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Tangible data: a systematic review of physicalization and its implications for interaction design

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Abstract. In recent years significant contributions have been made to expand the research area of data physicalization. The present study presents the results of a systematic literature review and an annotated portfolio analysis that frame the current state of the field, with particular attention to its implications for interaction design discipline. It outlines key outputs, methods, and domains that support tangible engagement with data, while also identifying critical challenges such as data mapping, interaction temporality, and contextual application. The study concludes by drafting promising research trajectories and by challenging dominant paradigms of data encoding, highlighting opportunities for designing more situated, embodied, and meaningful artefacts encompassing data physicalization.

Keywords: data physicalization; interaction design; literature review; data mapping

1 Introduction

The practice of data representation predates computing and human-computer interaction (HCI) by millennia. In fact, humans have been creating physical representation of data since at least 12.000 years BC to make sense of the surroundings, take collective decisions, and record phenomena for future generations. Today, data representation is a crucial area of inquiry when dealing with digital information and human engagement with it. While in the past computing was “condensed” and siloed into one room, today it is ubiquitous and pervasive, entering into environments, bodies, and crossing continents. A key consequence is that societies are becoming data-driven [1], with electronic devices (smartphones, computers, wearables) and the networks through which they connect generating daily enormous amount of data. Van Dijck (2014) uses the concept of datafication to describe how digital technologies record aspects of human lives and render them into digital information [2].

The rise of ubiquitous computing has *entangled* humans and technology to an extent that prompted researchers to establish a novel research area called human-data interaction (HDI). Elmqvist proposed the term referring to the manipulation and sensemaking of large and unstructured datasets [3]. Cafaro approaches HDI as the technological possibility of delivering context-aware data sensemaking through embodied interactions [4]. Other scholars use HDI to address the dynamics between individuals and the extensive collection and use of personal data in modern society [5]. HDI argues that data should be legible and negotiable, centring not only on large datasets but also on small, personally generated data as a counterpoint to the dominant big data paradigm—emphasising individuals' potential to collect, manage, and use data in meaningful and empowering ways.

But, *how do we give meaning to such data?*

Drawing from vital materialism, Lupton introduces the concept of data-sense—in juxtaposition to data literacy—to describe the practices through which data becomes knowable and usable. This steams from her understanding of data as co-created assemblages, where humans, technologies and the phenomena being measured are constantly negotiated among one another [6]. She characterises data as “lively” for several reasons: data are contingent, re-entering digital economies where they are repurposed and re-aggregated; they are dynamic rather than static, possessing their own social life; and they attempt to reflect actual lives, behaviours, bodies, and social activites. These novel forms and uses of personal data carry implications for people’s lives that they are still coming to understand [7].

As a result of these processes, the data-interaction design space is expanding, challenging current conventions, and proposing alternative narratives based on interactive and sensorial materials imbued with data. Tangible data representations (or data physicalization) emphasise the physical, spatial, and haptic dimensions, made possible by recent advancements in shape-changing interfaces, digital fabrication, and smart materials. The opportunities of this research areas are compelling, spanning from education, engagement with personal data, community-based activities, to data inclusivity for people with diverse cognitive and/or physical needs. At the same time, it presents significant challenges, including the need for design-infused methods, contextually grounded physicalizations, and greater clarity around the process by which data shift from fixed, unmodifiable information to a malleable matter: a material designed for activating different range of experiences and scenarios.

This article provides an analysis on the state of the art of the data physicalization domain across the fields of interaction design and digital fabrication. The results of systematic literature review and annotated portfolio are thoroughly presented. The discussion and conclusion identify opportunities, challenges, and design spaces to guide researchers and practitioners in the field towards designing meaningful physicalizations. Ultimately, this study answers the following research questions:

RQ1. What are the ways through which designers in HCI approach data physicalization, and its challenges?
RQ2. Which are the main physicalization outputs?

2 Related work

2.1 Tangible user interfaces and the tangible turn

The origin of data physicalization can be traced back to foundational work on tangible user interfaces (TUIs) developed in the late 1990s at the MIT Media Lab under the guidance of Hiroshi Ishii. TUIs were conceived as a way to "give physical form to digital information" and enable its physical manipulation [8]. This marked a shift from purely graphical user interfaces to tangible interaction, often referred as the "tangible turn" within the HCI community. The tangible turn emphasises embodied form of interaction where digital content is represented and manipulated through physical objects, allowing users to engage with computational data in a more intuitive and hands-on manner. The evolution of TUIs has played a significant role in the development of tangible representations of abstract datasets.

Meanwhile, the concept of embodiment applied to the HCI field enhances bodily engagement with digital information. Drawing from the phenomenological approaches of Martin Heidegger, Ludwig Wittgenstein, and other twentieth-century philosophers, “embodied interaction" is an approach that emphasises bodily ways of knowing when interacting with software systems, rather than disembodied rationality [9].

Later, Hornecker and Buur [10] expanded the scope of TUIs by introducing tangible interaction design, which broaden the focus from the interface to the interaction it enables, including its spatial, cultural, and social dimensions. Bakker et al. [11] build upon this perspective by conceptualising and testing embodied schemas and variables that can be embedded within interactive artefacts. The researchers define patters of interaction that are embodied into our ways of approaching physical and spatial objects. For instance, the embodied IN–OUT schema is also embedded in language and abstract thought. When someone says *I am in love* they unconsciously apply the IN–OUT schema to structure their understanding of the abstract concept of love—conceptualising love as a container, and themselves as an entity either inside or outside of it [11].

Zhao and Vande Moere [12] are among the firsts linking embodiment to the design of “data-oriented artefacts”. Data are translated into physical form through a phase of data mapping, which relies on metaphors as associations between the abstract data and the person’s prior experience. Therefore, metaphors are valuable tools to draw an unknown domain back to a known array of life experiences and knowledges.

2.2 Feedback and feedforward in interaction design

Besides being approached as input or output of a machine, data can be leveraged as material for design. Since the publication of Donald Norman’s “The Design of Everyday Things”, the concepts of feedback and perceived affordance have been fundamental in shaping the interaction of an artefact. Feedback provides users with confirmation that their actions have been registered, while affordances indicate possible interactions within an interface. Then, Djajadiningrat et al. [13] introduced the concept of feedforward to the HCI community, emphasising the importance of communicating the purpose of an action before it is performed. They argue that, particularly for electronic products, feedforward might be more relevant than affordance alone. A well-designed system, according to their framework, must integrate both feedforward and feedback to create a clear coupling between action and response. According to Vermeulen et al. feedforward bridges the cognitive gap between the user’s intention and the system’s response by communicating what will happen as a result of an action [14]. However, the effectiveness of feedforward is not guaranteed; it may be hidden, leaving users uncertain about the expected outcome, or false, leading users to anticipate an incorrect result.

While feedback and feedforward are well-established in interaction design, their application within emerging fields such as data physicalization is limited. Daneshzand et al. [15] explored this through an expert study using KiriPhys, a kirigami-inspired paper-cutting technique for tangible data representation. A key finding was the importance of feedforward: designers' anticipatory thinking about how physical forms will be interpreted by users. Embedding such mechanisms helps users intuitively grasp the meaning of a physicalised dataset before interaction occurs. Another study introduces a feedback and feedforward matrix, categorising data physicalizations according to their configuration—whether static, user-constructed, or dynamically evolving over time [16].

2.3 From information visualization to data sculpture

Information visualization (InfoVis) derives from multiple disciplines, including graphic design, journalism, cartography, and computer science [16]. InfoVis can be broadly defined as "the representation and presentation of data to facilitate understanding" [17]. In their "Data Visualization Handbook", Koponen and Hildén [16] categorise visualizations based on their purpose, whether explanatory or exploratory, and the type of information they represent, whether conceptual or measurable. In other words, exploratory visualizations make data about invisible, hidden, or complex phenomena perceptible [18], like air pollution or sea level rise.

Gaver and Boucher [38] introduce a fundamental distinction between captured and readymade data. Captured data refers to information actively gathered by researchers, often through sensors or direct measurements, later processed and represented in various forms. In contrast, readymade data, inspired by Duchamp's artistic concept of readymades, consists of datasets that pre-exist, produced for different purposes elsewhere, but later repurposed within new contexts of analysis and representation. This differentiation highlights how data is not only something to be collected but also something that can be reinterpreted and recontextualised.

A data visualization is experienced through a process of encoding and decoding, which targets primarily the visual sense. Encoding involves translating raw data into visual elements—such as dots, lines, sise, colour, and position. This phase is largely managed by information and graphic designers, and it involves a vast array of visual variables, whose choice is guided by principles of perceptual psychology to ensure that visual changes clearly reflect variations in data [20].

Decoding is the reverse process. During perception, the viewer deciphers visual variables by identifying quantities, trends, and relationships. Interpretation involves drawing on prior knowledge to construct meaning and understand the story behind the data. When such knowledge is lacking, designers play a crucial role in bridging the gap through signifiers that guide correct interpretation. Data physicalization borrows many of these encoding variables from InfoVis, adapting them to leverage the affordances of physical materials.

Zhao and Vande Moere were among the first to conceptualise physical data representations through the notion of data sculpture — physical artefacts made from materials such as metal, wood, or plastic that render complex data perceptible beyond the visual sense. Central to this concept is embodiment: the physicality of a sculpture offers a more visceral and intuitive understanding of abstract data by engaging multiple senses [12]. The choice of material is integral to this process, affecting how audiences perceive and interpret the encoded information. A well-known example is "Perpetual Plastic" by Liina Klauss, Skye Morét, and Moritz Stefaner, which visualises global plastic waste streams using actual plastic debris found on beaches, while highlighting how mismanaged waste ends up in the ocean.

These approaches highlight the importance of multisensory engagement, moving beyond visual cognition towards more embodied experiences. Unlike data sculptures, which carry a strong artistic purpose, data physicalization broadens this idea by integrating technologies such as shape-changing interfaces — dynamic

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representations that adapt in response to user interaction [23]. The foundational definition was established by Jansen et al. (2015), who describe data physicalization as *"a physical artefact whose geometry or material properties encode data"*[24]. This conceptualization has since informed related notions, including embedded data physicalization [22]; autographic visualization [23]; data objects [24]; data agents [25]. Building on this, Burzio and Ferraro [26] analyzed existing definitions to map the landscape of physical data representation identifying forms such as data sculptures, materialised objects, and narrative physicalizations—each enabling distinct modes of engagement, from observation to reflection.

Together, these contributions form the theoretical foundation upon which this study builds, as further discussed in the following sections.

3 Methodology

3.1 Systematic literature review

This study aims at answering the following research question: *What are the ways through which designers in the HCI approach data physicalization, and its challenges?*

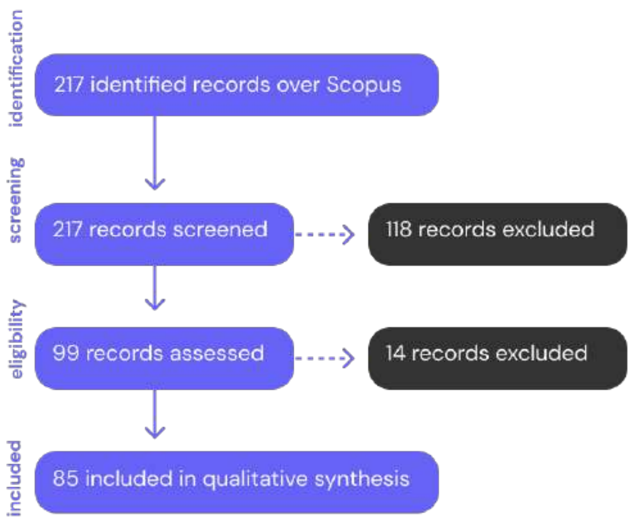

Fig. 1.. Four-steps PRISMA diagram of the study.

The literature review unfolds in two main phases. First, an explorative, narrative review was performed to approach the topic and select the keywords for the systematic review, which allowed authors to gather a corpus of studies published in a certain timeframe and within certain disciplinary areas. The PRISMA methodology was adopted, as outlined in [27], structuring the systematic review into a four steps process: identification, screening, eligibility, inclusion (Figure 1).

Identification. In the first phase, a comprehensive search query was executed on the Scopus repository, yielding a total of 217 results. The search was conducted within a temporal frame from 2008 to 2024 and was filtered to include both journal articles and conference papers. The search keywords—including "data physi*", "data tangib*", and "data material*"—emerged from the initial narrative review of the literature. Both authors iteratively refined and tested different query strings before settling on the most appropriate combination, ensuring coverage of relevant work on tangible data representation beyond those explicitly framed as data physicalization.

Screening. During the second phase, all 217 results underwent a rigorous screening process based on four criteria: i) relevance of the abstract, ii) relevance of keywords, iii) language (English), and iv) inclusion of journal articles or conference papers. This process led to the exclusion of 118 records.

Eligibility. In the third phase, 99 records were deemed eligible for further analysis. The eligibility criteria applied were: i) full-paper relevance and availability, ii) exclusion of two-dimensional visualizations, and iii) exclusion of physical models that were not categorised as physicalizations. A total of 14 records were excluded during this phase.

Inclusion. A total of 85 records were included in the meta-analysis. Data was organised and reviewed using Zotero, where relevant sections were annotated and codes assigned to each paper. Both authors coded the literature independently and subsequently compared and discussed their findings to strengthen consistency. Excel was used to track the four phases of the review and document exclusion reasons. LitMaps and Gephi supported the visualisation of the literature, including the citation network presented in Figure 2, which highlights the most cited works and key contributors to the field.

Coding was first conducted independently on the full dataset. In cases of disagreement, a discussion was estalished until consensus was reached. This iterative reconciliation process led to minor refinements of category definitions and clearer operational criteria for inclusion.

A notable takeaway from the network is the significant rise in publications on this topic over the past five years, alongside the identification of foundational papers in the field [22, 28, 29].

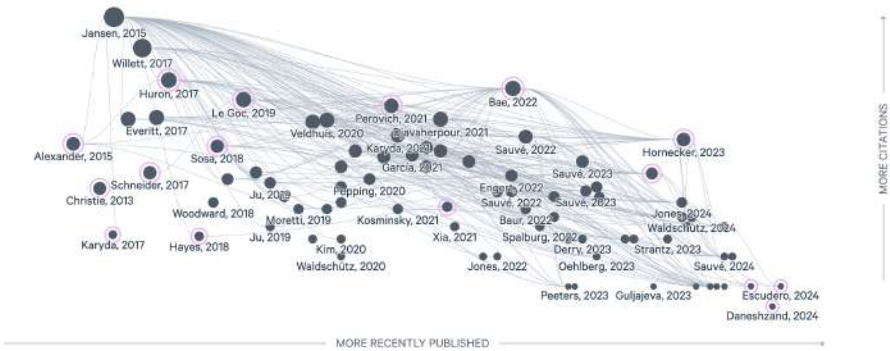

Fig. 2.. Citation network using the Litmaps tool.

Meta-analysis. The analysis of the included papers followed a structured approach. First, each record was summarised, highlighting key contributions and relevant keywords. These summaries were written separately from the original abstracts to emphasise the most relevant aspects. A similar approach was applied to keywords, where the authors assigned standardised terms across all records to facilitate literature mapping and network analysis.

Based on these summaries, broader thematic categories were established to systematically map and annotate codes from the literature, providing an overview of the state of the art. The identified categories were: (i) theoretical contributions, (ii) methods and toolkits, (iii) technologies for physicalization, and (iv) domains and case studies. Each paper was classified under one or more categories, with assigned codes refined in a second iteration to ensure consistency, in a collaborative work between authors. The categorised data were then exported in CSV format and used to generate a visualization map, enabling a comprehensive overview of contributions and gaps within the field.

In a following iteration, the papers were analyzed to answer the second part of the research question: tracing both current and emerging challenges in physicalization research. The findings of this meta-analysis are presented in Section 4.

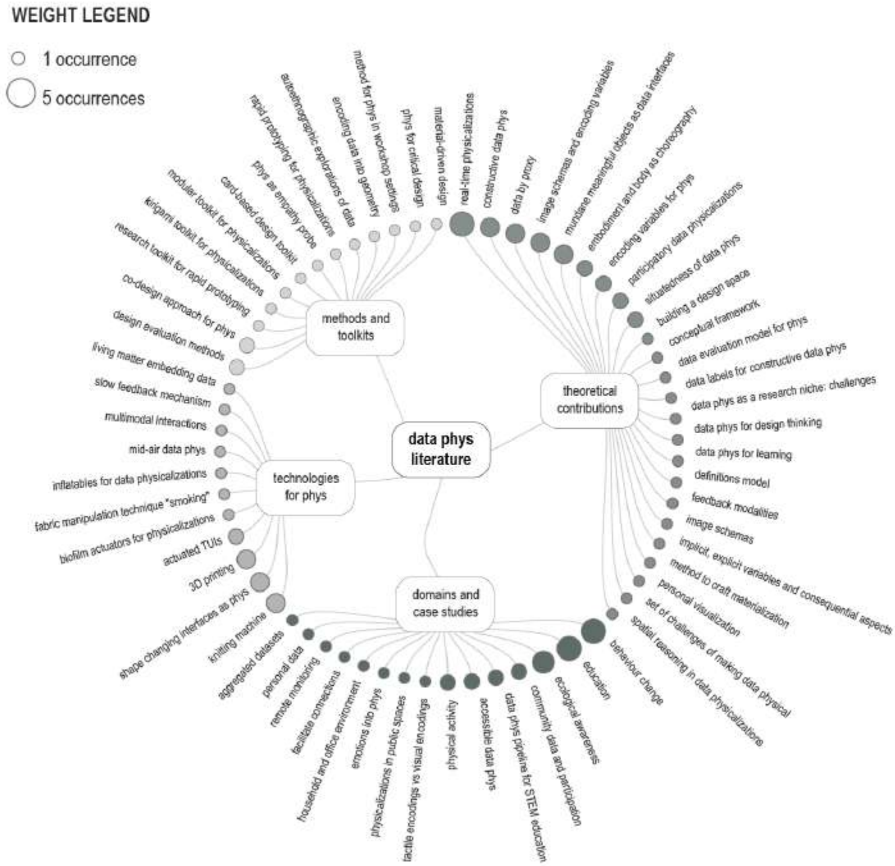

Fig. 3.. Visualisation map of the meta-analysis. Credits: authors

3.2 Annotated portfolio

Following the literature review, the authors examined real-world examples of data physicalization to gain deeper insight into its practical applications and manifestations. An annotated portfolio brings together individual artefacts as a systematic body of work illustrating how specific types of artefacts manifest in practice [30], bridging theoretical insights with tangible implementations.

Case studies were drawn from both academic and grey literature. Academic sources included conference papers and pictorials, while grey literature encompassed design-oriented platforms and exhibitions, offering a broader perspective physicalization beyond academic settings.

Case selection followed a purposive sampling strategy aimed at capturing diversity in typology, interaction modality, material approach, and domain of

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application. Cases were identified through conference proceedings (e.g., ACM CHI, TEI, IEEE), design exhibitions, and curated online platforms focused on data physicalization and tangible interaction. Selection criteria included: (i) explicit encoding of data into physical form or material properties; (ii) clarity of documentation (visual and textual); and (iii) relevance to interaction design.The final portfolio does not aim at exhaustiveness, but at representational breadth, allowing comparison across heterogeneous manifestations of physicalization.

The process involved collecting a wide range of case studies, annotating them into visual cards, and selecting the most relevant examples according to specific criteria.

Fig. 4.. Two examples of case studies cards for the annotated portfolio.

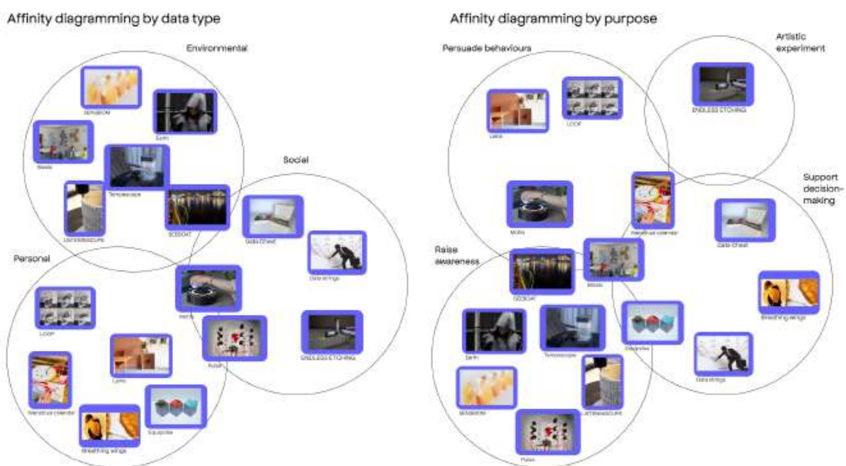

Fig. 5.. Affinity diagramming of the case studies (partial view; all 30 cases included in the full analysis, see Appendix 1).

Each card was documented on a shared Figma board, and it included key annotations: (i) artefact's title and author(s), (ii) images, (iii) typology of the product, (iv) technique used, (v) intended purpose of data physicalization, vi) whether data changes over time, and lastly vii) whether it is for personal or collective use (Figure 4). Once all visual cards were annotated, affinity mapping allowed to cluster cases according to emerging patterns, similarities, and contrasts across annotations such as technique, data encoding, and intended purpose. This process allowed the authors to draw cross-cutting insights from the portfolio as a whole, rather than treating each case in isolation (Figure 5). A complete overview of all cases and their annotations is provided in the Appendix 1.

Several cases were intentionally excluded to maintain alignment with the definition of data physicalization as a physical object whose geometry or material properties encode data [28]. Excluded cases included tracking devices that display data without physically encoding it, data edibilization—the encoding of data through edible materials [31]—and data sonification—the encoding of data through sound [32]—as these modalities do not rely on material or geometric encoding of information.

The final portfolio comprised 30 case studies of physicalizations, ranging from product, interior, interaction, to material design. Appendix 1 presents their full analysis. This structured collection provided a comparative foundation for analysing the diversity of physicalizations and their underlying design principles, while also highlighting the limited presence of physicalizations deployed in real-world contexts.

4 Results

Results from the meta-analysis of the literature review and the annotated portfolio are synthetised in this section. The discussion section will build on these insights, highlighting key gaps, design trajectories, and critical considerations.

3.2 Epistemological perspectives on data

Scholarly research adopts different epistemological perspectives on data, which shapes how it is interpreted, represented, and engaged with across disciplines. Consolidated approaches in data visualization and InfoVis often align with a positivist perspective, treating data as objective, quantifiable, and pre-existing entities to be revealed through structured representation [29]. Meanwhile, approaches within interaction design embrace a constructivist stance, viewing data as something that is actively shaped by human perception, context, and engagement. Recent contributions from InfoVis similarly highlight the situatedness of any representation [34]. Situatedness aligns with embedded data representation [22], where data is not merely displayed but deeply integrated into objects or spaces in a way that makes it inextricable from the context it represents.

A material perspective on data is advanced by Offenhuber [23, 35], who argues that data is not merely abstract information but is inherently tied to its modes of representation. He conceptualises data as something that inscribes itself within material traces, shaping and being shaped by the environment in which it is recorded. This perspective challenges the notion of data as a neutral or detached entity and instead frames it as deeply embedded in the physical and material realms from which it emerges. Building on Barad's theory of agential realism [36], Sanches et al. [37] propose an entangled view of data, suggesting that data does not exist independently but rather co-emerges through the intertwined processes of observation, interpretation, and materialization. This relational understanding of data emphasises the active role of the observer in shaping what is considered data, rejecting a clear-cut distinction between subject and object in data generation.

Autobiographical and embodied methods further interrogate the relationship between data and its representation. Several studies have explored self-tracking and autobiographical approaches as means of obtaining, annotating, and interpreting personal data [25, 39, 40], linking it to lived experience. These practices implicitly reject the notion of data as objective or *raw*, instead asserting that data is always processed, interpreted, and shaped: never truly raw but inherently *cooked*. Derry (2023) investigates the embodiment of data through choreographic performance, demonstrating it as something that can be physically enacted rather than merely visualised [41].

Collectively, these perspectives illustrate the multiplicity of data interpretations, moving beyond a singular, objective notion of data (data as the latin *datum,* fundamental unit of information) to a more nuanced understanding that considers its material, contextual, entangled, and performative dimensions. Such approaches expand the possibilities for interaction and engagement with data, revealing its inherently constructed and situated nature.

4.2 Physicalization definitions and domains

The majority of studies refer to the foundational definition by Jansen et al. [28], advancing it in different ways, either by focusing on specific aspects or by proposing closely related concepts. As introduced in the related work section, a foundational concept introduced by Zhao and Vande Moere is that of data sculptures [12], physical artefacts designed to enhance people's understanding of datasets. Figure 6 summarises this ecosystem of definitions.

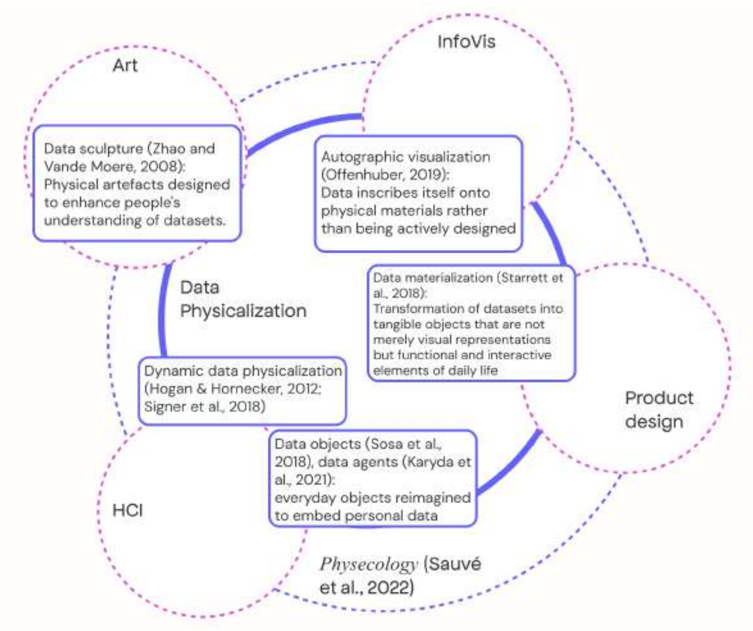

Fig. 6.. The ecosystem of data physicalization definitions and related areas

While data sculptures are a form of physicalised data, that they function more as tools for reflection rather than interactive experiences. A different take on physicalization is given by concepts like data manifestation [42] and autographic visualization [23]. These approaches are particularly relevant for environmental data, where natural processes leave material traces. An example is the project "Solar Totems" by Charles Sowers, which uses sunlight to record atmospheric conditions on a wooden log. In this case, data is not designed or represented by designers but rather it emerges directly from environmental interactions.

Majority of works on data physicalization emphasises the integration of data into the very structure and materiality of objects, shifting from representational models to artefacts in which data is embedded as intrinsic design element [43]. Beyond shaping an object's geometry, data can also influence an artefact's behaviour, introducing a dynamic dimension to physicalization. Hogan and Hornecker [45] were among the first to explore how interactive and responsive behaviours could serve as a means of encoding data, suggesting that movement, adaptation, or even reactive transformations could extend the communicative potential of physical artefacts. Hogan and Hornecker's interpretation of physicalization is further expanded by Signer et al. [46], which propose a framework for dynamic physicalizations, and by Queiroz et al. [47] proposing dynamic physicalizations using augmented reality (AR) virtual content.

Affectivity and meaningfulness are also explored in physicalizations, with data objects defined as mundane objects which embed data and they can be seen as *data interfaces* [24]. Similarly, the concept of data agents [25] fosters emotional and meaningful connections with information, where data is not strictly encoded in forms, rather co-created through users' interactions, evolving alongside their experiences.

Despite this conceptual advancement, frameworks that account for the intentions and experiences surrounding physicalizations remain limited. What constitutes a meaningful data physicalization is still emerging, as scholars begin to frame these artefacts within wider, entangled socio-material networks. In this direction, the notion of *physecology* acknowledges the hybrid and context-dependent nature of many real-world data physicalizations [48], taking into account data type, interaction mechanisms, spatial configuration, and audience engagement. This shifts physicalizations as static representations to embedded, dynamic elements within everyday environments, serving a variety of purposes ranging from facilitating quantitative understanding and supporting qualitative insights to enabling relational and experiential exploration [33].

In education, data physicalizations have been shown to enhance engagement and conceptual understanding by offering multisensory and embodied ways of interacting with complex information [48, 49, 50]. Within the realm of community engagement, physicalizations are increasingly used to communicate local or civic data in ways that foster public awareness, dialogue, and collective sense-making [48, 51, 52]. In the domain of personal wellbeing, physicalizations support reflective practices by making personal data more tangible and emotionally resonant [53, 54]. This includes sensorial engagements with intimate, bodily data such as menstruation, sleep, or mood [55] [40]. Guo et al. explore physicalizations of fitness data in public contexts, evaluating their effect to stimulate and motivate outdoor physical activities [53]. Kaziunas and colleagues propose the term *lived data* in describing DIY hacking and tracking efforts of people with diabetes, where such practices of *living with data* shape people's lives and interpersonal relationships [56].

Literature uncovers environmental awareness projects that situate physicalised data in public or semi-public spaces to evoke reflection and behavioural change [57]. Furthermore, data physicalizations have shown promise in accessibility-focused applications. By encoding data through physical and haptic modalities instead of, or in addition to, visual ones, they can enhance information access for blind and low vision individuals [58]. This aligns with inclusive design principles and expands the reach of data-driven insights.

The literature and annotated portfolio analysis shows that physicalization outputs take different forms, ranging from interactive experiences, everyday objects, personal physicalizations, to research toolkits, and approaching data in different ways throughout the design process. The following scheme summarises and outlines the four main physicalization outputs.

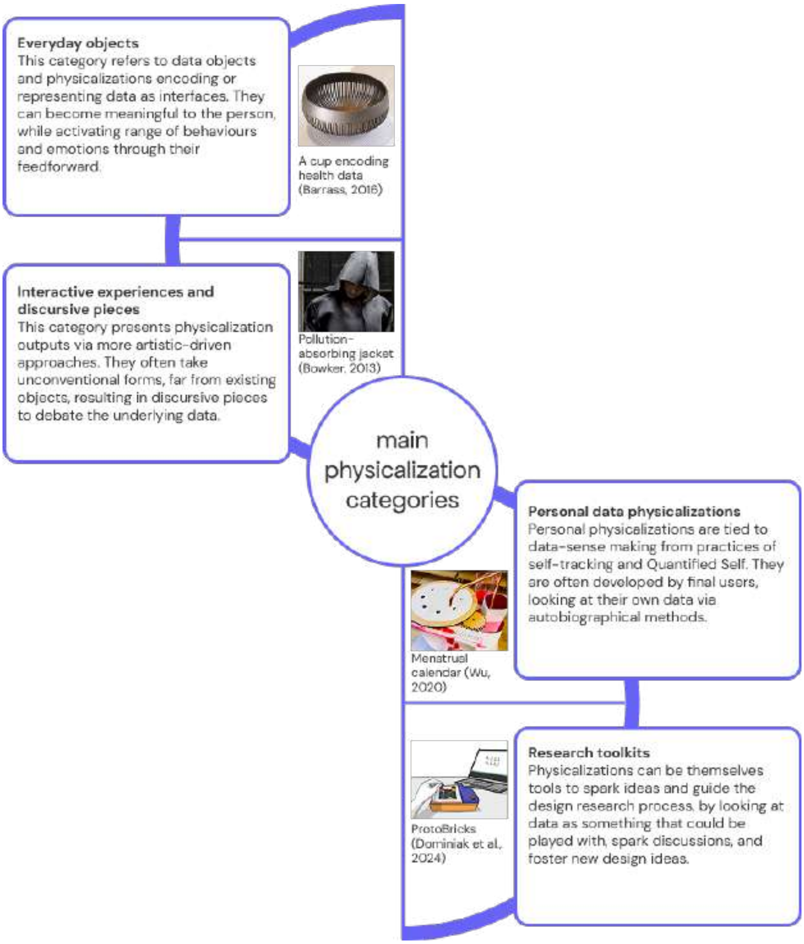

Fig. 7.. Summary scheme of the main physicalization output categories.

4.3 Encoding and co-creating data: two sides of the same coin

The annotated portfolio shows a correlation between the way data are shaped within the artefacts and the way users interact with it. Data range from being encoded into the artefact to being co-created by many actors.

Users interact with it in different ways: from simply reading the physicalization in an analogue manner, as they would an InfoVis, to physically feeling it because of its bodily qualities, or engaging through other sensorial modes of interaction.

From this matrix several findings emerge, including the methods used to shape physicalizations, and the enabled interaction possibilities.

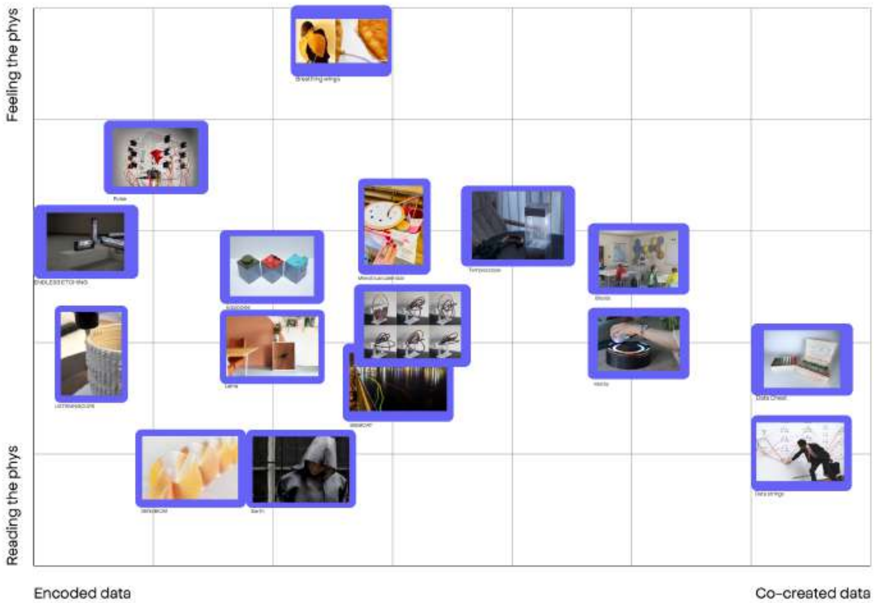

Fig. 8. Case studies matrix

Both literature and portfolio analysis show that designers and researchers tackle physicalizations by adapting methods deriving from HCI and design alike. Authors divide the methods emerged in three main categories: i) hacking digital fabrication; ii) co-design processes; iii) emerging materials and technologies. The final category is the most heterogeneous one, collecting emerging technologies and responsive materials which could be used for dynamically physicalise data.

Hacking digital fabrication. Literature shows established design processes and pipelines to design static data physicalizations, encoding a datasets into an object's geometry and shape. A key aspect of this process is its connection to digital fabrication techniques, where data is converted into machine-readable formats like G-code for 3D printing, CNC machining, or laser cutting, effectively inscribing the dataset into the object's form and structure. Desjardins and Tihanyi [44] illustrate a method to encode sound datasets in ceramic cups through coding and digital fabrication, introducing the concept of data tactility. In ListeningCups, ambient audio recordings were collected from various environments. The decibel levels were processed and translated into G-code, mapping sound intensity to specific 3D printer behaviours. Porcelain cups were then fabricated using a ceramic 3D printer, where printer pauses—based on sound levels—created tactile bumps on the cup's surface. A polygonal base allowed controlled deformation, emphasising tactile design to foster reflection and emotional engagement with the data. In this case, researchers tackle an emerging method of 3D printing ceramics combined with software programming to physicalise meaningful sound data.

Fig. 9. ListeningCups, credits: Desjardins and Tihanyi, 2019

Other examples include the work by Jones et al. [51], which adapted a circular knitting machine to physicalise visitors at a local art gallery during the pandemic recovery year. Daneshzand et al. [61] introduced KiriPhys, a data physicalization technique based on kirigami, the Japanese art of paper-cutting. The method encodes data through a pattern of cuts and joints, forming distinct loops that create visual structures in the material. Dynamic physicalizations using digital fabrication are presented in the works of Veldhuis et al. [49], Everitt and Alexander [59], and Waldshütz et al. [60].

Co-design processes. Data physicalization could be co-created through a bottom-up approach serving as decision-making tools for communities. Gwilt ad Davis [62] use co-design processes among different stakeholders in an university campus to make energy consumption data meaningful. Other examples concern constructive physicalizations in public spaces, built collectively by citizens, such as Data Strings from Domestic Data Streamers. The installation portrays several data types with different values, and people passing by build their own graph by fixing a thread on data values that they believe appropriate. The carefully designed installation by Domestic Data Streamers ensures citizens' willingness to generate a collective piece of data physicalization.

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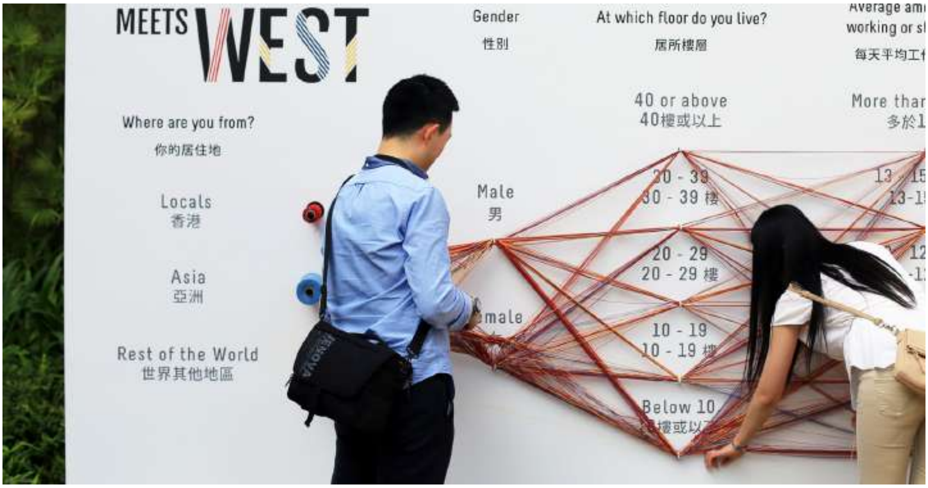

Fig. 10. Data Strings, credits: Domestic Data Streamers

Emerging materials and technologies. A growing body of work in HCI and design research explores how emerging materials and technologies—such as soft robotics, shape-changing interfaces, and bio-inspired systems—can enable new ways of feeling and experiencing data physicalization. Boem and Iwata [63] introduce the project Vital + Morph, which explores the use of shape-changing interfaces for data physicalization in remote health monitoring, offering a rich and emotionally resonant way to experience clinical data. Waldschütz et al [64] introduce pneuCNTRL, a compact, programmable system for air pressure control, enabling the dynamic shaping of inflatable structures for data physicalization and HCI research.

Bio actuators are being explored for physicalization. Teuling et al. [65] introduce chitosan, a biodegradable and humidity-responsive actuators which could enable data interactivity through its embedded shape-changing properties. Presented at Milan Design Week in 2023, the project Sensbiom of the design studio craftingplastics! is a collection of biopolymer lattices which are able to change colour evidencing UVR exposure by signaling real-time changes in Milan's solar radiation to make visitors aware of invisible threats. Drawing connections between living materials and data physicalization, Kim [66] argues how DNA-based data storage presents groundbreaking opportunities for physicalization and long-term interaction design, yet also calls for critical reflection on its ethical, communicative, and usability challenges within HCI. These examples are unlocking new directions merging physicalization with responsive and alive materials.

4.4 Data mapping and encoding variables

The methods classified above—digital fabrication hacking, co-design processes, and emerging materials and technologies—produce outputs with different properties and behaviours. Three main categories emerge from the analysis: static, constructive, and dynamic physicalizations. Static physicalization does not update or change in response to new data inputs. Constructive physicalization focuses on the physical construction, manipulation, and assembly of artefacts that represent data [67]. Dynamic physicalization, on the other hand, updates in real-time or at intervals based on new data inputs [46].

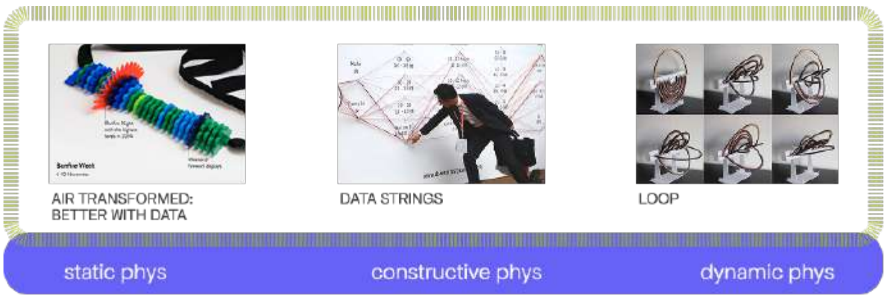

Fig. 11. Static, constructive, dynamic physicalizations. Credits: authors

But, *how are data embedded in those outputs?*

Several researchers outline encoding processes from raw data to physicalization. In 2009, Paneel and Roberts defined a 5-phases process for haptic data visualization (HDV): i) load data; ii) enhance and filter; iii) generate haptic model; iv) render; v) sense [33]. Here data are selected, simplified, and mapped to haptic variables such as force, vibration, or texture. Developers and designers must choose which data aspects to emphasise (e.g., trends vs. raw values) and how users will navigate and interact with the visualization. According to the researchers, mapping data to haptic variables is complex, as it depends on both perceptual clarity and device limitations.

Jansen and Dragicevic [68] extend the classical infovis pipeline to better accommodate non-traditional and physical data representations. Their model introduces additional stages that go beyond digital rendering, including physical instantiation, perception, and insight formation, emphasising the role of the user's embodied interaction with visualizations. They highlight the transformation of raw data while accounting for information loss at each level. Signer et al. [46] define a design space and grammar tailored for dynamic data physicalization. Their framework includes stages namely data interpretation, intermediary representations, physical output, and user interaction. Their work offers a foundational step towards scalable pipelines for developing dynamic physicalizations.

Crucial phase of the physicalization process is data mapping, with a key role played by encoding variables. In a foundational work, Griffin [69] divides haptic sensations into three categories: those derived from touch (tactile), those derived from kinesthesia - bodily movement or tension (kinesthetic), and those derived from visual analogues (i.e., variables that can be perceived by both vision and touch). Ranasinghe and Degbelo [70] propose a review of variables including physical, visual, haptic, dynamic, sonic, olfactory, gustatory. Their framework could be further strengthened by more explicitly connecting encoding variables with perceptual mechanisms and considering how metaphors can enhance the effectiveness and meaning of physicalizations.

Zhao and Vande Moere define three levels of metaphorical mapping when defining data sculptures, from abstract sculptures with non-intuitive encoding, requiring the viewers to learn how to interpret them, to direct mappings between data and physical form, offering clear and immediate understanding. The authors note, however, that these categories are not absolute: factors such as cultural context and individual subjectivity can shift a work from one category to another.

In their work Baur et al. [72] map multimodal variables currently found in physicalizations based on embodied ways of knowing such as *center-periphery*, *front-back*, *near-far*, *up-down* and so on. Studies are now exploring and systematising interactive schemas and variables for physicalization, using prototyping materials in workshop settings [72]. Other studies focus explicitly on metaphors instead of variables when defining tangible interaction designs. That suggests that data are not encoded in artefacts via coded steps, but rather embodied through bodily metaphors adopted by people since their infancy [11]. In his work, Offenhuber argues that the physicalization field should include forms of data that are not symbolically encoded, but that are physicalised through autobiographical processes [35]. On a similar note, Gwilt argues that encoding processes present factual data effectively but often fail to evoke emotional or critical engagement [62]. In a comprehensive work, Hornecker et al. analyzed 25 physicalization examples proposing a structured framework to evaluate physicalizations, consisting of explicit variables, implicit properties, and consequential aspects. Explicit variables encode data directly and extend beyond visual variables to include visual, haptic, auditory, and other sensory modalities [73]. Implicit properties refer to design aspects that influence user experience but do not directly encode data (e.g., material symbolism, spatial placement, interaction style). Lastly, consequential aspects are the unintentional features that still affect the perception and interpretation of data, such as shadows or weight. Overall, scholars are moving from the encoded-decoded ways to represent data, acknowledging the ephemeral, unpredictable and multimodal properties of physicalizations.

5 Discussion

The literature review and annotated portfolio analysis aimed at answering the research questions:

RQ1. What are the ways through which designers in the HCI approach data physicalization, and its challenges?
RQ2. Which are the main physicalization outputs?

This section will discuss the results and provide considerations for researchers and practitioners interested in designing physicalizations. Specifically:

- *the ways through which designers approach data physicalizations*, in terms of processes and methods, by providing an integrated tool to craft physicalizations;
- *its challenges and opportunities*.

5.1 Design challenges for physicalizations

Physicalising temporalities. As mentioned in the related work section, feedback and feedfoward can be used to frame the interaction (at least on a general level) of an interactive artefact. The same concepts can be challenged if approached through the lens of time. Vallgårda et al. introduce "temporality of interaction", referring to the ways time shapes meaning and aesthetics of interactions [74].

This becomes challenging when examining data physicalizations through the lens of temporality [26]. Giving the distinction between static, dynamic, and constructive physicalization, a central question arises: how long is data considered *physicalised?* At what point does a physical change in an artefact transition from being a form of feedback to acting as feedforward, or even become a static representational state within a system? Physical transformations—such as shifts in shape, color, or vibration—are often understood as feedback: tangible reflections of sensed data or environmental phenomena. Yet these same changes can also guide future user actions, taking on a feedforward role. The temporal unfolding of these transitions can vary greatly, especially in physicalizations employing slow, gradual transformations, such as the case study "Sensbiom" by the studio craftingplastics!, which represents UV radiation exposure in real-time through material responses.

Drawing from Vallgårda's concept of temporal form in interaction design, we can understand data physicalizations not just as static objects, but as experiences that evolve through time, inviting users to engage with data as an ongoing process rather than a one-time revelation. In cases of constructive physicalization, where the artefact responds to or is shaped by user actions, feedback and feedforward may

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even coexist, blurring conventional distinctions. Ultimately, the temporal dynamics of data physicalization challenge us to reconsider its role—not simply as a means of representation, but as a temporal interface through which people come to know, anticipate, and interact with data. Here, the user's role becomes central: they are not passive recipients, but active participants in shaping the physicalization and the meaning it conveys over time.

Vocabulary of variables. Considering recent research directions, the authors suggest using the word variables alone, to include autographic ways to incribe data, such as material traces [27]. The term encoding variables evoke precise and strict data mappings, excluding implicit, spontaneous, and less rigorous physicalization processes. By using the term variables, authors emphasise how they cannot be used alone rather coupled with appropriate metaphors to best convey meaning. Authors draw from the literature a gap: the absence of a systematic tool that brings together: i) how data are objectively embedded in the artefact (variables), ii) the embodied thinking through which they are encoded (metaphors), iii) the purpose that guides the alignment between variables and metaphors, and iv) indications of temporality, that is, how variables evolve over time.

The authors propose an integrated variables + metaphors scheme, summarising prior research, particularly the framework of Bakker et al. [11], Ranasinghe and Degbelo [70], and Baur et al. [72]. The scheme is a tool tailored for practitioners, as well as interaction design and HCI students, intended to support the design process of artefacts embedding data (Figure 12).

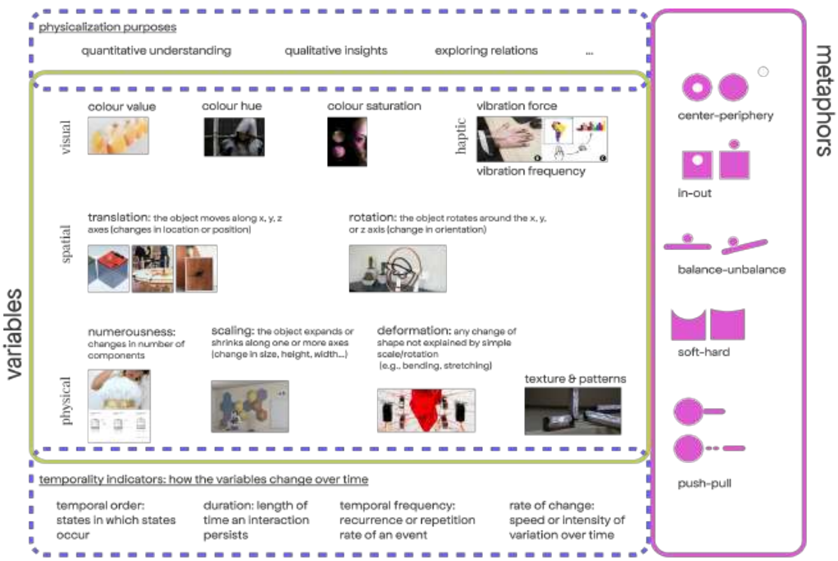

Fig. 12. Variables+metaphors scheme

The scheme outlines how different components work together in the design of a data physicalization. It begins with the physicalization purpose—such as supporting quantitative understanding, qualitative insight, or the exploration of relations—as this goal helps guide the selection of variables and metaphors. For example, if the purpose is to explore relations, a metaphor like balance–unbalance may be particularly fitting. Variables are then grouped into visual, haptic, spatial, and physical categories, while metaphors provide the embodied reasoning that shapes how these variables are chosen and interpreted. Finally, temporality indicators define how the physicalization unfolds over time—capturing the order, duration, frequency, and rate at which variables change—thus contributing to the aesthetic character of the interaction experience.

To illustrate how the Variables + Metaphors scheme can support design practice, herafter we describe the case study of Sensbiom.

In this case, the purpose of the physicalization is environmental awareness, making invisible UV radiation perceptible in everyday life.

- Variables include *colour change intensity (from yellow to orange/red), material translucency, and spatial exposure to sunlight*. These are coupled with the metaphor of *sensitivity* where material transformation reflects bodily exposure to environmental conditions.
- Temporality unfolds in real time, as the material gradually changes according to solar radiation levels (duration and rate of change).

Through this lens, the scheme clarifies how purpose, embodied metaphor, variables, align in shaping a meaningful interaction.

5.2 Meaningfulness in data physicalization

Drawing on the concept of lived data interpretation [6], as well as approaches in human-data interaction [3, 4, 75], users play a key role not only in interpreting the physicalised data, but also in constructing it. Particularly, physicalizations of data linked to their lived experiences, or embedded in everyday objects which evolve or grow with them.

Mekler and Hornbæk propose a five-component framework for understanding how users experience meaning in HCI [76]. Grounded in psychological research, the framework emphasises meaning as a subjective, moment-to-moment experience that spans cognitive, emotional, and motivational dimensions. It offers a tool for analyzing, designing, and evaluating interactive systems beyond usability or pleasure. Karyda et al. build on this meaningfulness framework to explore how physical representations of personal data can foster self-reflection through subjective experiences of meaning. Across three critical design projects, they use the framework to analyze participants' interactions with tangible *data agents* (objects embedded with personal data), such as a jazz CD based on social media data that triggered a participant to reflect on her online identity. The authors found that different data agents prompted distinct levels of reflection, with connectedness consistently acting as a foundation.

In data representation practices, meaningfulness is often framed in terms of efficiency and measurable effectiveness—how clearly and accurately the data is conveyed to the user. However, this perspective can be challenged by designerly approaches to data physicalization, which emphasise not only the functional clarity of a representation but also its emotional, behavioural, and visceral impact. Furthermore, research highlight how elements of situatedness (embedding the physicalization in the context where the data is from), and participation (engaging public in data creation processes) should be key [77]. A physicalization may resonate with users, prompt reflection, or spark engagement even if the underlying data is not fully grasped. This suggests that meaning in interaction can emerge from aesthetic, sensory, and interpretive dimensions that go beyond informational accuracy. Embracing this broader view allows for richer, more human-centered interpretations of what it means for data to be understood or meaningful.

5.3 Emerging materials and data mapping: an unexplored territory

An open question in the data physicalization field is how data can be embedded in materials that possess their own responsiveness or intelligence, such as smart materials, bio soft robotics, or bio-actuators. While traditional data physicalizations rely on controlled and clearly defined encoding variables like location, shape, or texture, working with responsive or living materials challenges these conventions and invites a rethinking of established design processes. When materials behave in unexpected ways, the act of data mapping becomes a negotiation between the agency of the material and the intentions of the creator. This shift introduces a degree of unpredictability and emergent behaviour, where outcomes are no longer entirely predefined but shaped through interaction. In this scenario, the implicit properties and consequential actions of physicalizations highlighted by Hornecker and Hogan gain increasing significance [73].

Historically, data representation has emphasised precision, clarity, and stability. However, several of the works reviewed in this article suggest a shift, pointing toward deeper connections between data physicalization and concepts of livingness, responsiveness, and material agency. These approaches call for alternative ways of experiencing and interpreting data, ones that may be less about delivering fixed information and more about engaging with data as something dynamic, evolving, and materially expressive.

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6 Conclusion and future work

This article offers a comprehensive review of data physicalization and its implications for the interaction design domain, with a specific focus on how designers approach methodological, technical, and conceptual challenges of physicalization. Through a systematic literature review based on PRISMA protocol, and an annotated portfolio of 30 case studies, the study maps out a multifaceted landscape where data physicalization intersects with product design, interaction design, InfoVis, and co-design practices.

The review identifies several key dimensions of the field: evolving definitions of data physicalization, varied domains of application (ranging from education and personal health to civic engagement and environmental awareness), and the diverse types of physicalization outputs (e.g., everyday objects, discursive artefacts, autobiographical visualizations, and research toolkits). It highlights three dominant methodological approaches—hacking digital fabrication, co-design, and emerging materials and technologies—that designers employ to engage with tangible and embodied data. Also, how the way data are shaped within the artefacts and the way users interact with it are interconnected.

By bridging theoretical perspectives with empirical analysis, the article contributes to expanding the conceptual toolkit of interaction design. It emphasises the importance of temporality, situated meaning-making, and material agency in physicalizations, challenging conventional representational models grounded in encoding-decoding schemas. The discussion of metaphors, implicit variables, and performative dimensions of data offers new pathways for exploring more inclusive, embodied, and reflective interactions with data.

Building on the findings of this study, future work will pursue several directions. First, the proposed variables+metaphors scheme, which integrates both explicit encoding variables and embodied metaphors, is currently being tested in a series of mini-workshops with design researchers and students. These workshops aim to refine the scheme and evaluate its usability as a tool for guiding the design and analysis of physicalizations. The scheme currently focuses on haptic and tactile dimensions: expanding it to include variables and metaphors for the auditory channel will enhance its accessibility potential.

Second, the research will expand on the notion of implicit properties—such as material symbolism, spatial affordances, and temporal cues—and their impact on user experience. This direction includes an ongoing study on chart accessibility and tactile memory, specifically targeting blind and low vision (BLV) individuals. The goal is to explore how data physicalizations can be designed to activate and support multisensory memory recall, embodied cognition, and alternative modes of data literacy.

Third, emerging materials—such as responsive materials, soft robotics, or Engineered Living Materials (ELMs)—will be reviewed to assess how material responsiveness can be incorporated into data mapping and physicalization pipelines. This might rethink current assumptions about control, legibility, and stability in data representation, toward more open-ended and unpredictable data interactions.

Future work should also consider the role of meaningfulness in data physicalization. Prior research suggests that meaning in interaction goes beyond informational accuracy, involving subjective, situated, and embodied dimensions shaped by users' lived experiences and emotional responses. Frameworks such as Mekler and Hornbæk's highlight how connectedness, coherence, resonance, purpose, and significance contribute to meaningful user engagement [78]. While not central to this paper, these perspectives point to an important direction for expanding how we understand—and design for—interpretation in data physicalizations.

As with any review-based study, this study is subject to limitations. First, the scope of the literature review was constrained to studies that explicitly reference "data physicalization" "tangible data" or "data materialization" in their titles, abstracts, or keywords. While this targeted strategy ensured a coherent corpus, it may have inadvertently excluded relevant works using alternative terminologies or conceptual framings. Besides, the analysis focuses primarily on visual and haptic modalities, with limited coverage of cross-sensory physicalizations, including auditory or olfactory mappings.

In conclusion, this study not only synthesises existing knowledge but also invites a reorientation of how data is conceptualised, embodied, and designed for interaction. It lays a foundation for future research to move beyond static representation and toward living, meaningful, and materially expressive engagements with data in everyday life.

Artificial Intelligence (AI) declaration. AI tool Microsoft Copilot was used solely for proofreading and language refinement, helping the non-native English-speaking authors enhance clarity and consistency without affecting the scientific content.

CRediT author statement. **Giorgia Burzio:** Conceptualization, Methodology, Formal analysis, Writing – original draft preparation, Visualization. **Venere Ferraro**: Conceptualization,Validation, Writing – review and editing, Supervision.

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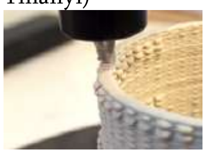
APPENDIX 1

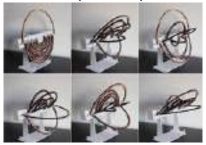
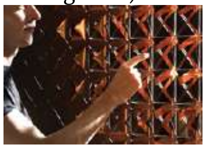
Table 1. Annotated portfolio of 30 case studies

N.	Name	Type of artefact	Technique	Aim	Phys type	Data type	Sensory modality	Bodily engagement
1	Alma Smart Underwear (Alma) 	Underwear embedding sensors	Digital technologies, sensors	Increase understanding of data, improve data tracking	Dynamic phys	Personal	Vision, touch	Feeling data
2	Air Transformed (Posavec, Quick) 	Necklace as "data interface"	3D printed and laser cut beads	Raise awareness on air quality, increase understanding of data	Static phys	Environmental	Vision, touch	In between reading and feeling data
3	Bloats (Besana) 	Wall modules changing shape	Shape changing materials, sensors, actuators	Raise awareness on air quality, support decision making	Dynamic phys	Environmental	Vision	Reading data
4	Breathing Wings (Tsaknaki) 	Soma design	Craft with inflatables	Raise awareness about breathing	Constructive phys	Personal	Haptic, kinesthetic	Feeling data

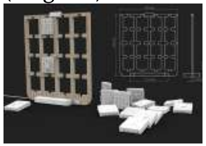
5	Chemo singing bowl (Barrass) 	Bowl shaped through encoded data	Digital fabrication	Raise awareness about personal medical data	Static phys	Personal	Vision, touch	In between reading and feeling data
6	DataChest (Wijers et al.) 	Toolkit for assembly physicalization	3D printed components	Increase understanding of data, support decision-making	Constructive phys	Multivariate	Vision, touch, haptic	Reading data
7	Data Domestication (Nicenboim) 	Domestic installation	Digital fabrication, sensors	Raise awareness, support decision-making	Dynamic phys	Environmental	Vision	Feeling data
8	Data Strings (Domestic Data Streamers) 	Public installation	Craft	Increase understanding of data, co-creation	Constructive phys	Multivariate	Vision, touch	Reading data
9	Drum roll (Fischer et al.) 	Public installation	Digital technologies, sensors	Artistic creation, hedonistic purposes	Dynamic phys	Environmental	Sound	Feeling data

10	Earth (See the Unseen) 	Pollution absorbing jacket	Materials science	Raise awareness, support decision-making	Dynamic phys	Environmental	Vision	Feeling data
11	Endless etching (van Schie) 	Interactive installation	Self-learning algorithm	Artistic creation, hedonistic purposes	Dynamic phys	Computational	Vision	Feeling data
12	Equipoise (Åsberg) 	Domestic installation physicalising purchases	Digital fabrication, digital technologies	Increase understanding of data, support decision-making	Dynamic phys	Personal	Vision, sound	Feeling data
13	FRANK (Amorim et al.) 	Interactive material	Material changes shape according to the level of closeness of the person’s hand.	Capturing data	Dynamic phys	Multivariate	Haptic, touch	Feeling data
12	Hathor (See the Unseen) 	Make-up pigment	Materials science	Raise awareness, hedonistic purposes	Dynamic phys	Environmental	Vision	Feeling data
13	Human-cloud project	Public installation to connect with the climate	Digital fabrication, craft	Raise awareness, hedonistic purposes	Constructive phys	Environmental	Vision, smell	Feeling data

	(Staņislavskis) 							
14	Interactive NeuroKnitting: Knitting with Your Brain (Varvara et al.) 	Installation, research probe	Digital fabrication (circular knitting machine)	Research, hedonistic purposes	Dynamic phys	Multivariate	Vision	Feeling data
15	Kuddi (Ívansdóttir et al.) 	Soma design for menstrual wellbeing	Digital fabrication, digital technologies	Increase understanding of data, support decision-making	Dynamic phys	Personal	Touch, haptic	Feeling data
16	Laina (Menheere et al.) 	Furniture as "data interface"	Digital technologies, sensors, fabrication	Support decision-making, persuade behaviours	Dynamic phys	Personal	Vision	Reading data
	Listening cups (Desjardins & Tihanyi) 	Cups shaped through encoded data	Digital fabrication, sensors	Raise awareness, artistic creation	Static phys	Environmental	Touch	Reading data

17	LOOP (Sauvé) 	Domestic installation for tracking physical exercise	Digital fabrication, sensors	Support decision-making, persuade behaviours	Dynamic phys	Personal	Vision	In between reading and feeling data
18	Lotus (Studio Roosegaarde) 	Interactive installationt that fold open in response to light	Craft	Artistic creation, hedonistic purposes	Dynamic phys	Environmental	Vision	Feeling data
19	Menarche bits (Søndergaard et al) 	Soma design for menstrual wellbeing	Digital technologies, actuators	Increase understanding of data, support decision-making	Constructive phys	Personal	Haptic, kinesthetic	Feeling data
20	Minimal machines (Matters of Activity) 	AR framework for data capture	AR and tracking device	Capture data	Constructive phys	Multivariate	Vision (AR)	Feeling data
21	Motiis (Pepping et al.) 	Domestic object communicating to parents children emotions during game play	Digital technologies, digital fabrication	Support decision-making, raise awareness	Dynamic phys	Multivariate	Haptic	Feeling data

22	Ovum (Homewood et al.) 	Domestic object visualising fertility data	Digital technologies, digital fabrication, craft	Increase understanding of data, persuade behaviours	Dynamic phys	Personal	Vision	In between reading and feeling data
23	Pulse: animated heart shows sentiments (Kison) 	Public installation	Digital technologies, craft	Raise awareness, artistic creation	Dynamic phys	Social	Vision	In between reading and feeling data
24	SeeBoat (Perovich and Valdez) 	Public installation (collective and social use)	Digital technologies, sensors, fabrication	Raise awareness	Dynamic phys	Environmental	Vision	In between reading and feeling data
25	Sensbiom II (crafting plastics! & DumoLab Research) 	Public installation	Bioresponsive materials, digital fabrication	Raise awareness, increase understanding of data	Dynamic phys	Environmental	Vision	In between reading and feeling data
26	Solar totems (Sowers) 	Public installation	Craft	Artistic creation, capture data	Dynamic phys	Environmental	Vision	Reading data

27	Tactivity (Sarghini) 	Tactile game based on textures	Digital technologies, digital fabrication	Enhance tactility for blinds	Constructive phys	Multivariate	Touch, haptic, sound	Feeling data, reading data for BLV
28	Tempescope (Kawamoto) 	Domestic object visualising weather	Digital technologies	Artistic creation	Dynamic phys	Environmental	Vision	In between reading and feeling data
29	Though a patriarchy would privilege the changelessness of the sun over the inconstancy of the moon and you (Wu) 	Domestic installation	Digital technologies, digital fabrication	Increase understanding of data, persuade behaviours	Dynamic phys	Personal	Vision	Feeling data
30	Vital+morph (Boem et al.) 	Domestic interactive object	Digital technologies, digital fabrication	Increase understanding of data, persuade behaviours	Dynamic phys	Personal	Touch, haptic	Feeling data