalization, to the technique used, or the “final result”, treating the DP as an installation piece. An extensive review of DPs was conducted by Bae et al. (2022). They targeted the case studies as either “led by context”, “led by interaction”, or “led by structure”. In their analysis they identified key challenges, such as scalability, reproducibility, and balancing complexity with user comprehension to be addressed for the field to mature.

This paper's analysis suggests that physicalizations rarely are tested in actual contexts. One of the exceptions is Motiis, which at the time of writing the system was being assessed with 17 parent-child pairs through on-site evaluations (Pepping et al., 2020). Besides user testing, the design of this DP is shaped from the interaction between the children’s emotions and the parents’ response to them.

Another example is Bloats. The DP senses and renders air quality data through shape change. It interacts with teachers and students by communicating the IAQ levels and suggesting best practices and behaviors, such as opening windows for better air circulation, and so on. In a very indirect way, users’ actions update and change the physicalization.

Authors strongly believe that DP can open several design spaces for a more engaged interaction with data, supporting cognition, decision-making, and sensemaking (Dragicevic et al., 2020). To do so, the research community should elaborate a cohesive framework including processes, tools, and evaluation methods to design DP. This includes testing interactions as much as possible with real examples. This study tested an annotated portfolio that was presented to the students in the form of images and sometimes video. This limitation might have hindered "unexpected" interactions that could have happened if interacting physically with the physicalizations. Nonetheless, these first results will be further tested and validated in RtD led case studies as next steps.

Temporality as key to approach feedback and feedforward in DPs

All the DP presented here explore different temporality interpretations when considering the interaction between person, artifact, and data. In a relevant work on the topic, Vallgårda et al. (2015) introduce the concept of temporality of interaction, which refers to the way time shapes and is shaped by interactions in the design of interactive artifacts. Authors argue that interaction design should not only consider the static physical form of an artifact but also its temporal form, meaning the unfolding of interactions over time.

On a more nuanced level, Vallgårda et al. described all temporal forms of interactive artifacts as processes that evolve in response to user inputs or environmental changes. Temporality can include immediate interactions (e.g., button presses) as well as longer processes (e.g., a device adapting over hours or days).

Such an aspect is particularly challenging when discussing Data Physicalizations. For instance, how long can data be considered "physicalized"? At what point does the physicalization transition from being feedback to feedforward, or even become merely a "representational state of being" within a system?

Changes in the geometry or material property of an artifact can be considered feedback on the physicalization of data. In other words, datasets, environmental phenomena, or tracked information are sensed and translated into tangible form, and the feedback is the artifact changing shape, color, vibrating, and further on.

But that same feedback can become feedforward, suggesting to users what will happen when performing an action. The intercurrent time can unfold over a longer period. This might be the case for DP Laina and Loop, physicalizing exercise data through slow feedback mechanisms. The intercurrent time can unfold over a longer period like Sensbiom, which represents UVR exposure to users in real-time. In other cases, feedback and feedforward are the same thing or happening simultaneously: this is the case for constructive DP where the data physicalization is actuated by users' interaction (Data Strings, DataChest).

Ultimately, the relation between data physicalization and time is a complex one, requiring perhaps novel concepts beyond feedback and feedforward. This complexity lies in the same purposes of DP: informing, supporting decision-making, and making data knowable and usable. In this scenario, the role of the humans around the physicalization is essential, since they do not merely observe such data representations, but they shape the DP itself with their interventions.

Conclusion and future work

This paper, situated within doctoral research carried out at the Design Department of Politecnico di Milano, presents the results of a case studies analysis of Data Physicalization, mapping an interconnection between the data encoding level and user engagement through the established concepts of feedback and feedforward. Through an annotated portfolio followed by an activity with 96 students, authors draw several findings, mainly that the way data is encoded in the artifact not only significantly affects the shape of the DP but also impacts user interaction. Moreover, the paper discusses the prominent role of temporality when approaching DP artifacts.

The analysis could be intended as a potential tool in a broader design framework aiding into the design and evaluation of DP by examining the relationship between data encoding level and the user interaction. Future activities include Research-through-design (RtD) experimentations with personal and intimate data, leveraging temporality and embodiment as key concepts to design the user interaction. At this stage the work presents limitations. The findings need to be further validated by performing an analysis on a larger number of case studies. Moreover, this work approaches static, constructive, and dynamic physicalizations altogether, while separate concepts beyond feedback and feedforward might be more appropriate. Ultimately, authors question the efficacy of feedback and feedforward when dealing with matters such as data, envisioning perhaps novel and unique concepts to approach this emerging area.

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