Towards Context-Sensitive Physicalization Design:

Exploring the Perception of and Interaction with Physicalizations

Kim Henrica Petronella Sauvé, BSc, MSc
School of Computing and Communications
Lancaster University

A thesis submitted for the degree of
Doctor of Philosophy

August, 2023

I dedicate this thesis to my mum, for the incredible person she is,
and to my dad, for the amazing person he was.

Declaration

I declare that the work presented in this thesis is, to the best of my knowledge and belief, original and my own work. The material has not been submitted, either in whole or in part, for a degree at this, or any other university. This thesis does not exceed the maximum permitted word length of 80,000 words including appendices and footnotes, but excluding the bibliography. A rough estimate of the word count is: 66066

Kim Henrica Petronella Sauvé

Towards Context-Sensitive Physicalization Design:
Exploring the Perception of and Interaction with Physicalizations
Kim Henrica Petronella Sauvé, BSc, MSc.
School of Computing and Communications, Lancaster University
A thesis submitted for the degree of *Doctor of Philosophy.* August, 2023

Abstract

Data physicalization, defined as physical artifacts that encode data in their 3D form, is an emerging field within Human-Computer Interaction. As the field continues to evolve, there remain conceptual and empirical challenges to overcome, including the comprehension of people's perceptions and interactions with the tangible aspect of physicalizations. Hence, more research is needed to foster advancement in the field and ensure that physicalizations reliably and effectively communicate information.

Previous research often uses either a device-centric approach, emphasizing technology and interaction techniques, or a domain-centric approach, leading to custom-designed artifacts for specific applications with limited generalizability. In contrast, this thesis aims to obtain a deeper understanding of the ramifications of physicality and contextual factors on people's interactions with physicalization design, independent of implementation.

The thesis commences with a meta-review to understand state-of-the-art physicalizations in relation to their surrounding audience and context. The first study investigates the perception of abstract bar chart physicalizations, revealing that people's perception of physical information is directly influenced by user orientation. The second study explores people's strategies for reconfiguring bar chart physicalizations, showing that they generally employ two approaches: proximity and atomic orientation changes. These findings inform the design of a bespoke toolkit utilized in the third study to examine the construction and labeling of physicalizations. This final study illustrates how data labeling plays a crucial role in the creation process, final visualization design, and across orientations.

The contributions of this thesis include a conceptual framework to describe physicalizations in relation to their context, a novel methodology to investigate the influence of physicality on people's interactions with physicalizations across orientations, and empirical findings on people's perception, reconfiguration, and labeling of physicalizations. The ultimate aim is to guide future research toward designing context-sensitive physicalizations that either minimize or leverage the influence of orientation on people's interactions with physicalizations.

Publications

Parts of this work have been published in peer-reviewed publications and journal articles. Below are the references of these publications at the time of writing:

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

Kim Sauvé, David Verweij, Jason Alexander, and Steven Houben. 2021. Reconfiguration Strategies with Composite Data Physicalizations. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. ACM, New York, NY, USA, Article 471, 1–18. https://doi.org/10.1145/3411764.3445746

Kim Sauvé, Miriam Sturdee, and Steven Houben. 2022. Physecology: A Conceptual Framework to Describe Data Physicalizations in their Real-World Context. In *ACM Transactions on Computer-Human Interaction (TOCHI)*. 29, 3, Article 27 (June 2022), 33 pages. https://doi.org/10.1145/3505590

Kim Sauvé, Argenis Ramirez Gomez, and Steven Houben. 2022. Put a Label On It! Approaches for Constructing and Contextualizing Bar Chart Physicalizations. In *CHI Conference on Human Factors in Computing Systems (CHI '22)*. ACM, New York, NY, USA, Article 82, 1–15. https://doi.org/10.1145/3491102.3501952

Other co-authored work that has been published during the PhD that is related to the topic but not directly included in this thesis:

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

Kim Sauvé, Saskia Bakker, Nicolai Marquardt, and Steven Houben. 2020. LOOP: Exploring Physicalization of Activity Tracking Data. In *Proceedings of the 11th Nordic Conference on Human-Computer Interaction: Shaping Experiences,* *Shaping Society (NordiCHI'20)*. ACM, New York, NY, USA, Article 52, 1–12. https://doi.org/10.1145/3419249.3420109

Kim Sauvé and Steven Houben. 2021. Towards an Ecology of Interconnected Data Devices. In *CHI'21 Workshop Human-Data Interaction through Design*.

Kim Sauvé and Steven Houben. 2022. From Data to Physical Artifact: Challenges and Opportunities in Designing Physical Data Artifacts for Everyday Life. *Interactions* 29, 2 (March - April 2022), 40–45. https://doi.org/10.1145/3511670

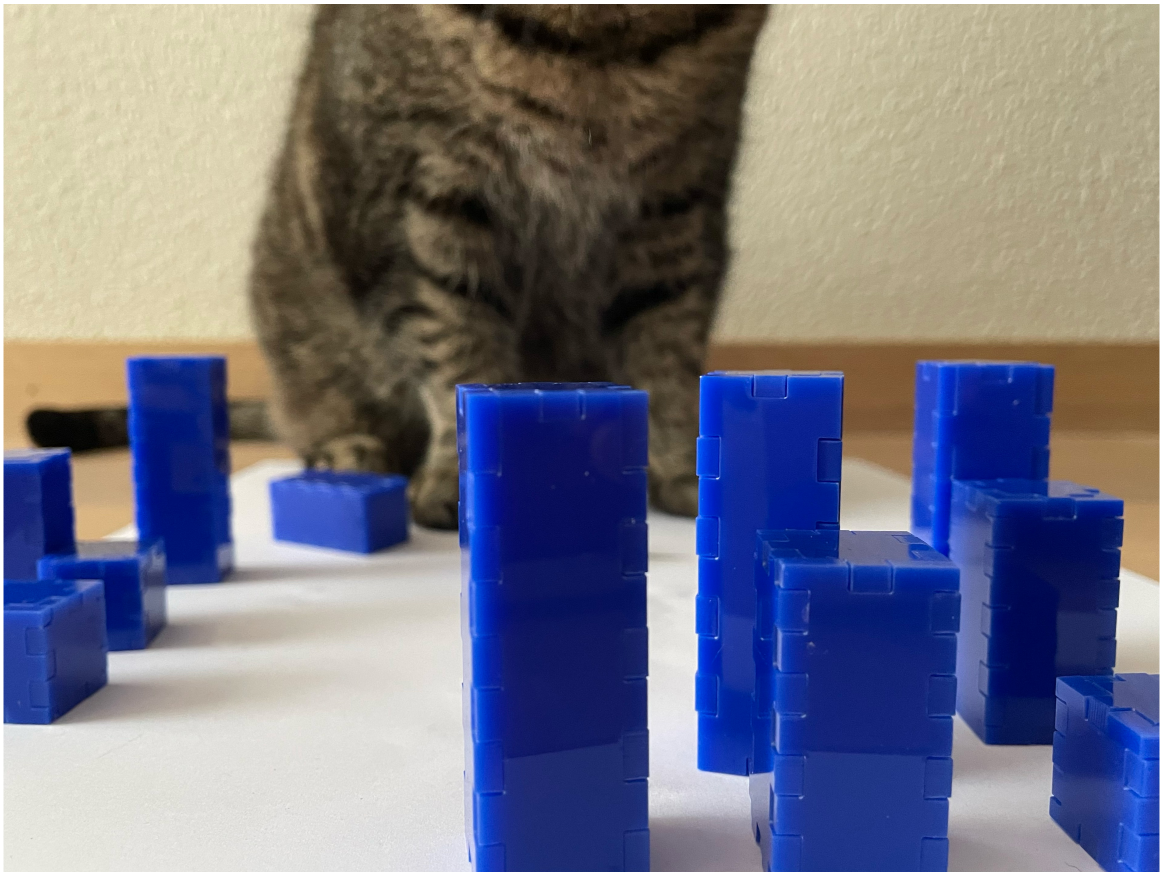
Brigitte Stegers, **Kim Sauvé**, and Steven Houben. 2022. Ecorbis: A Data Sculpture of Environmental Behavior in the Home Context. In *Proceedings of the 2022 ACM Designing Interactive Systems Conference (DIS'22)*. ACM, New York, NY, USA, 1669-1683. https://doi.org/10.1145/3532106.3533508

Kim Sauvé, Yvonne Jansen, and Pierre Dragicevic. 2022. Edo: A Participatory Data Physicalization on the Climate Impact of Dietary Choices. In *Proceedings of the 2023 ACM Conference on Tangible, Embedded, and Embodied Interaction (TEI'23)*. ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3569009.3572807

Kim Sauvé, Hans Brombacher, Rosa van Koningsbruggen, Annemiek Veldhuis, Steven Houben, and Jason Alexander. 2022. Physicalization from Theory to Practice: Exploring Physicalization Design across Domains. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems (CHI EA '23)*. ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3544549.3573824

Other co-authored work that has been published during the PhD but is not related to this thesis:

Kamil Rogoda, Piotr Daniszewski, Kamil Florowski, Rishab Mathur, Kourosh Amouzgar, James Mackenzie, **Kim Sauvé**, and Abhijit Karnik. 2022. FoodChoices(Q): Exploring the design of a serious game proxy for Likert-style survey questionnaires. In *Proceedings of the ACM Human-Computer Interaction*, 6, CHI PLAY, Article 236, 15 pages, https://doi.org/10.1145/3549499



Acknowledgements

I would like to express my deepest gratitude to my PhD supervisor Dr Steven Houben for his exceptional guidance and engaging discussions throughout my research journey. His insightful mentorship and advice have been instrumental in shaping my academic and professional growth and helping me navigate the academic landscape with confidence.

This thesis embodies the collective support, encouragement, and love of many exceptional individuals around me. I am profoundly grateful for their contributions, which have shaped this four-year experience. To those I may not have mentioned, please know that I have not forgotten you – *dankjewel*.

Dank jullie wel to my friends, who have been a constant source of camaraderie and encouragement during this challenging yet rewarding experience. Whether within the academic landscape or beyond, within the UK or elsewhere, your friendship has provided me with much-needed *gezelligheid*, and each of you holds a special place in my heart. Special thanks to Argenis, Pierre, Claudia, Boyeun, Hayat, Chris, Ludwig, Tom, Franzi, Josh, and James for our memorable day trips, countless coffee conversations, and baking endeavors. I am also deeply grateful for the longstanding friendship with Helena, Iris, and Milou. Though we may not live close by, our call walks and *gezellige* girl weekends always make me feel at home.

Duizendmaal dank to my immediate family, my Mum, brother Bram, and Bert, for their unwavering support and encouragement throughout this experience. Bert and Mum, thank you for helping me make the big move from the Netherlands to the UK, driving my life's belongings in 10 moving boxes back in January 2019. Bram, our deep conversations about everything and anything have provided me with food for thought and laughter when I needed it most. Mum, you have been both a mother and father figure, instilling in me a creative and determined nature from a young age. Your unwavering strength and support have been an anchor in my life. I would also like to extend my gratitude to my wider family, particularly my grandparents, Oma Nelly, Opa Sjef, Oma Riek, and Opa Mies, for shaping my formative years.

Speciale dank to my partner Dom, whose unconditional love, understanding, and support have been my rock throughout this journey. His presence, listening ear, comforting shoulder, warm hugs, and contagious laughter have been a source of strength and stability. Together, we navigated the final sprint of our PhDs, keeping each other sane and reminding each other of all the great things outside of academia.

Lastly, I would like to acknowledge my late father. Though our time together was tragically brief, your memory and influence continue to resonate with me. Your kindness, wisdom, humor, and love you shared with our family have left an indelible mark on my character. This thesis stands as a tribute to your spirit and the lasting impact you have had on my life.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

“We are ready to question the impersonality of a merely technical approach to data, and to begin designing ways to connect numbers to what they really stand for: knowledge, behaviors, and people.” – Giorgia Lupi

Data is becoming more and more ubiquitous; modern technologies such as wearables, IoT devices, sensor systems, and crowd-sourced tools are revolutionizing the way data can be accessed and used by bigger audiences than ever. In this context, ‘data’ includes a wide spectrum of types and fidelity of datasets ranging from direct ‘raw’ data (e.g. sensor readings) to aggregated datasets (i.e. a snapshot of local air pollution). However, it is important to note that raw data is not immediately meaningful or actionable.

This increased access to data allows people to collect, explore, visualize, and share it in new ways. Through the processing and interpretation of data, it can be transformed into meaningful or actionable insights. This is where *data* transitions into *information*. Information provides context, understanding, and knowledge that can be utilized for various purposes. In doing so, people might learn more about themselves, such as monitoring their health, online activity, or places visited; but also about their (social) surroundings, such as their neighborhood’s energy usage, the impact of collective sustainable life choices, or the local weather. Hence, these modern technologies are becoming a leveraging tool for reflection, discussion, and decision-making.

One way to meaningfully embed data into everyday experiences and bridge the gap between people and datasets is through the introduction of physical representations of data[1]. Data physicalizations (or *physicalizations*) are defined as physical artifacts that encode data in their physical 3D form [108]. Hence, they lift data from a digital screen and give it material presence in the physical world. Within the realm of Human-Computer Interaction (HCI), there is a breadth of existing work in the

---

[1] For more information on other methods of embedding data into everyday experiences, please refer to the Background (Section 2.2).

research area of physicalization, ranging from 3D printed data sculptures for personal reflection [119, 216], to custom-made toolkits that can be used to construct your own visualizations by hand [65], to fully actuated systems that can be touched and manipulated for the interrogation of data [221]. These examples are not mutually exclusive or exhaustive, but are demonstrative of a spectrum of novel form factors that can stimulate human senses in new ways. This is beneficial as it can make data more accessible and engaging. For instance, the ability to touch and interact with this data through physicalizations can facilitate information retrieval [107], improve memorability [214, 215], and open up new pathways for people to change or interrogate data ad hoc. Moreover, research suggests that the use of tangible technologies can enhance understanding and learning [172]. Furthermore, their physicality can promote collaboration and shared sense-making [108] and physicalizations have the ability to reach larger audiences through their public location and/or physical scale [143].

However, if we want to use physicalizations to communicate (complex) information for multiple purposes on a large scale, there are some fundamental challenges that we have yet to overcome. Although physicalizations have existed for a long time [53] and are an established concept by now [108], we still know very little of *how they are used by people*. The dominant focus of research on the development of the concepts around physicalization has been *device-* and/or *domain-centric*. The device-centric approach concentrates on the detailed device, apparatus, or mechanisms that enable physicalization [4, 44, 61, 167, 220]. However, this approach is largely driven by current technological limitations, which hinders the ability to fully operationalize the visions behind physicalization into interactive systems. On the other hand, the domain-centric approach focuses on custom-made implementations for a wide range of specific domain applications, such as personal informatics [e.g. 91, 119, 187, 225], sustainability [e.g. 20, 186, 209], education [e.g. 232, 244], and office vitality [e.g. 29, 42, 208]. This approach often involves design and field studies that provide rich qualitative insights, but may be less generalizable. Both approaches make valuable contributions, but their focus on specific areas also means that other essential topics, such as user perception or broader context of use, are less well explored and understood as they rarely are included in the main focal point when discussing 'physicalization' conceptually. Recently, research has begun to show an interest in the contextual factors that influence the use of physicalizations. For instance, research by Dumičić et al. [55] has surveyed the diverse range of topics and themes of current physicalization work (e.g., medical sciences, geography, psychology, and urban environments), while Bae et al. [13] have found that state-of-the-art physicalization research often does not take into account the location or intended audience for which the physicalization is designed. This implies that current physicalization research does not give enough consideration to physical and contextual factors and more effort is necessary to understand physicalizations in relation to the broader context of use.

This thesis proposes to shift the focus of physicalization research from a device- and/or domain-centric approach to investigating the implications of physicality and the surrounding physical environment of physicalizations. By actively considering the impact of physical and contextual factors, we aim to gain a deeper understanding of how physicalizations are experienced and interacted with in physical 3D space. More specifically, this thesis starts with a meta-review to analyze current state-of-the-art physicalization work in a real-world setting, followed by in-depth empirical investigations of the effects of physicality on people's interaction with bar chart physicalizations. By doing so, it aims to advance physicalization research by deepening our understanding of how the physicality and physical context of physicalizations influence the way people perceive and interact with tangible information.

1.1 Research Challenges

In contrast to visualization [164, 238], the digital predecessor of physicalization, there are not many established rules, guidelines, or best practices when it comes to physicalization design. Additionally, existing guidelines from visualization are only partly informative for and transferable to physical space; the physical and tangible nature of physicalizations inherently makes them susceptible to their surrounding audience and context, and all interactions that can exist within and around them. To give some examples, viewing 2D or 3D visualizations on a screen is less susceptible to the viewing angle and perspective of the user than viewing a physicalization in physical space; manipulations of data in physical space can go beyond touch displays, mouse, or other controller interactions; and physicalizations can be deployed in many different locations and used by different audiences. Hence, for us to design physicalizations that can be effectively perceived and interacted with, there are several fundamental challenges to overcome. In this thesis, the focus is on four challenges which will each be detailed below.

1.1.1 Physicalizations in Context

Although physicalization is a relatively new research area in HCI, over the past fifteen years a wide variety of physicalization systems have been introduced [53, 54]. On a conceptual level, there have been different conversations in the field on how to define what constitutes a physicalization. In 2015, Jansen et al. [108] proposed the working definition for physicalization as *"a physical artifact whose geometry or material properties encode data"*. While this definition accurately describes the fundamental idea of the physicalization of data – it can also be interpreted and operationalized across a range of different forms and for a variety of audiences and contexts [13, 53, 54, 55]. This is also evidenced in the many ways in which physicalizations (and related artifacts) are described, including *data sculptures* [251], *casual information visualizations* [179], *constructive visualizations* [99], *embedded data representations* [243], and *dynamic composite data physicalizations* [134]. Additionally, there are various interaction forms possible, such as using gestures [220], the manual re-arrangement of data objects [100, 107], or the pushing/pulling of physical bar charts [221]. Lastly, research outside the field of physicalization has previously shown that context is as important as the artifact or device itself [1, 52]. This raises questions on how this knowledge transfers to the use of physicalizations in the real world. Therefore, in order for the research area to mature, a comprehensive understanding of how physicalizations manifest in the complexity of the real world is essential. It is important to establish a shared vocabulary to allow for a unified discussion of physicalizations in relation to their context of use, for state-of-the-art work as well as future physicalization design.

1.1.2 Perception and User Orientation

Besides the lack of clarity on how to conceptually discuss physicalizations in relation to their physical context, there are several empirical challenges in studying the physical nature of physicalizations. Hence, there is a need to investigate the implications of the inherent physicality of the physicalization itself, starting with the perception of physical information.

As a consequence of the three-dimensional nature of physicalizations, information retrieval is sensitive to the angle and perspective changes of the viewer. Factors such as occlusion, depth perception, and height estimation in physical space can prevent the viewer from effectively extracting information. Moreover, what happens when multiple people observe the same physicalization from different angles or perspectives?

Although some prior work acknowledges the possibility of perspective being an influence on how physical information is perceived [83, 165, 221], *no prior studies have actively considered the relation between user orientation and perception.* The focus is often on individual interaction from a single position, which might originate from interactions as we know them with 2D visualizations. Examples include collaborative settings in which users are limited to one viewing angle, or physicalizations in which accompanying interfaces, labels, or legends are placed in a particular direction, which biases the viewing angle [62, 64, 221]. This single-perspective approach conflicts with the argument that physicalizations foster collaboration and allow for interactions around them [108], which works on the assumption that physicalizations effectively communicate data in all directions, and to all users equally. This assumption should be investigated as the consequences can be problematic for data interpretation and make physicalizations ambiguous. If people have different perceptions when viewing a singular physicalization from several perspectives, they will interpret the data in varying ways. Therefore, a systematic and principled approach is needed to understand how the orientation of an individual influences their perception of data. This can guide the design of physicalizations that consider observation from multiple perspectives.

1.1.3 Interactions with Physical Information

Beyond the observation from multiple perspectives, physicalizations fundamentally afford physical interactions (such as touching, grabbing, and pushing) and some form of reconfiguration as their physicality encourages people to interact with their tangible elements. In many instances ([e.g. 77, 100, 133]) these physicalizations support data curation and input where users can physically rearrange data points. The unique affordances and characteristics of physicalizations make them distinct from 2D visualizations, unlocking novel human-data interaction approaches.

However, we still lack an *understanding of the practices, strategies, and approaches people take when interacting with physicalizations*. At present, the interactivity of physicalizations is often bound to the limitations of the technology used, hence, they are also explored and studied in those terms. This means that the study of users' interactions with these systems is currently restricted to implementation-dictated interactions, potentially conflicting with users' preferred or spontaneous interaction strategies. Therefore, it is important to further develop our understanding of approaches to and interactions with physicalizations. This will inform how we might better support users' approaches to reorganizing and manipulating data in physical 3D space.

1.1.4 Contextualizing Physical Structures

For physicalizations – as with 2D visualizations – the inclusion of data labels, axes values, legends, and annotations are in many cases fundamental to contextualizing the presented data. They provide people with anchor points and visual guides on how to interpret the data. Particularly because of the challenges associated with user orientation and perception as mentioned above, such labels and annotations are instrumental in helping people make sense of the presented data. Despite the obvious importance of providing guiding context to visualizations, prior work on physicalizations [53, 54], *does not actively consider the labeling of physical data points and structures*. Work that does consider labeling of physicalizations in some form [e.g. 186, 221, 232], often use very different approaches that are not systematic or even consistent with each other.

However, a physicalization relies on contextual information to be effective; the physicality and spatiality of physicalizations explicitly open up questions such as (i) where to locate different kinds of labels (such as title, axes labels, and data values) in relation to the canvas and/or other data points, and (ii) how this is affected by user orientation (e.g. when multiple people are looking at the physicalization from different perspectives). Therefore, it is important to treat the act of 'data labeling'[2] as an active part in the creation of and interaction with physicalizations. To this end, we can draw upon the methodology and principles of constructive visualization [99], which explores the ways in which people translate data into physical representations. However, unlike current constructive visualization research, this thesis aims to integrate labeling as an essential step in the physicalization process, instead of a secondary process [100, 246]. This will inform how we can effectively label future physicalizations, taking into account spatiality, user orientation, and perception.

1.2 Research Questions

These four challenges indicate that the impact of contextual factors and physicality on how we interact with physicalizations is not well understood. On a conceptual level, we do not have the vocabulary to discuss physicalizations in relation to their physical context. On an empirical level, we know very little about the influence of physicality on the way people perceive and interact with physicalizations. Therefore, there is a need to shift the focus from a device- and/or domain-centric view towards (i) the conceptual physical context surrounding physicalizations, and (ii) the empirical implications of physicality on people's interactions with physicalizations. Therefore, the main research question addressed in this thesis is:

Main RQ: How do physicality and physical context influence people's interaction with physicalizations?

To help answer the main RQ, four sub-research questions were formed, RQ1–RQ4. Each subsequent question builds upon the previous one and will be elaborated on below:

RQ1: How can physicalizations be understood in relation to their audience and real-world context?

The first research question aims to analyze current state-of-the-art to understand how physicalizations more generally are used in context. 'Context' refers to the variety of possible audiences and physical spaces surrounding physicalizations that are deployed in the real world. Currently, existing research shows a variety of ways in which physicalizations are described, implemented, and deployed, which prevents researchers from having a unified discussion of physicalizations in their context of use. Therefore, the objective for RQ1 is to obtain a comprehensive understanding of the

---

[2] Not to be mistaken with the term 'data labeling' as used in Machine Learning to describe the annotation of raw data to train a classifier.

use of physicalizations in a real-world context. This will contribute to a more unified conceptual understanding of how physicalizations function in a wider interaction context and will help contextualize the work done for RQ2–RQ4.

After obtaining a conceptual understanding of the state-of-the-art and its relation to physical context more generally, this thesis aims to understand the implications of physicality on people's perception of physicalizations in further detail, leading to RQ2.

RQ2: What is the relation between user orientation and the perception of physicalizations?

As physicalizations encode data in their physical 3D form, the orientation in which people are viewing the physicalization may impact the way information is perceived. However, this relation between user orientation and perception of physical properties is not well understood or studied. From an empirical perspective, human perception is the root concept that will inform all other aspects of physicalization design, such as interaction techniques, actuation mechanisms, and means for collaboration. Hence, this thesis seeks to understand how people perceive physical information from different orientations, as this will ultimately influence their sense-making of and interactions with physicalizations. Therefore, the objective for RQ2 is to provide a first characterization of the relation between user orientation and the perception of physicalizations. This will provide an initial understanding of how to design physicalizations that consider the way in which information is perceived across different perspectives.

RQ3: What are people's reconfiguration strategies in relation to the physical structure of physicalizations?

Beyond the perceptual benefits of presenting data physically in people's surroundings, physicalizations also facilitate the physical reconfiguration of tangible data points, either done by people or the system itself. This creates new opportunities for interaction and engagement, such as data input and curation through dynamic and reconfigurable physicalizations. However, there is a lack of understanding of people's strategies and behaviors when directly manipulating physical data points as part of a physicalization. Therefore, the objective for RQ3 is to obtain an understanding of peoples' reconfiguration strategies in relation to the physical structure of physicalizations. This will inform the future design of interactions with dynamic reconfigurable physicalizations that utilize physical 3D space.

RQ4: How do people construct and label physicalizations as part of a constructive visualization process?

After the investigation of the perception and reconfiguration of physicalizations in isolation, this thesis aims to evaluate these activities as part of an overall sense-making process. Similar to 2D visualization, for physicalization the inclusion of contextual information – such as data labels, axes values, legends, and annotations – is often fundamental for the sense-making of the presented data. However, in contrast to 2D visualization there are no established guidelines or best practices when it comes to providing contextual information in physical 3D space. As studying the inclusion of contextual information in isolation would be artificial, this research question aims to investigate this as part of a construction and labeling process: integrating perception, reconfiguration, and labeling activities. The objective is to understand the role of data labeling (i) as part of the creation process, (ii) in the resulting visualization design, and (iii) when viewed from different orientations. This will contribute to the further development of labeling methods for future physicalizations, considering user orientation and physical 3D space.

1.3 Research Scope

The research of this thesis lies on the intersection of the fields of Human-Computer Interaction and Visualization.

Human-Computer Interaction (or HCI in short) is defined as *"a discipline concerned with the design, evaluation, and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them"* [202]. Visualization[3] is defined as *"the use of computer-supported, interactive, visual representations of data to amplify cognition"* [31].

Physicalization shows methodological overlap with HCI in terms of the design, evaluation, and implementation of interactive computer-supported representations of data for human use. More specifically, to support people to effectively perform a range of tasks such as learning, problem-solving, and decision-making. This is where Physicalization also overlaps with Visualization, as both are data representations to aid human cognition. However, the difference lies in physicalization going beyond mere digital representations to trigger visual senses, and exploring how data can be represented through other physical means. Therefore, physicalization excludes systems that only convey data through digital screens (which is Visualization) but includes systems that involve, for example, shape-changing surfaces [e.g. 62, 136], so long as the physical properties of these systems are used to convey data.

---

[3] Visualization can be further divided into Scientific Visualization (SciVis) and Information Visualization (InfoVis) dependent on whether the data representation is given or chosen. However, in line with prior work [108, 164], this thesis will use Visualization as an overarching term for simplicity.

For the design and evaluation of physicalizations, not only computer-supported implementations are of relevance, as these are constrained by current technological advances. Hence, there is a precedent approach of performing evaluations with static physicalizations as a proxy to inform and inspire the design of prospective physicalizations including interaction and actuation. This is exemplified in prior work on the perception of and interaction with static physicalizations [107, 109, 214, 215], and is also the prominent methodological approach in this thesis.

This thesis aims to contribute to physicalization research by combining existing methodological approaches and theoretical knowledge from HCI and Visualization, and expand our knowledge of how people use physicalizations. The broader implication of this work is that it will contribute to our understanding of designing physicalizations that effectively communicate information, without ambiguity in their perception or interactions, and are appropriate for their context of use. Ultimately, this will make physicalizations more trustworthy gateways to data and empower people to use them for a variety of purposes.

1.4 Methodology

The goal of this thesis is to advance the understanding of how physical context and physicality influence people's interactions with physicalizations. To answer the main research question, this thesis follows an Inductive-Deductive Method [144, 150], which strives to obtain knowledge about the real world through testing hypotheses in controlled experiments. Hence, research activities consist of cycling between theory and observation to develop and test hypotheses that can explain real-world phenomena. More specifically, a series of three empirical lab experiments were conducted. The first two experiments discussed in Chapter 4 and Chapter 5, were performed in a single session to investigate different implications of physicality for the interaction with physicalizations in isolation. The third experiment, which is described in Chapter 6, was conducted separately to explore additional aspects of physical context and physicality.

The apparatuses designed for these empirical studies are informed by a subset of physicalizations – 3D bar charts – as previously used in physicalization research. 3D bar charts are a simple and effective way to display data and provide a physical representation that is easy to comprehend and allows for quick and straightforward comparisons of values. In addition, they are versatile and can be used to display a wide range of data types, such as numerical, categorical, and ordinal data, making them a useful tool for a variety of design [e.g. 62, 134, 143, 220, 221] and empirical studies [e.g. 100, 107, 109, 214, 246]. The physical 3D bar chart builds upon the traditional 2D bar chart as known from visualization [164], and stems from one of the first graphic methods as developed by Playfair [41, 207]. Graphical bar charts are also a standard

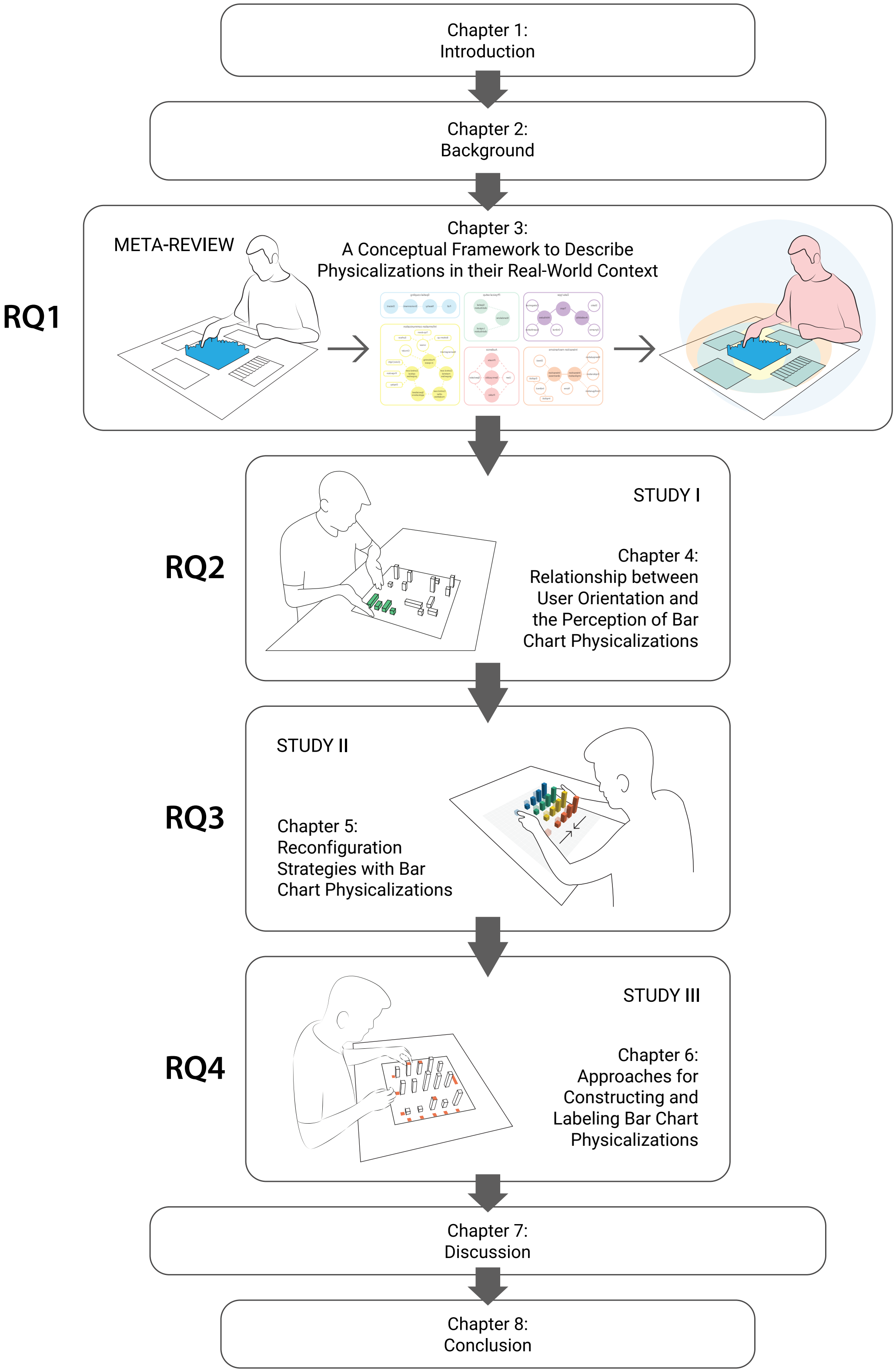


Figure 1.1: Visual overview of the research methods used in this thesis and how they map to the thesis structure.

way of visualizing data in other fields such as finance, statistics, social sciences, and health care. In this thesis, the 3D bar chart was applied as a commonality throughout the empirical contributions to create consistency across the different lab experiments and to be able to generalize the findings of this thesis to prior design and research that involved physical and/or graphical bar charts. Figure 1.1 provides an overview of the specific methods used to answer each sub-research question:

Chapter 3 describes a meta-review of 60 representative physicalization papers to investigate the use of state-of-the-art physicalizations when deployed in the real-world (RQ1). This is done through an interpretative approach [182] of two iterations: (i) inductive labeling and affinity diagramming [145] to develop overarching clusters, and (ii) deductive categorization with the same corpus to validate the initial set of labels and overarching clusters. From our findings, we identified six key dimensions and introduced the term *physecology* as a conceptual framework to describe physicalizations in their surrounding context. The six dimensions are inspired by existing theories and concepts from both within physicalization research as well as related research fields.

Chapter 4 describes a task-based lab study with abstract bar chart apparatuses to investigate the relation between user orientation and the perception of physical information (RQ2). The study tasks are based on low-level analysis tasks known from 2D visualization [6, 239], performed across four different orientations to systematically investigate the influence of user orientation on identifying clusters, filtering anomalies, and finding extremum. It should be noted that while the data collection for Chapter 4 and Chapter 5 occurred simultaneously, the subsequent analysis, interpretation, and reporting of the findings were performed separately for each chapter to maintain the integrity of the individual research questions and objectives outlined in the thesis. The findings are reported using descriptive statistics and synthesized through the introduction of *orientation consistency* (OC); a metric to describe the participants' consistency across orientations and tasks, and thus the influence of user orientation on the perception of physical information.

Chapter 5 describes a task-based lab study using similar abstract bar chart apparatuses as Chapter 4 to investigate reconfiguration strategies with bar chart physicalizations (RQ3). The study tasks involve the reorganization of identified clusters, based on presentation mapping [246]. This was asked across two levels of restriction: a *restricted phase* allowing the change of a single object to emulate interaction of limited form with actuated systems [e.g. 69, 220], and an *unrestricted phase* allowing the change of multiple objects to emulate complete freedom of interaction as for example seen in constructive visualization [e.g. 100, 246]. To reiterate, the data for this study was collected during the same session as the previous study (Chapter 4). Participants' reconfigurations were analyzed using evaluation methods for cluster analysis (Davies-Bouldin index [47]) to extract changes in the *cohesion* and/or *separation* of clusters. Findings are reported using descriptive statistics to discuss predominant reconfiguration strategies across and per physicalization.

Chapter 6 describes a lab study with a custom-made toolkit of building blocks and paper labels to investigate the construction and labeling of bar chart physicalizations (RQ4). In contrast to the method used in Chapter 4 and Chapter 5, involving abstract apparatuses and tasks, this study includes exemplar datasets and concrete creation tasks to investigate participants' sense-making (as part of a design process). Different coding schemes were developed to analyze participants' labeling activities (i) as part of the creation process, (ii) visualization design, and (iii) when the physicalization was viewed from different orientations. Findings are reported using descriptive statistics to discuss the role of labeling in the creation, design, and viewing of physicalizations.

1.5 Contributions

The work presented in this thesis makes the following conceptual, methodological, and empirical contributions to HCI research:

Physecology: a conceptual framework to describe physicalizations in context
Through a meta-review of state-of-the-art physicalization work we contribute a conceptual framework that describes physicalizations in relation to their surrounding audience and context: the *physecology* (RQ1, Chapter 3). This framework discusses all design elements – physical and digital – that constitute a physicalization and unites it through six design dimensions: (i) data type represented, (ii) method of information communication, (iii) interaction mechanisms, (iv) spatial coupling of input/output, (v) physical setup, and (vi) type of audience.

A novel method to investigate the perception, reconfiguration, and labeling of physicalizations
We contribute a novel method to investigate (i) the relation between user orientation and the perception of bar chart physicalizations (RQ2, Chapter 4); (ii) the relation between reconfiguration strategies and the physical structure of bar chart physicalizations (RQ3, Chapter 5); and (iii) the role of labeling in the construction process, visualization design, and across orientations of bar chart physicalizations (RQ4, Chapter 6). Accordingly, we designed and introduced novel apparatuses, procedures, and terminology, which are further detailed below:

- **Tailored apparatus, procedure, and method of analysis to study physicalization components in isolation (perception in Chapter 4 and reconfiguration in Chapter 5), informed by related research fields.** To investigate the perception (Chapter 4) and reconfiguration (Chapter 5) of physicalizations we designed abstract bar charts applying concepts from 2D visualization and psychophysics, such as pre-attentive properties [238] and the classification of physical space by Kirsh [121]. To analyze participants' consistency across orientations (Chapter 4) we introduced *orientation consistency* as new terminology for a measure of *the consistency of user responses to low-level analysis tasks across different orientations.* To analyze participants' reconfiguration strategies (Chapter 5) we used evaluation methods for cluster analysis (Davies-Bouldin index [47]) to extrapolate cohesion and separation changes in clusters, and introduced terminology to describe the observed reconfiguration characteristics.

- **Tailored apparatus, procedure, and method of analysis to study the labeling of physicalizations as part of a larger sense-making process, informed by related research fields.** To investigate the act of labeling physicalizations (Chapter 6) we designed a custom toolkit with physical tokens informed by constructive visualization methodology [99], but with the inclusion of textual labels. We created different coding schemes to analyze participants' labeling activities as part of the creation process, visualization design, and when viewing bar chart physicalizations from different orientations.
- **A novel setup across experiments (RQ2–4, Chapter 4–6) introducing viewing from multiple orientations.** Throughout the three lab experiments we applied viewing from four different orientations as a consistent measure: for RQ2 to investigate consistency in low-level analysis tasks across four orientations; for RQ3 to counterbalance the influence of perspective when investigating reconfiguration strategies; and for RQ4 to investigate the possible change in label placement across orientations after the creation task.

Presentation of empirical findings on the perception, reconfiguration, and labeling of bar chart physicalizations

We contribute empirical evidence and extrapolate new knowledge on the perception, reconfiguration, and labeling of bar chart physicalizations (RQ2–4, Chapter 4–6).

- **The perception of bar chart physicalizations is directly influenced by user orientation.** We found that the perception of physical information is directly influenced by user orientation and can be explained through three types of occlusion: proximity, continuity, and atomic orientation occlusion.
- **Proximity and atomic orientation changes are two main strategies to reconfigure bar chart physicalizations.** We found that the two main reconfiguration strategies to reorganize bar chart physicalizations are proximity and atomic orientation changes to improve the cohesion and/or separation of

clusters. Additionally, we provide a further dissection of strategies in relation to different physical structures.

- **Labeling plays a role in the creation, visualization design, and when bar chart physicalizations are viewed from different orientations.** We found that the construction and labeling of physicalizations is a highly intertwined process, data labels are integrated with physical constructs in the final visualization design, and these are both influenced by orientation changes.

1.6 Thesis Structure

For an overview of the thesis structure see Table 1.1:

Chapter 2 presents an overview of the background of physicalization research. It discusses the variety of definitions for physicalization, existing empirical and conceptual work in the field, insights from related fields, and identifies four significant research challenges for physicalization as a research area that lead up to the sub-research questions of this thesis.

Chapter 3 tackles RQ1 and presents a conceptual framework to describe state-of-the-art physicalizations in their real-world context: the *physecology*. It introduces six design dimensions that aim to describe all physical and digital elements of a physicalization in relation to its audience and surrounding context. The work presented in this chapter was originally published in the ACM Transactions on Computer-Human Interaction journal [193].

Chapter 4 presents the investigation of RQ2 to understand the relation between user orientation and the perception of abstract physicalizations. It discusses the findings on three low-level analysis tasks across four different orientations and introduces the concept of Orientation Consistency. Finally, it discusses the influence of three types of occlusion on the perception of physical information. The work presented in this chapter was originally published in the 2020 CHI Conference on Human Factors in Computing Systems [191].

Chapter 5 presents the investigation of RQ3 to understand people's reconfiguration strategies for physicalizations. It discusses the findings on two clustering tasks with different levels of restriction and characterizes the different reconfiguration strategies observed. The work presented in this chapter was originally published in the 2021 ACM CHI Conference on Human Factors in Computing Systems [194].

Chapter 6 presents the investigation of RQ4 to understand the role of data labeling in the physicalization creation process, final visualization design, and when viewed from different orientations. It discusses the design of a custom-made toolkit and the findings on the construction and contextualization process, the visualization design, and the influence of orientation. The work presented in this chapter was originally published in the 2022 ACM CHI Conference on Human Factors in Computing Systems [192].

Chapter 7 revisits the research questions and discusses the overall findings. It delves into the main contributions of the thesis, supplemented with other insights gained, and implications for future work. Finally, it proposes the concept of *context-sensitive physicalization design* and describes strategies to either alleviate or leverage the impact of user orientation for more effective and reliable future physicalization design.

Chapter 8 provides a conclusion of the thesis work.

Thesis Chapters	**Research Questions**
Chapter 1: Introduction	**Main RQ**: How do physicality and physical context influence people's interaction with physicalizations?
Chapter 2: Background	
Chapter 3: Meta-review A Conceptual Framework to Describe Physicalizations in their Real-World Context	**RQ1**: How can physicalizations be understood in relation to their audience and real-world context?
Chapter 4: Study I Relationship between User Orientation and the Perception of Bar Chart Physicalizations	**RQ2**: What is the relation between user orientation and the perception of physicalizations?
Chapter 5: Study II Reconfiguration Strategies with Bar Chart Physicalizations	**RQ3**: What are people's reconfiguration strategies in relation to the physical structure of physicalizations?
Chapter 6: Study III Approaches for Constructing and Labeling Bar Chart Physicalizations	**RQ4**: How do people construct and label physicalizations as part of a constructive visualization process?
Chapter 7: Discussion	
Chapter 8: Conclusion	

Table 1.1: Overview of the thesis structure and related research questions.

Chapter 2

Background

To clarify how the thesis work builds on prior ideas and concepts around physicalization, we briefly present the background of data physicalization and the different definitions used to describe them, reflect on insights from related research fields, discuss previously conducted studies and developed conceptual models in physicalization research, and finally, summarize the identified research challenges in the field.

2.1 Data Physicalization

Physicalizations come in many different shapes and forms [53], and have been around for and evolved over centuries [53]; Around 8000 BC, before written language was developed, the Sumerians already utilized clay tokens to record numerical quantities of goods [195]. Thousands of years later, the Incas used quipus [9], which consisted of intricate collections of knotted chords of various lengths and colors to externalize information. Nowadays, beyond handmade representations of data, physicalizations can represent data through 3D printed data sculptures [119, 216], actuated physical bar charts [221], and other specialized applications. Herein, we discuss the different definitions that exist for physicalizing data and go into further detail on each of them.

2.1.1 Definition(s)

Although people have been creating physical depictions of data for centuries [53], only more recently this has been identified as an emerging research area [108, 251]. In 2008, Zhao and Vande Moere [251] introduced the term *data sculpture* as *"a data-based physical artifact, possessing both artistic and functional qualities, that aims to augment a nearby audience's understanding of data insights and any socially relevant issues that underlie it"*. This term puts emphasis on the artistic and social nature of physical depictions of data. Later in 2015, Jansen et al. [108] defined *data physicalization* or *physicalization* as *"a physical artifact whose geometry or material properties encode data"* [108], which is now commonly used to describe physical depictions of data.

The inherent physicality of physicalizations presents the following benefits. Physical interaction with data can increase user engagement, facilitate understanding and learning, and make data more accessible [108]. The ability to actively touch a physical depiction of data also facilitates effective information retrieval from data physicalizations [107]. Finally, physicalizations allow for social interactions around them to facilitate collaboration and shared sense-making [108]. Prior work on interaction with physicalizations demonstrated different interaction techniques to systems ranging from static [e.g. 107] to fully actuated representations [e.g. 221]. These include the manual re-arrangement of static data columns or data points to organize exemplar data [100, 107], stacking physical tokens to construct individual data points [77], performing gestures in the air to control data filtering of dynamic physical bar charts [220], and pushing/pulling individual bars of a bar chart to change a data point's value in a linear manner [221].

Beyond the definition by Jansen et al. [108], there are many more ways in which physicalizations (and related artifacts) have been described. *Casual information visualization* [179] acknowledged there are motivations beyond information retrieval such as more ambient, social, or artistic depictions of data for it to be used in everyday life. Others have focused on the reconfigurable nature of physicalizations, such as *constructive visualizations* [99] which center on the manual reconfiguration of physical tokens as a visualization authoring tool, or *dynamic composite data physicalizations* [134] which further characterize the manual and/or actuated reconfiguration of a collection of physical objects to depict data. Lastly, *situated* and *embedded data representations* [243] focus on the integration of visual and physical depictions of data in physical spaces. Hence, there are a variety of ways to describe physical representations of data, and these definitions have different vocal points or topics of inquiry. Below, we go into more detail on each of these types.

2.1.2 Data sculpture

A *data sculpture* is *"a data-based physical artifact, possessing both artistic and functional qualities, that aims to augment a nearby audience's understanding of data insights and any socially relevant issues that underlie it"* [251] and was one of the earliest phrases to describe the emerging research area of physicalization. Currently, the term typically refers to physicalizations that show more artistic and creative depictions of data to encourage informal reflections [158]. Hence, the vocal point that distinguishes data sculpture from physicalization is the emphasis on engaging the audience with informal reflection through abstract or metaphoric depictions associated with the dataset, rather than merely focusing on functionality and information retrieval. Example works include data sculptures on the topic of sustainability, such as visualizing the climate impact of dietary choices [186] or everyday activities [209]; and personal health and well-being, such as 3D printed artifacts to depict physical activity [119, 216].

2.1.3 Constructive visualization

Constructive visualization work explores how to author and construct depictions of data through free reconfiguration of non-actuated token-based physical data representations [99]. In other words, the physicalization is constructed by placing building blocks (tokens) on a blank 'canvas'. This supports data authoring through the reconfiguration of physical tokens, for example by stacking and/or changing the spatial relations in a plane. These interactions allow the construction and curation of data from scratch but are constrained by components such as token unit, token grammar, and assembly model [99]. Example works make use of tangible tiles [65, 100, 246], but also more complex token grammars such as Cairn [77] for situated data collection of a maker community, or more freeform tokens from household objects for the creation of personal physicalizations in the home [226].

2.1.4 Composite physicalization

There are many examples of physicalizations where direct interaction with the data forms their core modus operandi [100, 106, 107, 134, 221]. Following the work of Le Goc et al. [134], this subset of physicalizations can be defined as *composite physicalizations* which consist of *"multiple elements whose typology can be reconfigured or can reconfigure itself"* [134]. Composite physicalizations thus allow manual (through user input) or automatic (through machine actuation) updates of the location and orientation of the data objects while keeping the basic building blocks internally consistent. Therefore, they show overlap with constructive visualization (Section 2.1.3) in terms of interaction mechanisms, as well as shape-changing interfaces (Section 2.2.2) in terms of actuation mechanisms and implementation.

Whilst interaction with composite physicalizations involves both physical and computational elements, only the physical elements dictate the complexity of interactions possible. Hence, when designing these systems, the *level of granularity*, *degree of manipulability*, and *level of actuation* [134] of the overall composite physicalization depends on the number of physical elements involved and the extent to which these can be rearranged or can rearrange themselves (i.e. without human intervention). Example works of composite physicalizations are the manually rearrangeable 3D bar charts by Jansen et al. [107] that allow for the reconfiguration of predetermined 'buckets' of data points that cannot reconfigure themselves, tangible tiles by Huron et al. [100] that support free reconfiguration of a non-actuated token-based physicalization, or Zooids [133] which are wheeled micro-robots that can be controlled and manipulated by the user as well as relocate themselves.

2.1.5 Situated and Embedded Data Representations

Several efforts have been made to describe the different ways in which physicalizations but also screen-based visualizations can be *situated* in their physical environment [159, 241, 243]. In 2016, Willett et al. [243] defined these *situated data representations* as *"data representations whose physical presentation is located close to the data's physical referent(s)"*. In this context, a physical referent is *"the physical object or physical space to which the data refers"* [243]. This work was later complemented by a literature survey by Bressa et al. [25] further discussing different perspectives of situatedness for 44 example works.

Moreover, Willett et al. [243] introduced *embedded data representations* to differentiate between data representations that visualize data in close proximity of the physical referent (which are situated), and representations that spatially coincide the data with the referents. Hence, rather than merely locating the data representation in the relevant location, it is completely integrated with the corresponding physical components of the real world. To give some examples, Activity Wallpaper [203] provides a *situated visualization* of the noise levels of a café over time through wall projections, Infotropism [90] is a *situated physicalization* using living plants next to two different containers to display how much of the trash got thrown away or recycled, and SiteLens [241] is an example of an *embedded visualization* using augmented reality to overlay CO sensor data onto the respective urban areas.

2.2 Related Fields of Data Physicalization

Data physicalization as a research area is most closely related to work on visualization [163, 164], tangible user interfaces [67, 198], shape-changing interfaces [4, 183], and ambient information systems [178]; but has emerged as its own field of inquiry over the past ten years. In this section, we will discuss each of these related fields and their relation to physicalization in more detail.

2.2.1 Visualization

In 1999, Card [31] defined *visualization* as *"the use of computer-supported, interactive, visual representations of data to amplify cognition"* [31]. Nowadays, physicalizations are the physical analogy of visualizations, going beyond the visual channel and encoding data into physical representations [108]. Historically, visualization has been further divided into two parallel streams of work, *scientific visualization* (scivis) and *information visualization* (infovis), which differentiate themselves dependent on whether the spatial representation of the data is *given* or *chosen* [162, 164]. In other words, scivis focuses on visualizing accurate representations of data that already have a physical or spatial form in the real world, whereas infovis focuses on creating real-world representations of abstract or intangible concepts [166]. Example works of scivis physicalizations are ProjecTable [124, 223] and PARM [180, 181], which visualize geographical data through projections on top of a physical terrain model of a landscape; but also computational thermoforming [196] which can be used to precisely map color and texture when creating the physical rendering of a physicalization. Example works of infovis physicalizations are Weather Report [115], which visualizes weather data through animated color-coded projections on a steel structure full of white balloons; VizTouch [26] which explores 3D printing as a quick and automated way to fabricate tactile visualizations; and the 'family toolkit' [131] which allowed parents to log and share data of their newborn to health care professionals.

Beyond the two main streams of work in visualization, other branches have been proposed to describe visualizations with different aims than purely informative. To give an example, Pousman et al. [179] proposed *casual information visualization* (casual infovis), as an overarching term for ambient, artistic, and social infovis and other outliers that are part of, but different from more traditional infovis. They recognized that visualizations might have other goals than increasing knowledge, which are more of a reflective nature. Example works are a set of explorative visualizations of the sound of laughter [248], and an interactive clock that visualizes calendar information to encourage people to reflect on their routines [135].

Visualization as a research area shows common ground with the majority of existing physicalization work, as it is concerned with obtaining an understanding of how to translate raw data to adequate visual representations, which is respectively exploring how to physically encode data for physicalizations. In 1983, Bertin [18] provided the first systematic overview of *visual encodings*, which are visual variables such as position, size, shape, color, and motion that can be used to represent different visualization properties. Subsequently, the field of visualization expanded, and in the realm of more sophisticated visualization techniques, surveys were conducted to showcase the breadth of work in visualization and how it makes unique use of combinations of visual attributes [3, 85, 117]. For example, the 'visualization zoo' survey by Heer et al. [85] demonstrated various techniques for representing diverse data types, such as time-series data, maps, and networks. These techniques leverage visual attributes like position, size, shape, and color to effectively convey information. Later, in 2013, Jansen and Dragicevic [106] introduced the *extended infovis pipeline model* to take into account not only visual variables but also physical variables of physicalizations. They describe this final step as the *rendering* of data from a visual encoding to a final physical form in the real world [106].

However, whereas the field of visualization has established guidelines and classifications on how to visually encode data [163, 164, 238] and methods to systematically evaluate their effectiveness [6, 239], this is less so for the field of physicalization. Although concepts from visualization are not completely transferable to 3D physical space, they are an important starting point to inform and progress on the design, evaluation, and implementation of physicalizations.

2.2.2 Shape-Changing Interfaces

Shape-changing interfaces [4, 183] are computer-supported systems that use change in physical shape or material as input-output modalities and can actuate themselves and/or be actuated by the user [4]. The field of shape-changing interfaces aims at using physical qualities to enhance people's interactions with digital information, showing common ground with physicalizations. Hence, work on shape-changing interfaces can inform the design of dynamic and interactive physicalizations in three ways.

First, existing design work and classifications on actuation mechanisms for shape-changing interfaces can be utilized to visualize changes in data and allow for real-time data representations. Shape-changing interfaces come in many different forms, ranging from actuated bar charts in a fixed grid [69, 136, 221], to freely re-arrangeable wheeled micro-robots [133], to dynamic structures of expandable rings [45] or elements suspended on actuated strings [61]. Taher et al. [222] provided a classification of different actuation techniques, distinguishing between electromechanical actuators (e.g., motor-driven bar chart systems [136, 69, 221]), fluid-based actuators (e.g., a pneumatic truss-based system [82] or small hydraulic modules [161]), smart materials (e.g., machine-knitted smart textiles [147]), and magnetic actuation [219, 249]. This variety of actuation techniques can provide insights into how to actuate individual data points in a physicalization.

Second, interaction techniques from shape-changing interfaces can facilitate the design of exploration and manipulation mechanisms of physical data points in physicalizations. For shape-changing interfaces, interaction often occurs by pushing and pulling the actuated data points directly [221] or via gestures [136]. However, there are example works on configurable platform systems [61, 167] that especially lend themselves for physicalization; TRANS-DOCK [167] explores the use of mechanical transducers to convert linear motion to a range of more expressive and dynamic motions, and STRAIDE [61] is a modular system that allows for each data point to be replaced with different interactive elements (e.g., touch input) which can be interacted with in a variety of ways (e.g., grab, deform, or drag).

Third, conceptual frameworks on shape-changing interfaces can be informative for the physical encoding of physicalizations. To give an example, the classification by Rasmussen et al. [183] describes different types of shape change (e.g., form, volume, and texture) and ways of transformation (e.g., speed, tempo, and frequency), that can guide how to physically represent changes in data or how to transform data from one snapshot or dataset towards another.

2.2.3 Tangible User Interfaces

Tangible user interfaces (TUIs) are a type of interfaces that *"give physical form to digital information, employing physical artifacts both as representations and controls for computational media"* [230]. Hence, the interface uses physical objects to provide a natural way for users to interact with digital media. This can include a range of input and output modalities, such as touch [111], gestures [137], building blocks or bricks [97, 175], and printed paper markers [252], but also more traditional forms of interactions such as physical dials and sliders [17, 34]. Physicalization and TUI research have similar characteristics, but differ in focus: TUI research focuses on *input* – allowing for interaction with digital information through physical objects – while physicalization research concentrates on the *output* – conveying digital information through physical representations [108].

The goal of TUI research is to make technology more accessible and intuitive to use, creating more engaging and immersive user experiences. However, the definition of a TUI can vary based on the context in which it is used, and researchers and practitioners have continuously developed and refined it over time [198]. Ishii et al.'s [103] work on Tangible Bits was one of the first discussions of TUIs, focusing on the translation of digital information into physical objects. Later concepts broadened these ideas with various conceptual frameworks, such as describing different spatial relations between humans and tangible user interfaces [67] and the social aspects of tangible interaction [93]. These TUI frameworks, similar to research on shape-changing interfaces, can be applied to physicalization design. For instance, Fishkin's taxonomy [67] can inform the different embodied relations users can have with physical interfaces and the levels of metaphor that can be ascribed to the shape and/or motion of interactive elements. In addition, more recent technical evaluations, such as the investigation of the impact of 3D targets' width, height, and distance on user pointing performance [63], can inform how the form factor of physicalizations and direction of movement by the user can affect their interaction with physical data points.

Example works of TUIs for physicalization include Tangible Landscape [157], a physical landscape model involving sand that allows for interactions such as sculpting, marking, and drawing to explore topographical properties; (Dis)Appearables [168], which explores the use of wheeled robots that can appear and disappear with different stage designs to demonstrate a range of applications; and reacTable [111], a tabletop system that allows multiple musicians to control music and sounds through touch, rotation, and relocation of artifacts.

2.2.4 Ambient Information Systems

Since the taxonomy by Pousman and Stasko [178], the most commonly used term for any ambient or peripheral representation of data is *ambient information systems*. However, other common names are ambient displays [105, 151, 185, 233], peripheral displays [153], or glanceable displays [78] which seem to be used almost interchangeably. Ambient information systems are characterized by their often abstract representation of relevant but not crucial data and their ability to shift between the periphery and center of attention [178]. They often consist of aesthetic physical artifacts that blend in with their surroundings and visualize changes in the data through subtle cues, such as movement [105, 187], light [185, 233], projection [224], or a combination of modalities [95].

The area of ambient information systems resonates with physicalization as it can be a means to physically represent data for other uses than purely informative, especially if the aim of the physicalization is to visualize data that is important but not crucial for its user. The benefit of this kind of system is the ability for coincidental encounters of the users with their data, providing new opportunities for reflection and non-obtrusive integration of data in their everyday life. Examples of ambient physicalizations are Breakaway [105], which is a small sculpture that changes shape to visualize the user's posture during office work; The Clouds [185], which consists of two moving clouds suspended from the ceiling in a university building to visualize the number of people taking the stairs or elevator; SensaBubble [197], a mid-air display system that uses projections in conjunction with scented fog-filled bubbles to communicate visual and olfactory information; Physikit [95], which is a set of physical cubes that visualize real-time environmental data through different modalities (sound, vibration, light, and movement) and can be placed anywhere in the home; and LOOP [187, 190], which is a ring sculpture that changes shape according to the activity levels of its user.

2.3 Data Physicalization as a Research Area

Data physicalization is defined as *"a research area that examines how computer-supported, physical representations of data (i.e., physicalizations), can support cognition, communication, learning, problem-solving, and decision-making"* [108]. Herein, we will review previous work on the evaluation and implementation of physicalizations, as well as consider the various conceptual frameworks that have been developed to understand their design and use.

2.3.1 Study and Use of Physicalizations

Prior work in the area of physicalization has frequently adopted either a *device-centric* approach, resulting in a focus on the apparatus and interaction techniques [4, 108], and evaluations based on available technologies; or a *domain-centric* approach, resulting in tailor-made artifacts for specific applications [91, 188, 187, 208], thus allowing for less generalizability. These contributions are mainly concerned with the physicalization itself, isolated from the surrounding physical world it exists within. Looking at empirical research in the area, exemplar studies have explored topics such as the influence of physical shape on perceptions of size [109], the cognitive benefits of touching a physicalization for memory [107], and the comparison of the memorability of physicalizations to that of digital visualizations [214, 215]. Lastly, design [62, 134, 220] and field studies [95, 186, 187] show the myriad of different ways in which system infrastructures are designed and how they are used and appropriated in context. To give some examples, the design explorations of PolySurface [62] and Zooids [134] both aim to demonstrate the variety of their possible domain applications, but use different implementations and interaction mechanisms to do so. PolySurface [62] combines an on-surface projection and a grid of individually actuated pins that can be controlled through interactive buttons, whereas Zooids [134] makes use of a collection of wheeled micro-robots that can be controlled through both direct (touch) and indirect (tablet) interaction. Regarding field studies, different appropriations and deployment methods exist, for example Physikit [95] was under shared responsibility and control of a household to visualize environmental data in their home through an interactive tablet interface, whereas LOOP [187] independently visualized personal data from an individual (without user intervention) for it to be observed by the household.

2.3.2 Surveys and Conceptual Models

Together with introducing the working definition for physicalization in 2015, Jansen et al. [108] also laid out a research agenda for the field of physicalization. Herein, they acknowledged the challenges of translating established concepts from visualization into the field of physicalization. For example, they discuss the research challenge of identifying *physical variables* (additional to *visual variables* [18]) as physicality can go beyond solely visual concepts, and we need to identify these to understand the design space of physicalization. In 2020, Dragicevic et al. [54] provided a further overview of the research area of data physicalization, categorized by different motivations to create and use them.

Moreover, different conceptual models have been introduced to expand our understanding of physicalizations and provide new ways of describing them. Examples are conceptual models such as the *extended infovis pipeline model* [106] – which describes the complete process from raw data to a visualization rendered in the physical world – and the *physical rendering process* [50] – which unpacks the 'rendering' process of the prior model in further detail. Finally, the recent book *Making with Data* [101] explores the diverse ways in which artists, designers, and researchers created physicalizations through the use of handcraft and everyday objects, community participation, digital fabrication, actuated systems, or environmental forces.

These prior surveys and models shaped the scope and agenda of data physicalization as a research area, and provide important insights on how to bring physicalizations into existence within the physical world. However, this could be expanded with further reflections on how physicalizations coexist with their surroundings beyond the realization of the physical representation.

2.4 Research Challenges for Physicalization

Physicalizations have the potential to provide tangible, manipulable representations of data that can support a range of tasks including sense-making, decision-making, and collaboration. However, in order to fully realize the potential of physicalizations and achieve widespread adoption for various purposes, there are several fundamental challenges that must be addressed. Hence, the overarching research question addressed in this thesis is:

Main RQ: How do physicality and physical context influence people's interaction with physicalizations?

This section further outlines research challenges observed from literature, discusses prior research efforts to address them, and how they formed the sub-research questions.

2.4.1 Physicalizations in Context

Physicalization is a relatively new area of research in HCI, yet over the past fifteen years, a wide variety of physicalization systems have been introduced [53, 54]. Conceptually, there have been various discussions in the field about how to define physicalization. In 2015, Jansen et al. [108] proposed a working definition of physicalization as *"a physical artifact whose geometry or material properties encode data"*. While this definition accurately captures the fundamental concept of physical data representation, it ignores any acknowledgment of how physicalizations manifest in the complexity of the real world. This is also reflected in state-of-the-art physicalization research often concentrating on the design of the apparatus, device, or mechanisms that enable the physical representation of data [4, 108]. Furthermore, design explorations [62, 134, 220] and field studies [95, 186, 187] outline the challenges of using physicalizations as mediators for complex tasks, and the importance of making them intuitive and context-sensitive interfaces for interaction with data.

Recent efforts have been made to start to comprehend the wider context of physicalizations through literature reviews [e.g. 55] and conceptual frameworks [e.g. 13]. Dumičić et al. [55] analyzed 163 publications on physicalization artifacts and demonstrated the diverse range of data themes and topics they encompass (e.g., personal data, medical sciences, and geoscience), the variety of design purposes (e.g., tool for tracking and communicating personal data, research/education tool, artwork, public display), and provide a list of researched impacts (e.g., assist with understanding data, user engagement, hedonic experience, impact on behavior/motivation). Bae et al. [13] analyzed 47 publications and discussed the variety of audiences, locations, and data sources that occur for existing physicalization work. They found that approximately a third of their corpus provided little to no information about the target location, and almost a fifth did not explicitly specify their audience. This suggests that state-of-the-art physicalization research does not actively consider contextual factors and that more work is needed to be able to describe physicalizations as part of a wider real-world context.

2.4.1.1 Insights from Related Research Areas

As aforementioned, research on physicalization shows close relation with the research areas of visualization [163, 164], tangible user interfaces [67, 198], ambient information systems [178], and shape-changing interfaces [4, 183]. In contrast to physicalization research, research outside the field has focused more on the role of context, showing it is as important as the artifact or device itself [1, 22, 52]. For example, Fishkin's framework [67] on tangible user interfaces (TUIs) illustrates how users can have different forms of embodied relations to the physical interface. Likewise, work on *proxemic interaction* [15] shows the intricate relations that exist between people, digital devices, and the surrounding environment. Knowledge in these areas is transferable to physicalizations, such as insights on the directness of interaction [183]; the coupling between user and system [67]; the intricate relations between people, devices, and their surroundings [15]; as well as the situatedness of visualizations in their physical context [25, 243].

2.4.1.2 Research Question 1

To summarize, the working definition for physicalization could benefit from expansion as prior work shows a variety of ways to describe, operationalize, and deploy example systems, beyond the scope of the current working definition. Moreover, contributions in the research area tend to be device- and/or domain-centric and would benefit from considering a further context. Conceptual models have been proposed inside and outside the field that already expand on these two approaches, but so far no attempt has been done to synthesize these concepts specifically tailored for the field of physicalization. Hence, we propose to consider physicalization together with its surrounding context of use and discuss them together to expand our vocabulary for and understanding of physicalizations in the real world. Therefore, the first sub-research question we seek to answer in this thesis is:

RQ1: How can physicalizations be understood in relation to their audience and real-world context?

2.4.2 The Challenges of User Orientation and Perception

Although a large body of work exists within the field of physicalization, the influence of user orientation on physical properties has so far not been actively studied. User orientation is a general problem across fields, for example in holographic displays [88] and tabletop systems [83, 165]. However, these systems are based on visualizations with an inherent 2D character, whereas physicalizations make use of tangible 3D objects, which extend the area from a plane in space [54]. Most related work does not actively consider that physicalizations could be perceived differently from different angles and/or perspectives. This is exemplified in physicalizations that come with a complementary digital interface placed on one side of the system [62], prompting people to interact with it from a single side. Another empirical example is that many of the users' creations on ShapeCanvas [64] were dependent on the reading direction and user orientation, such as names, facial expressions, symbols, and a game simulation using 'up and down'. In contrast, some prior work does acknowledge the possibility of perspective being of influence on perception but provides no further characterizations. For example, in EMERGE [221] the 3D nature of the system allows people to observe it from different perspectives which can help to confirm relations in the data. Lastly, CairnFORM [45] is a prototypical 360-degree readable, physical ring chart to increase the readability of data from multiple angles in public spaces.

2.4.2.1 Insights from Related Research Areas

Incorporating intuitive deduction based on existing literature and theoretical understanding from related research areas, such as psychophysics [206, 14], physiological physics [228, 129], and human visual perception [8], provides valuable insights into how the influence of perspective on perception can be understood. By examining established concepts and principles in these fields, logical conclusions can be drawn regarding the expected impact of perspective on the perception of physical information.

Looking at prior findings from psychophysics [206] we can make presumptions about the perception of physical objects in general. For instance, the early work by Baird [14] shows the complexities of the perception of size and distance. However, to further deepen our understanding of perception in the context of physicalizations, it is crucial to consider the influence of user perspective. An interesting finding is the radial-tangential illusion [8], illustrating that lengths presented away from and towards the body are perceived to be larger than lengths that are presented from side to side to the viewer. This indicates that the perceived length of an object depends on its orientation relative to the viewer's perspective.

Moreover, exploring the literature on human visual perception allows for intuitive deductions about the impact of perspective on depth cues and spatial relationships inherent in physical shapes. Research at the intersection of psychophysics and human visual perception has considered how people construct spatial relationships [8] and whether these are constructed through object-to-object or self-to-object comparison. Additionally, depth cues such as shading, relative size, and overlapping contours, provide valuable information for perceiving three-dimensional objects. For instance, physiological physics literature describes the concept of *occlusion contour* [228, 129], which explains how objects partially occluding each other can create ambiguous occlusion contours, making it challenging to extract specific information from individual physical shapes. When viewing physicalizations from different angles, it can be inferred that these depth cues will vary, resulting in a perceptual shift in the understanding of the displayed information.

However, it is important to note that much of this prior work has primarily utilized drawings rather than actual physical 3D objects, and in the few studies using actual physical stimuli, participants' heads were usually fixed [14]. Therefore, there is a gap in our understanding regarding the specific influence of perspective on the perception of physical 3D objects.

2.4.2.2 Research Question 2

The consequences of the lack of understanding of the relation between user orientation and perception are profound as people might interpret data differently depending on what side of the physicalization they are viewing. This could impact collaboration and create discrepancies between people leading to incorrect interpretations. When viewed from different perspectives, none of the studies on physicalization take user orientation into active consideration and therefore its relation to perception remains unclear. Additional work is needed to characterize this relationship and provide guidelines on how to build physicalizations utilizing the full potential of physical space in conveying information. By incorporating intuitive deduction alongside empirical studies, we can strengthen our understanding of the underlying mechanisms driving the perception of physicalizations. In summary, while prior research in related areas offers valuable insights into perception, further exploration of the influence of perspective on perception adds a crucial dimension to understanding the intricacies of physicalizations. Therefore, the second sub-research question we seek to answer in this thesis is:

RQ2: What is the relation between user orientation and the perception of physicalizations?

2.4.3 The Challenges of User Reconfiguration

The physical aspect of physicalization allows for touch-based interactions, but this is rarely utilized. Most physicalizations primarily rely on the visual representation of information rather than the ability for people to directly touch and manipulate it. Those that do incorporate physical interaction often require indirect interaction through nearby devices [e.g. 136, 186, 223] rather than direct manipulation of the physicalization itself. The examples that do involve direct interaction [e.g. 69, 134, 221] tend to be limited by the technologies available and are often studied in this context, leading to a lack of understanding of how people would naturally interact with physicalizations.

Generally, there are three main categories of reconfigurable physicalizations. (i) *Static physicalizations* allow the user to manually reconfigure predetermined 'buckets' of data points (i.e. per category or year), with the physicalization unable to reconfigure itself [107, 119, 216]. For example, Jansen et al. [107] investigated how users interpreted rows of physical bar charts that could be manually rearranged. (ii) *Constructive visualizations* [99] (as discussed in Section 2.1.3) allow the free reconfiguration of non-actuated token-based physicalizations [77, 100, 226, 246]; instead of manipulating 'buckets' of data, users manually rearrange individual data points. For instance, Huron et al. [100] investigated the use of physical *tokens* as a data authoring tool for non-experts. (iii) *Shape-changing interfaces* [183] (as described in Section 2.2.2) support interaction with *dynamic* physicalizations which, due to their ability to actuate, can respond to interaction as well as initiate changes themselves [53, 69, 133, 136, 221]. For example, Taher et al. [221] investigated the use of automated physical bar charts to explore and present exemplar data. All three approaches support the organization of data by direct physical manipulation, whether or not it is by comparing predesigned 'buckets' of data, constructing them with data points from scratch, or exploring them dynamically.

The ability to reconfigure physical data points can be beneficial for exploring, manipulating, or configuring the underlying data of a physicalization [106, 108], but further empirical research is needed to fully understand this. Some previous empirical work has focused on specific aspects of reconfiguring physicalizations. Jansen and

Hornbæk [109] demonstrated that the perception of size for physical bars is consistent with 2D visualizations, yet different for physical spheres. Stusak et al. [214] compared the memorability of 2D paper visualizations to that of 3D bar chart physicalizations and found no significant difference, though the physicalizations were perceived as easier to remember. Taher et al. [221] and Everitt et al. [64] observed that participants mainly interacted with the most accessible physical bars along the edges of a system's grid, illustrating how the implementation can influence interaction. Lastly, Jansen et al. [107] found that touching a physicalization can be a cognitive aid for memory.

2.4.3.1 Insights from Related Research Areas

The cognitive benefits attributed to the ability to touch physical information and use the body and physical world to make sense of information are not limited to physicalization, but are also discussed in research areas such as visualization [80], TUIs [120, 198], educational psychology [172], and cognitive sciences [23, 122, 123].

For example, research in cartography and geographic visualization has shown that touch can more effectively convey certain data types, such as ordinal information, compared to others, such as nominal information [80]. From a cognitive science perspective, it is known that external representations can enhance cognitive power in various ways [122] and that epistemic actions–physical interactions with no specific goal–can aid in the sense-making of the information at hand [123]. Additionally, research in educational psychology suggests that the direct manipulation of tangible technologies (or TUIs) promotes understanding and learning [172]. While these works provide evidence of the cognitive benefits of physical touch, it remains unclear how to operationalize this in physicalization design.

2.4.3.2 Research Question 3

In summary, while many existing physicalizations rely mainly on a visual representation of information rather than direct touch interaction, previous research has demonstrated the cognitive benefits of physical touch for understanding information. However, there is a lack of understanding of how to incorporate these benefits into physicalization design, and reconfigurable physicalizations present both opportunities and challenges for interactive systems supporting direct physical manipulation. Therefore, it is important to examine people's reconfiguration strategies in order to inform the design, data presentation, and actuation mechanisms of future reconfigurable physicalizations. Hence, the third sub-research question this thesis seeks to address is:

RQ3: What are people's reconfiguration strategies in relation to the physical structure of physicalizations?

2.4.4 The Challenges of Labeling Physical Information

Looking at the use of data labels in existing physicalization research, we observed that state-of-the-art (summary in [54, 108]) pays little attention to data labeling. Thus, other means are often required to contextualize the data represented, such as prior knowledge, the use of an external device to reveal data, or no means to extract details (i.e. because the intention is purely aesthetic and/or by estimation). Particularly exploratory physicalizations such as *data sculptures* [19, 160, 216, 251] or data installations with complex ecosystems [95, 155, 186, 187] do not provide on-physicalization labeling. Physicalizations that do use labeling in some form, do so in a myriad of different ways. Examples of interactive systems are work from Veldhuis et al. [232] that presented textual information in a single direction, or Taher et al. [221] that used multiple displays to provide two duplicates for the x-axis and y-axis (and only shows categorical/sequential data but no values or legend for values). Examples of static physicalizations are work from Jansen et al. [107] that compared on-screen 3D bar charts with labels floating in space in the reading direction of the viewer, with physical 3D bar charts that represent the same labels sideways in a counterclockwise direction (with the addition of an engraved transparent acrylic back wall to show scale); and Danyluk et al. [46] that used similar physical 3D models but then with alternating reading directions on different sides of the base. Gourlet and Dassé [77] built a physicalization where the reading direction was aligned in 4 different directions, oriented by each side of the table. Stusak et al.'s [215] work on physicalizations used numeric values on the physical bar charts, labels for countries on the flat surface, and a transparent background panel with scales. Finally, recently Ren and Hornecker [184] explored physicalizations that were annotated with a basic legend on one side of the visualization.

While these labeling approaches are generally well-designed, their variety opens up questions around what strategies or approaches can be used for the labeling of physicalizations. Furthermore, because of the intrinsic three-dimensionality and physical nature of physicalizations, they can be used, observed, perceived, and approached from different directions, making the process of labeling even more challenging. From a conceptual and theoretical perspective, we also observed that labeling is never explicitly included in the definition and scope of physicalization [108], the rendering process [50], or a recent reflection on the research domain of physicalization [54]. Hence, there are currently no principles or standard ways to label in physical space when it comes to reading direction, text orientation, and location in relation to physical data points and the canvas.

Constructive visualization [99] is concerned with describing and exploring the methods, strategies, and tools that help people transform data into physical representations. However, currently these models and approaches for constructive visualization do not include data labeling as an active component in the construction process (visualization mapping), but rather treat annotation of data (presentation mapping) as a secondary process after the construction of the physical form factor. Both Huron et al. [100] and Wun et al. [246] included annotation as a subsequent task to the construction task, while Fan et al. [65] left it up to the participant to use pre-made braille labels in their visualization. They observed that the construction of physicalizations results in an *interrelation principle* [246], as moving physical elements influences multiple parameters of the visualization pipeline at once. For example, placing physical objects in the canvas – *loading data* [246] – also requires considering their position relative to other data objects – *visual mapping* [246] – and their position on the canvas – *presentation mapping* [246]. We suspect that because of this *interrelation principle*, the labeling of physicalizations will similarly be intertwined into the overall process.

2.4.4.1 Insights from Related Research Areas

Visualization [18, 35, 37, 164, 238] has a long-standing tradition, rooted in a history of cartography and later in computer graphics, of labeling and annotating visual representations of data. Many of these labeling practices have now been operationalized into toolkits, default visualizations, and best practices [e.g. 79, 170]. As described by the 'Data Design Standards' [79]: *"Labels make it easier for users to understand data visualizations by using text to reinforce visual concepts. Labels are traditionally used to label axes and legends, however, they can also be used inside of data visualizations to communicate categorical, sequential, or value attributes"*. In recent years, labeling research has mainly focused on novel forms of graphic algorithms and approaches to handle label placement in complex visualizations [2, 38, 57, 139] including a focus on automation [142], 2D graph layout techniques [72], or best practices for 'good' label placement [236]. Nonetheless, as suggested by Brath [24] "*3D InfoVis is here to stay*", meaning work has also looked at labeling interactive 3D visualizations [5] or 3D geo-referencing [48]. With the move to a more interactive 'human-data interaction' approach, new insights around semantic or interactive versions of visualization labels have been introduced [234], opening new possibilities for touch-based or even physicalizations. A recent concept in the field of visualization that operationalizes this increased interactivity is the *extended infovis pipeline model* [106]. This model explains the translation from raw data to a visualization that can be rendered in the physical world. It distinguishes between *data transformation*, *visual mapping*, *presentation mapping*, and *rendering*. Especially visual and presentation mapping are of importance to discuss here, as it explains the difference between creating the initial *abstract physical form* and the fully-specified *visual presentation* [106]. According to the infovis pipeline, elements such as axis labels, grid lines, legends, and captions are *decoration* operations as part of *presentation mapping*. However, the precise way in which these grids, legends, or captions should be designed in physical 3D space is not specified nor defined.

Text orientation and readability of labels is also a concern for work on virtual reality [28, 199] and previous work has combined physicalization or visualization with VR environments. For example, Ren and Hornecker [184] explored the differences between physicalization and VR simulation and use basic text labels next to the bar chart in both approaches. Ulusoy et al. [231] explored VR models of bar chart physicalizations that were annotated with labels and presented on different scales (i.e. hand-size versus room-size) in virtual space. Finally, Danyluk et al. [46] compared physical and VR visualizations, again leveraging data annotations and labels around 3D bar charts.

Lastly, outside the context of physicalization, work has explored how to position and orientate text, illustrating that there are different ways in which text can be represented in 2D and 3D space. These studies discuss for instance text orientation [81], horizontal versus vertical reading [177], left-to-right versus top-to-down reading [74], and the influence of 3D rotations on reading speed [242]. These findings from HCI studies agree with literature from the vision community that also demonstrates the impact orientation has on reading speed [250].

2.4.4.2 Research Question 4

To conclude, the research area of visualization has a long history of labeling and annotating visual representations of data. However, there is a lack of research on how to translate this to labeling physicalizations in physical 3D space. Existing physicalizations include data labels in a variety of ways, or do not include labeling at all, indicating a need for further research on the role of data labels in contextualizing physicalizations. Hence, the fourth sub-research question addressed in this thesis is:

RQ4: How do people construct and label physicalizations as part of a constructive visualization process?

2.5 Conclusion

To conclude, the literature shows that there are many different ways in which physicalizations are described, such as data sculptures, constructive visualizations, and composite physicalizations. Additionally, prior design and field studies show the variety of ways physicalizations can be implemented and interacted with in context. Furthermore, previous empirical work illustrates the challenges of implementing physicalizations in physical 3D space, as their physicality and tangibility make them inherently susceptible to their surroundings. These observations come together in the following general challenges for the field of physicalization regarding the implications of physicality and contextual factors: how physicalizations manifest in the complexity of the real world, how people's perception of physicalizations is influenced by perspective, what people's reconfiguration strategies are regardless of technological advances, and how to contextualize physicalizations in 3D space. Therefore, there is a need to expand the focus of physicalization research from device- and/or domain-centric towards (i) treating them as part of a larger ecology, and describe and study them in relation to their surrounding context and audience; and (ii) analyzing them on a more fundamental level to understand the ramifications of physicality on people's interactions with physicalizations.

Chapter 3

Physecology: A Conceptual Framework to Describe Physicalizations in their Real-World Context[1]

This thesis aims to investigate the implications of physical context and physicality on people's perception of and interaction with physicalizations. As a first step, we aim to develop a comprehensive understanding of how state-of-the-art physicalizations are used in a real-world context (as described in the first research challenge in Section 2.4.1). While the working definition [108] provides the fundamental groundwork for conceptualizing physicalization, in practice many physicalization systems go beyond the scope of this definition as they consist of distributed physical and digital elements that involve complex interaction mechanisms. Hence, the definition crystallizes the immediate properties of physicalizations, but the wider context is less well described. Therefore, this chapter seeks to answer RQ1: *how can physicalizations be understood in relation to their audience and real-world context?*

To do so, we base our inquiry around building and exploring the definition and construction of the 'ecologies' that make up data physicalization research. Based on our reflections on physicalization and a selection of related literature, we introduce *physecology* (a neologism of 'physicalization' [108] and 'ecology' [73] – see Section 3.3) as a unit of analysis that considers this important wider context surrounding physicalizations, and unites it through six design dimensions: (i) data type represented; (ii) method of information communication; (iii) interaction mechanisms; (iv) spatial coupling of input/output; (v) physical setup; and, (vi) type of audience. We

---

[1] This chapter is adapted from the journal article published as: **Kim Sauvé**, Miriam Sturdee, and Steven Houben. 2022. Physecology: A Conceptual Framework to Describe Data Physicalizations in their Real-World Context. In *ACM Transactions on Computer-Human Interaction (TOCHI)*. 29, 3, Article 27 (June 2022), 33 pages. https://doi.org/10.1145/3505590

build directly on the broadly accepted definition of 'physicalization' [108] and extend it with these intertwined dimensions to provide a further conceptual understanding of how physicalizations are used in real-world scenarios. To evidence our thinking, we describe a selection of existing research on physicalizations through these six lenses, illustrating how their properties go beyond the scope of the current working definition of physicalization. Based on the review of these dimensions of the conceptual framework, we discuss existing archetypes and opportunities for further research and design implications.

This chapter aims to expand the working definition of data physicalization, considering the complete 'ecology' [73, 113] that makes a physicalization, and introduce the term *physecology* to encompass the relationship between all design elements – physical and digital – surrounding a physicalization. Further, we contribute an overview of the design dimensions of a physecology, to provide conceptual clarity on the design space of physicalizations, and outline possible future work in this area.

3.1 Rationale & Case studies

To motivate our work we will first discuss five case studies, using varied examples from related work, to illustrate how the current definition of physicalization is wider than just its physical or material properties, and how it does not provide a further explanation or dissection of all the different features of these systems. For each of the examples we reflect upon (i) what information is represented, (ii) how this information is represented, (iii) how the information can be changed and/or interacted with, (iv) what the input/output mapping is, (v) what the physicalization setup consists of, and lastly (vi) who is engaging with the physicalization in what way.

We have chosen these five case studies to give a sense of the breadth of the existing work in data physicalization, and how research in this field differs by approach and deployment. The justification for the selection of these five particular works is to create a complementary set of representative examples that illustrate the variety in features of existing systems beyond the scope of the working definition. Table 3.1 shows the direct comparison of the case studies based on the factors above (i-vi).

3.1.1 Case Study 1: Physikit

Physikit [95] is a system consisting of a digital screen-based touch interface to control physical cubes (PhysiCubes) containing different physical properties (such as light, vibration, and movement), for members of a household to visualize real-time environmental data (for example air quality, temperature and humidity) in their home environment. Hence, the physicalization of Physikit is not solely a physical data embodiment, but includes an input interface to control the output visualization

	Physikit [88]	Econundrum [176]	PARM [170]	Mill Road [119]	EMERGE [210]
What information is represented?	Real-time online environmental data	Real-time online personal data on climate impact of dietary choices	Terrain data of national park from static file	Community voting data from static file	UK rainfall data and survey data from static file
How is this information represented?	Movement, light, sound, and vibration	Height change (from ceiling) and colored LED lights	Set of projections	Chalk spray stencils	Height change and colored LED lights
How can the information be changed and/or interacted with?	Reconfiguration of the cubes via touch interface	Submission of input data via mobile application	No interaction	Submission of input data via button system	Exploration of data via the physical bars and surrounding displays
What is the I/O mapping?	Interaction via medium surrounding the physicalization	Interaction via medium surrounding the physicalization	No mapping	Interaction via medium at a distance from the physicalization	Interaction with physicalization and via surrounding medium
What does the physicalization setup consist of?	Physicalization and tablet	Physicalization and mobile application	Physicalization, projection and display	Physicalization and button voting system	Physicalization and four tablets
Who is engaging with the physicalization and in what way?	Household interaction, visitors to home can spectate	Employees own and interact, visitors to workspace can spectate	Visitors to open day can spectate	Members of the public can interact and spectate	Open-ended user engagement

Table 3.1: An overview of case studies illustrating how their features surpass the physical properties of a physicalization and include a wider interaction context.

(PhysiCubes). The user interaction is meant to reconfigure the settings for the cubes, whereas the input comes from an online database. Moreover, the cubes can be moved around and appropriated in the home environment, so input and output can happen in different locations and at different times. Additionally, beyond the physical form or material properties of the PhysiCubes, their multimodal output (such as vibration, airflow, and light) is the actual method of communicating the data visualization. Lastly, multiple users within the household can interact with the digital touch interface and appropriate the PhysiCubes in their home, which has implications for different user roles and social interactions with the system. In contrast, visitors to the home would be mere spectators of the visualization (Physicubes).

3.1.2 Case study 2: Econundrum

Econundrum [186] is a ceiling-mounted physical display that maps users' dietary choices to carbon emissions, encouraging food habits that might produce lower environmental impact. The installation collects personal data on food consumption via a simplified mapping of 10 food types over four meals and three portion sizes. This real-time data provides categorical and quantitative information, shown via colored LED lights, icons, and height change (distance from the ceiling) indicating the overall level of climate impact for each user. Users input their data via a mobile application, either in close proximity to the physicalization situated in their shared workspace, or remotely. The audience, comprising workspace users contributing to the system, also included visiting spectators from the university building who could view and discuss the data.

3.1.3 Case Study 3: PARM

Projection Augmented Relief Models or PARM [180, 181], represents a technique used to map digital information to a physical display in a semi-public space. In the case of a more recent study [180], the physicalization presented a Digital Surface Model (DSM) of terrain data in the English Lake District national park. Digital imagery is projected from above onto an accurate 3D model of the park, and cycles through a set number of projections, highlighting places of interest, footpaths, and environmental conditions amongst others. Although users can touch the surface, it provides no interactive capabilities. The setup uses a display to extend the spatial model and provide extra information to the spectators, made up of visitors to the Sticklebarn pub (situated in a valley in the heart of the English Lake District).

3.1.4 Case Study 4: Mill Road

Mill Road [127, 128] was an urban visualization project consisting of voting systems placed in local shops and chalk images stenciled onto the roads of the street used to engage the local community. The research collected communal data consisting of perceived differences between the two ends of the same road (such as the feeling of safety, and wellness) which was voted upon by members of the public. The data was input using three buttons with icons, for example, wellness on a three-point scale represented by a sad, neutral, or happy face. The collected data was stenciled onto the pavement outside each voting station every other day using colored chalk spray in an isotype-inspired [171] visualization of 10 human-like figures categorized by three colors, each one representing 10% of the votes. A comparative piece was placed at the railway bridge dividing each end of the road. Members of the public indirectly influenced the visualizations using the voting boxes in the local shops and cafes, and could see the aggregated data the following day on the pavement. Those who had not voted inside the shops were also able to view and comment on the data, and engage in open discussions with the local community.

3.1.5 Case Study 5: EMERGE

EMERGE [220, 221] is a tabletop-sized interactive bar-chart driven by 100 linear actuators in a 10×10 grid, built solely to display physical data in an interactive way. The device falls into the dual remit of data physicalization but also that of shape-changing interfaces. In the published work, EMERGE displays one of two datasets – either 100 years of rainfall in the United Kingdom or measures of 'appropriate' behavior taken from a survey of college students in the 1970s. Although these datasets are used as examples, other CSV files can be uploaded. The height of each bar represents the input value and is comparable with its neighboring bars. Interaction occurs either directly on the physical surface (for example push, pull, and tap) or from tablets positioned on each side of the array (such as scroll and select). The bars can be highlighted or hidden, and hidden parts of the dataset can be navigated to by using the tablets to scroll left or right. The setup is a meter-tall cabinet that houses the mechanisms that drive the bars, with a tablet on each side of the 10×10 grid. Each bar contains an LED array that can change color, and switch on/off, according to its programming – although the color does not communicate data directly. The current publications suggest single-user input, but the tabletop nature of the device, and the availability of tablets, could support up to four users or observers at one time.

3.1.6 Case Study Summary

As illustrated by the above five case studies, and as summarized in Table 3.1, each of the exemplar systems has a unique composition of digital and physical features – beyond mere physicalization – that together allow for the communication of and interaction with data. To give an example, the information presented can range from a real-time online dataset to a static file, and the information can be presented in different ways, such as changes in height, projection, or even chalk spray stencils. Moreover, the change of information can be done for different reasons (for example reconfiguration, data input, or exploration) and through different means (such as indirectly via a touch interface or mobile application, or by directly touching the physicalization), which also shows in the implementation of the system setup (for example the inclusion of tablets or displays). Lastly, physicalizations can exist in different contexts (for example at home, workspace, or pub) and can have different kinds of audiences (such as users and/or spectators).

3.2 Method

In this chapter, we reflect on how physicalizations are used in context. Through a meta-review, we derive key insights, concepts, and design dimensions that characterize and expand the concept of physicalization into a wider *physecology*. The goal is to demonstrate that physicalizations are part of a wider ecology of input, output, and mediating mechanisms that collectively create an effective and interactive system (physecology). We report the results of a meta-review based on an analysis of a representative set of 60 physicalization papers.

3.2.1 Selection and Corpus

Based on the insights from analyzing the case studies discussed above, we compiled a list of selected physicalizations. We used the 'List of Physical Visualizations' from Dragicevic and Jansen [53] as a starting point for our analysis, including examples from the 'Active physical visualizations' tab and excluding any submissions that included disclaimers such as 'not a physicalization'. We also conducted a systematic search in the ACM Digital Library (May 2021) to include research papers for this analysis, focusing on recent publications (from 2004 onward). We chose the ACM Digital Library as it is the primary research repository for physicalization research. Our search terms included '*physicalization*', all combinations of '*physical*' with '*(data) visualization*', '*data representation*', '*constructive visualization*', and '*data sculpture*'. A subsequent search of the IEEEXplore database (using the same keywords) resulted in an additional 3 relevant papers [133, 216, 221]. These search terms slightly broaden the scope of physicalization in an attempt to be inclusive in criteria. As a result, there might be a few examples that present edge cases in relation to the core definition of physicalization.

We excluded contributions on *shape-changing interfaces*, *TUIs*, *ambient information systems*, and other related artifacts that did not focus on *physicalization* specifically. We excluded speculative or conceptual work with no technical realization or implementation of a physicalization system. Additionally, we included 4 relevant examples of *analog physicalizations* [66, 77, 100, 225] to complete the selection, as their manual reconfiguration possibilities afforded the same degrees of input as interactive physicalizations. For a complete sample list see Table 3.2[2].

3.2.2 Analysis

We argue that most of the current exemplar implementations of physicalizations in the real world go beyond the working definition. Therefore, for the analysis we applied an interpretive approach [182], based on (i) the researchers' own experiences and observations, (ii) the case studies as described above, and (iii) reflections on literature of physicalization research and related fields.

The analysis was performed in two iterations. First, we performed an initial labeling of all physicalizations followed by affinity diagramming [145], and constructed overarching clusters using axial coding (these clusters were the foundation for the final set of six dimensions). Afterward, we applied a deductive approach with the defined overarching clusters and labels to cross-reference the final categorization of the physicalizations. We used Excel to visualize trends and patterns to reveal certain archetypes of physicalizations, and populated a digital Miro board with imagery and text of the samples for mapping out the connections between the design dimensions.

The final six dimensions are inspired by existing concepts and theoretical frameworks from within and outside physicalization research. More specifically, the dimension of *Data type* follows Munzner's visualization classification [164] and *Information*

---

[2] Sample list data: https://physecology.github.io/dataphys/

					Static	Dynamic	Categorical	Ordinal	Quantitative	Positioning in space	Control optical properties	Control material properties	Specialized applications	No interaction	Direct interaction	Indirect interaction	Manipulation	Exploration	Configuration	Full	Nearby	Environmental	Distant	Standalone	Spatial Distribution	Logical distribution	Private	Semi-public	Public	Open-ended
#	SAMPLE	VENUE	YEAR	REF	DATA TYPE					INFO COM				INTERACTION						I/O COUPLING				SETUP			AUDIENCE			
1	XenoVision Mark III		2004	[66]	x		x		x	x	x					x			x		x					x				x
2	Garden of Eden		2007	[51]		x			x			x		x											x				x	
3	Wable		2007	[118]		x			x	x						x		x			x					x		x		
4	Centograph		2009	[216]	x				x	x						x		x			x					x		x		
5	DataMorphose		2009	[109]	x		x		x	x	x			x											x					x
6	Poly		2009	[47]		x		x		x				x										x				x		
7	Pulse		2009	[117]		x		x		x				x										x				x		
8	Virtual Gravity		2009	[82]	x				x	x	x					x		x			x					x				x
9	Clouds	UbiComp	2010	[175]		x			x	x						x	x						x	x				x		
10	Dust Serenade		2010	[51]	x				x				x			x		x			x			x						x
11	eCLOUD		2010	[72]		x	x		x		x	x		x											x				x	
12	Relief	TEI	2010	[127]	x		x		x	x	x					x		x			x			x						x
13	Tidy Street	Pervasive	2010	[19]	x		x		x		x		x	x											x				x	
14	Recompose	CHI EA	2011	[20]	x				x	x	x				x	x	x	x		x	x			x						x
16	Emoto		2012	[159]	x		x				x					x		x			x					x			x	
17	Pulse: Tangible Line Graph		2012	[145]		x			x	x						x			x		x			x			x			
18	Chaotic Flow		2012	[137]	x				x				x	x										x				x		
19	Point Cloud		2012	[129]		x			x	x				x										x						x
20	Season in Review		2013	[123]	x			x			x					x		x			x					x				x
21	inFORM	UIST	2013	[65]	x		x		x	x	x				x	x	x	x		x	x			x						x
22	Pneumatic Charts		2013	[51]	x				x				x	x										x				x		
23	Tidal Memory		2013	[194]		x			x				x	x										x					x	
24	SweatAtoms	CHI	2014	[111]	x				x				x			x	x					x				x	x			
25	Activity Sculptures	IEEE	2014	[205]	x				x				x			x	x						x	x			x			
26	Drip-by-Tweet		2014	[199]		x		x					x	x										x				x		
27	#Good vs. #Evil		2014	[54]		x		x		x				x										x						x
28	Tangible tokens	IEEE	2014	[93]	x				x	x					x				x	x				x						x
29	x.pose		2014	[34]		x			x			x				x	x					x		x						x
30	Mood Squeezer	CSCW	2015	[67]		x	x				x					x	x						x			x		x		
31	Passim		2015	[81]	x		x				x			x										x						x
32	Tempescope		2015	[107]		x	x						x			x			x			x				x	x			
33	Visualizing Mill Road	CHI	2015	[119]	x			x					x			x	x						x			x			x	
34	Wage Islands		2015	[95]	x				x	x			x			x		x			x					x			x	
35	Actuated Prism Map of Italy		2016	[143]	x				x	x						x		x			x					x				x
36	Dataponics	DCS	2016	[31]		x			x			x				x	x					x				x	x			
37	FizViz		2016	[190]		x	x		x	x	x					x			x				x			x		x		
38	Physikit	CHI	2016	[88]		x			x	x	x		x			x		x	x			x				x	x			
39	Podium		2016	[97]		x			x	x						x			x		x					x		x		
40	ShapeCanvas	CHI	2016	[60]	x		x		x	x	x					x			x		x					x				x
41	Squeezy Green Balls	CHI PLAY	2016	[103]		x		x			x					x	x				x					x		x		
42	EMERGE	IEEE	2017	[210]	x		x		x	x	x				x	x		x		x	x					x				x
43	Microsoft Research Physical Charts	CSCW	2017	[131]		x			x	x				x											x				x	
44	Torrent	TEI	2017	[166]		x			x				x			x	x					x		x				x		
45	EdiPulse	CHI	2017	[110]	x				x				x			x	x					x				x	x			
46	Cairn	DIS	2017	[73]		x			x	x					x		x			x				x				x		
47	Damião's Dataphys Project		2017	[123]	x		x				x					x		x			x					x				x
48	PolySurface	DIS	2017	[58]	x		x		x	x	x					x		x			x					x				x
49	Yellow Dust		2017	[29]		x			x				x	x										x					x	
50	Personal Physicalization Construction	CHI	2018	[214]		x			x	x					x		x			x				x			x			
51	The Long Run		2018	[105]	x				x	x						x		x			x			x				x		
52	Living Map		2018	[51]	x				x			x		x										x						x
53	ON BRINK		2018	[200]		x			x				x	x											x					x
54	Zooids	IEEE	2019	[124]	x		x		x	x	x				x	x		x	x	x	x					x				x
55	CairnFORM	TEI	2019	[43]		x			x	x	x			x										x					x	
15	PARM	Pers Ubiquit Comput	2019	[170]	x				x		x			x											x			x		
56	CoDa	TEI	2020	[220]	x				x	x	x				x	x		x	x	x	x					x		x		
57	Econundrum	DIS	2020	[176]		x	x		x	x	x					x	x					x				x		x		
58	ProjecTable	PEARC	2020	[212]	x		x		x		x					x		x			x					x		x		
59	LOOP	NordiCHI	2020	[177]		x			x	x						x	x					x				x	x			
60	Tactile Data Representations	ASSETS	2020	[62]	x				x	x					x				x	x				x						x
	TOTAL				32	28	18	7	48	33	25	5	16	19	9	37	16	19	11	9	23	9	5	26	7	27	9	19	10	22

Table 3.2: An overview of the 60 data physicalizations included in the sample list used for the analysis, of which 29 samples are publications (indicated by venue) and 31 non-academic work. Included is an overview of how they are represented in the six key design dimensions: (i) data type, (ii) information communication, (iii) interaction mechanisms, (iv) spatial coupling, (v) physical setup, and (vi) audience. The data type dimension is subdivided into data availability (dark purple), and data attributes (light purple); the interaction mechanisms dimension is subdivided into interaction directness (dark orange), and implication (light orange).

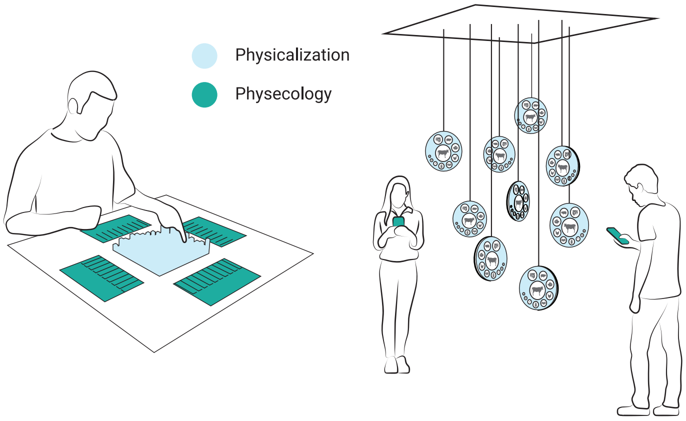


Figure 3.1: Sketches of EMERGE [221] and Econundrum [186] illustrating the concepts of ‘physicalization’ and ‘physecology’.

communication expands on the actuation technologies as proposed by Dragicevic et al. [54]. *Interaction mechanisms* synthesizes *interaction types* – as discussed by Jansen et al. [108] – and *interaction directness* – from literature on shape-changing interfaces [183]. Lastly, *Spatial input & output coupling* and *Physical setup* are derived from a taxonomy on TUIs [67] and cross-device interactions [27], and applied in the scope of physicalization.

3.3 Physecology as Conceptual Framework

To discuss physicalization and its inherent properties, we introduce the term ‘physicalization ecology’, or *physecology*, to describe *the relations between the different design elements – physical and digital – of a physicalization, and their coupling to the audience and (physical) surroundings.* We apply the concept of *ecology* from Gibson [73], and extended by Jung et al. [113], describing the relations among interactive artifacts in people’s surroundings [27, 149]. Hence, *physecology* describes how the design elements of a *physicalization* interact and/or coexist with one another, and interact with people and the surroundings. Subsequently, each *physecology* has an ‘audience’, which is composed of ‘users’ who own and actively engage with the physecology, but as a result of their physicality and spatiality, physecologies are also perceivable to a wider group of people, whom we describe as ‘spectators’. This type of audience plays a more passive role and merely observes the physecology.

To clarify the differences between the concepts of *physicalization* and *physecology*, we compare the case studies of EMERGE [220, 221] and Econundrum [186] as introduced earlier (see Figure 3.1). For EMERGE [220, 221], the grid of physical bar charts in

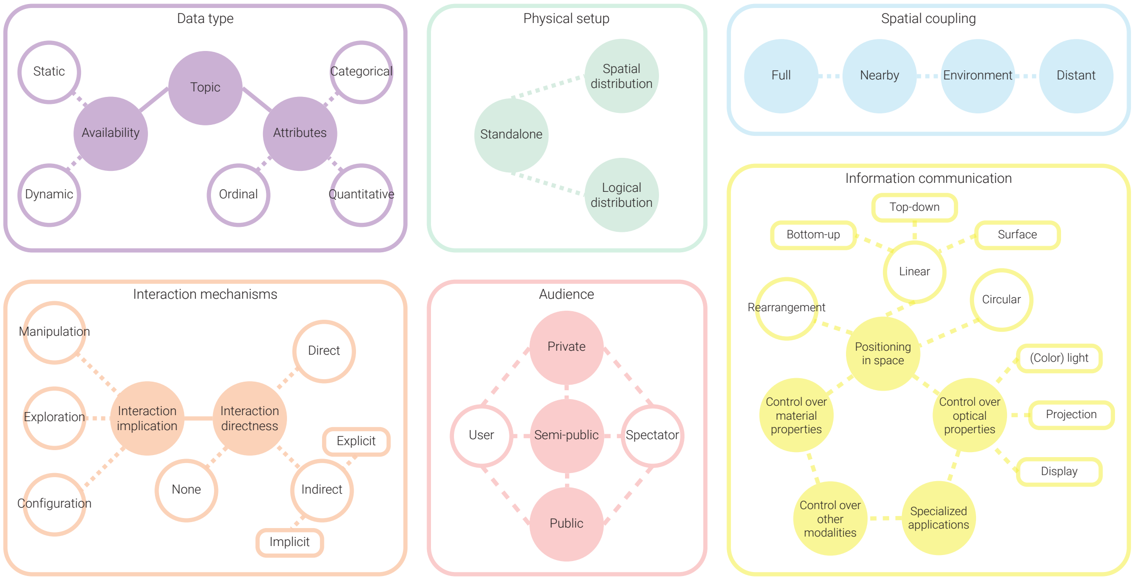


Figure 3.2: An overview of six key dimensions of a physecology with a detailing of the relationships within each dimension. Within each dimension, solid circles represent main categories, and the unfilled circles – subcategories. Circles connected by solid lines are categories that are always present within the dimension, whereas circles connected by dashed lines indicate (sub)categories that are discretionary and/or non-mandatory.

the center of the system represents the *physicalization*, whereas the complete system including the digital touch interfaces and interactions around the system represents the *physecology*. Similarly, for Econundrum [186], the physical installation of disks suspended from the ceiling represents the *physicalization*, whereas the complete system (including the mobile application and interactions that occur around the installation) represents the *physecology*.

In the following sections, we discuss six key design dimensions of a physecology (Figure 3.2) that we extracted from our analysis: (i) data type, (ii) information communication, (iii) interaction mechanisms, (iv) spatial input-output coupling, (v) physical setup, and (vi) audience. In the remainder of this section, the number of samples described is in relation to the total number of 60 samples in our corpus.

3.3.1 Data Type – What information is represented?

The fundamental goal of physicalization is to communicate information by means of a physical representation. Hence, it is important to consider what information is actually communicated and for what purpose. Herein, we first reiterate and describe the datasets represented in the sample list, to facilitate the unpacking of the following design dimensions. *Data type* refers to how the data relates to the *users* of the physecology, which we define as the people that engage and interact with the system, either in a remote or co-located fashion. From our analysis of the sample physicalizations we observed a wide variety of (ii) data availability, (iii) data attributes, and (iii) data topics, which we will discuss below.

3.3.1.1 Data Availability

Following the visualization classification from Munzner [164], we can distinguish datasets based on their temporal nature, or in other words their *data availability* [164]. Therefore, we consider a dataset to either be *static* or *dynamic*, which also resonates with the concepts of *one-shot* versus *repeated propagation* as introduced by the extended infovis pipeline model [106].

- **Static** (f *(frequency)* $= 32$) refers to a dataset that is offline and/or in a static file, hence the data is over a fixed time frame and does not allow for further forward propagation after the initial file is created. From our sample list we observed that the *specialized topics* ($f = 9$), *geospatial* data ($f = 4$), and *configurable platforms* ($f = 10$) are often of a static nature. For a more detailed description of the topics see Section 3.3.1.3.

Some special cases of personal and community data topics involved multiple static datasets, which were added or replaced over different time periods. The static visualization of Mill Road [127] was updated every other day by manually stenciling a static chalk visualization, using the dataset of the previous day. Similarly, Tidy Street [20] was updated on a daily and weekly basis. Both SweatAtoms [119] and Edipulse [118] involved the daily 3D printing of static data objects in the evening at home, based on the dataset of the current day. Lastly, Activity Sculptures [216] involved 3D printed static data objects that were delivered to the participants every one to three days. Still, we consider these examples one-shot propagations (although happening multiple times), as the changes to the data can not be reflected on the same single physical representation, but require a new snapshot of data every time.

- **Dynamic** ($f = 28$) refers to a dataset that is online and occurs from a dynamic stream, that can either be updated through local sensing or outside the scope of the physecology. Here, repeated propagation can take place, as changes to the data can be presented on the same single physical representation. From our sample list, we observed that data topics such as *personal data* ($f = 7$), *city & environmental data* ($f = 6$), *community data* ($f = 5$), and *online activity* ($f = 5$) are often of a dynamic nature. For a more detailed description of the topics see Section 3.3.1.3.

The speed in which this data is updated can be immediate (real-time) such as every 30 seconds [186], or represent particular time frames (intervals) such as every half hour [185] or hourly [187, 205]. In the special case of Mood Squeezer [71], while maybe not a classic example of physicalization, the mood data of a workplace community was dynamic, and collected in real-time – but the floor display visualizing the aggregated mood by color was only activated for a two-hour period during the day.

3.3.1.2 Data Attributes

Again, based on the classification from Munzner [164], we can take a closer look at the *data attributes* that are represented in our sample list, which are defined as *"some specific property that can be measured, observed, or logged"* [164]. Herein, we distinguish between changes in categorical and ordered data attributes, resulting in three attribute types: *categorical* ($f = 5$), *ordinal* ($f = 7$), and *quantitative* ($f = 35$). Lastly, we observed 13 samples with changes in *both categorical and quantitative* data.

- **Categorical.** Categorical or nominal data can distinguish whether two or more things are similar or different. Of all 60 samples, 5 samples included the change of categorical data (and no ordinal or quantitative changes). Examples from the list are Tempescope [114] (weather conditions), and although not a typical physicalization example, Mood Squeezer [71], showing mood by color.

- **Ordinal.** Within ordered data attributes, the first type we discuss is ordinal data. This involves data that shows a well-defined ordering, but does not support direct mathematical comparison. Of the 60 samples, 7 samples included the change of ordinal data (and no categorical or quantitative changes). Example physicalizations are Poly [49] (polls), Drip-by-Tweet [210] (votes), and Season in Review [132] (baseball stats).

- **Quantitative.** The second type of ordered data is quantitative data, which involves a measurement that does support direct mathematical comparison. Of all 60 samples, 35 samples involved the change of quantitative data (and no categorical or ordinal changes). Example physicalizations are manifold, and could be further divided into discrete (countable) and continuous (measurable) data. Examples that visualize discrete data are Virtual Gravity [89] (frequency of search keywords), Wable [126] (online activity), and Chaotic Flow [146] (bike traffic). Examples of visualizing continuous data are Garden of Eden [53] (air pollution levels), Torrent [176] (flutists' muscle tension), and Living Map [53] (rainfall).

3.3.1.3 Data Topic

Analyzing the topic of the visualized data, we observed that the relation of the user to the dataset can be discussed in order of scalability, ranging from personal to more public information. The data topics among the 60 sample physicalizations are:

- **Personal data** ($f = 10$) represents data that is directly related to the user, such as their physical activity measured by activity trackers (for example Dataponics [33], Edipulse [118], SweatAtoms [119], LOOP [187], and Activity Sculptures [216]), their daily online activity (for example x.pose [36], Wable [126], and Pulse [154]), the climate impact of personal dietary choices [186], and a myriad of manually logged topics such as mood, distractions during writing, and places visited [225].

- **Community data** ($f = 7$) refers to accumulated data related to a particular co-located community of users. Example works include tracking the number of co-workers in an office building taking the stairs [185], or tracking their mood through choice of color [71]. Other example works include neighborhoods, such as tracking the collective energy usage of Tidy Street [20], collecting votes on a variety of local topics on Mill Road [127], or varied data measurements on community life (such as number of passing vehicles) on Tenison Road [140]. Lastly, there are examples that investigate whether university staff and students recognize themselves in statements on sustainable behaviors [110], or collect data on the variety of practices people perform in a fabrication lab [77].

- **City & environmental data** ($f = 9$) refers to data that is not directly connected to the user, but relates to their place of residence. Example works visualize live feeds of local weather conditions [114, 138], environmental data (for example temperature) [95], air pollution [30], daily tide levels in San Francisco [205], bicycle traffic in Copenhagen [146], and city data (for example power usage) of Palo Alto (Pneumatic Charts [53]). Other examples involve the comparison of environmental data across the world, such as air pollution levels (Garden of Eden [53]) or weather conditions [76] of different global cities.

- **Online activity** ($f = 7$) refers to accumulated data regarding online behavior, that goes beyond a single user or co-located community of people. Example works include online voting [49, 210]; frequency of emotional expressions on weblogs [125], particular Twitter hashtags [56], or keyword search queries [89]; tweets during one day of the Olympics [169]; and social media rankings of brands [104].

- **Geospatial data** ($f = 4$) refers to data that describes features of the earth's surface, such as elevation and landscape attributes (for example the XenoVision Dynamic Sand Table [70], Relief [136], PARM [180], and Projectable [223]).

- **Specialized topic** ($f = 12$) refers to systems that are dedicated to visualizing statistical information on a specific topic. Example works include: a selection of global statistics [43], summertime rainfall in Europe (Living Map [53]), costs of healthcare for different age groups in the UK [112], regional statistics for Italy [152], affordable rent for low-wage workers in NYC [102], baseball statistics [132], keywords used in news articles [227], Bitcoin blockchain data [211], and renewable energy forecasts [45]. Additionally, we observed some specialized topics with a more artistic expression such as visualizing sound waves (Dust Serenade [53]), different world-views using geopolitical data [87], and visualizing flutists' muscle tension during choir concerts [176].

- **Configurable platform** ($f = 11$). Lastly, we observed a group of systems that were not dedicated to one particular dataset, but were presented as a configurable platform system. The current systems were using exemplar data for the purpose of research and development, and were designed to support a variety of possible datasets. Example works include actuated research prototypes such as Recompose [21], PolySurface [62], ShapeCanvas [64], inFORM [69], Datamorphose [116], Zooids [133], FizViz [201], EMERGE [221], and CoDa [232]; and analog prototypes such as Tactile Data Representations [66], and Tangible Tokens [100].

3.3.1.4 Data Type Summary

To conclude, the sample list shows a variety of data topics, varying in scale and relation to the user. Regarding the changing data attributes, more than half of the samples ($f = 35$) involve the change of solely quantitative data, followed by the change of both quantitative and categorical data for 13 samples. Regarding the availability of data, we observed that the majority of dynamic data streams involved topics more related to the user, whereas static data files involved more public and environmental topics. Relating this back to the physecology concept, reflecting on the data availability helps us understand to what extent the data is more or less directly related to the physicalization. Static data is inherently integrated into the physicalization, whereas dynamic data can be more flexible, for example the coupling can be closer or further away, either within or outside the physecology. In the case of personal or community data, it is likely that the creation of the data stream occurs within the physecology as it concerns data closely related to the user in the immediate environment of the physicalization. In contrast, in the case of more public, environmental, or online data, these data streams are less bound to a location or specific user group, hence likely occurring outside the physical scope of the physecology. Figure 3.2 shows the relations between the three data type concepts. In the next section, we discuss how the data is reflected in physicalization changes.

3.3.2 Information Communication – How is the information represented?

Information communication refers to the method that is used in the physicalization to represent *changes* in *states* of the data. While the working definition for physicalization suggests that the information is purely communicated through (change in) physical or material form, *this is rare in practice*. To give an example, in the case of Econundrum [186], movement along a linear path *and* changes in colored LED light are used to 'update' the data. The method of information communication in this case is a combination of positioning in space – which resonates with change in physical form – but additionally the control of optical properties is used (change in visual form). Hence, the working definition can only partly accommodate the changes observed (as also illustrated by the case studies). Additionally, we observed that more than half of the samples ($f = 33$) use physical movement (change in shape and geometry) to communicate information changes, but only 5 samples applied change in material properties.

We acknowledge there have been different prior ways in which the mapping of raw data to visual or physical forms have been suggested. Bertin [18] provides the first systematic overview of visual encodings: *visual variables* such as position, size, shape, color, and motion that can be used to communicate different characteristics in a visualization. However, physicalizations go beyond purely visual characteristics, which was accommodated in the extended infovis pipeline model [106]. This model proposes *rendering* to describe the final step from visual encoding to an actual physical form and bring it *"into existence in the physical world"* [106]. This rendering process is later further unpacked by Djavaherpour et al. [50], identifying how design and fabrication tools are used to realize exemplar systems. However, interactive physicalizations communicate changes in data states through changes in visual and/or physical characteristics, which goes beyond the rendering phase.

Dragicevic et al. [54] introduced a classification of different actuation technologies that are relevant for *dynamic* data physicalizations: *positioning in space*, *control over shape and geometry*, *control over material properties*, and *specialized applications*. However, the classes of 'positioning in space' and 'control over shape and geometry' are not mutually exclusive. Dependent on the abstraction level, many physicalizations fit both categories, by treating them either as a collection of individual data points (positioning in space) or as a whole (shape and geometry). For example, a pin-based shape display system such as inFORM [69] could be classified as the positioning of individual data points in space as well as control over the shape and geometry of the installation as a whole. As there are diverse ways in which prior work describes the communication of data through a visual or physical form (such as visual variables, rendering, or actuation technologies), we propose *information communication* as an inclusive term, focusing on characterizing how *changes* in data are realized. We take the classification of Dragicevic et al. [54] as starting point, and based on our observations of the sample list, we propose an extended overview of actuations (or manual changes) for the communication of data. We include (i) a further dissection of how positioning in space manifests in the samples, and (ii) provide a vocabulary for the other types of change we observed beyond physical and material form. We distinguish the following methods of information communication by a physicalization (see Table 3.3).

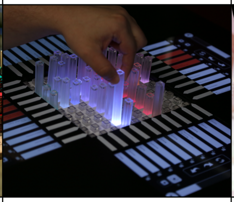
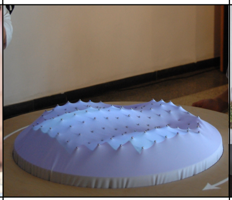
3.3.2.1 Positioning in Space

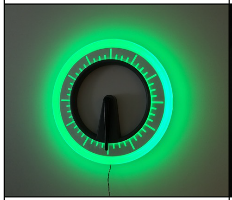
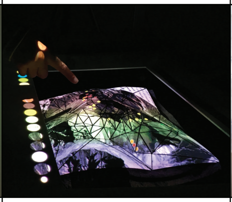
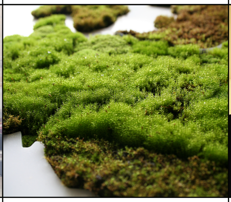
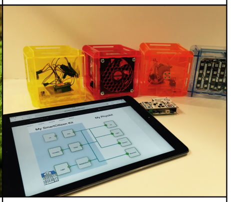
Spatial positioning describes the positional control of independent objects in 2D or 3D space. More than half of our samples ($f = 33$) involved some form of motion to communicate changes in the data, of which 28 involved actuated positioning of objects and 5 involved the manual positioning by the user. For physicalizations that operate in the 2D space, such as a tabletop or other flat surface, we observed mainly the *rearrangement* of objects. This refers to the addition or extraction of objects to create changes in data, either by means of a manual (such as Cairn [77], and Tangible Tokens [100]) or actuated rearrangement (for example Zooids [134]).

For example in 3D space, the most observed type of positioning in space was by means of a *linear motion* ($f = 20$), either from *bottom-up* (for example inFORM [69] and EMERGE [221]), *top-down* (such as Poly [49] and Clouds [185]), or horizontally in 3D space (for example Pulse [154] and CairnFORM [45]). Additionally, we observed a particular archetype that involved the change of multiple data points at once, through a 3D pin layout, creating the appearance of a *surface motion*, which resonates with the notion of 'control over shape and geometry' by Dragicevic et al. [54]. Although these systems are constrained to a grid, they allow for the realization of interactive surfaces with high precision and control. Example surface-based visualizations with connected or merged data points are Relief [136], PolySurface [62], and Point Cloud [138].

As well as linear motion, we also observed *non-linear* and *circular motions*. Examples of physicalizations using a *non-linear motion* are DataMorphose [116] and #Good vs. #Evil [56], respectively using spanned and moving sails, and cars following a race track in their visualizations. Examples of physicalizations that make use of a *circular motion* are FizViz [201], and LOOP [187].

Relating this type of information communication back to the changing data

Positioning in space				
Rearrangement	Linear motion			Circular motion
	Bottom-up motion	Top-down motion	Surface motion	
				
Cairn [73]	EMERGE [210]	Econundrum [176]	Relief [127]	LOOP [177]

Control optical properties		Control material properties		Other modalities
(Color) light	Projection & display	Opacity	Natural growth	Vibration
				
FizViz [190]	PolySurface [58]	eCLOUD [72]	Living Map [51]	Physikit [88]

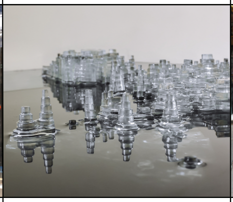
Specialized applications			
3D printing	Air	Liquid	Chalk spray
			
Activity Sculptures [205]	Pneumatic Charts [51]	Wage Islands [95]	Mill Road [119]

Table 3.3: An overview of the different types of information communication, each with an exemplar system.

attributes, we observed that of 33 samples, 31 used positioning in space for quantitative data change, and 2 samples to change ordinal data. These observations resonate with visualization literature that established previously that positioning in space is the most powerful visual variable to communicate information [18, 164].

3.3.2.2 Control over Optical Properties

Less than half of the samples ($f = 25$) encoded data through the change of optical properties. In other words, this involved controlling *visual* properties such as (colored) light ($f = 9$), projection ($f = 9$), and display visualizations ($f = 7$). To clarify, we distinguish projection as a projected image on the surface of an artifact, whereas (colored) light comes from a light source within the artifact. Hence, they differ in terms of technical realization, but also what you can use it for conceptually. Lastly, this application of control over optical properties is not to be mistaken with *fixed optical properties*, such as material color (for example Wable [126] or Cairn [77]), nor with the *change of material properties*, for example the change of texture or opacity (as discussed below).

For the examples that incorporate light changes in their visualization, we observed that 7 samples use color hue to communicate categorical data (such as ShapeCanvas [64] and Econundrum [186]), and 2 samples use color saturation to show quantitative data (for example CairnFORM [45] and Tidy Street [20]). PARM [180] and PolySurface [62] are examples of projection; and CoDa [232] and the Dataphys Project [43] examples of display use. To clarify, the examples incorporating displays ($f = 7$) are still considered physicalizations, as the displace is either (i) accompanied by another form of information communication (for example positioning in space [116]), or (ii) involves another physical element (such as static bar charts that light up [43]).

Relating this application of information communication back to the data attributes changed, we observed that of all 25 samples, for 13 samples the control of optical properties was used to change categorical data, for 10 samples to change quantitative data, and for 2 to change ordinal data. This resonates with prior work in visualization, that describes how color hue and saturation are effective means to respectively visualize categorical and quantitative data [18].

3.3.2.3 Control over Material Properties

For 5 samples we observed that the change of material properties was used to encode data. This method is not to be mistaken with fixed material properties, such as texture (for example PARM [180]), that remain unchanged, but refer to the material properties that are actively used to communicate changes in the data. Example physicalizations that showed control over material properties, through opacity change, were eCLOUD [76], and x.pose [36]. Other examples that could be considered as control over material properties are the samples involving the manipulation of natural growth such as Garden of Eden [53], Living Map [53], and Dataponics [33], that control the carbon dioxide levels and/or soil hydration to visualize topics such as air pollution, rainfall, and activity data.

Relating this method of information communication back to the data attributes changed, we observed that all 5 samples were used to change quantitative data. Additionally, the control over material properties of a physicalization is the method that, together with positioning in space, resonates most with the working definition of physicalization, as it concerns changes to its inherent material properties. However, as our sample list illustrates, currently there is not much related work that truly accomplishes this.

3.3.2.4 Specialized Applications and Control over Other Modalities

The 16 remaining physicalizations do not fit any of the change types as mentioned above, and represent edge cases, as they encode data in varied, specialized and/or novel ways. Examples are the use of fabrication methods, other modalities, or visualizations with an ephemeral character [51]. Physicalizations include 3D printing (for example SweatAtoms [119], Activity Sculptures [216], and Edipulse [118]), the use of vibration (for example Physikit [95]), air flow (for example Dust Serenade [53] and Pneumatic Charts [53]), liquids [146, 210, 176], water vapor [114, 30], or even piles of soil [211].

Contrasting this type of information communication with the data attributes changed, we observed that 12 samples changed quantitative data, 2 ordinal, and 1 categorical data. Specialized applications in particular show how considering the wider physecology can be beneficial in understanding information communication of physicalizations. The use of fabrication techniques illustrates how a physicalization is dependent on physical and/or digital elements that are not inherent to the physicalization, but necessary to create the visualization.

3.3.2.5 Information Communication Summary

So far we discussed the different methods in isolation, however, they are not mutually exclusive, and can co-exist in physecologies. A total of 17 samples include systems using multimodal information communication, combining two or more methods. Example physicalizations are Physikit [95] (circular motion, vibration, and airflow), eCLOUD [76] (opacity and display), and PolySurface [62] (surface motion and projection).

Another observation we made whilst cross-referencing data attributes and information communication, was the general use of positioning in space to change quantitative data ($f = 31$), control of optical properties to change categorical data (f

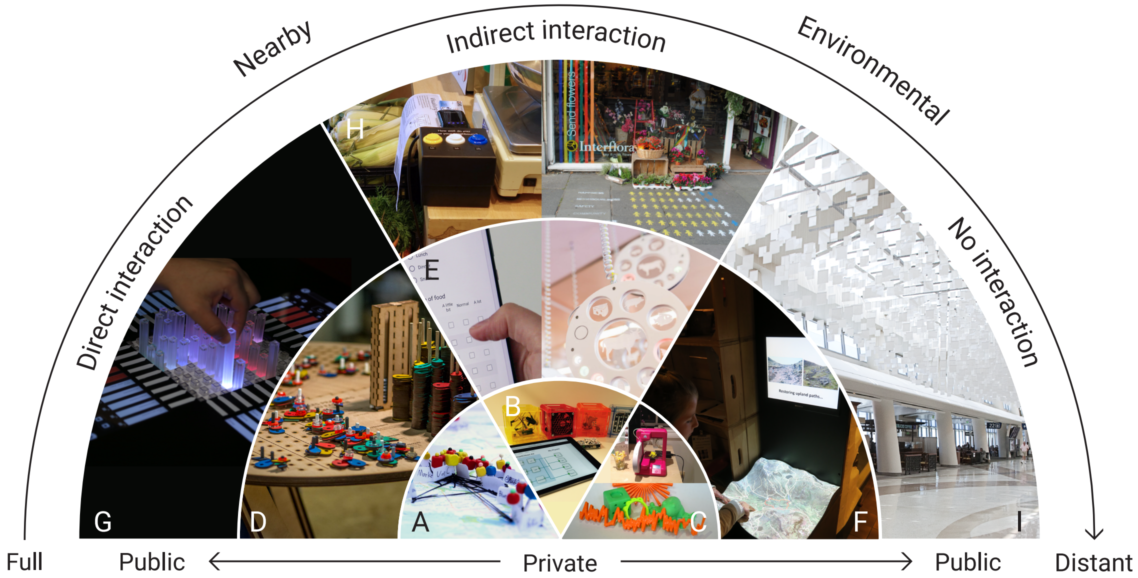


Figure 3.3: An overview of nine exemplar physecologies, illustrating how they position on different design dimensions. The directness of interaction is shown in the three slices from left to right (direct to no interaction), the spatial coupling is shown in the arc from full (left) to distant (right), and the privacy of the audience is represented from middle (private) to ends (public). The physecologies included are: (A) Personal Constructive Physicalization [225], (B) Physikit [95], (C) SweatAtoms [119], (D) Cairn [45], (E) Econundrum [186], (F) PARM [180], (G) EMERGE [221], (H) Mill Road [127], and (I) eCLOUD [76].

$= 13$) or quantitative data ($f = 10$), and ordinal data changes were performed through a variety of ways. More specifically, of all 60 samples, 10 have the specific combination of positioning in space to change quantitative data, while control of optical properties changes categorical data. Lastly, we observed the trend that categorical information, which was not part of the changing data, was regularly represented by inherent material properties, such as color ($f = 14$). These observations confirm prior findings from visualization literature [18, 164]: the effectiveness of using positioning in space to represent (changes in) quantitative data and color or brightness for categorical data. Figure 3.2 provides an overview of the different types of information communication as discussed in this section.

3.3.3 Interaction Mechanisms – How is the information changed and/or can it be interacted with?

Whereas the physicality and tangibility of physicalizations inherently afford interaction [106, 108], the majority of interactions in existing systems part of our corpus do not occur on the physicalization itself. Instead, interaction is mediated by another source that is not inherent or intrinsic to the physicalization (for example a sensor, touch interface, or digital switch), but a necessary component within the physecology that allows for interactivity. This observation was true for more than half of both published (f = 16) and non-academic samples (f = 16). The *interaction mechanisms* as discussed below focus on the interactions that occur between the physecology and the *user*, which includes the people that 'own' and/or engage with the system.

Looking at the actual types of interactions that took place, we observed the following actions for 41 samples of our list: *direct interactions* such as manual rearrangement (f = 4); *indirect* but *explicit* interactions such as gestures (f = 2), the use of controlled objects (f = 4), buttons (f = 6), touch interfaces (f = 4), tangible user interfaces (f = 2), digital interfaces (f = 2), or phone or web applications (f = 4); *indirect* but *implicit* interactions through sensor data (f = 8); and *both* explicit (in)direct interaction (f = 5) by touching the physicalization (direct) together with an indirect method as mentioned before. In this section, we further discuss the *directness* and *implications* of the interactions we observed.

3.3.3.1 Interaction Directness

Considering the *directness* of interaction, we distinguish three different types based on Rasmussen et al.'s [183] classification of interaction with shape-changing interfaces (see Figure 3.3). We observed that over half of the samples (f = 32) involved *indirect interaction*, almost a third involved *no interaction* (f = 19), only 4 samples involved *direct interaction*, and 5 samples a combination of *both direct* and *indirect interaction*.

- **No interaction.** Physicalization changes are solely used as output and disregard user input, or creators do not disclose information on user input (for example open-ended configurable platforms). These physicalizations can still be observed and perceived by their audience, however, there is no direct relation between their actions and the visualization. Examples are public installations such as Yellow Dust [30], and Microsoft Research Physical Charts [140]; and research prototypes such as ON BRINK [211], DataMorphose [116], and Living Map [53].

- **Direct interaction.** Direct interaction occurs when physicalization changes are used as both input and output. Physicalizations that involve direct interaction are systems that, for example, allow for the manual rearrangement [66, 77, 100, 225], or touching of the physicalization elements [69, 134, 221]. This interaction type is likely to occur for physecologies that use rearrangement or bottom-up motion to communicate information (Table 3.3).

- **Indirect interaction.** Physicalization changes are used as output, but are based on remote user input. When looking at indirect interaction, based on [183] we made the division between *implicit* and *explicit* indirect interaction. Implicit indirect interaction refers to situations in which the user may not realize that their actions are used as input for the physicalization. Example physicalizations that involve indirect implicit interaction are systems that use sensor data as input, such as x.pose [36], LOOP [187], and Clouds [185]. Explicit indirect interaction describes situations in which the user consciously performs actions as input for the physicalization. Examples that involve explicit indirect interaction are systems that use gestures [136]; tangible [89, 223], touch [43, 62, 95, 132], or digital interfaces [70, 227]; phone or web applications [114, 154, 186, 201]; slider, dial and/or press buttons [102, 104, 126, 127, 152, 169]; or designed [71, 110] or existing objects [112] for interaction.

Lastly, we observed 5 samples that combined explicit direct and indirect interaction, using direct touching of the physicalization in combination with gestures [21], controlled objects [69], buttons [232], or touch interfaces [134, 221].

3.3.3.2 Interaction Implications

Apart from the directness of the interaction, we also analyzed the *implications* of these interactions, which describes the way in which the action changes the data visualization conceptually, such as changing the scale or adding a data point. For this we used the work from Jansen et al. [108] and Jansen and Dragicevic [106], which discusses types of physical interactions with data physicalizations, and describes the difference between *exploring*, *manipulating*, or *reconfiguring* data (elaborated upon below). We observed the following frequencies in our sample list: exploration ($f = 14$), manipulation ($f = 14$), configuration ($f = 8$), and combinations of two out of three ($f = 5$).

- **Exploration.** We define *exploration* (similar to Jansen's 'exploration' [108]) as the act in which the input is used to assist in the task, such as navigating through or filtering the data. Examples are Wable [126] in which you can explore personal online activity over time through a slider button and Relief [136] in which you can move and scale a 3D landscape through hand gestures.

- **Manipulation.** We define *manipulation* (similar to Jansen's 'manipulation' [108]) as the act in which the output is used to assist in the task, for example to correct, update, or collect data. Example physicalizations are Cairn [77] in which data collection of creative practices in a fabrication lab happens through manually stacking and positioning tokens of different shapes and colors, and Activity Sculptures [216] in which sensor data of the user's physical activity influences the shape of 3D printed objects.

- **Configuration.** Lastly, we define *configuration* (similar to Jansen's 'reconfiguration' [108]) as the act in which the input and/or output is used to reconfigure the task, for example to switch between components of the task or change the selected dataset. Example physicalizations are Physikit [53] in which a tablet is used to connect the PhysiCubes to different data streams, Zooids [134] in which the physicalization objects and/or tablet are used to change the axes of the visualization, and Pulse [154] in which the device is rotated as a whole to switch between three information feeds of the user's choice.

3.3.3.3 Interaction Mechanisms Summary

In summary, the most frequently occurring directness of interaction was indirect interaction for more than half of the samples ($f = 32$), followed by no interaction for almost a third of the samples ($f = 19$). Indirect interaction happens in an explicit or implicit way. However, there are cases in which this might be ambiguous or dynamic. To illustrate this, we take the physecology of Mill Road [127] as an example. The input for the visualization happens through small voting devices inside shops along a street, and the output occurs a day later in front of each of the respective shops through a stenciled visualization. Hence, there might be an explicit indirect interaction in case users are aware of their voting showing in the stenciled visualization. However, it can also occur that users are unaware of their prior input being of influence on the visualization at the current day. Hence, there are cases in which the directness may differ between users and/or change over time.

Cross-referencing the data topic with interaction mechanisms, we observed that city and environmental data are likely to have no interaction ($f = 7$); personal data ($f = 9$) and specialized topics ($f = 8$) are likely to be indirectly interacted with; and community data ($f = 5$) and the configurable platforms ($f = 10$) are likely to allow for both direct and indirect interaction. The most observed implication of interaction was exploration ($f = 19$), followed by manipulation ($f = 16$), and configuration ($f = 11$).

Lastly, the high number of indirect interactions that we observed in our samples – for both published and non-academic work – is indicative of the need for the physecology concept, as users do not interact with the physicalization itself, but with another medium in proximity to the system. Introducing the physecology allows us to fully describe and incorporate the different interaction possibilities in one overview model. Figure 3.2 shows an overview of the interaction mechanism concepts and their relations.

3.3.4 Spatial Input & Output Coupling – What is the spatial mapping between the user and the physecology?

The working definition of physicalization suggests a full coupling between user input and visualization output. As all information is meant to be communicated in the materiality and form of a physicalization, changing it would mean a direct interaction with the physical objects. In contrast, we observed a wide range of spatial couplings between user and visualization, from a coupling within close proximity to a distant coupling (see Figure 3.3). Moreover, this is not just our observation, but was observed and discussed before in the related field of TUIs [67]. Although TUI research is a considerately different and broader field than physicalization, they both are concerned with the directness of user interaction and the relations that can exist between the technology and the user. Hence, frameworks from TUI can be operationalized for physicalization. For this dimension, we apply Fishkin's taxonomy [67] in the scope of physicalization, and categorize the spatial coupling between input and output by the following four layers: *full* ($f = 4$), *nearby* ($f = 18$), *environmental* ($f = 9$), and *distant* ($f = 5$). Additionally, we observed 5 cases of nearby to full coupling, and 19 cases of no coupling (as a result of no interaction).

3.3.4.1 Full Coupling

"The output device is the input device: the state of the device is fully embodied in the device" [67]. In this case, the users can directly interact with the physicalization, manipulating the visualization ad hoc. This form of coupling comes the closest to the current definition of physicalization, as the physicality of the physicalization affords to be touched and interacted with directly, yet this rarely happens. Hence, in comparison to the other couplings possible, full coupling shows the largest overlap between the physicalization and the physecology. Example physecologies that show a full coupling are Cairn [77], Tangible Tokens [100], and Personal Physicalization Constructions [225], as they allow for the manual rearrangement of data points to update the visualization.

3.3.4.2 Nearby Coupling

"The output takes place near the input object, typically, directly proximate to it." [67]. In this case, the user can perform explicit, but indirect interactions with the physecology, through a nearby medium that is not directly part of the physicalization. The focus of the input is strongly coupled with the output and the medium is co-located to the physicalization (for example displays, digital switches) within the physecology. Example physecologies that show a nearby coupling are ShapeCanvas [64], ProjecTable [223], and Podium [104]. Additionally, we observed the specific coupling of *nearby to full* for 5

samples, as these physecologies allow for the direct interaction with the physicalization, as well as with another co-located medium (such as Zooids [134], EMERGE [221], and CoDa [232]).

3.3.4.3 Environmental Coupling

"The output is 'around' the user" [67]. In this case, the user only interacts indirectly with the physicalization, either implicitly or explicitly, through a medium that is in the surrounding of the physicalization, within the physecology. Example physecologies that show an implicit environmental coupling are LOOP [187] and Dataponics [33], in which an activity tracker senses the steps of the user and feeds it into the visualization in their home environment. Examples that show an explicit environmental coupling are Physikit [95] and Econundrum [186], in which users either use a tablet or mobile phone to make changes to the visualization that is co-located in their home or work environment.

3.3.4.4 Distant Coupling

"The output is 'over there', on another screen, or even another room" [67]. In this case, the user interacts indirectly with the physicalization. The visualization output can be distant in both spatial and temporal ways, for example in a different location and/or at a different time than the input happens. Hence, the user might be unaware of their relation to the visualization output (implicit indirect interaction). Example physecologies that show a distant coupling are Clouds [185], for which the interaction happens through sensor mats on the stairs and the visualization is in the center of the building; and Mill Road [127], for which the interaction happens inside shops and the visualization is created a day later outside the respective shops.

3.3.4.5 Spatial Coupling Summary

From our observations we conclude that a full coupling relates strongly with direct interaction; a nearby to full coupling correlates strongly with the combination of direct and indirect interaction; nearby, environmental, or distant coupling with indirect interaction; and no coupling with no interaction.

Cross-referencing the spatial coupling with interaction implications, we observed that a nearby coupling most likely serves the exploration of data ($f = 13$), whereas for an environmental ($f = 7$) and distance coupling ($f = 4$) this is manipulation. Lastly, the high number of physecologies with no coupling ($f = 19$), can be explained by them not allowing for any form of interaction, hence there is no relation between the user and the physecology.

3.3.5 Physical Setup – How does the physecology function as a whole?

Whereas static physicalizations typically have one physical setup, for many existing interactive systems we observed that there are mechanisms outside the physicalization that are crucial to make it interactive. In the previous section, we discussed the conceptual coupling between physicalization components and surrounding users. Herein, we discuss the physical setup and distribution of physecology components. This resonates with a taxonomy on cross-device interactions [27], that describes the different distributions that can exist between digital devices. Although a physecology does not merely consists of digital devices, the taxonomy provides distribution concepts that apply to physecologies.

3.3.5.1 Standalone Physicalization

Physicalizations that function as a standalone device with no dedicated additional physical or digital components, which we observed for 26 samples. In this case, the physicalization is the mere facilitator of interaction (if any), without any external elements within the physecology. Examples are analog physicalizations [66, 77, 225]; non-interactive installations or data sculptures [87, 125, 146]; and configurable platform systems [21, 69]. This group includes physicalizations that extract data from an external source – such as an online cloud or web space – as these distributions are spatially disrupted and not trivial for the single device or artifact to be interactive with the audience. Examples are Point Cloud [138], Tidal Memory [205], and Drip-by-Tweet [210].

3.3.5.2 Physecology with Spatial Distribution

This refers to a physicalization and one or more additional co-located physical or digital components, for the purpose of (i) extending the visualization, or (ii) providing additional information. This relates to the cross-device notion of *spatial distribution* [27], and was observed for 7 of our samples. Example physecologies are PARM [180] which uses a projection on top of a physical terrain model with a display extending the physicalization of a landscape; and Tidy Street [20] which uses EL wire displays [3] to show energy usage per household, extended by a chalk visualization on the street showing the collective usage.

---

[3] EL wire comes in a range of colors and consists of a thin copper wire covered in a plastic material that produces light when alternating current is applied.

3.3.5.3 Physecology with Logical Distribution

This includes a physicalization and one or more additional physical or digital components, either remote or co-located, to serve the following purposes: (i) enabling the exploration of or navigation through the visualization, or (ii) facilitating the reconfiguration or manipulation of the visualization. This relates to the cross-device notion of *logical distribution* [27], and was observed for 27 of our samples. Examples are Virtual Gravity [89] in which a navigation dial and touch interface allow for the *exploration* of frequency of search keywords, visualized by two actuated physical bar charts; Econundrum [186] in which a phone application allows for the *manipulation* of a ceiling installation, visualizing climate impact of dietary choices by height and color; and Podium [104] in which a dial button allows for the *configuration* of social media channels, to see how a brand ranks on each of these, visualized in height.

3.3.5.4 Physical Setup Summary

In general, we observed that standalone physicalizations are likely to visualize a static dataset, since this does not require any additional sensing or interaction capabilities elsewhere to function; or in the case of a dynamic dataset, allow for direct manipulation on the visualization. Likewise, a spatial distribution is likely to visualize a static dataset, merely to further inform the user. In contrast, a logical distribution is likely to visualize a dynamic dataset, merely allowing the exploration, manipulation, or configuration of it.

Cross-referencing the physical setup with spatial coupling and interaction directness, we observed that all 7 physecology samples with a spatial distribution, involved no interaction, and subsequently no spatial coupling. Similarly, of all 27 logical distribution physecologies, 24 solely involved indirect interaction. Lastly, standalone physicalizations were the only group of physecologies that involved direct interaction ($f = 4$), among all other forms.

The concept of physecology is not to be mistaken with the concept of 'composite data physicalization', which describes physicalizations that consist of *"multiple elements whose typology can be reconfigured or can reconfigure itself"* [134]. Whereas this concept is concerned with the internal structure of a physicalization (such as the updating of location or orientation of data points), physecology additionally considers factors externally to the physicalization (for example physical and/or digital elements as part of the factual setup, but also conceptual relations such as interaction mechanisms and audience). To give an example, the system of Zooids [134] is a dynamic composite physicalization. However, the physecology of Zooids further explains the logical distribution between a touch interface (tablet) for explicit indirect interaction with the wheeled robots, complementary to the possibility of directly interacting with them.

3.3.6 Audience – Who interacts in what way with the physecology?

The working definition of physicalization is user agnostic and does not explicitly acknowledge the user or their relation to the system. Hence, it remains unclear what the implications of a physical representation are for the type of *audience* one can expect. In our analysis, we distinguish between two types of audiences. We define the *user* as the people that own, operate, and/or engage with the physecology. However, the physicality and spatiality of physecologies make them perceivable to a wider group of people, which we define as *spectators*.

Inherently, there are different types of audiences involved in the physical depiction of data. For instance, for a physecology in the home context, the household represents the *direct users* and anyone visiting is a *spectator*. Herein, we discuss three context types that correlate to the extent the audience of the physecology is private or public:

3.3.6.1 Private

This was observed for 9 samples, and concerns physecologies meant for the domestic context, for example for individual use [187, 225], or for it to be shared by a household [95]. Private physecologies are likely to visualize personal data, such as Dataponics [33], LOOP [187], and Activity Sculptures [216], and users interact repeatedly with the visualization, for example multiple times a day. The occasional spectators of a private physecology are visiting friends or family.

3.3.6.2 Semi-public

This was observed for 19 samples, and concerns physecologies meant to be used by a particular community, for example an office or company space [71, 104], university building [110, 185, 186], community space [77], or events such as a conference [146, 223], award show [210], or concert [176]. Similar to private physecologies, users interact regularly with the visualization, for example on a daily or weekly basis. Hence, semi-public physecologies are likely to visualize personal or community data. Physecologies of this type can expect more regular spectators than private ones, since their context often concerns spaces that can be visited by a larger variety of people. Whereas most physecologies of this type contain both users and spectators, we observed cases in which only spectators occurred [125, 140, 146].

3.3.6.3 Public

This was observed for 10 samples, and concerns physecologies meant to be available for the general public, for example in public spaces such as museums [205], airports [76], outside squares [30], or neighborhoods [140]. Public physecologies are likely to visualize community data [20, 127, 140], or city and environmental data [30, 76, 205]. In case the physecology contains users ($f = 5$), they are likely to interact with it on a less regular basis than a private or semi-public physecology. To give an example, physecologies in neighborhoods [20, 127, 140] are probably visited on a weekly or monthly basis and show data relevant to the co-located communities. In contrast, physecologies in airports [76] or museums [102, 205] are probably visited on a yearly or one-off basis.

3.3.6.4 Open-ended

Lastly, there were example physecologies that do not clarify a specific context, which was observed for 22 samples. For these examples we did not create a further division between users and spectators, since these are very context-dependent. Example physecologies are design prototypes [138, 211], research prototypes meant for case studies [62, 100, 134] or lab studies [221]; prototypes as a result of workshop events [56]; or graduation projects [36, 87, 89, 116].

3.3.6.5 Audience Summary

To conclude, we observed a combination of both users and spectators across contexts of different privacy, but with differing frequencies in their encounters with the physecology. Cross-referencing context and data topics, we observed that physecologies in a private context tend to visualize more personal data, whereas semi-public and public contexts show a wider variety of data topics.

So far we have discussed the users and spectators as two types of audience, but did not yet describe the dynamic between them. As an example we take public physecologies as part of a neighborhood [127, 20, 140]. All people part of the neighborhood community are initially spectators, as they might be unaware of the meaning of the visualization and/or their relation to it. However, after interaction occurs with the physecology, for example for Mill Road [127] when a prior spectator makes use of the voting devices available in the shops, they become a user and contribute to the upcoming chalk visualization in the street. Likewise, spectators of a semi-public physecology such as Clouds [185], become implicit users once they interact with the sensor matts and contribute to the interactive ceiling installation. These observations resonate with findings from prior work in public displays [235], discussing the transitioning from implicit to explicit interaction zones. Hence, the audience has a temporal and spatial nature, and can change over time and be dependent on location. Figure 3.2 shows how the different concepts within the audience dimension relate to each other.

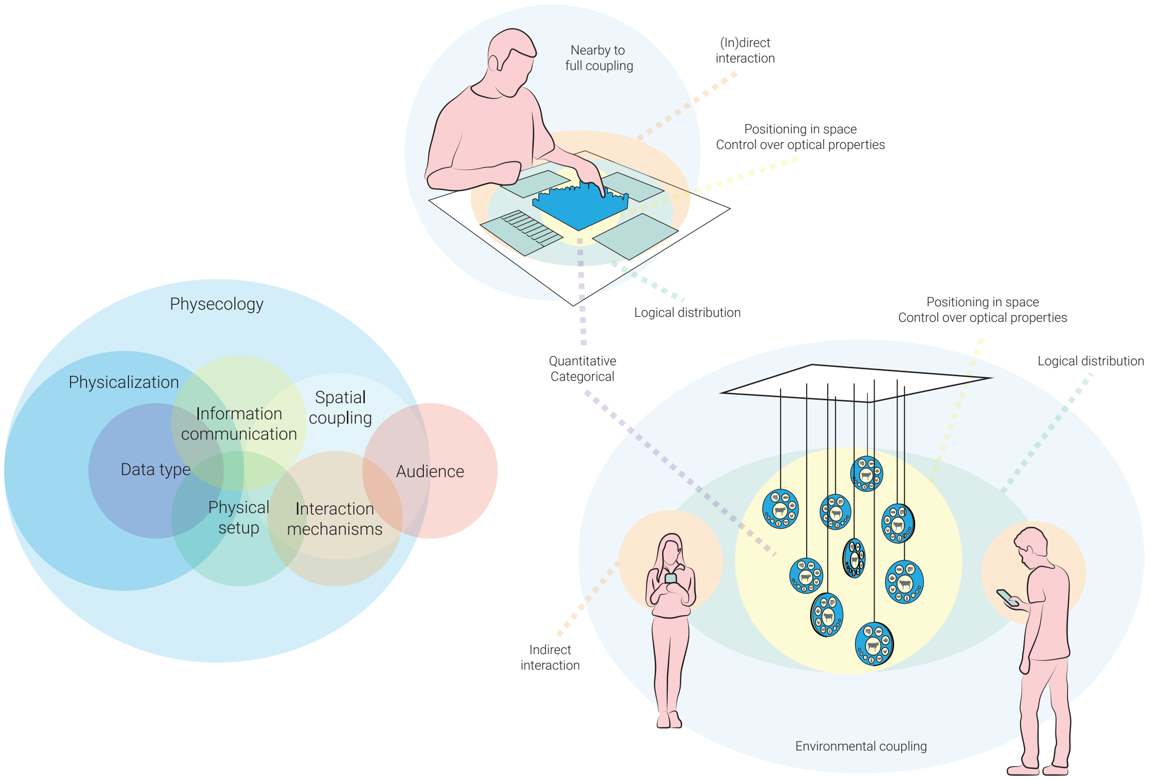


Figure 3.4: A diagram showing the relation between a physicalization and the physecology it belongs to, and how the different design dimensions position themselves within these two concepts and in relation to each other. Additionally, the two illustrations show how the design dimensions manifest in exemplar systems, EMERGE [221] and Econundrum [186].

3.3.7 Physecology – How do the design dimensions interact with one another?

Herein, we further discuss the intrinsic relations that exist between the design dimensions of a physecology, as illustrated in Figure 3.4, and use the case studies as examples. The *physicalization* forms the core of the *physecology*, encompassing the *data type* inside, while showing strong relations with the *physical setup* and the method of *information communication*. To give an example, EMERGE [221] communicates information through the positioning in space of physical bar charts, and can be directly interacted with by the user. Similarly, Econundrum [186] communicates information through positioning in space as well, though top-down instead of bottom-up. In contrast to EMERGE [221], the interaction is not directly with the physicalization, but indirectly through a mobile application.

All other design dimensions position themselves around the physicalization in the physecology space. The data availability (for example static or dynamic) and data attributes (for example categorical or quantitative) are interconnected with the method of communication and the physical setup necessary to interact with this data. Subsequently, the distribution of the physical setup dictates how the data is represented (information communication) and interacted with (*interaction mechanisms*), either by means of direct or indirect interaction, via a logical or spatial distribution. To give an example, Econundrum [186] visualizes dynamic data (personal food consumption) changing both quantitative and categorical properties, through positioning in space (quantitative) and the control of optical properties (categorical). The physical setup involves a logical distribution between a mobile application and the physicalization so that users can provide data ad hoc, allowing the visualization to be dynamic. In contrast, PARM [180] visualizes static data (landscape features) changing solely categorical properties through control of optical properties. The physical setup involves a spatial distribution between a digital display and the physicalization so that users can be informed about the information presented, but can not interact with it.

The *spatial coupling* is an overarching dimension describing the interactions of the *audience* with the other design dimensions within the physecology. For the example of Econundrum [186] the spatial coupling is environmental, as users perform indirect but explicit manipulations to the data visualization by submitting data entries to the system, while being co-located with the physicalization in their shared workspace. Contrasting, for the example of EMERGE [221] the spatial coupling is nearby to full, which reflects in the (in)direct exploration of static data by touching the physicalization directly or the touch displays nearby (logical distribution).

In this work, we aim to illustrate how prior work on physicalization goes beyond the current definition – assigning the core value of physicalization to its inherent physical and material properties – and identified six key dimensions that together form a physecology. The *Data type* dimension shows how differences in the availability of data, data attributes, and topics dictate other elements within and outside exemplar physicalizations. The *Information communication* dimension demonstrates that there are more ways of visualization possible – beyond changes in physical or material form – such as the control over optical properties, other modalities, and the use of specialized applications, that are currently not acknowledged in the definition. The *Interaction mechanisms* dimension discloses how more than half of existing prior work uses indirect interaction with the physicalization through another physical or digital medium. Hence, we need a physecology to be able to conceptually position the different levels of directness, intention (for example implicit or explicit), and implications of interactions in relation to the physicalization. The lens of the *Spatial coupling* dimension on prior work shows that user input can be more or less spatially related to the physicalization, which influences the coupling between input and output. The *Physical setup* dimension describes how a physecology can be beneficial in mapping out the additional physical and/or digital elements external to the physicalization, but crucial for the visualization and/or interaction with the system. The *Audience* dimension allows us to incorporate the different relations people can have with a physicalization (for example user or spectator) and how they can change over time.

To conclude, we treat physicalization, defined as a data embodiment through material and geometric properties, as part of a larger ecology with several design dimensions: the physecology. There are many dialectical relations between these dimensions, that go beyond the concept of physicalization, and collectively create an interactive data visualization. Hence, it is important to consider the concept of physecology in future work on the physicalization of data.

3.4 Discussion

The central goal of our work is to unpack how physicalizations are used in real-world scenarios. Through a meta-review of selected physicalizations, we derived six key design dimensions of a *'physecology'* which describes the necessary context around physicalizations. In this section, we reflect further on (i) the need for *physecology* as a unit of analysis and design, (ii) the relationship between the physicalization and wider physecology, and (iii) the further opportunity to develop strong conceptual interaction models to help identify the precise role of physicalizations for complex activities.

3.4.1 Physicalizations in Context

The dominant focus of research on the development of the concepts around 'physicalization' has been *device-* and/or *domain-centric.* The device-centric approach focuses primarily on the detailed device, apparatus, or mechanisms that enable physicalization [4, 108]. This approach is mainly driven by the current *absence* of high-fidelity technical solutions that operationalize the visions behind physicalization into some form of interactive system. On the other hand, the domain-specific approach concentrates on the design of tailored physicalizations for specific application areas. These systems are often evaluated through design and field studies, which provide valuable qualitative insights but may lack generalizability. Consequently, this focus on specific areas implies that other important topics, such as data mapping, user perception, or the wider context of use are less well explored and understood as they rarely are included in the main unit of analysis when discussing 'physicalization' conceptually.

In contrast, our meta-review of physicalization literature and discussion of selected case studies demonstrate the need to consider the wider context around interaction with physicalizations. Based on our analysis, we argue that the surrounding context plays an equally – *if not more* – important role in the way people actually interact with physicalizations. Our case studies, but also the wider design space analysis highlight that, in most cases, the physicalization is only a part of a solution designed to enable people to explore certain datasets. Our findings suggest that physicalization designs and systems in fact *require* a wider ecology of sensors, input technologies, and other mechanisms to function, and that the physicalization is rarely used as a standalone device. Moreover, the highly tangible and physical nature of physicalizations requires a strong grounding to the *context of use* and *variety of possible user groups*. Our empirical observations are in line with wider views on the importance and relevance of 'context' for the use, application, and appropriation of technology [1]. While there is significant previous research highlighting the importance of context in HCI [1, 240], for physicalization this remains underexplored – both conceptually and technically.

Therefore, we believe that while the topic of physicalization does influence the way data is materialized into information, it is essential to recognize the commonalities shared by physicalizations. These include considerations of audience, interaction mechanisms, and the broader contextual factors that shape the design and use of physicalizations. By addressing these shared aspects – while acknowledging the specificity and uniqueness of each physicalization instance – we aim to contribute to a more comprehensive understanding of physicalization design beyond the device and domain-centric perspectives.

Data physicalization is historically, conceptually, and fundamentally closely related to and derived from the field of visualization, which explains why the explicit inclusion of physical context has not been actively considered. The creation of data visualizations in a 2D digital space is inherently different from the creation of physicalizations in physical 3D space, which requires a more thorough consideration of contextual factors. While this notion of context, situatedness, or spatial referencing is increasingly recognized as an important aspect for visualization [25, 243], there are few attempts to include physical context into the fabric of information visualization. It is important to note that the context of use is indeed central to visualization, as it is generally targeted to a specific task. However, the inclusion of physical contexts, such as the surrounding environment, tangible interactions, and spatial relationships, has received less attention in the visualization community due to the predominantly digital and 2D nature of traditional visualizations.

Additionally, the translation from established visualization terminology into physicalization concepts remains a fundamental challenge. We observed that the wider practices of physicalizations and their surrounding physecologies do not necessarily follow standardized visualization concepts or ideas. As a result, there is no straightforward vocabulary available to describe these physicalization concepts in a consistent manner. To give an example, *information communication* is a hybrid of conceptual models such as *visual variables* [18] – assigning visual encoding – and *rendering* [50, 106] – developing from visual encoding to physical form – and actuation technologies [54] – the implementations to accomplish changes in data states. This lack of consistent vocabulary and concepts makes it difficult to perform a uniform analysis of the visualization strategies employed in physicalizations.

The effects of a lack of consideration of the wider context around physicalizations are also increasingly demonstrated in empirical research. Recent studies [107, 191, 194] demonstrate that selected physicalization designs simply do not meet their assumptions around how they visualize data to users, or how they provide singular interaction patterns. For example, studies demonstrate the different perceptions of size across physical shapes [107], the different perceptions of physical information in general across perspectives [191], and people's different interaction strategies when organizing physical information [194]. These empirical studies suggest that current strategies for physicalization are often inconsistent for elements of context such as size, orientation, or interaction. This is mainly caused by a limited understanding and conceptualization of the context surrounding the use of these physicalizations. These empirical findings and critiques are echoed by field [95, 186, 187] and design studies [62, 134, 220] that illustrate the challenges in how physicalizations mediate complex activities and support reflexive and context-sensitive interfaces to data. For example, one of the key arguments for 'physicalization' is that it enables and supports collaboration around a 3D model of data. However, empirical and field studies suggest that this is not the case because of a lack of tools and mechanisms to handle this collaborative context.

Grounded in our reflections on physicalization literature, we discuss the *'physecology'* as a unit of analysis that integrates this important wider context in the form of six design dimensions. The central contribution of the concept of physecology is the *explicit acknowledgment of the importance of the wider context and audience surrounding physicalizations.* It builds directly on the widely accepted definition of 'physicalization' [108] and extends it with an interconnected set of design dimensions (see Figure 3.4) that are directly inspired and supported by previous work on context [1, 253], tangible user interfaces [67, 92, 198], and situated and embedded visualization [25, 243]. These design dimensions are not mutually exclusive or individual lenses on the physicalization, but are deeply intertwined and inherent characteristics of the reality of how physicalizations are actually used in real-world scenarios. The physecology as a unit of analysis proposes that physicalizations are part of a wider dynamic and evolving ecology of artifacts, tools, and spatial relations. While these six dimensions – *data type, information communication, physical setup, spatial coupling, interaction mechanisms,* and *audience* – are a starting point to unpack the properties of a physecology, we accept that other dimensions or more precise refined breakdowns of existing dimensions are possible – and arguably necessary as we move forward with building an understanding of physical data representations.

As physicalization research further matures we anticipate these dimensions to be built upon and expanded, but this work provides a starting point for conceptual clarity on context-sensitive physicalization design. The general goal of our reflections is to provide a shared vocabulary to allow for a unified discussion of physicalizations in context – the physecology. This is not only to better understand the landscape of existing physicalization research (and its gaps), but also to reveal opportunities for future work. The framework can be informative in different stages of design research practices around physicalization, for example, in the initial phases of the process it can function as a set of design principles that can be operationalized in the creation of physicalization systems, interaction techniques, and specific domain applications. In later phases of the process, it can be used as criteria for heuristic evaluation or qualitative sense-making of observations from in-the-wild studies.

3.4.2 Relation between Physicalization and Physecology

The introduction of the *‘physecology’* has conceptual and technical implications for physicalizations. While at first observation it becomes clear that without a *physicalization* there can be no *physecology*, our analysis of literature indicates that the opposite also applies: in many cases there is no ‘functional’ interactive physicalization without a wider physecology. For example, in the case of EMERGE [221], the physicalization would lose substantial interactive possibilities if the touch displays around the physicalization were removed. Or for Physikit [95], the removal of the tablet-based configuration tool to configure and explore data from sensors would render the physical data cubes into useless bricks. These additional interfaces – or components of the physecology – are not ‘add-ons’ but a fundamental part of the full design or system required to make the physicalization work and be useful. There is, thus, a deep – potentially dialectical – relationship between both the physicalization, which is the *actual physical data or information visualization model*, and the physecology, which represents the *wider interaction context*. Both levels of the unit of analysis (physicalization and physecology) are deeply intertwined and can only be understood, studied, and – we argue – designed with this relation in mind. Furthermore, the dynamic and evolving nature of this ecological view, suggests that the surroundings and audience of a physecology will change over time. While this observation holds for any type of human-computer interaction, the physicality of the physicalization demands that the notion of context becomes a fundamental aspect of the design process. As physicalization research matures, we suggest that active consideration of the *'physecology'* will be a necessary step to transform physicalizations into practical applications, real-world field deployments, and specialized domains. We suggest that our framework can help reframe the *design* and *analysis* of existing and new physicalizations. The current design dimensions can function as new lenses or perspectives that provide concepts, vocabulary, relations, and concrete examples of how to operationalize the physecology.

One central observation from our analysis is the wide variability in which physecologies are designed. Particularly the design dimensions on *audience*, *interaction*, *spatial coupling*, and *physical setup* show that there are many different strategies and interaction models possible when interacting with physicalizations. We observe that most 'interactive' physicalizations require additional input devices, sensor mechanisms, and a wider interaction context. This opens up interesting questions around the *scale* and *dynamics* of physecologies. Examples in our corpus demonstrate that physicalizations can reach audiences ranging from one individual user, to groups of ten people, all the way to thousands of passersby. Moreover, many papers in our corpus implicitly report how user groups change over time, where spectators become users, or user groups shrink or grow in size. This observation has implications as it suggests that because of the physicality and the embeddedness of physicalizations in real physical space, there will almost always be multiple user roles and audiences. Even physicalizations designed for individuals will be seen, and perhaps analyzed and used by others. This user-multiplicity is, thus, a fundamental aspect of physicalization and should be considered as a first-class problem or requirement when designing the mapping, form, and interaction of physicalizations. Our analysis also shows differences in *time*, as most physicalizations are in fact not 'real-time' but enable configuration or interaction with different levels of *temporality*. This means that within the physecology, users can configure or interact with data across various instances of time. In some cases (for example in Physikit [95]) the time delay between interaction with the data (where a data source is selected and configured) and the actual visualization of data (triggered by a change in the date) can be months or even years.

While it is rare in our corpus to see multiple physicalizations inside the *same* physecology, it is conceptually possible and even desirable [189]. Indeed, many physicalizations already communicate different forms or types of data using singular interfaces, so the logical next step is to move to a multiplicity of physicalizations within one physecology. These issues of dynamic scale – in space, data, time, and audience – are currently rarely considered as part of the design of physicalizations. However, as suggested by previous literature that takes an ecological view on interactive technology [27, 113], this highly dynamic characteristic of 'ecologies' of technology is fundamental and should be considered as a key design objective for physicalizations. Finally, there are a range of physical data installations (for example Roam-io [94] and VoxBox [75]) that technically fall outside of the strict definition of 'physicalizations', yet have very similar goals and overlapping attributes and characteristics that could be included into a physecology. While their analysis is beyond the scope of this chapter, we suggest that further analysis in future work could analyze these physical data installations as physecologies, thus, suggesting that physecology could be an umbrella term that binds together all physical data artifacts, and installations.

3.4.3 The Need to Develop New Interaction Models

Research on 'physicalization' [4, 108] tends to focus on new interaction techniques and approaches that provide a *direct* and real-time interface to the physical data format [134, 212, 222]. In contrast, more than half of the physicalizations in our corpus – both published and non-academic work – only support *indirect* interaction with physicalizations through external devices (such as tablets, phones, and sensors) or more implicit means. This implies that those physicalizations would simply be non-interactive if not directly supported by additional interaction devices. However, most research in physicalization does not explicitly acknowledge the importance of these external configuration or interaction devices and very little is known about their design, operation, and general usability. This is surprising and problematic as their design is instrumental and centrally important to actually making the physicalization work. Moreover, as described in the previous section, the mere physicality, changes in scale and/or user base, and temporality of interaction with physicalizations imply that the wider interaction model across the entire physecology must be considered. User multiplicity, the distance of interaction, and temporal offset of input and output are just a few examples of key elements of the physecology that needs to be supported and included in the interaction design with physical data representations.

While the design dimensions of the *'physecology'* unpack the basic mechanisms for how physicalizations are used in the physical world and broader context, the dimensions do not explicate detailed interaction models. However, as physicalizations are a subset of tangible user interfaces (TUIs) and more general 'Ubicomp' devices, there is a range of interaction models that actively incorporate wider context, and even ecological views, into their fundamental operation. Example candidates for interaction models for physicalizations include spatial models (such as Proxemic

Interaction [15] or the Situative Space Model [174]), or context models (such as Activity-Based Computing [16] or Context-Awareness [1]) and other 'embodied interaction' models [52, 198]. Furthermore, as physicalizations are increasingly used as 'public installation', there is a need to better connect this work to the interaction models of 'Public Displays' [39, 235]. One other approach to rethink interaction models within the physecology is to reframe the physicalization to an individual 'device' that could potentially be updated, replaced, changed, or shared within a multi-device ecology or system [27, 96], thus, leveraging 30 years of research into cross-device interaction techniques, user interfaces, and data and information models. Finally, as the fundamental goal of interactive 'physicalizations' is to dynamically visualize data, future work would need to consider how interaction models within the wider physecology relate to interaction models from the information visualization perspective [106, 156, 163]). While these approaches do not dictate specific ways of interaction within the physecology, leveraging these prior conceptual interaction models and approaches can unlock new ways of addressing the *user experience design* of physecology that explicitly acknowledges the entire context and situatedness of the physicalization.

3.5 Conclusion

In this chapter, we analyzed a selected corpus of publications and non-academic work in the field of physicalization, showing properties that go beyond the scope of the working definition of physicalization. From our findings we identified six key dimensions that extend the current definition, and introduced the term *physecology* as a concept to describe a physicalization inside a wider interaction context. Our work contributes (i) a detailed analysis of a corpus of exemplar physicalization work, (ii) a conceptual framework to describe the design space and relations between physicalization and physecology, and (iii) reflections on what this means for future physicalization research.

In the next chapter, we will shift our focus from considering contextual factors surrounding physicalizations to more closely investigating the implications of physicality on the perception of the physicalization itself. More specifically, we will study the relation between user orientation and the perception of physical information (RQ2).

Chapter 4

Relationship between User Orientation and the Perception of Physicalizations[1]

In the previous chapter, we analyzed a representative sample of state-of-the-art physicalizations to understand how they coexist as part of a broader physical context. From this meta-review we know that physicalizations can be implemented in diverse environments, communicate data through various means, and be used by different audiences. Now that we established more conceptual clarity on the design space of physicalizations, we shift our attention to a more fundamental problem that underlies all physicalization design; people's perception of physical information in 3D space.

This chapter focuses on a specific aspect within the expansive Information Communication dimension of the physecology (see Figure 4.1). To effectively communicate information in any form, it is essential to comprehend how the physical elements of a physicalization translate to physical space and are perceived by people. By examining the relationship between user orientation and the perception of physical information, we aim to further deepen our understanding of how information is effectively conveyed through physicalization. Currently, the relation between user orientation and the perception of physical information is not well understood (as detailed in the second research challenge in Section 2.4.2). The orientation in which the user is viewing the physicalization may affect how the information is received, as the physical 3D shapes used to convey the data may appear dissimilar from different perspectives and angles, leading to ambiguity about the meaning of the information. Until now, little is known about the influence of user orientation on the perception of physical properties. Therefore, this chapter aims to systematically investigate the

---

[1] This chapter is adapted from the paper published as: **Kim Sauvé**, Dominic Potts, Jason Alexander, and Steven Houben. 2020. A Change of Perspective: How User Orientation Influences the Perception of Physicalizations. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376312

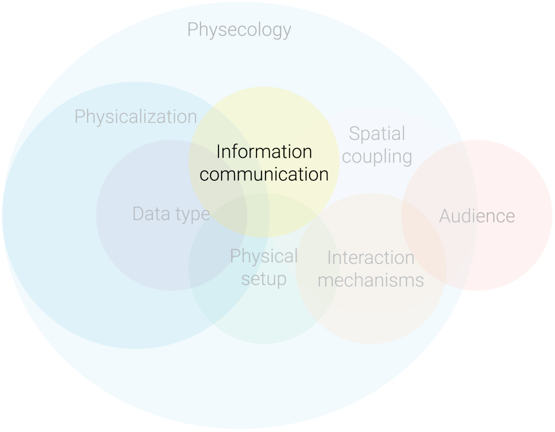


Figure 4.1: A diagram of how Chapter 4 positions itself within the physecology framework: the investigation of the relationship between user orientation and the perception of physical information is a key component of the Information Communication dimension.

perception of exemplar physicalizations when viewed from different orientations (RQ2).

To examine the relation between orientation and physical information communication, we conducted an experiment with 6 exemplar physicalizations and presented them from 4 different perspectives to evaluate information retrieval across perspectives. The design of the 6 physicalizations is informed by prior work into physical 3D bar charts [53, 64, 69, 220]. Our study with 20 participants evaluates the influence of users' orientation on how they perceived the physicalizations during multiple tasks.

Our results indicate that orientation directly impacts perception, leading to strong inconsistencies in the way the physicalization communicates information. We contribute (i) a confirmation of the relation between user orientation and the perception of physicalizations, and (ii) provide a first characterization of the variability and complexity within this relation. In this chapter, we elaborate on the study rationale and the designed physicalizations, and describe the conducted study. Finally, we will present and discuss the findings and provide recommendations for future work.

4.1 Rationale

By studying the relation between user orientation and data perception we can examine to what extent physicalizations become ambiguous when viewed from different perspectives. Ambiguity is problematic as an important incentive for data physicalization is to effectively communicate information through physical properties. For example in EMERGE [221], all participants moved between at least two sides of the system and performed different movements such as head tilting and leaning over the top during the study. It was however unclear if these movements were performed to counteract occlusion or were strategies for reading the data more accurately. A central question (RQ2) is: *what is the relation between user orientation and the perception of physicalizations?* Our work aims to address this question by examining (i) how people perceive data from different perspectives and (ii) how the perception differs across perspectives and/or people.

We propose a systematic approach to investigating the complex relationship between user orientation and perception of 3D physicalizations. For this study, we define orientation as the *user's perspective view of the physicalization*. We acknowledge that user perception is not only susceptible to rotation in the plane, but also for example by angular view, which is a conjunction of the user's height and the height of the physicalization. However, we study orientation as a first step in developing a better understanding of user perspective on perception of data physicalizations. By examining different low-level analysis tasks across orientations, we can draw conclusions about the consistency of perception across these tasks. We propose ***orientation consistency*** as new terminology for a measure of *the consistency of user responses to low-level analysis tasks across different orientations*.

In order to measure orientation consistency for exemplars of physicalizations, we applied low-level analysis tasks known from visualization [6, 239]. Specifically, we focus on familiar concepts in data interpretation such as *clustering* similar elements, *filtering* for a particular condition, and *finding* the *extremum* within the given dataset [6].

4.2 Method

The goal of our study is to investigate the impact of 90-degree changes in orientation on the perception of bar chart physicalizations. We hypothesize that orientation directly influences the perception of the physicalization and results in discrepancies and ambiguity in the way data is interpreted. For this study we rotate exemplars of physicalizations by 90 degrees on a flat plane, resulting in 4 orientation conditions. More specifically, we want to understand the relation between orientation and perception on three different layers: (i) per physicalization, (ii) per participant, and (iii) for different types of low-level analysis tasks (clustering, finding anomalies, and extremum). We focus in this study on static representations of data to keep the number of factors and the duration of the experiment under control.

4.2.1 Design

We choose a set of 6 physicalizations to represent a range of complexity that would provide enough depth to compare different low-level analysis tasks. Figure 4.2 shows

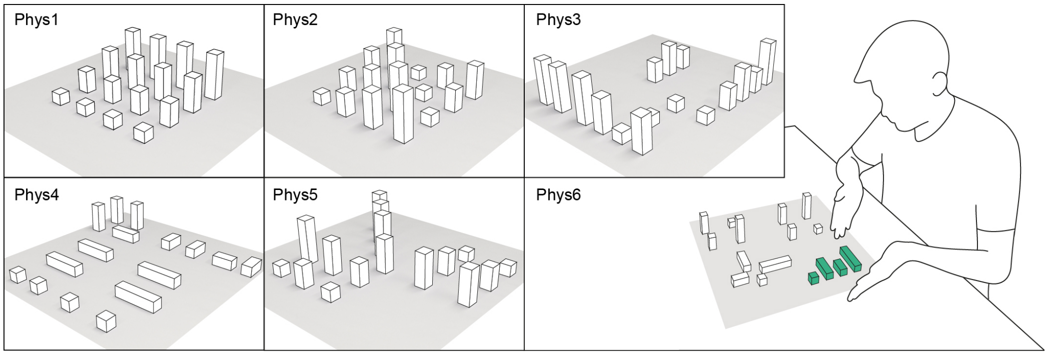


Figure 4.2: The 6 exemplar physicalizations (Phys1 – Phys6) and a depiction of the experiment setup. The physicalizations were presented to participants from 4 different orientations according to the vertices of the plane. Participants completed 3 tasks including clustering, filtering, and finding the extremum in the abstract 'data'.

all 6 physicalizations and in the remainder of the chapter we refer to them as *'phys1–6'*. Each physicalization consists of 16 blue acrylic objects: 4 cubes of 20mm and 12 cuboids with 4 of each length: 40, 60, and 80mm. The shape of the objects is derived from the well-known static physical bar charts previously used for physicalization [53]. We explicitly chose not to include indicators of data mapping, to avoid recognition bias[2] in the study. Therefore, the physicalizations are not explicitly based on an underlying dataset, but rely on intrinsic and relational properties of the objects in line with the definition of physicalizations.

To create a diverse and balanced set of layouts, we utilized the Gestalt principles of *proximity*, *continuity*, and *similarity* [238]. These principles guided the arrangement of objects, with the intention to engage diverse perceptual and cognitive processes. Simultaneously, we maintained consistency in the blue cuboids, to mitigate biases that could arise from dissimilar colors or other attributes.

In addition, we considered the concept of pre-attentive processing [238], which refers to the ability to quickly and effortlessly perceive certain visual attributes before conscious attention is fully engaged. By using simple numerosity, consistent shapes, and controlled layout variations, we aimed to facilitate pre-attentive processing. The layouts of the 6 physicalizations were created by applying different physical properties informed by what is known in 2D visualization as pre-attentive visual properties [238]. Therefore, we choose to use 16 objects for each physicalization, varying them in 4 lengths to achieve approximately equal density while promoting straightforward numerosity perception [238].

To summarize, the Gestalt principles [238] influenced the overall design and

---

[2] The possible pre-existing association one can have with a dataset due to their prior knowledge, occupation, etc.

organization of the layouts, while the concept of pre-attentive properties [238] informed the selection of visual attributes that could be rapidly and effortlessly perceived. By integrating both aspects, our goal was to design a complementary set of layouts that would elicit different perceptual and cognitive experiences, while ensuring consistency and avoiding the introduction of bias. We elaborate on each of the properties below:

4.2.1.1 Property 1 – Proximity

"Spatial proximity is one of the most powerful perceptual organizing principles and one of the most useful in design" [238]. Things that are closer are perceptually clustered together. In our designs, we employed the Gestalt principle of proximity [238] to create differences in internal and external distances between objects on the 2D plane. For example, in phys1 and phys2 internal proximity is constant, visually creating one cluster. Whereas in phys6 internal distance is smaller than external distance, resulting in the objects most likely being perceived as 4 clusters (Figure 4.3). Additionally, proximity was used to make two different types of spatial relations, either in a grid or linear fashion (in a horizontal, vertical, or diagonal direction).

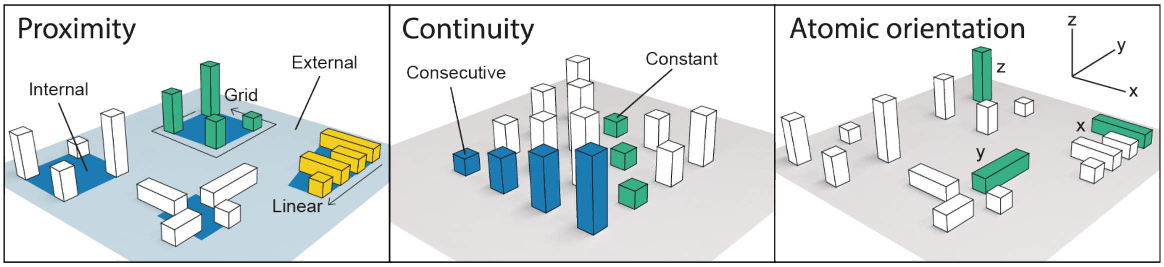


Figure 4.3: Illustration of different physicalization properties, which were changed across the exemplar physicalizations.

4.2.1.2 Property 2 – Continuity

Continuity, another fundamental Gestalt principle [238] assumes connectedness and can, in this instance, occur by height or orientation. In our study, continuity by height was either created by using objects of similar size or placing objects of increasing size in a consecutive manner. This respectively results in *constant* or *consecutive* continuity (Figure 4.3). Continuity in orientation is realized by aligning seemingly separate objects to form a single line or shape.

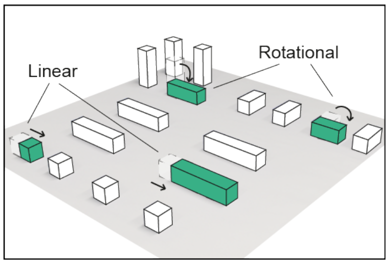


Figure 4.4: Phys4 contained deliberate errors in atomic orientation of one object in each cluster, if clustered on proximity and orientation.

4.2.1.3 Property 3 – Atomic orientation

We translated the Gestalt principle of similarity [238] into the design property of atomic orientation. In this context, atomic orientation refers to the individual orientation of the cubes/cuboids in the physicalization, specifically in the x, y, or z plane (Figure 4.3). Four of the physicalizations have only up-right oriented objects, while two have mixed orientations, with phys4 containing a deliberate error in the orientation of one object per cluster (Figure 4.4). By manipulating the atomic orientation, we were able to create more or less similar layouts while maintaining the consistency of the blue cuboids. While the translation of the Gestalt principle of 'similarity' to 'similarity in atomic orientation' can be seen as a creative adaptation – as it typically refers to visual attributes such as color, shape, or size – in our specific context of physicalizations using blue cuboids, where maintaining consistency in color and shape was desired, exploring similarity in orientation was a valid alternative to introduce variations while keeping other attributes constant.

For the purpose of our study, we intentionally created physicalizations containing edge cases of the different properties, resulting in the different aspects possibly opposing each other. For example, in phys1 (Figure 4.5), according to the *proximity* between objects or their *orientation* it is 1 cluster (1C), however assessing them by *continuity* it results in either 4 clusters of objects of constant sizes (4 clusters type 1 or in other words 4C-T1) or 4 clusters of objects of consecutive sizes (4 clusters type 2 or 4C-T2).

4.2.2 Setup

The working area is a white fixed square canvas of 40 × 40 cm to not reveal changes in orientation. Above the table was a camera providing a top-down view of the participants' gestures and interactions with the physicalizations (Figure 4.6). We presented each physicalization from 4 orientations – *North, East, South, West* (Figure 4.7) – to cover the major viewing angles. The 24 tasks were randomized using the Latin square method to avoid learning effects due to specific layouts. While

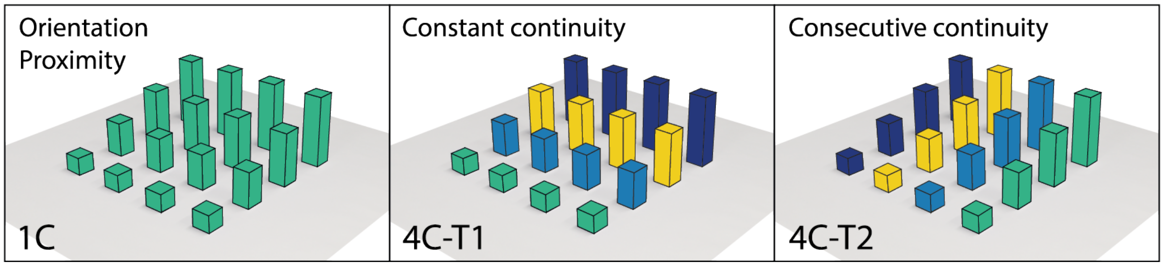


Figure 4.5: Phys1 cluster formation for (i) proximity or orientation, (ii) constant continuity or (iii) consecutive continuity.

the participants finished the task, the researcher would build the successive task with a second set of objects.

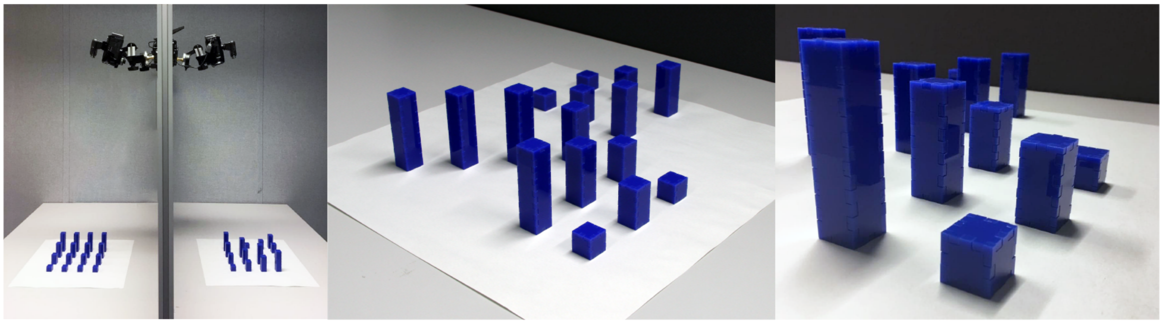


Figure 4.6: Experiment setup and a close-up of the acrylic objects.

4.2.3 Participants

We recruited 20 participants (9 identified as female, 11 as male) with an average age of 27 years ($\sigma = 5.92$). The only prerequisite for eligibility was that participants are fully (or corrected to fully) sighted as we were interested in visual perception of physical compositions that could represent data.

4.2.4 Procedure

At the start of the study, we provided an introduction, participants signed a consent form and we collected demographics. We explained the goal of the study: to understand how people observe physical objects that represent (abstract) data. We gave participants a set of general instructions and one example task was performed to make them familiar with the tasks and procedures. We instructed the participants to look at the physicalization from a fixed position and to not move their head. We

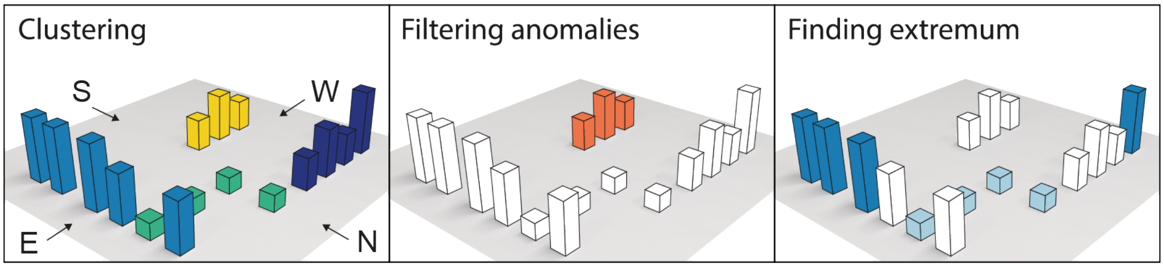


Figure 4.7: Illustration of the 3 low-level analysis tasks for each physicalization and from each of their orientations.

did not constrain participants in their physical movements, allowing slight natural movement. However, they were not allowed to lean down, move around, or touch the physicalization, therefore their movements did not fundamentally change their perspective. We provided them with the definition of a cluster: *a set of objects that you think belong together; it is not about the atomic properties of each object, but about their relation to each other.*

During the study, participants were consecutively presented with 24 different physicalizations, the 6 physicalizations each seen from the 4 orientations. To make the concepts of 'identifying data clusters, anomalies, and extremum' accessible, we used the terminology 'identifying groups, standouts, and highest and/or lowest values'. For each of the 24 physicalizations, the same set of low-level analysis tasks were performed (Figure 4.7), and the following 3 questions were asked:

Question 1: Can you identify any groups of objects? To capture which object relations the participant observed, we asked them to identify any clusters of objects they perceived. We asked them to point out the clusters with their hands to capture the exact location and structure of each cluster.

Question 2: What is the group that stood out first to you? To capture the anomalous cluster of objects that initially drew attention, we asked the participant to point out which cluster they saw first. In this way, we could collect both the absolute location and the structure of the anomalous cluster, given that they answered at least one to the previous question.

Question 3: Can you point out the highest and lowest value(s)? To capture the perceived extremum (minimum and maximum), we asked the participant to point out what they perceived as one or more lowest and highest values. We omitted any reference to size being indicative of high or low values and left it open to participants' own interpretation.

OC-Value	Elaboration	Orientation Consistency
OC-1	Four distinct orientations	1/4
OC-2	Two identical orientations	2/4
OC-3	Three identical orientations	3/4
OC-4	Four identical orientations	4/4

Table 4.1: OC-values for categorizing participants' consistency in a physicalization, across its orientations, for a given task.

4.2.5 Data Collection & Analysis

We recorded a top-down video of the tabletop and the hands of the participants. Additionally, the feedback of the participants was audio recorded. Lastly, the researcher made notes of the feedback during the experiment. During analysis, these worksheets were cross-referenced with video footage of the whole interaction. We applied a coding scheme to capture all *occurrences* of (i) identified number and type of clusters, (ii) anomalies, and (iii) extremum per orientation as well as across the 4 orientations. Moreover, we created a visual library to capture the clustering, filtering, and finding extremum process of each participant. These were visual representations of each occurrence to capture the high-fidelity information of abstract interpretations of the physicalizations, e.g., *number* and *type* of clusters (Figure 4.8).

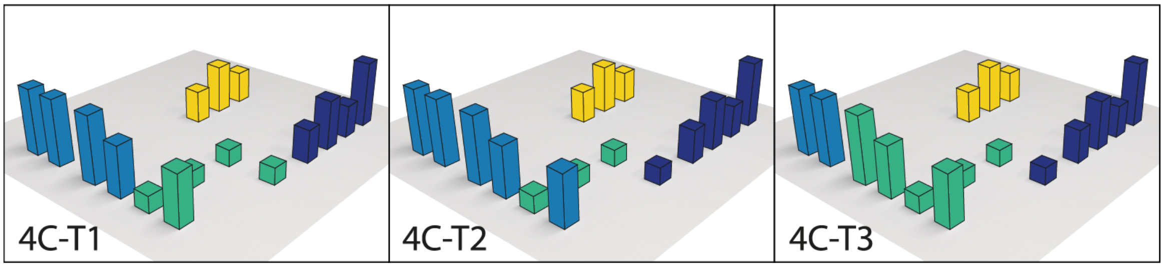


Figure 4.8: 3 types of clusters each containing 4 distinct clustering of objects identified for phys3. For each, #C refers to the number of clusters and T# refers to the specific type of clustering.

To analyze the impact of orientation on the 3 different low-level analysis tasks, we compared the 4 orientations of each physicalization for *each task* and for *each participant*. This comparison was to measure the consistency of a participant's perception of a physicalization across all 4 orientations. We refer to the 4 orientations as *North*, *East*, *South*, and *West*. To categorize participants' consistency and to facilitate our comparison, we assigned a value, the *orientation consistency* (OC) as shown in Table 4.1.

For example, a participant with OC-2 for a physicalization means that they completed a low-level analysis task consistently across 2/4 orientations. This means that they observed the data similarly for only 2 out of 4 orientations. Likewise, if a participant completed a low-level analysis task inconsistently across all orientations, i.e. 1/4, they would have a value of OC-1. This means there was no consistency in the way they observed the data across orientations.

Using this OC-value, we categorized 3 low-level analysis tasks over a total of 6 physicalizations and 20 participants resulting in 360 *instances* ($3 \times 6 \times 20$). One *instance* encompasses all 4 orientations (N, E, S, W) and has an assigned OC-value that represents one task completed by one participant for one physicalization.

Finally, in the case of OC-2, i.e. a participant completed a task consistently across only 2 orientations, the orientations can be either adjacent (Adj) or opposite (Opp) to each other. Considering this, we made the following subdivision:

(i) Identical adjacent orientations (e.g. N,E)

(ii) Identical opposite orientations (e.g. N,S)

(iii) 2 pairs of identical adjacent orientations (e.g. N,E - S,W)

(iv) 2 pairs of identical opposite orientations (N,S - E,W)

4.3 Findings

We report the general *orientation consistency* of the perception of clusters, anomalies, and extremum across physicalizations and participants. If orientation did *not* affect the perception of the physicalizations, 100% of the instances would be identical across all 4 orientations. Table 4.2 shows that for ***clusters***: 37% of the *instances* were identical across all 4 orientations, 27% were identical across 3 orientations, 33% across 2 orientations (20% were adjacent), and 3% were distinct across all 4 orientations. For ***anomalies***: 19% of the instances were identical across 4 orientations, 15% were identical across 3 orientations, 54% across 2 orientations (36% were opposite), and 13% were distinct across all 4 orientations. Lastly, for the ***extremum***: 29% of the instances were identical across 4 orientations, 21% were identical across 3 orientations, 23% across 2 orientations (17% were adjacent), and 28% were distinct across all 4 orientations.

This data confirms our hypothesis that perspective directly influences the user's perception of physical information, showing that across all tasks, participants, and physicalizations there is a *systematic lack of consistency* and perspective directly influences users' perception of physical information.

Task	4 Identical	3 Identical	2 Identical (Adj/Opp)	0 Identical
Clusters	37%	27%	33% (20% / 13%)	3%
Anomalies	19%	15%	54% (18% / 36%)	13%
Extremum	29%	21%	23% (17% / 5%)	28%

Table 4.2: Orientation consistency across participants per task.

Phys	4 Identical	3 Identical	2 Identical (Adj/Opp)	0 Identical
#1	10	4	6 (3 / 3)	0
#2	6	5	9 (4 / 5)	0
#3	2	3	13 (9 / 4)	2
#4	8	3	8 (6 / 2)	1
#5	5	12	3 (1 / 2)	0
#6	13	5	1 (1 / 0)	1

Table 4.3: Orientation consistency of clusters per physicalization.

Herein, we analyze the data on a per-task basis, specifically reporting on a breakdown per physicalization and per participant. We then discuss the relation to our hypothesis, providing a first characterization of the effects of perspective on the perception of physicalizations. Throughout this section, we use descriptive statistics to report our findings, supported by qualitative observations and quotes from participants.

4.3.1 Clusters

4.3.1.1 Orientation Consistency of Clusters per Physicalization

In this section, we elaborate on the *orientation consistency* of identified clusters across orientations per physicalization (Table 4.3). To reiterate, a cluster is a set of objects a participant considered to 'belong together' based on their relation to one another, i.e. 4 clusters refer to 4 sets of objects that the participant perceived as grouped.

For phys1 10 and phys6 13 participants saw identical clusters across all 4 orientations (OC-4), for phys5 12 participants saw identical clusters across 3 orientations (OC-3), and for phys2 9 and phys3 13 participants saw identical clusters across 2 orientations (OC-2). Lastly, for phys4 8 participants saw identical clusters across 2 orientations (OC-2) and 8 saw identical clusters across all 4 (OC-4). To summarize, orientation strongly influences the identification of clusters.

4.3.1.2 Orientation Consistency of Clusters per Participant

Considering *orientation consistency* for identifying clusters per participant, 6 participants frequently saw 4 identical clusters across all orientations (OC-4), with the outlier P5 who was 100% consistent across physicalizations. Further, 5 participants frequently saw identical clusters across 3 orientations (OC-3) and 6 participants saw identical clusters across 2 (OC-2). Lastly, 3 participants did not have a predominant OC-value. Among all participants, there were 3 who perceived 4 distinct clusters across all orientations. In summary, 11 participants have an *orientation consistency* of more than 50%, meaning that they perceived the same clusters across 3-4 orientations when looking at the same physicalization.

Several participants displayed an awareness of perspective changes and recognized the potential implications for their responses to the tasks. For example, P2 expressed concerns and curiosity about their consistency in completing the tasks and whether they observed similar clusters across orientations. Other participants quickly noticed that the six layouts were repeated across different orientations. For instance, P1 commented at the beginning of task 8 (phys4): *"This looks familiar! I'm starting to see a trend"*. Similarly, P7 remarked at the start of task 8 (phys4): *"[laughs] Ah, you just moved the number 5 or 6. I see, this is tricky. I think it's the number 5 that I've seen from this direction [gestures towards the right side of the layout], isn't it? I know it"*. Some participants openly acknowledged perceiving different clusters based on different perspectives. For example, P1 who had previously clustered phys5 into three groups, commented during task 22: *"Wow! It's super cool how it changes depending on the perspective! Now I see two groups"* (P1, phys5). Similarly, P3 expressed amusement, stating: *"[laughs] This is freaky, we've already done this. I see five groups [instead of four clusters]"* (P3, phys4). In contrast, P14 appeared to be conscious of the absolute positioning of physical objects and space, which allowed them to differentiate similar clusters across orientations, resulting in more consistent clustering across perspectives.

Phys	**# Clusters**	**1C**	**# 2C**	**# 3C**	**# 4C**	**# 5C**	**# Anomalies**	**# Extremum**
#1	3	1	-	-	2	-	7	10
#2	10	1	2	1	6	-	10	16
#3	17	-	2	5	7	3	14	36
#4	11	-	1	3	5	2	16	31
#5	12	1	2	4	3	2	9	42
#6	6	-	4	1	1	-	11	31

Table 4.4: Details the number of unique clusters, anomalies, and extremum identified by participants per physicalization.

4.3.1.3 Cluster Characteristics per Physicalization

The second column of Table 4.4 provides an overview of all occurrences of clusters that were identified per physicalization. In the consecutive columns a subdivision per number of clusters is provided, for example for phys1 a total of 3 occurrences of clusters were identified of which 1 type of 1 cluster (1C) and 2 types of 4 clusters (4C-T1 and 4C-T2) (Figure 4.5). However, as illustrated by Table 4.4 the number of clusters does not provide complete insight, for example for phys3 participants identified up to *7 different types of 4 clusters*. The total number of clusters in combination with the diversity in types of clusters is indicative for *orientation consistency*. For example, a higher total number of occurrences and/or cluster types implies a greater *inconsistency*. In the following section, we compare the frequently observed clusters, per orientation, for each physicalization and provide details on their characteristics.

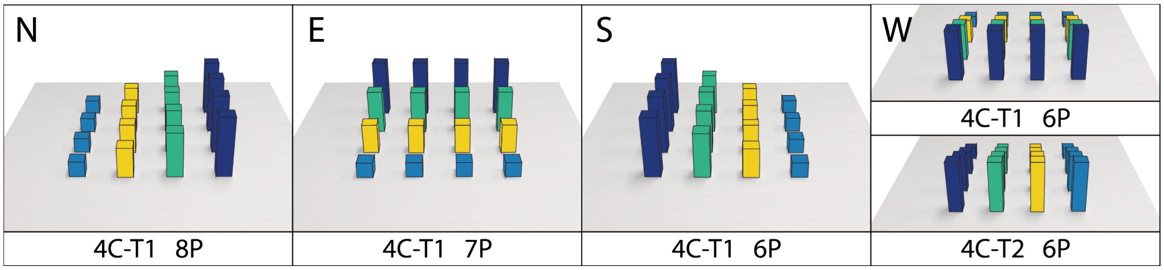


Figure 4.9: Phys1: Different types of clusters per orientation. #P is the number of participants that clustered phys1 in this way.

Physicalization 1 – 3 occurrences of clusters were identified, of which 1C (1 cluster) occurred frequently across all 4 orientations, in 8 to 11 participants (Figure 4.5). The second most observed occurrence was for 3 orientations, North, East, and South, 4C-T1 (4 clusters, type 1) and for 1 orientation, West, 4C-T1 and 4C-T2 were each observed as frequently (Figure 4.9). This could be explained by the continuity observed either horizontally or longitudinally from the participant. Generally, participants would describe the trend of phys1 as a quantity becoming smaller or larger (e.g., *"it is rising"*, *"it is growing"*) or as a move from a higher to a lower place or vice versa (e.g., *"it is going down"*). Moreover, P6 expressed the possibility of alternative trends for the East orientation, dependent on their perspective: *"If they're in columns, ascending, if they're in rows, they're all the same [constant height], however as one group, they're all vertical [upright]"*. In contrast, in West, the occlusion caused by the tall cuboids closest to the participant, is probably the reason for it being perceived either as columns or rows. For instance, P17 mentioned: *"from my perspective, I would see them more as actual columns as opposed to rows this time"*.

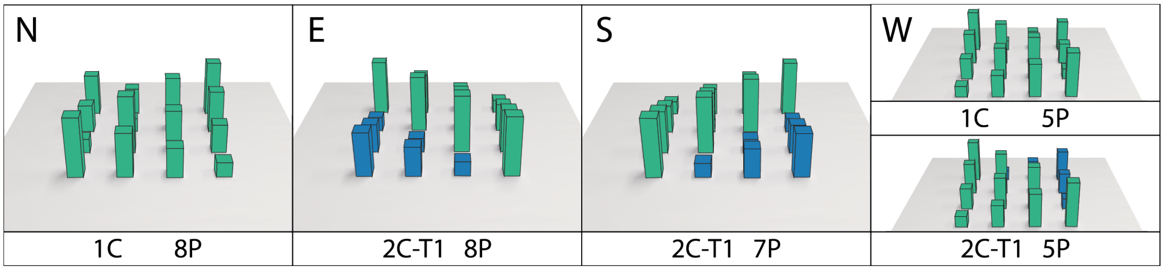


Figure 4.10: Phys2: Different types of clusters per orientation.

Physicalization 2 – 10 occurrences of clusters were identified, of which 1C and 2C-T1 occurred frequently across the orientations (Figure 4.10). For the North orientation the participants frequently saw 1 cluster. This could be explained by the occlusion of the smaller cubes furthest from the participant, making it appear as 1 cluster. In orientation East and South, 2C-T1 was frequently seen, which could be explained by the less elevated part of the physicalization being closest to the participant. Thus, not occluding other cubes and/or creating a distinct boundary between the two clusters. Participants used a variety of expressions to describe phys2, however, an overarching theme was associating it with natural phenomena such as a *"wave"*, *"pressure building"*, *"mountain, cliff, and valley"*, *"depletion and restocking"*, or *"slopes"*. Some participants specifically observed that each row and column consisted of four distinct consecutive units, leading them to describe it as a *"shifting wave that wraps around"* (P6) or compare it to a Latin square (P17).

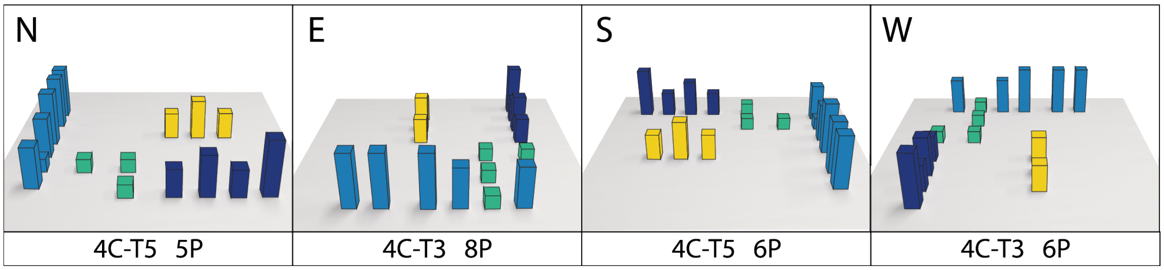


Figure 4.11: Phys3: Different types of clusters per orientation.

Physicalization 3 – 17 occurrences of clusters were identified, of which 2 types of 4 clusters occurred most frequently across the orientations. More specifically, for the opposites North and South, 4C-T5 was observed frequently, whereas for East and West this was 4C-T3 (Figure 4.11). The difference between the 4C-T3 and 4C-T5 lies in the clustering of the cubes. For North and South, one cube is occluded, and it becomes part of the longitudinal cluster on the side. The three other cubes are clustered together. In East and West, none of the four cubes are occluded, forming a continuous path. Participants commonly characterized the clusters on the outskirts (light-blue, green, and dark-blue in Figure 4.11) as having *"normal values"*, being *"connected"*, and related to *"axes"*. In contrast, the cluster in the center (depicted in yellow in Figure 4.11) was described as *"distinctive"*, an *"outlier"*, or *"standing alone"*. Furthermore, P9 described the cluster of four cubes (in green) as a separation mechanism between the two larger blue clusters. Finally, P16 provided a metaphorical interpretation of phys3: *"It's almost like an island [yellow cluster], and then this is the shore [other clusters], like the UK and Europe"*.

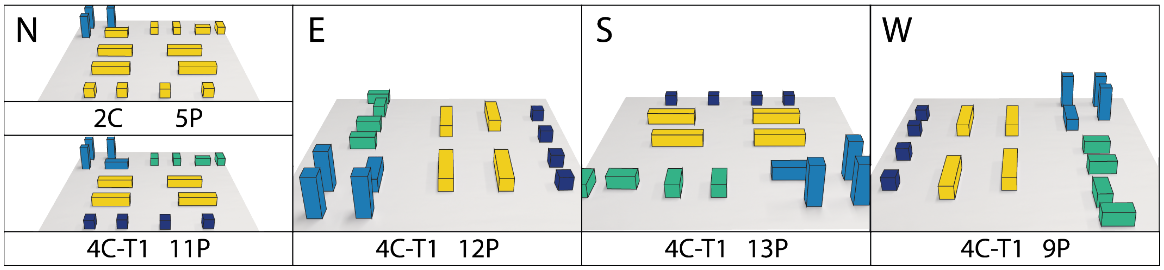


Figure 4.12: Phys4: Different types of clusters per orientation.

Physicalization 4 – 11 occurrences of clusters were identified of which 4C-T1 occurred frequently across all 4 orientations, in 9 to 13 participants (Figure 4.12). Additionally, 5 participants observed 2C in the North orientation. Participants tended to describe the horizontal objects as *"flat"*, *"stillness, not growing"*, and *"spread out"*. On the other hand, the three vertical light-blue objects were commonly described as *"up"*, *"tall"*, *"elevated"*, and even as *"growing in 3D"* (P11) or *"watching over the other clusters"* (P15). Some participants had unique ways of describing phys4 as a whole. For instance, P20 envisioned it as a scene: *"There's like a walkway or something here [points at yellow cluster] – that doesn't make any sense, but anyway – like a flow here [yellow cluster] and these are the outside walls [gestures towards both blue clusters and green cluster]"*. P6 attributed inconsistencies within each cluster to a creative narrative: *"I have a feeling that somebody tried to make them into 4 groups, but then there was an earthquake, and one of them fell on the side [flat-lying light-blue object], and the other ones got a bit shaky"*. Despite recognizing the influence of perspective, P16 described the following storyline for the East orientation: *"Although I recognize that these ones are standing up [3 upright light-blue objects], from this angle these look like they're the same height [all 4 light-blue objects] thinking about them in a 2D sense. [...] It almost feels like they're falling [green objects], and once they land they turn up [light-blue objects], like a narrative"*.

Physicalization 5 – 12 occurrences of clusters were identified, of which 3C-T1 occurred frequently across all 4 orientations, in 10 to 13 participants (Figure 4.13). Participants often described phys5 as taking the shape of an *"arrow"*, either pointing

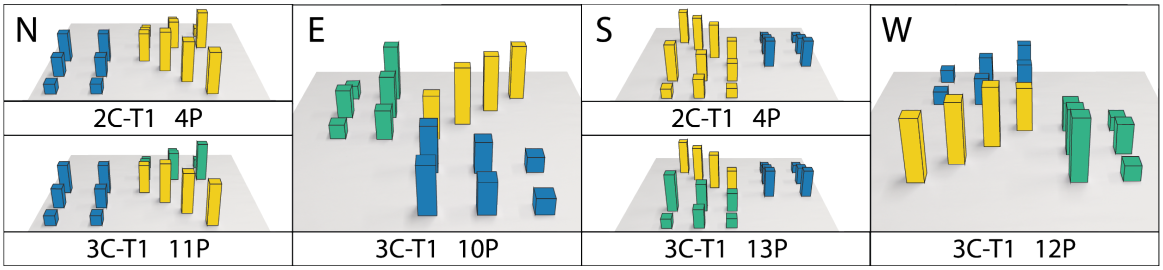


Figure 4.13: Phys5: Different types of clusters per orientation.

towards or away from them. Some participants also noted that the yellow diagonal cluster acted as a separation mechanism for the other two clusters. However, there were also more diverse descriptions, ranging from *"growing in groups"* and *"polarizing"* to *"coming together and rising up"* or moving towards a *"dead end"*. Further, 2C-T1 was observed by 4 participants in both North and South. Herein, the yellow cluster reminded P15 of spirals commonly seen in nature, such as phylogenetic trees. Finally, P3 commented that by moving slightly back and forward they could possibly see either two (2C-T1) or three clusters (3C-T1). Leaning forward allowed them to observe the diagonal cluster (yellow) distinct from the other cluster (blue), whereas sitting back this looked like one single cluster.

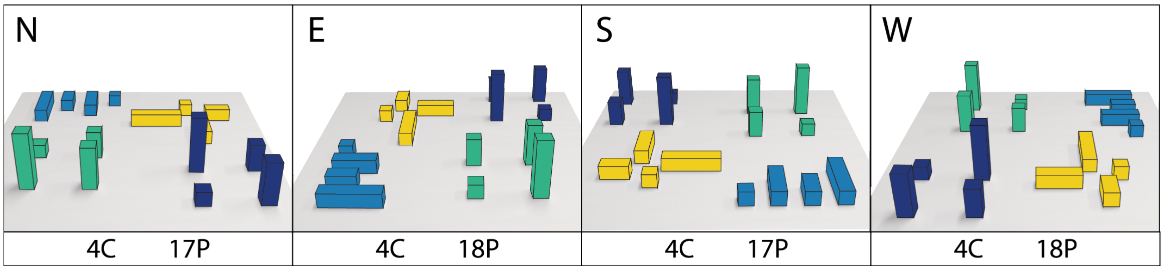


Figure 4.14: Phys6: Different types of clusters per orientation.

Physicalization 6 – 6 occurrences of clusters were identified, of which 4C-T1 occurred frequently across all 4 orientations, in 17 to 18 participants (Figure 4.14). This could be explained by the clear distinction between internal and external proximity of the clusters and therefore a general lack of occlusion. Several participants recognized two pairs of similar trends: either two upright clusters regularly described as *"up"*, *"elevated"*, or *"spiky"* versus two horizontal clusters described as *"flat"*; or two clusters exhibiting an alternating trend (blue clusters) versus an increasing trend (yellow and green cluster). Additionally, the green cluster was also described as a *"histogram"*, with P8 perceiving it as *"negative values growing downwards"* specifically for the North orientation. The yellow cluster was frequently described as a *"spiral"*, *"circular pattern"*, or *"growing from an origin"* and was even associated with a *"windmill"*. Moreover, P5 explained phys6 as a sorting mechanism from one cluster to another: *"Here it is kind of orderly [referring to the light-blue cluster], then it becomes a bit messy [yellow cluster], and then it becomes orderly again [dark-blue and green clusters]. Almost like it's transforming from this [pointing to the light-blue cluster] to this [pointing to the dark-blue cluster]"*.

4.3.1.4 Discussion: The Effects of Orientation on Data Clustering

A common theme that influences participants' ability to form clusters is the role of occlusion in perceiving the properties of the physicalization: proximity, continuity, and atomic orientation. We can categorize these into:

Continuity occlusion: A perceived array of objects seemingly intersected, preventing the participant from seeing the full continuity of them.

Proximity occlusion: The perceived distance between objects, appearing either further or closer together, depending on the perspective, preventing the participants from seeing the true proximity.

Atomic orientation occlusion: The perceived similarity between objects of different forms or perceived discrepancies between objects of similar forms, due to atomic orientation differences. For example, if you observe a cuboid directly in line with its square face it may appear as a cube.

For phys1-3 (Figure 4.9, 4.10, 4.11), *continuity occlusion* lead to different clusters being identified by participants across orientations. For example, in phys1 we can see that for the West orientation there was a split between 2 cluster types. This could be due to the constant continuity of the physicalization being occluded by the taller cuboids, resulting in some participants observing 4C-T2. Similarly, in phys2 for the East and South orientations, part of the constant continuity of the physicalization is occluded, creating a clear boundary between parts of the physicalization – which is not present in the other orientations. Finally, in phys3 the North and South most common cluster types were different than in East to West. As with in the other physicalizations, the constant continuity of the smallest cubes in North and South is occluded resulting in them not being considered as part of the same cluster.

For phys4 and phys5 (Figure 4.12, 4.13), both *continuity occlusion* and *proximity occlusion* influenced the formation of clusters across orientations. For example, in phys5, for the North and South orientations 2C-T1 was perceived by multiple participants. Compared to East and West, in the North orientation the front-right cluster occludes the back right-cluster affecting the perception of cluster proximity and continuity

Phys	4 Identical	3 Identical	2 Identical (Adj/Opp)	0 Identical
#1	7	3	9 (6 / 3)	1
#2	7	1	10 (5 / 5)	2
#3	3	6	8 (6 / 2)	3
#4	2	4	8 (8 / 0)	6
#5	4	2	14 (9 / 5)	0
#6	0	5	12 (9 / 3)	3

Table 4.5: Orientation consistency for anomalies per physicalization.

making the right cluster appear as one. This is the same in the South orientation, however, the continuity appears to be not occluded. For phys4, 5 participants clustered the physicalization by 2C as opposed to the more common 4C-T1. We believe this is due to a combination of *continuity*, *proximity occlusion* but also *atomic orientation occlusion*. For example, from the North orientation in phys4, the upright cuboids have their atomic orientation partially occluded due to the distance from the participant, resulting in perceived similarities in form, creating one potential cluster. In contrast, in the South orientation, these are clearly not occluded as they are closer to the participant and thus visible.

However, for phys6 (Figure 4.14), all participants identified the same types of clusters across the 4 orientations. We infer that this is because of the stark external proximity between 4 potential clusters. Moreover, there is a large amount of ambiguity across the clusters in terms of continuity and atomic orientation, leading to most participants using proximity as the main parameter for clustering.

In summary, *proximity occlusion*, *continuity occlusion*, and *atomic orientation occlusion* influence the way in which participants formed clusters. Most notably, the strategies some participants adopted to form clusters, i.e. initial anomaly filtering, meant that occluded aspects of a physicalization influenced the formation of clusters directly.

4.3.2 Filtering

4.3.2.1 Orientation Consistency of Anomalies per Physicalization

Table 4.5 shows the differences in *orientation consistency* of indicated anomalies across orientations per physicalization. To reiterate, an anomaly is a cluster of objects that initially caught the participants' attention. In summary, for all 6 physicalizations the majority of the participants indicated identical anomalies across 2 orientations (OC-2). In this case, OC-2 values were mostly adjacent to each other rather than opposite.

4.3.2.2 Orientation Consistency of Anomalies per Participant

If we look at *orientation consistency* for indicating anomalies per participant, 3 participants frequently saw 4 identical anomalies across all orientations (OC-4), 1 participant saw 3 identical anomalies (OC-3), and 11 participants saw 2 identical anomalies (OC-2). Lastly, 4 participants did not have a predominant OC-value for filtering anomalies.

4.3.2.3 Anomaly Characteristics per Physicalization

The eighth column of Table 4.4 shows an overview of all occurrences of anomalies that were indicated per physicalization. Below we will compare the frequently observed anomalies per orientation for each physicalization and provide details on their characteristics.

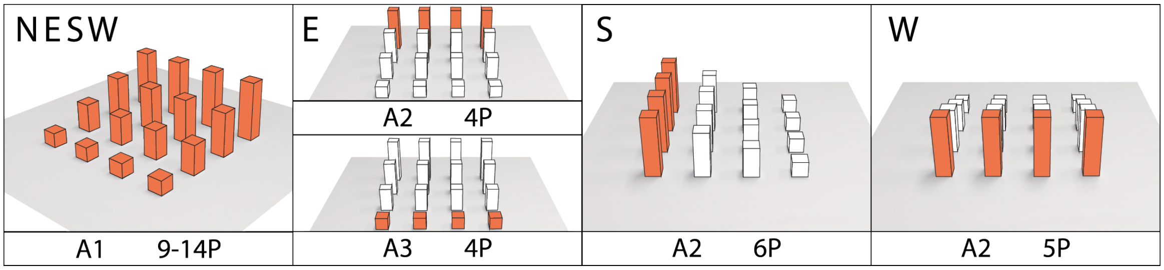


Figure 4.15: Phys1: Different types of anomalies per orientation. A# refers to the type of anomaly identified by participants.

Physicalization 1 – 7 occurrences of anomalies were indicated, of which A1 occurred frequently across all orientations, in 9 to 14 participants (Figure 4.15). A1 is when the participants indicated that the physicalization was anomalous as a whole or there was no anomaly at all. This can be explained by symmetrical proximity and clear continuity despite potential occlusion. The second most observed anomalies were A2 and A3 across the orientations East, South, and West. Regarding anomaly A3, P15 shared why the four front cubes appeared to have a stronger presence: *"These front ones [four cubes] feel more distinct than the others, they seem more like a key rather than their own axis, as in, they seem like the values [labels] rather than the data"*.

Physicalization 2 – 10 occurrences of anomalies were indicated, of which 3 anomaly types occurred most often, across orientations (Figure 4.16). A1 is when the participants indicated that the visualization was either anomalous as a whole or there was no particular anomaly at all, which occurred only frequently in the North orientation, in 9 participants. For East, the 3 anomaly types occurred equally (5 participants each) and for South and West A2 occurred most often. P13 saw anomaly

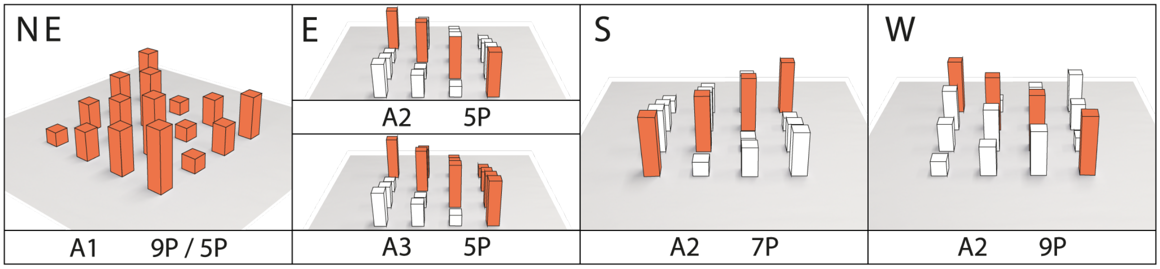


Figure 4.16: Phys2: Different types of anomalies per orientation.

A2 across all four orientations and expressed particular interest in the diagonal representation in phys2: *"That's my favorite one [phys2]. I like this line [pointing to the tallest diagonal objects]"*.

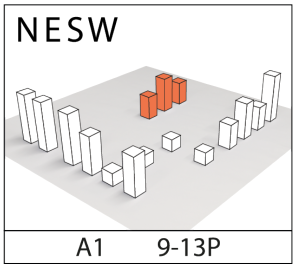


Figure 4.17: Phys3 anomaly.

Physicalization 3 – 14 occurrences of anomalies were indicated, of which A1 (Figure 4.17) occurred frequently across all 4 orientations, in 9 to 13 participants. The anomaly across orientations of phys3 can be attributed to the large external proximity between the three central objects and the surrounding objects in the physicalization. This separation was consistently noticeable regardless of orientation, as exemplified by P4: *"This is kind of connected [referring to the white objects], and this one [referring to the orange objects] is a bit alone"*.

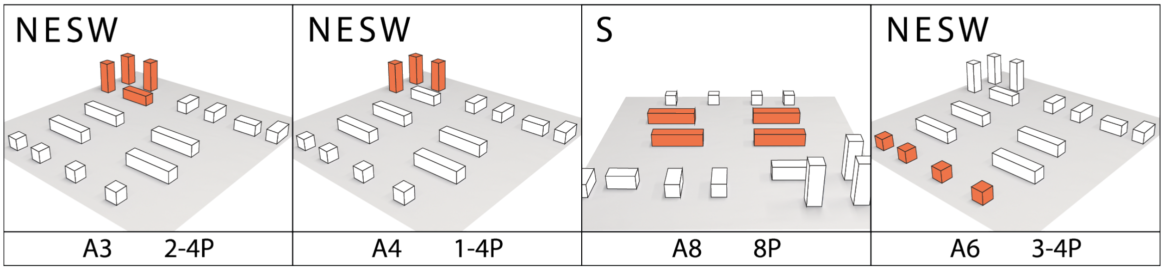


Figure 4.18: Phys4: Different anomalies across orientations.

Physicalization 4 – 16 occurrences of anomalies were indicated, of which A3, A4, A6, and A8 occurred frequently across orientations (Figure 4.18). However, no clear majority of participants were consistent across these 4 types. For instance, P1 described their decision-making process for anomaly A8 as follows: *"Probably this [anomaly A8], but I wasn't sure. So, I started thinking do these three objects [referring to the two 80cm objects closest to the flat-lying 60cm object among upright objects] belong together, or do these two objects [referring again to the two 80cm flat-lying objects] belong with these two objects [referring to the remaining two 80cm flat-lying objects]"*.

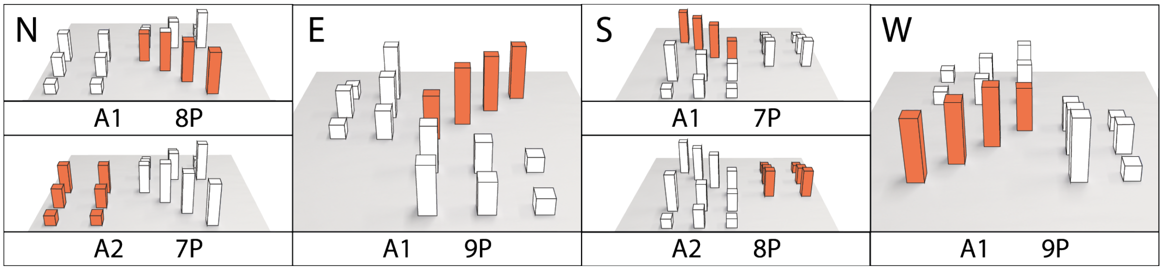


Figure 4.19: Phys5: Different anomalies for 2 orientation pairs.

Physicalization 5 – 9 occurrences of anomalies were indicated, of which A1 and A2 occurred frequently across orientations. As illustrated in Figure 4.19 in the opposite orientations East and West A1 occurred the most, whereas in North and South A1 and A2 occurred almost as frequently. For instance, P14 expressed attraction towards the A2 anomaly, highlighting its properties by stating: *"This one, because it's symmetric"*.

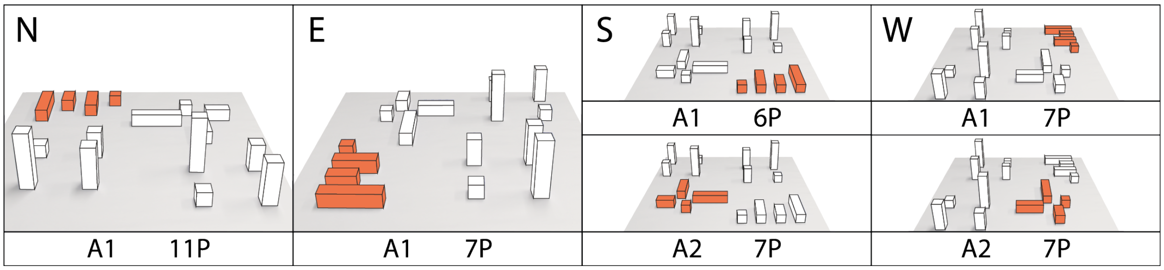


Figure 4.20: Phys6: Different anomalies for 2 orientation pairs.

Physicalization 6 – 11 occurrences of anomalies were indicated. For North and East A1 was observed frequently, whereas for South and West this was A1 or A2 (Figure 4.20). For the East orientation, P15 provided an interesting observation regarding anomaly A1: *"It's close, but it also looks a bit like the map of Great Britain or Ireland. It looks like it could be a map, and this one [other flat cluster] therefore could be a map as well. [...] Because they're flat and for some reason them being on* *the left is more obvious than in other configurations. [...] These ones [upright clusters] could be population or bird rates or anything interesting like that”.* Additionally, P8 offered the following explanation for the prominence of anomaly A2: *“The one that made the most impression was this one because it’s funny and looks like a windmill, so you don’t know what it’s supposed to show”.*

4.3.2.4 Discussion: The Effects of Orientation on Data Anomalies

Reflecting on the results described above, we observed two different themes that influenced participants’ filtering of anomalies. Firstly, participants described that they were more likely to observe non-occluded objects initially and therefore more likely to perceive them as anomalous.

Non-occluded clusters could either be the tallest objects and/or with a proximity noticeably distant from other clusters. For example, for phys1, the second most frequently observed cluster was the 4 tallest cuboids, which are not occluded from a single angle. Phys3 is an example of the 3 central objects being clearly distinct from the surrounding objects due to the large external proximity between them. In relation to this, non-linear positioning, such as tall, diagonally placed objects, was more likely to be perceived as anomalous by participants, for example in phys2 and phys5.

There is a clear relation between the previous clustering results and filtering anomalies, specifically the initial anomalies observed, and the most frequent clusters formed in each of the physicalizations. For instance, in phys2 the North orientation was generally identified as wholly anomalous or containing no anomalies. This was similar to the clustering for this orientation – mostly clustered as a whole.

Again, looking at phys2, in the 3 other orientations the diagonal, tallest, minimally occluded set of objects were identified as anomalous. This relates to the participants’ method of clustering the physicalizations into 2 clusters based on the level of occlusion, specifically from these orientations.

4.3.3 Finding Extremum

4.3.3.1 Orientation Consistency of Extremum per Physicalization

In this section, we elaborate on the *orientation consistency* of indicated extremes across orientations per physicalization (Table 4.6). To reiterate, an extremum is what a participant perceived as one or more lowest and highest values. In summary, for phys1 14 and phys2 8 participants saw identical extremum across all orientations (OC-4), for phys4 7 participants saw identical extremum across 2 orientations (OC-2), and for both phys3 and phys5 10 participants saw distinct extremum across all orientations (OC-1). For phys6 6 participants saw identical extremum across 3 orientations (OC-3) and 6 saw distinct extremum across all 4 (OC-1).

Phys	4 Identical	3 Identical	2 Identical (Adj/Opp)	0 Identical
#1	14	5	0	1
#2	8	5	5 (5 / 0)	2
#3	4	2	4 (4 / 0)	10
#4	4	4	7 (3 / 4)	5
#5	2	3	5 (3 / 2)	10
#6	3	6	5 (5 / 0)	6

Table 4.6: Orientation consistency for extremum per physicalization.

4.3.3.2 Orientation Consistency of Extremum per Participant

If we look at *orientation consistency* for indicating extremum per participant, 7 participants mostly saw 4 identical extremum across all orientations (OC-4), 1 participant saw 3 identical extremum (OC-3), 2 participants saw 2 identical extremum (OC-2), and 6 participants saw 4 distinct extremum across orientations (OC-1). Lastly, 4 participants did not have a predominant OC-value for finding extremum. Participants adopted different approaches when indicating extremum values. For instance, P15 seemed to invest effort in summing the total values of each cluster to make decisions on extremum among them. This approach resulted in very consistent extremum values across orientations (OC-4). On the other hand, P9 acknowledged that their extremum values were based on initial thoughts or instincts, leading to a score of OC-1. Similarly, P20 consciously selected a single lowest cube and the tallest cuboid, even though they were aware that these objects were identical to other cubes and tallest cuboids.

4.3.3.3 Extremum Characteristics per Physicalization

In the ninth column of Table 4.4 you can find an overview of all occurrences of extremum that were indicated per physicalization. As the variety in occurrences of extremum was high, we report on the frequently observed extremum for each physicalization, instead of per orientation, and provide an overall description of characteristics (Figure 4.21).

> *Physicalization 1* – 10 occurrences of extremum were indicated, of which E2 was observed most frequently across orientations, in 16 to 18 participants. However, an interesting outlier was observed in P10, who perceived phys1 differently in the West orientation, interpreting it as a 3D surface flipped on its side. This led to a different identification of extremum values: *"I would actually say this would be the lowest value [referring to the tallest cuboids] and this would be the highest value [referring to cubes]. [...] For some reason, it feels like you get a bit of a 3D-ish shape, where this [cubes] would be the top and this would be the bottom [tallest cuboids]".*

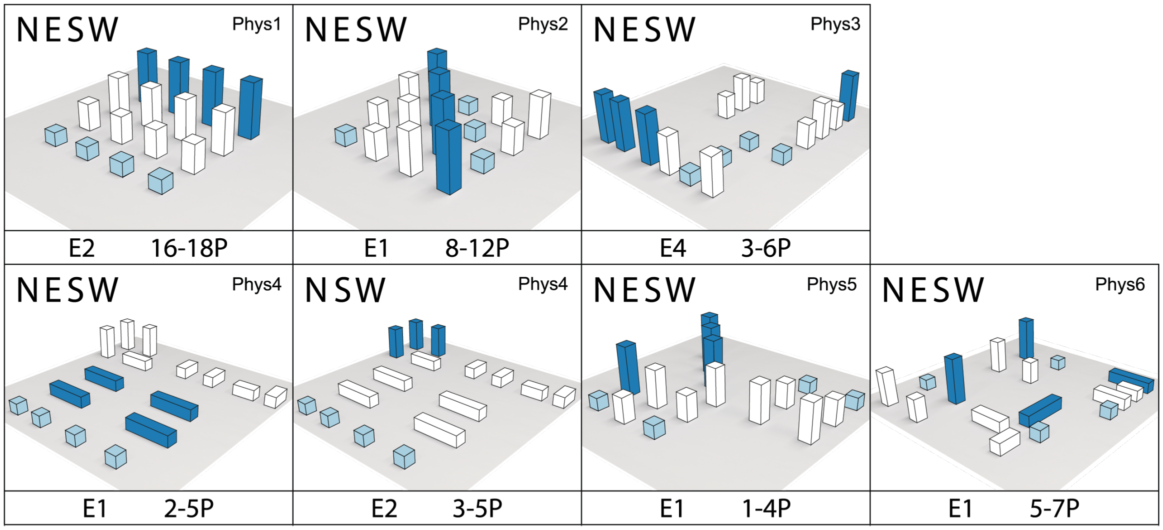


Figure 4.21: The most frequent indicated extremum per physicalization. E# refers to the type of extremum identified by participants.

Physicalization 2 – 16 occurrences of extremum were indicated, of which E1 was observed most frequently across orientations, in 8 to 12 participants.

Physicalization 3 – 36 occurrences of extremum were indicated, of which E4 was observed most frequently across orientations, in 3 to 6 participants.

Physicalization 4 – 31 occurrences of extremum were indicated, of which E1 and E2 were observed most frequently across orientations, in 2 to 5 participants. The observation of E2 can be explained by the difference in atomic orientation of the upright cuboids in the back left.

Physicalization 5 – 42 occurrences of extremum were indicated, of which E1 was observed frequently across orientations, in 1 to 4 participants.

Physicalization 6 – 31 occurrences of extremum were indicated, of which E1 was observed frequently across orientations, in 5 to 7 participants. Multiple participants made noteworthy observations during the study. They noticed that each cluster contained one object of each size, leading them to conclude that they had the same proportions, were equal in volume, or were similar in some way. As a result, these participants determined that there was no extremum at all within the clusters.

To summarize, agreement on physicalization extremum was generally low, with the exception of phys1 and phys2. The frequently observed extremums were generally defined by the absolute size of the objects – i.e. the smallest and largest.

4.3.3.4 Discussion: The Effects of Orientation on Data Extremum

From 2D information visualization literature, finding the extremum involves *"finding data cases possessing an extreme value of an attribute over its range within a dataset"* [6]. In the case of physicalizations, we can attribute this to objects that are the smallest and largest in the set in terms of absolute size. Our results support this, as participants frequently found extremum across physicalizations to be the smallest and largest objects. However, participants were influenced by other factors as well, such as the location of the object(s) on the grid and/or their atomic orientation.

As can be derived from Table 4.4 (column 9), there were many variations in the number of occurrences for different extremums per physicalization. Looking holistically at the different extremum found by the participants the following behaviors were observed: (i) Participants chose singular objects as the extremum for the entire physicalization, either as maximum or minimum values. (ii) Participants assigned a cluster of objects as the collective extremum for the entire physicalization, either as a maximum or minimum value. (iii) Participants assigned a single extremum on a per-cluster basis, for which they identified either maximum or minimum values.

The inconsistencies in these behaviors can be attributed to a common sense-making process the participants adopted that has emerged over the course of the discussion of our results. The occlusion of objects during the initial anomaly filtering process led to varied cluster formations and subsequently influenced the strategy for extremum identification, not only within a single physicalization but also within a participant.

Physicalizations with limited external proximity variances (phys1 and phys2) showed higher agreement on extremum. This could be due to the low proximity variance or symmetrical nature of the physicalization, but also due to limited occlusion of initially filtered anomalies. In this case, the tallest objects in phys1 and phys2.

4.4 Discussion

Our study shows the direct influence of user orientation on the perception of exemplars of physicalizations and physical information in general. Participants did not interpret information consistently which is indicative of physical layouts not being reliable in conveying data. Across participants, a common theme of a "sense-making" process arose. Parallels can be drawn between the low-level analysis tasks of 2D visualizations and the tasks undertaken in the study, i.e. clustering, filtering, and finding the extremum. While the study was designed to draw parallels from 2D visualization, it was not clear how changing perspective would influence information retrieval and overall sense-making. From the results discussed, we characterize the differences across perspectives in a sense-making process.

We postulate that occlusion is one of the primary reasons for inconsistencies in sense-making and information retrieval across perspectives. Occlusion can be differentiated by the properties of a physicalization, in terms of *proximity occlusion*, *continuity occlusion*, and *atomic orientation occlusion.* Occlusion directly affected the participants in their *filtering* of the data to identify anomalies. Participants adopted and described a strategy of initially *filtering* the data before *clustering*, and then finding the *extremums* based on the clusters.

While the influence of perspective, and thus occlusion, on information retrieval seems trivial, we provide a first characterization of the effect of changing perspectives on the sense-making process for proximity, continuity, and atomic orientation occlusions. We will further discuss how to build upon this initial understanding to create recommendations and physicalization frameworks for designers.

This chapter was successful in providing an initial characterization of the effect of changing perspective, however, the study has certain limitations. All exact occurrences of identified clusters, anomalies, and extremum were recorded. In the current study, due to the intentional ambiguity of the tasks, especially in finding the extremum, some occurrences showed partially overlapping elements. For example, similar objects were indicated as extremum across participants and orientations, however, they were not 100% identical to each other. There could be patterns and similar behaviors extracted from the data based on this overlap. Subsequently, this meant that there was a more detailed depiction of the participant's sense-making process that we have yet to understand. Further, participants conveyed their strategies and decision-making processes through body language, hand gestures, and verbal clarifications. Future work could explore this characterization further through qualitative analysis and interpreting the patterns in extremum, clusters, and anomalies.

The scope of this study was to examine the influence of user orientation on a physical structure independent of context. Therefore, we explicitly chose not to include indicators of data mapping, meaning participants could not use context to inform their decisions on filtering, clustering, and finding extremum. While we hypothesized that linear absolute size would be a clear gauge for scale and extremes, we observed that participants also used other factors such as location on the grid and/or atomic orientation. Future work is needed to further explore the implications of context on people's sense-making of physical information and examine the relation between data mapping scales of discrete objects and pre-attentive visual properties in physicalizations.

Regarding our measurement method of perspective, there were two limitations. (i) The angular view and height of participants may have influenced the perception of physical properties. However, we were interested in physicalizations that could be holistically explored, not just viewed from a fixed angle. (ii) We only examined 4 orientation conditions of 90 degrees, while physicalizations in general can be explored from 360 degrees. Our reason for constraining participant and physicalization movement is that we wanted to explicitly examine user orientation in a systematic way by reproducing the viewing biases. Further, we observed that participants exhibited minimal head and torso movements in order to readily perform the tasks, which indeed supports the notion of occlusion influencing sense-making. Hypothetically, if participants were allowed to move, it is expected that the effect of occlusion would be reduced or possibly eliminated. This could lead to a decrease in the impact of different orientations or perspectives, as participants are realizing they are observing the same layout. This aligns with the Gestalt principle that our understanding of what we see is shaped by the brain (e.g., simplified and organized) rather than solely relying on visual input [130]. However, even with the knowledge that they are looking at the same layout, factors like height, viewing angle, and individual perceptual differences can still introduce variations in their observations and judgments, especially when observing a physicalization at a glance. Future work is needed to investigate the influence of angular view, body motion on sense-making, and holistic exploration around the entire circumference of a physicalization on people's perception of the layout.

Other routes for future work include (i) investigating the influence of perspective during reconfiguration tasks: how could physical properties facilitate, persuade, or hinder the user? Also, do parallels exist between the strategies described in this chapter and strategies in reconfiguration? (ii) This work focused on 3D bar chart-like physicalizations, but other shapes and forms could be examined using similar methodologies. (iii) Finally, understanding whether collaboration around physicalizations amplifies or reduces the effects measured in our study.

4.5 Conclusion

In this chapter, we examined the relationship between user orientation and information perception of physicalizations. We conducted an experiment with 6 exemplar physicalizations and presented them from 4 different perspectives to evaluate information retrieval. Our study shows the direct relation between orientation and user perception of physical information. We also provide a first characterization of *orientation consistency* and observed the sense-making process guided by different types of occlusion. To conclude, it is imperative to carefully consider how the design of physicalizations might yield ambiguous perceptions of the information being conveyed. Future work is necessary to build upon this initial understanding to create generalizable frameworks and guidelines for physicalizations that consider the way in which information is manifested.

In the following chapter, we will apply the knowledge on the influence of perspective from this chapter to investigate people's interactions with physicalizations. Hence, we will use a similar methodology including tasks across orientations, to study people's reconfiguration strategies with exemplar physicalizations (RQ3).

Chapter 5

Reconfiguration Strategies with Physicalizations[1]

In the previous chapter, we have shown that there is a direct relationship between user orientation and the perception of physical information. In this chapter, we aim to extend this work by considering multiple orientations when investigating the reconfiguration of bar chart physicalizations (RQ3).

Physicalizations allow for the physical reconfiguration of data points, creating new opportunities for interaction and engagement. However, we still lack an understanding of how users approach and interact with reconfigurable physicalizations and the facets of their distinct qualities (as highlighted in the third research challenge in Section 2.4.3). Therefore, this chapter aims to investigate users' strategies when interacting with physical data points, e.g., in relation to each other, the canvas, and to themselves. In doing so, we can start to understand people's spontaneous reconfiguration strategies, regardless of any technological limitations or recognition biases, and with a higher degree of interaction possibilities.

In an effort to address the gaps in understanding users and their interaction with physicalizations that have been identified in the literature [93, 107] and as illustrated in Chapter 4 [191], this chapter focuses on the Interaction Mechanisms dimension of the physecology framework (see Figure 5.1). Specifically, we examine the direct interaction with reconfigurable bar chart physicalizations to inform the development of the next generation of interactive dynamic physicalizations. We conducted an experiment with 6 abstract exemplar physicalizations, informed by prior work on the well-known physical 3D bar charts [53, 64, 69, 221], to observe technologically unconstrained direct physical

---

[1] This chapter is adapted from the paper published as: **Kim Sauvé**, David Verweij, Jason Alexander, and Steven Houben. 2021. Reconfiguration Strategies with Composite Data Physicalizations. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21).* ACM, New York, NY, USA, Article 471, 1–18. https://doi.org/10.1145/3411764.3445746

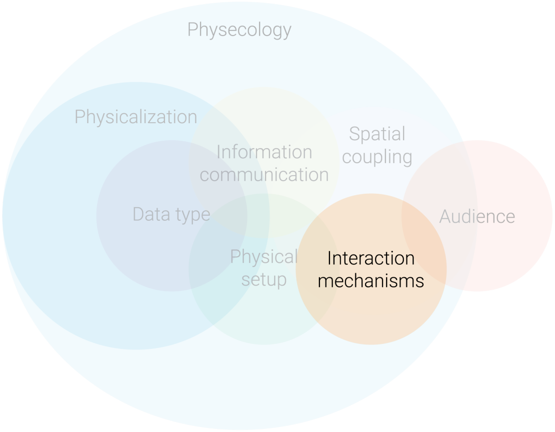


Figure 5.1: A diagram positioning Chapter 4 within the physecology framework. This chapter contributes to the understanding of specific elements of the Interaction Mechanisms dimension, such as the *direct interaction* with and *configuration* of physicalizations.

manipulation. We asked 20 participants to use any approach to reconfiguration to reorganize pre-identified clusters of data objects. Our key finding is the detailed breakdown of two main user strategies found for reorganizing physicalizations: *changes in proximity*, where objects are relocated in the same plane, and *changes in atomic orientation*, where objects are rotated. While these two strategies dominated and prevailed in our findings, they are not mutually exclusive and are complementary to other strategies, including the swapping and removal of data objects. Our contribution lies in our observation of the (dis)similarity of their use across different (exemplar) physicalizations and degrees of user restrictions. We detail these (dis)similarities per physicalization, across different physicalizations, and for two degrees of user restriction to reflect on generalizability across systems of different interaction possibilities. This contributes a first characterization of user strategies when reorganizing clustered data objects that are part of a larger physicalization. The real-world implication of this work is that, for a dynamic physicalization to allow for interaction, it should take into account these strategies in the interaction design, data presentation, and actuation mechanisms of the system.

5.1 Rationale

While we are starting to build clear insights into how physicalizations can be constructed using emerging technologies [69, 136, 220] and how they can encode data in specific application domains [64, 148, 213], there is currently little empirical work that examines the underlying mechanisms through which people interact with physicalizations (Chapter 4) [191]. We argue that understanding the underlying principles of *perception* and *interaction* with physicalizations is a necessary step to be able to design, build, and research effective and consistent physicalizations.

Prior work demonstrates that the perception of and interaction with visualizations can be successfully studied in isolation [59]. Examples in the realm of physicalizations include the perception of physical size [109], the influence of orientation on perception (Chapter 4) [191], and the interaction with physical data points [100]. These studies use abstract non-interactive 'data-agnostic' apparatuses to enable a systematic and principled approach that leads to novel insights that generalize to a wide range of systems and applications. However, there are currently no studies that elucidate the underlying principles and strategies of how people *interact with and reconfigure* physical information.

In this chapter, we adopt a similar approach – using methodologies and apparatus from static physicalization and constructive visualization – that enables us to study reconfiguration strategies using abstract data points that adhere to the rules of Gestalt [130]. This allows us to design the layouts of exemplar physicalizations in such a way that they are not based on a single dataset, but adhere to relational properties of objects and the visual perception of space (as per Gestalt) that forms the foundational theory for any physical representation. Gestalt is important for data visualization and physicalization since it is concerned with how the human brain perceives information and what perceptual properties are easier to interpret than others. To design physicalizations that are effective in communicating information through physical elements, it is important to adhere to these fundamental principles.

Our approach draws on prior work from the field of cognitive science on the use of physical space and clustering of physical (data) objects. Specifically, the proposed classification of Kirsh [121] explains that rearrangement of the position of physical (data) objects can serve three main purposes: (i) *spatial arrangements that simplify choice*; (ii) *spatial arrangements that simplify perception*; (iii) and *spatial dynamics that simplify internal computation*. To give an example, people *offload* mental effort into physical space by rearranging objects to simplify choice or to try out alternatives [121]. Hence, interaction with physical data objects goes beyond pure 'data interpretation' tasks but engages cognition and perception of physical space [121].

While our work builds principally on work in the field of physicalizations [108], this work is dominated by research on technology (new forms of implementing actuated physicalizations), and specific domains (implementing datasets in physicalizations). Because of the systematic lack of more principled and fundamental work, we build further on prior work in 2D visualization to inform our study setup. Our study operationalizes pre-attentive properties (e.g., visual salience) [Ch. 5 in 238] and Gestalt principles [Ch. 6 in 238] in the design of the stimuli. In our findings, we draw parallels between 2D visualization concepts [164] and our observations of reconfiguration in 3D space. To give an example, we discuss how the organization in 2D space (i.e., *separability* and *integrality* [164]) relates to proximity and atomic orientation changes in 3D space. Following 'data-agnostic' studies on 2D visual perception [10, 84, 204], we use data-agnostic 'abstract' 3D shapes to study interaction strategies based on proximity, orientation, and tangibility – not a specific dataset. This allows our study into interaction strategies to be independent of any dataset or domain, and more generally informative to future developments in this space. This is further supported by the use of a technology-agnostic setup (effectively accomplished through the use of static cuboids), allowing our findings to inform future technology approaches to physicalizations.

Our methodology, therefore, adopts the apparatus, number of participants, and setup from Chapter 4 [191], although we fundamentally study a different aspect of interaction with physicalizations. Where Chapter 4 [191] showed the direct relation between user orientation and *perception* of *static* physicalizations that could not be manipulated, this chapter studies the *interactions* with those physicalizations. As such we can start to understand how *interactivity* with physical data, and reconfiguration mechanisms used therein, can be supported in future physicalizations.

5.2 Method

The overarching goal of this study is to investigate data reconfiguration strategies on exemplar physicalizations. Specifically, we examine reconfiguration in physical bar-chart style physicalizations.

In this work, we use *data reconfiguration* to refer to the manual rearrangement of physical data objects to (re)organize a physicalization. This study adopts the apparatus, number of participants, and setup from Chapter 4 [191], and seeks to answer RQ3: *what are people's reconfiguration strategies in relation to the physical structure of physicalizations?* This question allows us to examine the intertwined relation between user actions, physicalization structure, and reconfiguration characteristics.

The two levels of interaction phases (two levels of restriction) were introduced to examine the extent to which participants can reorganize physical data objects and whether they use different reconfiguration strategies. Our study setup focuses solely on interaction, giving participants a degree of freedom in reorganizing data points that in 'real physicalizations' would break the data consistency. However, this approach enables us to reveal more general reconfiguration strategies that are not specific to one data context.

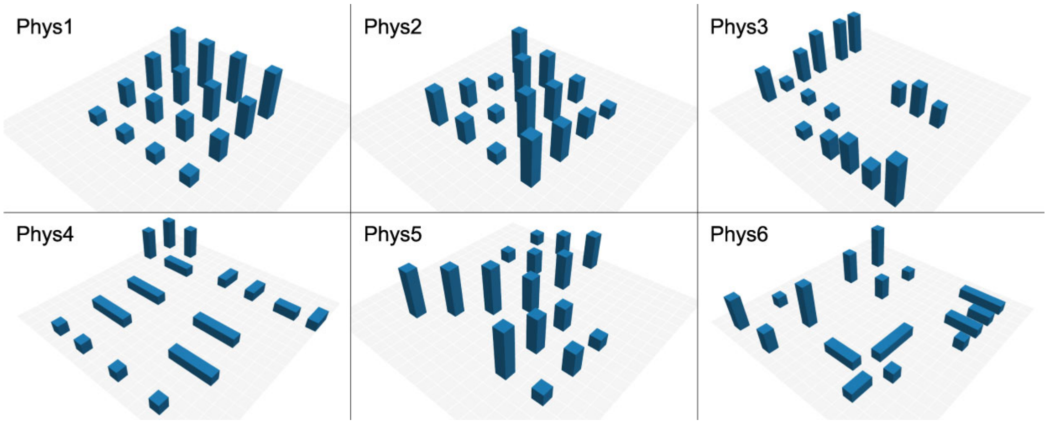


Figure 5.2: Overview of the 6 exemplar physicalizations in this study (phys1 – phys6).

5.2.1 Design

The design of the 6 exemplar physicalizations (referred to as *phys1* – *phys6*; see Figure 5.2) is informed by the well-known physical bar charts previously used in physicalizations [53, 221]. This set of physicalizations intentionally contains edge cases of different visual encoding. We thereby ensured that these included various visual obstructions, gradual and abrupt height differences, as well as clear and ambiguous distinctions of clusters, see Figure 5.2. This allows us to study reconfiguration strategies across a variety of spatial mappings, thoroughly exploring their effect on physical interaction with these mappings. Similar to work on 2D visualization [164], we varied the size (volume) and position (proximity), where we included the rotation of data objects in physical space. Each of the physicalizations consists of 16 blue acrylic objects that have four different lengths (Figure 5.3). This allowed us to create physicalizations with a range of complexity, while maintaining a similar density.

The layouts of the 6 physicalizations are not based on a concrete dataset, but on intrinsic and relational properties of objects, following the standard definition of physicalizations [108]. In the design process, we incorporated Gestalt principles, specifically *proximity*, *continuity*, and *similarity* [238]. These principles guided the arrangement of objects, aiming to elicit different perceptual and cognitive experiences while ensuring consistency in the blue cuboids to avoid introducing biases based on dissimilar colors or other attributes. To achieve this, we used *proximity* to differentiate between internal and external distances between clusters of objects on the 2D plane and created two types of spatial relations: in a grid (e.g., Figure 5.2, phys1) or a linear manner (e.g., Figure 5.2, phys3). *Continuity* was used to differentiate between perceived connectedness by using objects of similar size or objects of increasing size consecutively. We incorporated the principle of *similarity* in terms of atomic orientation, which refers to the rotation of an object around its own axes. This allowed us to differentiate the orientation of single objects within the physicalization, in the x, y, or z plane, while maintaining consistency in color and shape.

5.2.2 Setup

The lab-based study setup consisted of a white fixed square canvas ($40 \times 40\,\text{cm}$) and a camera above the table captured a top-down view of the participants' reconfigurations (Figure 5.3). We presented each of the 6 physicalizations from 4 sides to reduce the previously found influence of orientation in Chapter 4 [191], creating a total of 24 trials, which were randomized using the Latin square method.

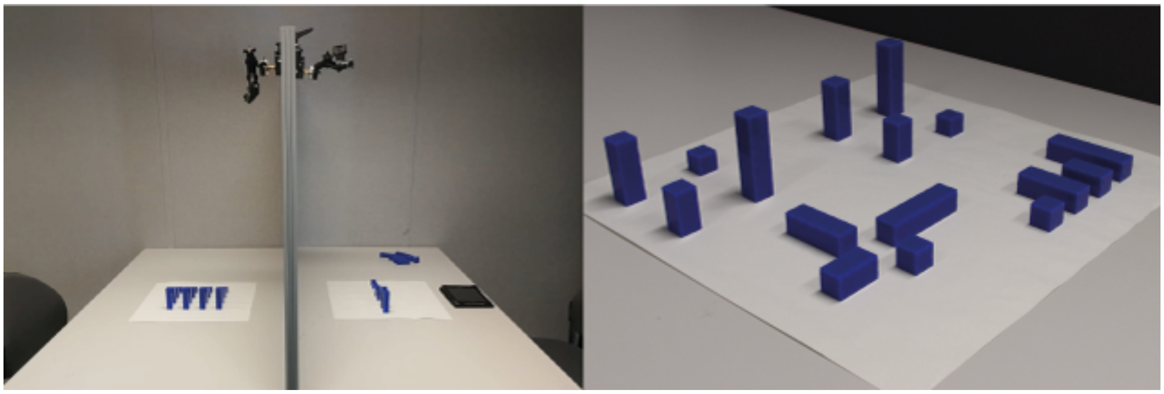


Figure 5.3: Study setup and exemplar physicalization made with acrylic objects.

5.2.3 Participants

A total of 20 participants were recruited (9 identified as female, 11 as male) with an average age of 27 years ($\sigma = 5.92$). The requirements for participation were that participants are fully (or corrected to fully) sighted and are physically able to reorganize physical objects.

5.2.4 Procedure

We introduced the participants to the study, asked them to sign a consent form, and collected their demographics. We explained the goal of the experiment – to understand how people reconfigure physical objects that represent (abstract) data – and walked them through an example trial to familiarize them with the procedure. We did not constrain participants in their reconfigurations, apart from that they were not allowed to stack the individual objects, as this would potentially alter the shape of the data points, rather than the presentation mapping on which this work focuses. We applied a think-aloud method for which we motivated the participants to speak their thoughts aloud while completing the trials as described below. During the study, we randomly presented participants with the 6 physicalizations, each seen from 4 sides, creating a total of 24 different physicalizations.

5.2.5 Tasks

The tasks are based on the process of *presentation mapping* [246], focusing only on the spatial organization of data. We asked participants to reorganize the physicalizations according to the clusters they perceived, making use of the canvas and available physical objects as constraints. The design of the tasks was influenced by Kirsh [121] who proposed that an effective means to simplify the perception of physical (data) objects is to spatially arrange them to reflect one's representation of the task. We deliberately use two levels of restriction (we refer to them as *phases*) to represent different 'degrees of freedom' found in related work: the change of a single object (*phase 1 – restricted*) relates to interactions of limited form in interactive systems [69, 221] and no restrictions (*phase 2 – unrestricted*) relates to complete freedom of interaction in work on constructive visualization [100, 246].

5.2.6 Participant instructions

Specifically, we asked participants, if they thought it was possible, to make the clusters they identified more distinct by reorganization in two phases. To make the concept of 'data clustering' more accessible, we used the terminology 'identifying groups' and explained the definition of a group as *a set of objects that you think belong together; it is not about the atomic properties of each object, but about their relation to each other.* For each of the 24 physicalizations, these two exact questions were asked sequentially:

> *Phase 1 (restricted): How would you make the groups you identified more distinct by moving one object?* To capture how the participants would reorganize the observed clusters with restriction, we asked them how they would make the clusters more distinct if they could only change one object. We asked them to perform the reconfiguration to capture the exact changes in the object's location and orientation on the canvas.
>
> *Phase 2 (unrestricted): How would you make the groups you identified more distinct by moving the least number of objects?* To capture how the participants would reorganize the observed clusters with no restriction, we asked them to continue on their result of phase 1 and perform another reconfiguration to capture the exact changes in objects' location and orientation on the canvas.

5.2.7 Data collection & analysis

We used worksheets with visual representations of the physicalization to capture the answers of the participants to the questions, and we annotated the changes made to the physicalization. To avoid ambiguity in capturing the changes the researcher would ask for clarifications in case user interactions were not explicit.

We made top-down video recordings of the tabletop and the hands of the participants, and audio-recorded their verbal feedback. We particularly considered participants' quotes to verify their intentions and to allow for more detailed reasoning. Lastly, the worksheets that the researcher used during the experiment were cross-referenced with the video recordings of the whole interaction.

We created a visual library to capture the end results of the changes made by each participant, for *phase 1* and *phase 2*. These were visual representations of the changes made, to capture the high-fidelity information of the physical manipulations performed on the physicalizations.

To analyze the reconfiguration strategies in more detail, we coded each phase, recording each object's position and orientation. This allowed us to cross-reference coordinate and atomic orientation changes of objects with the clustering data from Chapter 4 [191] to extract more detailed information in relation to the clusters identified. Hence, we can discuss the change in *cohesion*, which refers to the distance of objects to the centroid (mean coordinate) within a cluster, and the change in *separation*, which refers to the distance between centroids of clusters of objects. The calculation for cohesion and separation corresponds with common internal evaluation methods for cluster analysis. More specifically, we follow the approach used in the Davies-Bouldin index [47], in which they refer to intra- and inter-cluster similarity – our cohesion and separation respectively. The cluster validation is based on a 2D plane, not a 3D space (as participants were not allowed to stack objects). The performed reconfigurations in phase 1 are inherently included in the result at phase 2 due to the sequential nature of these phases. As such, the results of phase 2 represent all changes performed per trial.

5.3 Findings

Across all participants and physicalizations, for both the restricted and unrestricted conditions, we observed a diverse range of interaction approaches. Our findings categorize these into two predominant reconfiguration strategies: (i) *change in proximity* and (ii) *change in atomic orientation*. Overall, our study shows that – regardless of restrictions – participants were able and comfortable to perform reconfigurations to make the perceived clusters more distinct. In this section, we describe the observed reconfiguration strategies and how they can inform future work on interactions with dynamic physicalizations. We report on (i) the general reconfiguration strategies, (ii) the reconfiguration characteristics per physicalization, and (iii) discuss each of the reconfiguration strategies in further detail. We evidence our observations with descriptive statistics and discuss a selection of concrete examples from the 6 exemplar physicalizations.

5.3.1 Overall reconfiguration strategies

We present an overview of the general reconfiguration strategies used for the reorganization of physical data objects across all physicalizations and participants. **Overall, we observed changes in *proximity* and *atomic orientation* as the two main reconfiguration strategies.** Of all (480) trials, 52% involved the reconfiguration of an object at phase 1 (250 trials). All of these reconfigurations involved proximity changes of which almost a third also included additional atomic orientation changes (and 1 trial contained a removal strategy). This means that for 48% of all trials, no reconfiguration was performed at phase 1. Of all (480) trials, 80% involved the reconfiguration of one or more objects at phase 2 (386 trials). These reconfigurations all involved proximity changes of which almost a fourth included additional atomic orientation changes (and 19 trials contained other strategies). This means that for 20% of all trials, no reconfiguration was performed at phase 2.

To conclude, when only a single object could be reconfigured (phase 1), participants did so for approximately half of all trials (52%). When multiple objects could be reconfigured (phase 2), participants did so for the majority of all trials (80%). This means that with no restrictions at all, participants were most likely to make changes to the exemplar physicalizations. For both phase 1 and 2, all reconfigurations involved the change of proximity, and a minority (respectively 14% and 16% of all trials) involved the change of atomic orientation. So, regardless of restrictions, and if an action was taken to make clusters more distinct, changes in the proximity of objects were always used, sometimes (14–16%) in combination with the rotation of objects.

5.3.2 Reconfiguration characteristics per physicalization

In this section, we elaborate on the reconfiguration characteristics across phases per physicalization. To reiterate, for each physicalization there exists a total of 80 trials (20 participants × 4 orientations), each of which involves phase 1 (restriction of changing one object) and a continuation into phase 2 (no restrictions). Table 5.1 column 3 shows the number (and percentage) of trials that involved the change of a single object (phase 1) and the change of multiple objects (phase 2). The subsequent columns of Table 5.1 provide numbers of the different reconfiguration strategies within each phase.

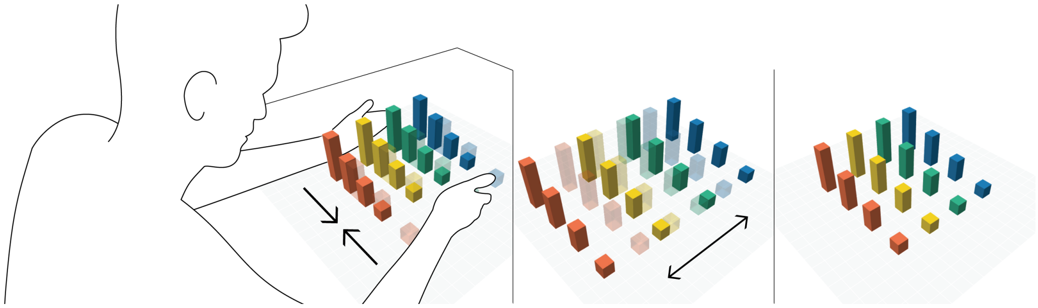


Figure 5.4: A digital render of one of the exemplar physicalizations (phys1, right), colors depict identified clusters by the participant. Various reconfiguration strategies were observed, including the increase of cohesion within clusters (left) and the increase of separation between clusters (middle).

5.3.2.1 Terminology

To describe the reconfiguration characteristics observed in our study, we introduce and define the following terminology for changes in the physicalizations after interaction:

C1 Proximity Change: one or more objects are relocated in the same plane. *For example, all objects in phys1 are moved closer together (see Figure 5.4, left).* Relocation is calculated based on each object's coordinates at their center on the x and y plane.

C2 Cohesion Change: objects have changed proximity (C1) such that the average distance of all the cluster's objects to the cluster's centroid has changed. *For example, in Figure 5.4 (left) all objects are moved closer together, increasing the cohesion of their clusters, but leaving the separation of clusters (C3) unchanged.*

C3 Separation Change: objects have changed proximity (C1) such that the average distance *between* all clusters' centroids has changed. *For example, in Figure 5.4 (middle) all objects are further apart, increasing the separation between clusters, but leaving the cohesion within clusters (C2) unchanged.*

C4 Atomic Orientation Change: one or more objects are rotated over any of their axes. We categorize three different atomic orientation changes we observed in our study: (i) *rotation within the plane* (x ↔ y; Figure 5.13B), (ii) *rotation from plane to space* (x/y → z; Figure 5.13A), and (iii) *rotation from space to plane* (z → x/y; Figure 5.14B). *For example, a long object laying flat is rotated from pointing east to north (i); is set up straight to point upwards (ii); or was standing and now laid flat (iii).*

			Proximity				Atomic Orientation			Other	
			Cohesion		Separation		x ↔ y	xy → z	z → xy	Swap	Rem.
P	ø	Changes	+	−	+	−					
1	1	3 *(4%)*	2 *(3%)*	1 *(1%)*	3 *(4%)*	-	-	-	-	-	-
	2	35 *(44%)*	23 *(29%)*	4 *(5%)*	16 *(20%)*	-	-	-	-	-	-
2	1	10 *(13%)*	3 *(4%)*	5 *(6%)*	9 *(11%)*	-	-	-	-	-	1 *(1%)*
	2	52 *(65%)*	25 *(31%)*	10 *(13%)*	40 *(50%)*	-	-	-	-	6 *(8%)*	-
3	1	76 *(95%)*	56 *(70%)*	19 *(24%)*	67 *(84%)*	44 *(55%)*	-	-	-	-	-
	2	79 *(99%)*	67 *(84%)*	23 *(29%)*	70 *(88%)*	47 *(59%)*	-	-	1 *(1%)*	-	-
4	1	74 *(93%)*	71 *(89%)*	5 (6%)	68 *(85%)*	21 *(26%)*	9 *(11%)*	37 *(46%)*	-	-	-
	2	80 *(100%)*	77 *(96%)*	14 *(18%)*	72 *(90%)*	45 *(56%)*	47 *(59%)*	46 *(58%)*	2 *(3%)*	-	-
5	1	59 *(74%)*	14 *(18%)*	6 *(8%)*	57 *(71%)*	2 *(3%)*	-	-	-	-	-
	2	79 *(99%)*	34 *(43%)*	9 *(11%)*	68 *(85%)*	12 *(15%)*	-	-	-	8 *(10%)*	1 *(1%)*
6	1	28 *(35%)*	20 *(25%)*	4 *(5%)*	25 *(31%)*	8 *(10%)*	14 *(18%)*	-	5 *(6%)*	-	-
	2	61 *(76%)*	40 *(50%)*	10 *(13%)*	47 *(59%)*	18 *(23%)*	15 *(19%)*	1 *(1%)*	5 *(6%)*	4 *(5%)*	-
Total	1	250 *(52%)*	166 *(35%)*	40 *(8%)*	229 *(48%)*	75 *(16%)*	23 *(5%)*	37 *(8%)*	5 *(1%)*	-	1 *(<1%)*
	2	386 *(80%)*	266 *(55%)*	69 *(15%)*	312 *(65%)*	122 *(25%)*	62 *(13%)*	47 *(10%)*	8 *(2%)*	18 *(4%)*	1 *(<1%)*

Table 5.1: Occurrence of changes and strategies applied per trial, per physicalization (P) after each phase (ø) across all participants. Cohesion refers to a change in the distance of objects within a cluster, and separation refers to a change in the distance between clusters. Increase and decrease are indicated by '+' and '–' respectively. Percentages per row are in relation to 80 trials per physicalization, the 'Total' row refers to all 480 trials.

5.3.2.2 Phase 1 per physicalization (restriction of changing one object)

Phase 1 represents the limited degrees-of-freedom interaction found in related work on interactive systems ([e.g. 69, 220, 136]). Across all reconfigurations at phase 1 (Table 5.1), for phys1 and phys2 the majority of trials did not involve the change of a single object. In contrast, for phys3-5 the majority of trials (95%, 93%, and 74%) did involve the change of a single object. For phys6, 35% of trials involved the change of a single object.

Figure 5.5 details the total objects that were changed at phase 1, showing an overview of the accumulated objects that were chosen for each physicalization. For phys6 there was a clear preference for three out of 16 objects (Figure 5.5, phys6, changed 6-8 times) and for phys3-5 there was a clear preference for a specific single object (Figure 5.5, phys3-5, changed 30, 56, and 47 times respectively).

Considering reconfiguration strategies per physicalization, we observe (see Table 5.1) that for phys1, phys2, phys3, and phys5 principally proximity changes were made (apart from a minor outlier) and for phys4 and phys6 a combination of proximity and atomic orientation changes were performed.

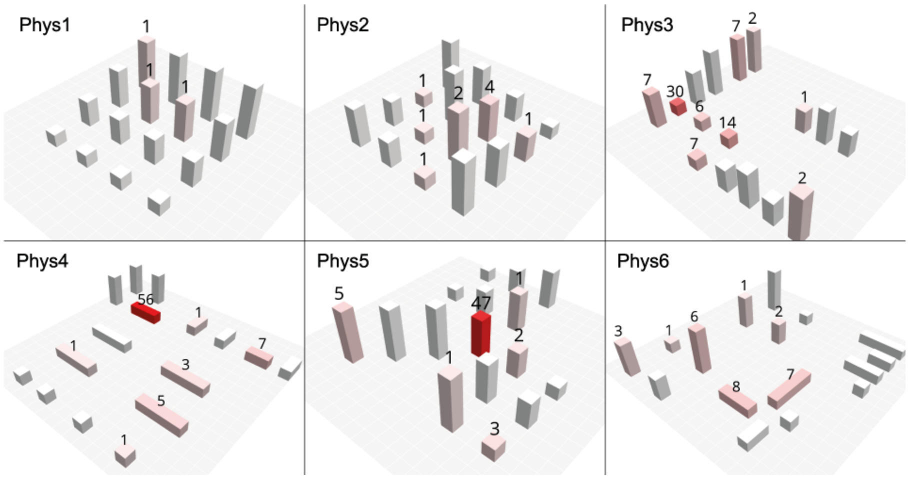


Figure 5.5: Objects changed at phase 1 per physicalization, ranging from 0 to 56. Color and annotations show frequency per object (0 values are omitted).

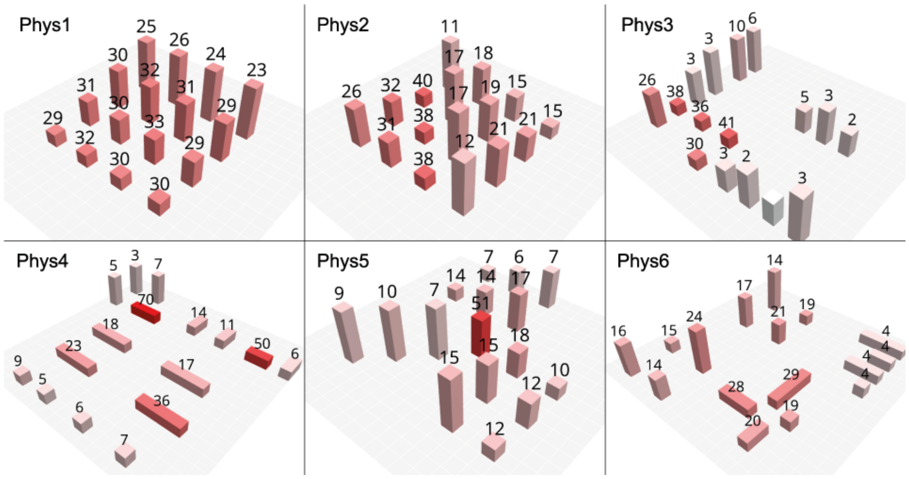


Figure 5.6: Objects changed at phase 2 per physicalization, ranging from 0 to 70. Color and annotations show frequency per object (0 values are omitted).

Phys	Phase 2	1	2	3	4	5	6	7	8	9	10	12	13	14	16
1	35	0%	0%	0%	11%	0%	0%	0%	0%	0%	0%	34%	0%	0%	54%
2	52	4%	8%	10%	13%	10%	25%	2%	0%	0%	6%	6%	0%	2%	15%
3	79	13%	43%	27%	6%	6%	4%	1%	0%	0%	0%	0%	0%	0%	0%
4	80	1%	34%	26%	13%	16%	4%	4%	0%	1%	0%	0%	0%	0%	1%
5	79	35%	24%	16%	10%	6%	1%	1%	0%	0%	1%	0%	4%	0%	0%
6	61	21%	11%	11%	33%	3%	2%	0%	11%	0%	0%	5%	0%	0%	2%

Table 5.2: The occurrence of changes at phase 2 (column 2) and the frequency of specific amounts of objects changed per trial (in % of all changes for that physicalization).

5.3.2.3 Phase 2 per physicalization (continuation of phase 1 with no restrictions)

Phase 2 refers to the free-form multiple degrees-of-freedom interaction possibilities as seen in related work on constructive physicalizations [99]. Looking at the reconfigurations performed at phase 2 (Table 5.1) for phys1, less than half of the trials (44%) involved any change of objects. For phys2 and phys6, this was for more than half of the trials (65% and 76%), and for phys3, phys4, and phys5 the majority of trials (from 99% to 100%). Figure 5.6 details the objects that were changed at phase 2, showing an overview of the accumulated objects chosen for each physicalization. Additionally, Table 5.2 shows the percentages for the total number of objects changed per physicalization.

Combining Figure 5.6 with Table 5.2, we can make the following conclusions for each physicalization. Our data shows that for phys1, the majority of reconfigurations involved exactly 12 or 16 objects (34% and 54%), with no specific preference for any set of cubes (see Figure 5.6). In contrast, participants used a varying number of objects for phys2 (Table 5.2) and showed a slight preference for which objects to reconfigure, reflected in various objects being chosen between 11 and 40 times (Figure 5.6). Phys6 involved the change of predominantly 1 or 4 objects (21% and 33%), which, with a slight preference for the bottom cluster, is reflected by the varying highlighted objects, being chosen between 4 to 29 times. For phys3 it varied between 1 to 3 objects (13-43%), with a clear choice of particular objects being changed 36, 38, or 41 times. Similarly, reconfigurations for phys4 primarily involved between 2 to 5 objects (13-34%), again, with a visible preference for some objects resulting in objects being chosen between 17 and 70 times. Lastly, for phys5, reconfigurations mostly involved 1 to 3 objects (16-35%), with a strong preference for one object being changed 51 times.

Considering the strategies used per physicalization at phase 2, we observed (see Table 5.1) that for phys1, phys2, phys3, and phys5 mainly *proximity changes* dominated (except for minor swapping in phys2 and phys5). For phys4 and phys6 we observed a combination of *proximity* and *atomic orientation changes*.

5.3.2.4 Reconfiguration strategies per physicalization

Combining the object frequency information from Figure 5.5 and Figure 5.6, and the occurrence numbers from Table 5.1 and Table 5.2, we can derive a general strategy per physicalization for phase 1 and phase 2. Figure 5.7 shows that for the majority of physicalizations an increase in cohesion and separation occur simultaneously, although with a different number of objects. Phys1 presents a special case as only cohesion or separation was increased, using 12 or 16 objects (Figure 5.7, phys1 – phase 2). Phys2 and phys5 are the only two physicalizations that show an example of an isolated

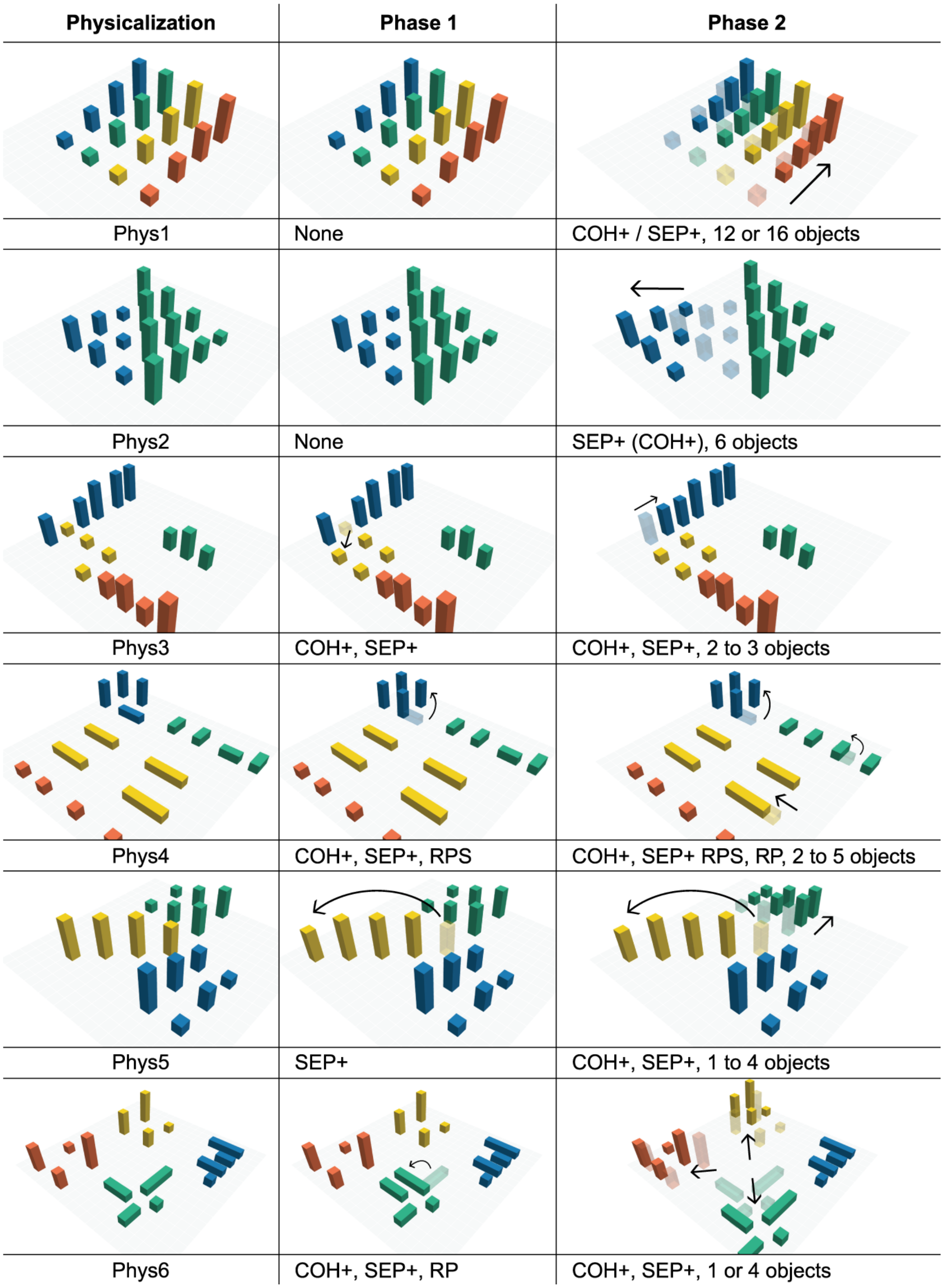


Figure 5.7: An overview of the main reconfiguration strategies observed per physicalization for both phases, including cohesion increase (COH+), separation increase (SEP+), rotation from plane to space (RPS) and rotation in the plane (RP). Colors are used to indicate identified clusters and shadows are used to show object positions prior to the changes made.

increase of separation (Figure 5.7, phys2 – phase 2, phys5 – phase 1). Lastly, phys4 and phys6 are the two physicalizations in which atomic orientation was part of the main strategy (Figure 5.7, phys4 – phase 1 and 2, phys6 – phase 1).

For phys1 and phys2 the overarching strategy at phase 1 was to not change any objects. The lack of change for these two physicalizations could be explained by the orderly arrangement of all objects, creating a constant internal structure. Therefore, it is difficult to effectively reorganize them by only changing a single object. For phys3 and phys5 the main strategy involved the change of a centrally positioned object (Figure 5.7, phys5 – phase 1) or one out of a selection of objects that were located on the conjunction of clusters (Figure 5.7, phys3 – phase 1). Hence, changing object locations was used to 'untangle' the overlapping relations, and improve the organization of the physicalization.

For phys4 the main strategy involved the change of atomic orientation of one or more objects. This was done to visually integrate with the atomic orientation of neighboring objects, while differentiating from the objects lying flat in the plane. This shows that manipulating the atomic orientation change of an object, inevitably influences its cluster's cohesion and separation, as the coordinates of the center of the object change. In this case, (the center of) the object got closer to its cluster centroid (Figure 5.7, phys4 – phase 1). The mixed orientations of objects within clusters invited participants to make changes to individual objects of different clusters. Lastly, the main strategy for phys6 was similar to phys4. However, at phase 2 we observed the increase of separation and cohesion over atomic orientation changes (Figure 5.7, phys6 – phase 2).

To summarize, our data shows that exemplar physicalizations with a constant internal structure are likely to involve either none or many changes (see phys1 and phys2); physicalizations representing overlapping cluster borders are likely to motivate a change of one or more centrally positioned objects (see phys3 and phys5) and; physicalizations with objects in mixed orientations likely result in rotation changes to integrate and/or differentiate their atomic orientation of objects (see phys4 and phys6). This demonstrates that when physicalizations show strong adherence to pre-attentive visual properties, then few if any interactions are performed – and vice versa. This means that clusters that are visually separate and have consistent orientations within, do not motivate participants to reconfigure them. Conversely, ambiguous separation and orientation of clusters result in reconfigurations to reduce that ambiguity.

5.3.3 Reconfiguration strategies across *all* physicalizations

In the following sections, we discuss reconfiguration strategies more generally and in relation to participant actions and physicalization structure. As a reminder, changes in *proximity* and *atomic orientation* were most frequently used across physicalizations.

Proximity changes occurred for all physicalizations, whereas *atomic orientation* changes occurred most prominent for phys4 and phys6. In the remainder, we further dissect these two main strategies and report on some outlying strategies that we observed.

5.3.4 Proximity as reconfiguration strategy

In general, proximity changes were observed in 249 trials at phase 1 (52%) and 385 trials at phase 2 (80%). To illustrate, for phys1, we primarily observed either the increase of cohesion, in which participants decreased the distance within clusters (Figure 5.4 left), or the increase of separation, in which participants increased the distance between clusters (Figure 5.4 middle). Within our study, we observed different ways in which cohesion and separation changes can coexist (Table 5.1) and we will elaborate on three of these for both phases.

5.3.4.1 Simultaneous cohesion & separation changes

The most common proximity approach we observed was the *simultaneous increase of cohesion and separation*. For all trials, this strategy was applied 157 times at phase 1 (33%) and 219 times at phase 2 (46%), especially for phys3 and phys4.

To illustrate this behavior for phase 1, we take phys3 as a concrete example, for which behavior of this type was observed across 52 trials (65% of phys3 trials). As shown in Figure 5.7 (phys3 – phase 1), the cube that created overlap with another cluster is moved out of that cluster and closer to the objects with similar properties, increasing the cohesion within the cluster and increasing the separation between clusters. For phase 2, similar behavior was observed across 60 trials (75% of phys3 trials). Subsequent to phase 1, an additional object was changed to again increase its cohesion within and separation between clusters (see Figure 5.7, phys3 – phase 2).

In summary, from all proximity changes observed, the simultaneous increase of cohesion and separation was the most common. It can be expected that moving objects closer within a cluster to make them more *cohesive*, simultaneously also creates more distance between clusters that make them appear more *separate*. This coupling is expected, since cohesion and separation have an intrinsic relation in our Gestalt-based layouts. We observed participants applying this strategy as an effective way to create visual consistency, avoid ambiguity, and clarify the spatial relations of objects.

It remains an open question as to what extent the simultaneous increase of cohesion and separation is intended and/or conscious. For example, from participants' comments it appears that, at times, the focus was mainly on one (increasing separation *or* cohesion), whilst the other was a 'by-product' of the changes made. Further research would be needed to unravel the sense-making of users in these reconfigurations, and whether their intentions and resulting layouts are consciously coupled.

		COH			SEP		
Phase	changes	+	−	+ −	+	−	+ −
1	250	33%	6%	2%	36%	4%	12%
2	386	49%	7%	7%	45%	5%	20%

Table 5.3: Percentages of the different combinations within cohesion (COH) and separation (SEP) changes across phase 1 and 2, either for increase only (+), decrease only (–) or both increase and decrease (+ –).

5.3.4.2 Cohesion changes

Looking at cohesion changes in isolation (Table 5.3, columns 3-5), we distinguish between occasions in which both the increase and decrease of cohesion occurred (COH+ –) and occasions in which this occurred in isolation from each other (either COH+ or COH–). From these three combinations, the *sole increase of cohesion* was observed most frequently (Table 5.3, column 3), which refers to shortening the distance of an object or objects to their cluster centroid. For all trials, this approach was taken 156 times at phase 1 (33%) and 233 times at phase 2 (49%).

At phase 1, increasing cohesion often involved the ‘pushing in’ of an object into the cluster it was assigned to (Figure 5.8A). At phase 2, increasing cohesion would be performed by moving multiple objects of a cluster closer together evenly (Figure 5.8B).

Interestingly, of all trials at phase 2, 34 (10%) involved a special increase of cohesion, in which the objects were moved towards each other until they were touching, creating an internal distance of zero (Figure 5.8C). Nine participants showed this kind of action across physicalizations, and specifically for phys1. Even more noticeable, P4 performed this action for 18 of all their 24 trials.

Although decreasing the cohesion is a somewhat counterintuitive strategy for reorganizing clusters, there were some outliers in which this was applied. One example is P15, who explained that they performed a *decrease of cohesion* for the single cluster they identified in phys2, to increase the visibility of all individual data points (Figure 5.9A). Further, P19 applied *simultaneous increase and decrease of cohesion* for 75% of their trials of phys1 and phys2 to disrupt any possible other trends and strengthen the clusters they identified (Figure 5.9B).

In summary, looking at cohesion changes in isolation, participants generally performed the increase of cohesion over the other two cohesion behaviors, often by ‘pushing in’ a single object into their cluster or moving multiple objects together evenly. This behavior resonates with achieving visual consistency within clusters. However, maintaining the exact internal structure of clusters seems to be less important. For example, rather than moving an entire cluster evenly away from another cluster,

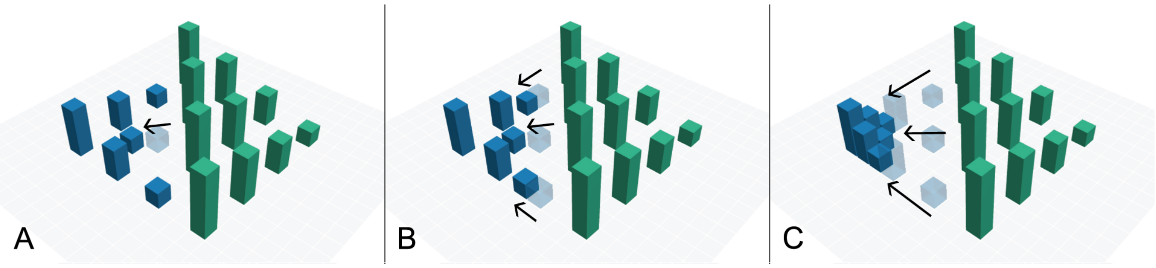


Figure 5.8: For phys2, an example of (A) phase 1 cohesion increase, (B) phase 2 cohesion increase, and (C) a unique approach to cohesion increase until objects are touching.

participants chose to move particular objects closer 'into' a cluster (Figure 5.8B). This means that the internal structure of the cluster and its location (the centroid) changed as well. In these approaches, the focus is on the cohesion of one particular cluster, over (i) the separation with other clusters and/or (ii) the location of the cluster in the complete canvas.

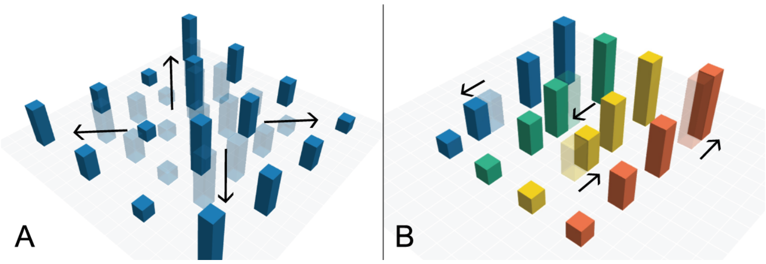


Figure 5.9: Examples of (A) cohesion decrease for phys2 and (B) simultaneous cohesion decrease and increase for phys1.

However, in some cases, deliberate attention to the overall physicalization was observed, resulting in seemingly counterintuitive behavior (i.e. cohesion decrease; Figure 5.9A) to reduce the occlusion of clusters and data points in the physical space. Here, the layout was treated as a whole, where the focus was on reducing ambiguity and/or improving the visual consistency of the entire layout, over the visual consistency and/or ambiguity of a singular cluster.

5.3.4.3 Separation changes

Looking at separation changes in isolation (Table 5.3 columns 6-8), we distinguish between occasions in which both the increase and decrease of separation occurred (SEP+ −) and occasions in which this occurred in isolation from each other (either

SEP+ or SEP–). From these three combinations, the *sole increase of separation* was observed most frequently (Table 5.3 column 6), which refers to increasing the distance between the centroids of neighboring clusters. For all trials, this approach was taken 171 times at phase 1 (36%) and 218 times at phase 2 (45%).

The general approach we observed for increasing separation, especially across phase 1, was the move of a single object to the opposite side of its cluster, to make this cluster appear more distant from the other clusters. A clear example is phys5, as one single object was relocated 47 times at phase 1 (59%). As can be seen from Figure 5.7 (phys5 phase 1), the relocation of the object does separate the clusters without changing the internal cohesion of that particular cluster (although the order of objects changes).

Across phase 2 we observed a general separation approach of relocating a complete cluster further apart from others, maintaining its internal structure (Figure 5.10B). However, unique variations of this separation behavior occurred, for example by moving parts of a cluster to increase the separation between (Figure 5.10C).

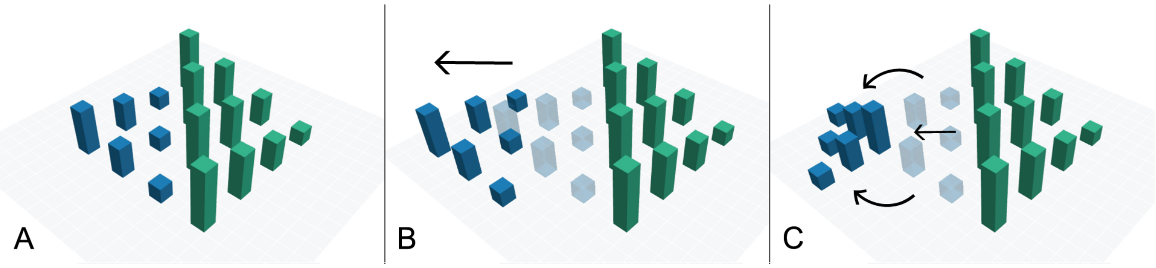


Figure 5.10: (A) Initial structure of phys2, (B) after separation increase, and (C) after separation increase by moving part of a cluster.

In comparison to cohesion, the *simultaneous increase and decrease of separation* occurred more often across phase 1 (12%) and especially phase 2 (20%). This can be explained by the occasional difference between the verbal explanations of participants and their execution of the change. To illustrate we use phys3 as an example (Figure 5.11). P8 explained that they wanted to increase separation for the cluster of 3 cubes, which is performed successfully from the largest cluster. However, simultaneously, the cluster of cubes comes closer to the two remaining clusters, decreasing separation.

In summary, looking at separation changes in isolation, participants' actions generally resulted only in an increase in separation, either by relocating a single object to the opposite side of its cluster, or moving a cluster's centroid further away from others. In a similar manner to cohesion, this behavior was expected as it resonates with achieving visual consistency between clusters. However, in contrast to a cluster's internal cohesion, cluster separation involves moving one or more clusters further apart, and, as such, is more dependent on the physicalization canvas as a whole. This

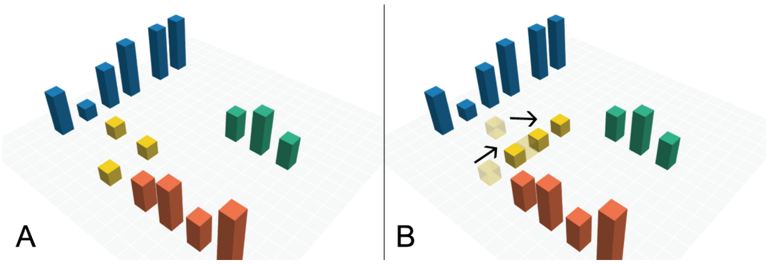


Figure 5.11: (A) Initial structure of phys3 and (B) after simultaneous separation increase with the largest cluster and decrease with the two remaining clusters.

potentially explains some observed behavior where participants moved a cluster further away from another, indirectly causing it to come closer to another neighboring cluster. Depending on the participant and task at hand, this might not have been the focus point of the participant.

It is important to note that cluster separation is rather susceptible to internal restructuring, as not only relative internal distances change, but also absolute locations (cluster centroids). To give an example, moving an object to the other side of its cluster, could leave the cohesion unchanged. However, this does alter the centroid's location and therefore the distance to any neighboring clusters. Since a cluster can contain more than one object, the potential to affect separation increases. Given our measure of separation (centroids' distance to their closest neighbors) many unintentional separation changes (either increase or decrease) could occur.

5.3.4.4 Discussion: Proximity as reconfiguration strategy

Within the reconfiguration strategy of proximity, the overarching approach was to simultaneously increase cohesion and separation. In other words, moving objects of a cluster closer together while also moving them as a cluster further apart from neighboring clusters. We additionally observed both approaches used in isolation (e.g., only cohesion) with a few combinations, some more intuitive than others (e.g., simultaneous increase and decrease of cohesion).

Our observations show parallels with 2D evaluation concepts such as *separability* and *integrality* [164], which refer to the extent to which multiple visual channels can be perceived or attended to independently. The simultaneous increase of cohesion and separation results in objects within a cluster becoming more integral, and objects between clusters becoming more separable. Hence, this is an effective means to create visual consistency in a physicalization and reduce any ambiguities.

Our observations also show differences with 2D visualization, in that perspective plays a central role in the perception of physical distance and space. Concepts such as separability and integrality can be perceived differently in 3D space compared to 2D space. For example, moving two clusters further apart so that they are positioned left and right from the viewer (along the x-axis) might visually appear more separate than two clusters being far and close (along the y-axis), as after moving them apart they might still occlude each other visually.

Counterintuitive behaviors can be discussed in light of physical distance and space as well. Those that we observed, such as simultaneous increase and decrease of separation, or the disruption of possible other trends, are difficult to explain from a purely visual encoding point of view. However, when taking into account the possible difference that exists between perceived physical information and actual information, these behaviors can be explained by looking at visual occlusion that can occur in physical space.

The observed simultaneous increase and decrease of separation can be explained by participants not seeing the true proximity between certain (clusters of) objects due to their perspective. In other words, some (clusters of) objects might appear visually closer or further apart than they actually are, depending on the perspective of the viewer, which affects the reconfigurations participants deem important to make the cluster(s) more distinct. This resonates with prior observations of *proximity occlusion* in Chapter 4 [191].

Likewise, the observed behavior of deliberately disrupting trends could be explained by participants not seeing the true continuity of certain (clusters of) objects due to their perspective. In other words, some (clusters of) objects might appear visually more or less connected than they actually are, which affects the reconfigurations participants deem important to make the cluster(s) more distinct. This resonates with prior observations of *continuity occlusion* in Chapter 4 [191].

5.3.5 Atomic orientation as reconfiguration strategy

Atomic orientation change occurs when one or more objects are rotated in any of their axes. In general, this reconfiguration strategy was performed for 66 trials at phase 1 (14%) and 78 trials at phase 2 (16%). Herein, we discuss three different approaches we observed in our study: (i) rotation within the plane, (ii) rotation from plane to space, and (iii) rotation from space to plane. We elaborate on each of these in the following sections, for both phases 1 and 2, and illustrate them with concrete examples from the physicalizations.

5.3.5.1 Rotation within the plane

We observed the approach of rotation within the plane 23 times at phase 1 (5%) and 62 times at phase 2 (13%), exclusively for phys4 and phys6. As a concrete example, we discuss the changes made for phys6 at phase 1 (Figure 5.12). All the observed rotations in the plane were performed using one of the two tallest objects of the green cluster in the bottom left of the plane (Figure 5.12A). Participants had different explanations for their actions, and performed them to either (i) increase separation to the closest upright cluster (Figure 5.12B), (ii) integrate with the atomic orientation within the cluster (Figure 5.12B), or (iii) increase separation to the other flat-lying cluster (Figure 5.12C). Lastly, at phase 2, two participants reverted their change and performed separation increase instead, preserving the initial structure of the cluster (Figure 5.12D).

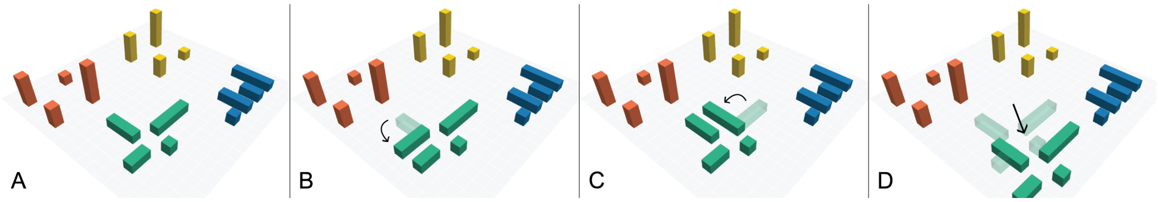


Figure 5.12: (A) Initial structure of phys6, and after rotation in the plane to either (B) increase separation with the upright cluster, (C) differentiate atomic orientation with the other flat cluster, and (D) for phase 2 separation increase instead.

To summarize, rotations within the plane of one or more objects were performed with different intentions, such as increasing separation or differentiating atomic orientation with other clusters. These rotations in the plane exclusively occurred for phys4 and phys6, which can be attributed to their objects having mixed orientations.

All rotations in the plane were performed using one of the larger objects. This is likely because their size has a larger impact on the visual consistency when its orientation changes, compared to smaller objects. The large (i.e. wide or deep) objects look visually different from the viewer's perspective when it is observed from a different angle. Therefore, especially with the restriction of changing only one object, rotating larger objects is an effective means to make clusters more distinct and improve the overall visual consistency.

5.3.5.2 Rotation from plane to space

We observed the approach of rotation from plane to space 37 times at phase 1 (8%) and 47 times at phase 2 (10%). However, looking solely at phys4, rotation from plane to space was performed 37 times at phase 1 (46%) and 46 times at phase 2 (58%). Hence, we will discuss phys4 as an example to illustrate this approach.

The general approach we observed across trials and phases for phys4 was the plane-to-space rotation of a specific flat-lying object (37 times), for it to integrate with the atomic orientation of its neighboring same-sized objects of the same cluster

(Figure 5.13A). In contrast to phase 1, in which this single rotation prevailed, in phase 2, two different types of rotations were performed equally as often (46-47 times; Figure 5.13A & B). So, in addition to the rotation from plane to space of the flat-lying object, a rotation of an object within the plane was performed.

As can be seen from Figure 5.13, three different approaches observed for phys4 at phase 1, would result in a similar final layout at phase 2. From the participants' comments, it became clear that these different approaches were related to the extent to which they perceived objects of similar size as either similar or different due to their atomic orientation. Participants aimed for visual alignment and made the collective atomic orientation more consistent per cluster; in the restricted phase 1 this led to varied rotations as the first preference, however, in the unrestricted phase 2 led to a similar visual outcome.

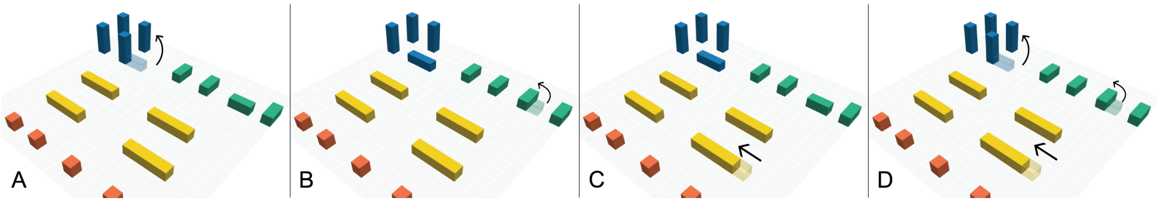


Figure 5.13: For phys4, (A) phase 1 rotation from plane to space, (B) phase 1 rotation within the plane, (C) phase 1 cohesion increase, and (D) although 3 different phase 1 actions, the same result at phase 2.

In summary, for rotations from plane to space, we generally observed that rotations of objects were performed to make the objects integrate more with the atomic orientation of the cluster they were assigned to. This held true for single changes (phase 1) and multiple (phase 2).

The layout with mixed orientations in phys4 motivated the approach of rotating objects from plane to space – and in particular a specific flat-lying object in the blue cluster. Due to its stark visual ambiguity within that cluster (i.e. being the 'odd one out'), it was primarily chosen in this approach (37 times). Hence, placing that object from flat to upright proves to be an effective way to improve the visual consistency of that particular cluster – more than a rotation within the plane would do for, i.e., the green cluster. This suggests that not all types of rotations in 3D space result in equally impactful visual results, and that rotations within the plane (between x and y) might be perceived as less impactful than rotations from plane to space (from xy to z) or vise versa (from z to xy).

In contrast to rotation within the plane (discussed earlier), rotation from plane to space was not frequently observed for phys6 ($\leq 1\%$). We observed that although the layout of phys6 uses mixed orientations, there is a stark separation in the proximity between four potential clusters, and within these clusters the orientation is fairly consistent – especially their orientation towards space. Hence, participants were less inclined to make rotations from plane to space to improve visual consistency.

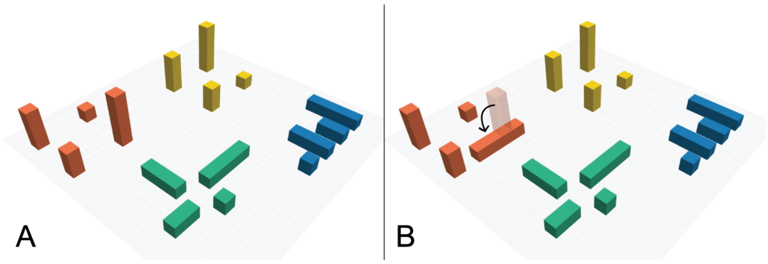


Figure 5.14: (A) Initial structure of phys6 and (B) after rotation of a single object from plane to space.

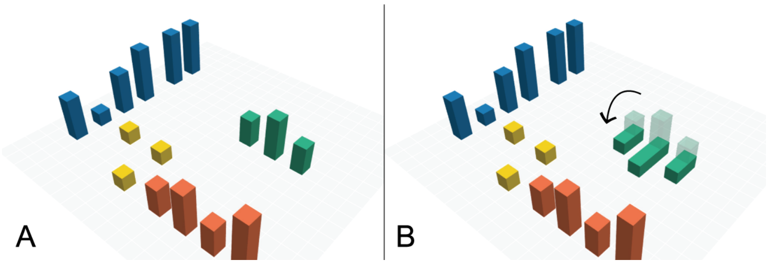


Figure 5.15: (A) Initial structure of phys3 and (B) after cluster rotation from space to plane.

5.3.5.3 Rotation from space to plane

We observed the approach of rotation from space to plane 5 to 8 times at phases 1 and 2 (1-2%), only across 3 physicalizations. As a concrete example, we discuss the changes made by P5 for phys6 at phase 1. We observed that they performed consistently the rotation from space to plane of one of the tallest upright objects (Figure 5.14). They and one other participant that performed this exact behavior (P11) explained that they aimed to differentiate between the two upwards clusters, by decreasing the consistency in object orientation of one of the clusters. In this way they would not have similar consistencies in orientation, hence becoming more distinct.

For phys3 at phase 2, we observed a unique case in P1, as they rotated one of the clusters from space to plane and explained that they intended to differentiate between the two clusters by changing the atomic orientation of one complete cluster (Figure 5.15).

In summary, for the approach of rotation from space to plane, we generally observed that rotations of one or more objects were performed to create a differentiation between clusters by creating inconsistencies in orientation. In phys6, for example, instead of strengthening the visual consistency within the clusters (as was seen for the previous two atomic rotation approaches), an ambiguity was introduced to make the cluster differ from another cluster that would otherwise appear similar. Likewise, in phys3, a complete cluster was made more ambiguous, to make the cluster stand out from the rest of the physicalization layout. We conclude that rotation from space to plane is particularly useful to create local ambiguities and to improve the distinction of clusters in the overall layout.

5.3.5.4 Discussion: Atomic orientation as reconfiguration strategy

Within the reconfiguration strategy of atomic orientation we observed three approaches: (i) rotation within the plane, (ii) rotation from plane to space, and (iii) rotation from space to plane. In general, we observed that rotations within the plane and rotations from space to plane were performed to increase separation and/or differentiate the atomic orientation with other clusters. For rotation from plane to space, the intention was to make the object integrate more with the atomic orientation of the cluster it was assigned to.

As opposed to flat 2D visualizations, which allow for rotation in solely x and y directions, rotation in physical space with the additional z-axis has different implications. We observed that rotations could either be used to integrate within or differentiate between clusters, which again shows parallels with the notions of integrality and separability from 2D visualization work [164]. However, it remains an open question to what extent rotations across the three axes are perceived similarly or equally, such as rotations in the plane versus rotations from plane to space. One example is, as illustrated in interactions with phys3 (Figure 5.15), a complete cluster that was reconfigured from space to plane to bring them to a ‘different dimension’ in relation to the clusters standing upright. Differently, for phys6, the atomic orientation change of a single object within a cluster was used to differentiate between clusters. Hence, it can be questioned if rotations across all three axes are perceived and utilized similarly, or that particular types of rotation can be used for different intentions and can have different implications.

We connect our work to prior findings from psychophysics on the notion of *radial-tangential illusion* [8], which describes that lengths represented away from and towards the body are perceived to be larger than lengths that are presented from side to side to the user. This indicates that the perceived length of an object depends on its orientation. Since we applied 4 orientation conditions for each of the 6 exemplar physicalizations, this would result in objects in some orientations being perceived as

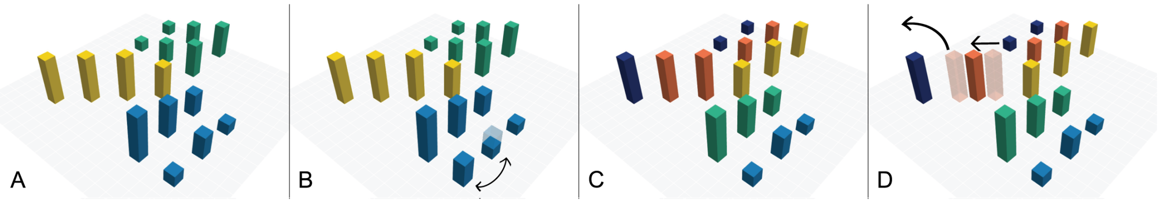


Figure 5.16: (A) Initial structure of phys5 as perceived by P14 (3 clusters) and (B) after the swapping of 2 objects (bottom left) to increase cohesion. (C) Initial structure of phys5 as perceived by P6 (5 clusters) and (D) after the removal of an object.

'tall' whereas in other orientations as 'wide'.

To give another example, if one observes two objects of similar size, one standing upright and one lying flat away from the user, they might be perceived more similarly, than the two same objects but then standing upright and one lying flat from side to side to the user. This can be explained by *atomic orientation occlusion* [191] (Chapter 4), which describes that due to different atomic orientations of objects, objects of similar size might look different and objects of different size might look similar.

To conclude, atomic orientation occlusion of physical data objects interacts/interferes with the concepts of integrality and separability in ways different from 2D visualization. Hence, it invites for further reconfiguration possibilities and/or different layers of information. It could be further explored how we can assign meaning to different types of rotation of data objects in physical space.

5.3.6 Other reconfiguration strategies

We observed other minor reconfiguration strategies for a total of 20 times across phases 1 and 2 (1-4%) but only for 3 physicalizations. We discuss all changes made, in which no proximity change and/or atomic orientation change occurred. These minor strategies almost exclusively occurred at phase 2.

The swapping of objects was observed 18 times at phase 2 (4%), across three physicalizations. Swapping refers to the instances in which no proximity or atomic orientation changes have been made, but two or more objects have swapped their location on the canvas. This approach generally was performed to either strengthen the perceived patterns or disrupt them further to put the emphasis on one larger trend. One example is P14, who swapped objects for 75% of their trials for phys5 (Figure 5.16B) to integrate the trend of that cluster with the other increasing trends.

Although removal was not part of the procedure instructions, we observed 2 cases in which a single object was removed. This was performed by P15 at phase 1 for phys2, and by P6 at phase 2 for phys5 (Figure 5.16). P6 removed one object and aligned the others to make sure all x and y rows and columns contained 3 objects. P15 explained they removed the object as they wanted to prevent possible other trends to be seen in the physicalization structure.

To summarize, in 20 trials, the reconfiguration strategies of swapping and removal were used to either strengthen the perceived patterns or to reduce the visibility of other trends. The swapping of objects was thereby used to improve the overall visual consistency of the physicalization layout, where the absolute location of the cluster (the centroid) remained unchanged. Visually, the changes made through swapping appear more subtly, as it improves the overall visual consistency (i.e. trends) without changing the location of a cluster. The removal of objects was used to 'declutter' the layout from any ambiguous data point or ambiguity in the trends perceived. However, whether and how we should anticipate this reconfiguration strategy is uncertain, as users effectively remove data points in the task of making clusters more distinct.

5.4 Discussion

In this chapter, we investigated people's spontaneous reconfiguration strategies for the reorganization of exemplar physicalizations (from the physical bar chart archetype) to make clusters more 'distinct'. Our findings show that proximity change was generally the most used strategy to reorganize clusters, primarily resulting in increased cohesion and separation. We observed that participants performed few or no changes in physicalizations with a constant internal structure (such as phys1 and phys2). Likewise, where the physicalization had a less distinct structure and higher separation (such as phys6) no changes were made. If physicalizations adhere strongly to perceptual properties, i.e. they are visually consistent and do not contain ambiguities, there is no need to manipulate them. In contrast, for more complex physicalizations, i.e. with mixed orientations or objects in a diagonal line (such as phys4 and phys5), diverse changes were made. If physicalizations adhere weakly to perceptual properties, i.e. the orientations are visually ambiguous, users are inclined to manipulate them to reduce or eliminate these ambiguities. Overall, our results suggest that future (dynamic) physicalizations should consider proximity changes as a main form of interaction, as it proves an effective way of improving visual consistency and reducing ambiguity in visualizations.

5.4.1 Differences between reconfiguration strategies with or without restrictions

We observed different reconfiguration strategies when comparing the two study phases. In phase 1 (with the restriction of changing one object), we generally observed participants increasing cohesion by 'pushing' an object into a cluster, often compromising the initial cluster structure. For phase 2 (no restrictions), increasing cohesion was achieved by moving objects of a cluster closer together. Similarly, when increasing separation in phase 1 participants would move an object to the other side of its cluster, visually changing the initial cluster structure, whereas for phase 2 the complete cluster would be relocated (maintaining the initial cluster structure). In other words, when participants were restricted to changing one object, they would sometimes compromise the visual consistency of the initial cluster structure, to increase cohesion and/or separation, whereas with no restrictions, they choose to maintain the cluster structure. Our study showed that regardless of more or less restrictions, participants were able to reorganize the physicalizations. As the design of reconfigurable physicalizations requires the consideration of the level of granularity, degree of manipulability, and level of actuation [134] this poses the question of what combination of limitations and freedom will support users in reconfiguring data. This opens up further questions about the extent to which future physicalizations should dictate and/or restrict the intended interaction with data.

5.4.2 Proximity and atomic orientation as novel encodings in 3D space

Our findings are in line with related work from shape-changing interfaces and constructive visualization that showed that proximity was used to differentiate between clusters of data [99, 221]. For example, in EMERGE [221], participants would hide irrelevant data to either emphasize or create a barrier between grouped rows, and with constructive token visualizations [100], participants would create differences in proximity in the canvas to show which data was more or less related within the visualization. These actions are equivalent to the increase of cohesion and separation we observed in our study, and also show parallels with the concepts of integrality and separability of 2D visualization [164]. However, related work remains close to the traditional visualization concepts of columns and rows, whereas the physical representation of data invites the more free-form use of 3D space. While work on constructive visualization [99] showed that some participants freely made use of the 3D space (e.g., creating rows and columns, but also combinations of plane and stacked organizations), actual interactive systems such as EMERGE [221] and ShapeCanvas [64] provide very limited physical manipulations considering data points are fixed and can only be moved up or down.

Extending related work, our work illustrates that participants were confident in performing spatial data object organizations on abstract physicalizations that went beyond the traditional representation of data. Although *proximity changes* came out as the most effective to reorganize physical data objects, our study also opened up the consideration of *atomic orientation* as a way to reconfigure data points. It could be a promising new way of encoding physical data, allowing for the indication of similar or different clusters, creating multiple 'dimensions' or categories, and allowing people to perform interactions between these dimensions by using rotation.

Our findings enable new opportunities for designing systems whose focus is not solely on linear manipulation. The rotation of data objects could allow for novel interactions with data representations. For example, rotating objects to put more or less emphasis on data points, make distinct dimensions or categories in the data, or allow for easier comparisons regardless of perspective. To conclude, future work could further explore how the atomic orientation of data points provides new ways of encoding data in 3D space. For example, dynamic physicalizations that allow for both human intervention and actuation to perform free-form cohesion and separation changes to organize data objects in physical space.

5.4.3 Reconfiguration for data presentation and organization in physical space

One of the key reasons for separating and organizing clusters is for data presentation. The utility of proximity and atomic orientation changes could be different between abstract physicalizations and concrete representations. Therefore, the free organization and presentation in space will not be suitable for all types of physicalization. To give an example, it might be more suitable for the communication of trends over actual data points. Related work on static physicalizations that use more expressive shapes [119, 216], could benefit from exploring organization in a broader sense and how it can support engagement and reflection.

Further utilizing the physical space for data organization also has implications for the interpretation of data. One example is, if we allow for the free organization of data points using atomic orientation, this might require a new approach to designing axes labeling to make sure that users are still able to read data accurately. Moreover, we need to be sure that one person's changes will be interpreted in the same way by others and how manual reconfiguration will exactly coexist in case of multiple users and/or with for example dynamic datasets.

Looking at an overview of example physicalizations [53] we believe that reconfiguration strategies can impact real-world applications. More concrete work on geographical data, molecular structures, and constructive visualizations (see [53, 99]) would benefit from incorporating cohesion and separation mechanisms in the interaction design and spatial layout of their physicalizations. Cohesion and separation could then be used to further communicate patterns, facilitate transformations, and inform data interaction with these physical systems.

For example, cohesion and separation changes could facilitate the tweaking of cluster algorithms in an exploratory manner, based on ad hoc and on-the-spot insights from the physicalization. If a researcher argues a data point is more strongly associated with a particular cluster due to their tacit knowledge – more than the visualization indicates – pushing that data point into the appropriate cluster then provides feedback for that algorithm. Allowing for reconfiguration hereby allows the researcher to add weights to the data points based on (interaction with) the physicalization itself. Another example use case would be to use cohesion and separation changes as transformations to the dataset – informing the actuation of the dynamic physicalization itself. Pushing objects closer together could result in the physicalization adapting its scale (e.g., from linear to logarithmic) to accommodate the changed data point, offering a quick and intuitive adaptation of the visualization without altering the underlying data value.

Whereas we observed a variety of reconfigurations among participants, the overarching goals were to (i) improve visual consistency and/or (ii) reduce or eliminate ambiguity in the physicalization. Expanding our findings beyond data analysis and presentation, the physical reconfiguration of information objects poses an interesting design strategy. Perhaps, tangible user interfaces (TUIs) could translate input into preferences and actionable results (e.g., smart home control) or be used as a management tool (e.g., with axes being priority, employees, urgency, etc.). The reconfiguration strategies can inform the composition of interactive elements in a TUI and provide design ideas for intuitive ways of interacting with these elements. To give an example, concepts such as cohesion, separation, and rotation can inform TUI themes such as *tangible manipulation*, *spatial interaction*, and *embodied facilitation* [93] and help inform how bodily interactions with physical objects in space should translate to underlying computation. One approach is to, for example, use cohesion and separation to clarify (spatial) relations between functionalities of the TUI elements, before and/or during interaction. The atomic orientation of TUI elements could be further explored as a means to perform rotations, allowing interactions on different 'dimensions'.

5.4.4 The future design of static, constructive and dynamic physicalizations

This study shows one example of using physical space, in a lab-based setup, which prompts us that there are many other things that should be examined. This includes improving the usability of data objects with different physical properties than, for example, bar charts and exploring future approaches to reconfiguration in space (degree of manipulability), such as stacking, 360 degrees rotation, and shape deformation. We provide a few suggestions about how this new knowledge on reconfiguration could be supported with three types of reconfigurable physicalizations.

Looking at static and constructive physicalizations, the data objects or 'buckets' of data could be designed in such a way that they allow for more effective comparison in 3D space. This includes their affordance to be compared with each other on multiple axes, or considering their rotation to create a high degree of encoded complexity when constructing visualizations from scratch. Future work could explore the design of combinations of these manipulations to utilize 3D space in physically authoring, analyzing, or presenting data representations.

For dynamic physicalizations, it could be beneficial to reconsider the current technology implementations and see how actuation plays a role in proximity and atomic orientation changes. In 3D space, data values are not solely communicated in height, but also, for example, by their location, orientation, size, shape, behavior, and all this in relation to other data objects and the user(s). Research in the field of physicalization should better understand what type of interactions and what relation between human intervention and system actuation allow the user to most effectively perform data organizations. The way that participants applied cohesion and separation changes in our work partially informs us on how we should implement these in transformations with and actuation of dynamic physicalizations. To give an example, dynamic physicalizations could be responsive before, during, and after (temporary) changes are made to further facilitate data reorganization and presentation.

5.4.5 Limitations

Our study has some limitations that we outline below. First, our study was conducted with a non-interactive prototype in an experimental lab setting. To avoid recognition bias, we used 6 designs that were abstract representations of data based on the physical bar chart archetype of physicalizations (such as [69, 136, 220]). Whilst our results generalize over these different exemplar physicalizations, it is unclear how they translate to other data representations, with diverse form factors and system implementations.

Second, whereas with 2D visualizations there are many kinds of interactions reported in the literature, our work explored basic reconfiguration strategies, not an exhaustive list of possible interactions. Future work is necessary to operationalize these reconfiguration strategies in the form of 'real' datasets and interactive systems to reveal the implications of context on people's sense-making, how someone else interprets one person's change, and how these manipulations change the underlying data model. However, our results are a first starting point for the design of such follow-up studies and systems.

Third, our analysis is based on final configurations at the end of phase 1 and phase 2, thus only provides two snapshots and does not capture the interaction process. These isolated experimental observations of the actions of participants, do not include participants' behavior and – except for anecdotal quotes – their 'intent'. One example is that some participants placed objects back to their original position at the end of phase 1, to start phase 2 with 'a clean slate', whereas others would make changes more ad hoc; and some participants would temporarily make changes to check if they created the result they desired and if not, undo the change. This resonates with the concept of *offloading* as discussed by Kirsh [121] and Liu and Stasko [141], which explains that rearrangement of physical objects can serve not only to highlight categories/clusters, but also to simplify choice and/or to prevent us from considering irrelevant alternatives. Future work could study in more depth how these strategies, and changes in strategies, match the participants' sense-making process.

Fourth, our study uses a non-interactive 'data-agnostic' approach as used in prior work that studied aspects of physicalization in isolation [100, 109]. It is also motivated by work from Elliott et al. [59] which describes experimental methods to study visualizations systematically by breaking them up into specific isolated topics and paradigms. An inherent limitation of this approach and methodology is the removal of context, as we studied reconfiguration independently from data actions with a real dataset. Our apparatus were abstract exemplar physicalizations (similar to [109]) and the tasks were focused on spatial clustering. Hence, the reconfigurations that participants performed in our study had the aim of rearranging data points, rather than transforming them. Future work could study the further implications of context on people's interactions with physicalizations and how cluster reconfiguration could be mapped on data transformations.

5.5 Conclusion

This chapter reports on the extent to which participants were able to use reconfiguration to reorganize physical data objects within a physicalization. We conducted an experiment with 6 exemplar physicalizations and asked participants to reorganize them using reconfiguration with or without any restrictions. Our study shows that changes in proximity and atomic orientation are the two main reconfiguration strategies that were used to reorganize physical data objects into distinct clusters. Additionally, we provide a further dissection of these strategies and illustrate how these allowed for the change of cohesion and separation of clusters. With our work, we aim to inform the future design of interactions with dynamic physicalizations, which can go beyond the use of the plane and utilize the physical 3D space.

In the subsequent chapter, we will utilize the work on the influence of perspective on people's perception of (Chapter 4) and interaction with abstract bar chart physicalizations (this chapter), to investigate the role of data labeling when constructing bar chart physicalizations from scratch (RQ4). Therefore, in contrast to the abstract apparatuses and tasks used in Chapter 4 and this chapter, the following chapter will use exemplar datasets and concrete creation tasks to study participants' sense-making of physicalizations across orientations.

Chapter 6

Approaches for Constructing and Labeling Physicalizations[1]

In contrast to screen-based visualizations, there is currently a very limited understanding of how to label or annotate physicalizations to support people in interpreting the data encoded by the physicalization (as further discussed in the fourth research challenge in Section 2.4.4). In the preceding chapters, we investigated the influence of physical context on physicalizations more generally, and the impact of physicality on the perception and reconfiguration of bar chart physicalizations. In this chapter, we investigate the role of data labeling when constructing and contextualizing physicalizations in physical 3D space. With contextualization, we refer to the inclusion of contextual elements such as data labels, axes, legends, and annotations to support the extraction of information from physical representations of data.

From a conceptual viewpoint, the current definition of physicalization [108] focuses on materiality and does not highlight 'data labeling'[2] as an explicit part of the physicalization itself. However, a physicalization cannot do without context; the physicality and spatiality of physicalizations explicitly open up questions such as (i) where to locate different kinds of labels (i.e. title, axes labels, and data values) in relation to the canvas and/or other data points, and (ii) how this is affected by user orientation (e.g., when multiple people are viewing the physicalization from different perspectives). More fundamentally, it remains unclear why, how, and when 'data labels' should be included in the design, construction of, and interaction with physicalizations.

---

[1] This chapter is adapted from the paper published as: **Kim Sauvé**, Argenis Ramirez Gomez, and Steven Houben. 2022. Put a Label On It! Approaches for Constructing and Contextualizing Bar Chart Physicalizations. In *CHI Conference on Human Factors in Computing Systems (CHI '22)*. ACM, New York, NY, USA, Article 82, 1–15. https://doi.org/10.1145/3491102.3501952

[2] Not to be mistaken with the term 'data labeling' as used in Machine Learning to describe the annotation of raw data to train a classifier.

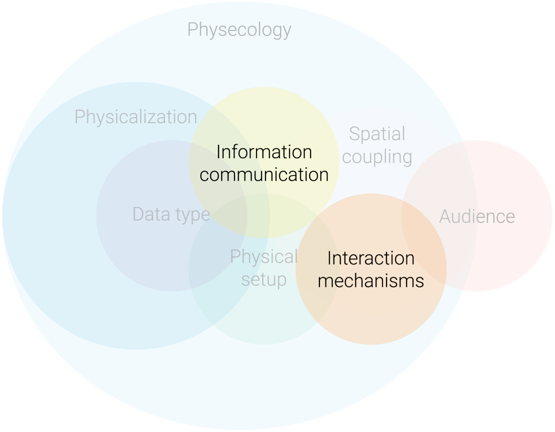


Figure 6.1: A diagram illustrating the position of Chapter 6 within the physecology. This chapter explores the role of data labeling in constructing and contextualizing physicalizations in physical 3D space, bridging the dimensions of Information Communication and Interaction Mechanisms.

Research on constructive visualization [99] focuses on explicitly understanding the translation process from raw data to physical form. While this approach has provided detailed insights into the construction of data points and structures of the physicalization, they similarly do not actively include data labeling in the authoring of physicalizations. For example Fan et al. [65] provide ready-made braille labels but leave contextualization of data open to participant's choice, and both Huron et al. [100] and Wun et al. [246] include the annotation of data as a subsequent task to the construction task. As observed by Wun et al. [246], the creation of physical data representations results in an *interrelation principle*: the placement and rearrangement of physical data objects in space – *loading data* – simultaneously influences the *visual mapping* and *presentation mapping* of a visualization. In line with this observation, we propose and argue that the act of 'data labeling' should be an active part of this process, further intertwining the construction and contextualization of physicalizations.

This chapter, which bridges the dimensions of Information Communication and Interaction Mechanisms within the physecology framework (see Figure 6.1), explores the creation process of physicalizations as a holistic endeavor rather than studying isolated components. By investigating the role of data labeling, we aim to enhance our understanding of how physicalizations can effectively communicate information, considering both the interaction mechanisms involved and the broader context of information communication.

In this chapter, we aim to answer RQ4: *how do people construct and label physicalizations as part of a constructive visualization process?* As studying data labels in isolation is artificial, our research explores the role of ‘data labeling’ in the entire construction process of bar chart-type 3D physicalizations [100]. We follow the approach from constructive visualization research, and *“study human behavior independently from the design of specific software tools”* [100] to inform the design of future physicalizations. To study this process, we designed a toolkit that allows for the creation of data visualizations in 3D space and includes data labeling as a ‘building block’ alongside the use of physical 3D tokens. We conducted a study with 16 participants who completed a total of 32 construction tasks. We contribute (i) an understanding of the role of data labeling in the construction and contextualization of physicalizations, (ii) an overview of how textual and physical constructs coexist in visualization designs, and (iii) reflections on coping strategies for contextualizing bar chart physicalizations across orientations in physical space.

6.1 Rationale

The focus of this study is to build a better understanding of the role of *labels* in physicalizations. With **data labels** or **data labeling** we refer to annotations that, like visualizations on a screen, highlight axes, data points, legends, and other visual structures that support people in reading and interpreting data effectively. While prior work has considered the labeling of physicalizations in various forms, these have almost always been post hoc activities from a necessity to counter some of the open challenges or common problems in physicalizations. Therefore, there are no real insights or principled approaches into how, if, and when to label physicalizations. While we can borrow initial insights from screen-based visualizations [5, 57, 79, 164], many of these do not translate directly to the context of physicalizations. Because of their physicality, people have very different strategies for perceiving, using, and interacting with physicalizations. This implies that more systematic research into labeling strategies and practices is needed to explore how physicalizations can be labeled effectively – taking into account their specific challenges around spatiality, user orientation, and perception.

As labeling is difficult and artificial to understand in isolation, we specifically examine labeling as part of the general construction process of physicalizations. Building upon the *interrelation principle* introduced by Wun et al. [246], we argue that it cannot be understood or studied in isolation. The interrelation principle suggests that constructing physicalizations is a highly intertwined process that combines various aspects of the *extended infovis pipeline model* [106]. For instance, when introducing a new token to the visualization, one must simultaneously decide how it is positioned in relation to other tokens and how it fits within the overall composition of the canvas. By studying and documenting the strategies that people take for labeling data, axes, clusters, and entire physicalizations, we can learn more about the role of labeling in the overall construction process, and also about how non-experts view physical structures and data points in relation to a given dataset. While studying the labeling of existing physicalizations might help build some insights into how data labeling works, we argue that this would also be a post hoc activity that reduces labeling to a second-class aspect of physicalization – where we suggest it should be a fundamental and inherent part of the overall physicalization design. As such, our study methodology studies labeling in combination with other constructive visualization processes [100, 246].

6.2 Methodology

The goal of this study is to investigate the role of data labeling (i) during the creation process of a physicalization, (ii) within the resulting visualization design, and (iii) when viewing the visualization from different orientations and perspectives. Our study is designed to document and highlight strategies and approaches towards constructing a 3D bar chart physicalization and annotate them with contextual labels using a custom design toolkit and methodology. We designed a task that required participants to build two physical visualizations given a toolkit including a set of physical colored blocks and textual labels. During the task, the researcher presented the participant with one dataset at a time and prompted them to build the resulting data using the toolkit. After the creation process, participants were asked to reflect on their visualization design during an integrative process, as the canvas was rotated in increments of 90 degrees. On each rotation, participants were required to observe their visualization from the new viewing angle, and (if desired) make changes to their labeling.

6.2.1 Apparatus

We created a custom-made toolkit including plastic building blocks and paper labels inside a storage box. The toolkit follows [100, 246] in providing a set of custom tools aiming to avoid the artificial constraints introduced by existing systems, as they are often limited by the technologies used. We discuss each of the components below:

6.2.1.1 Building blocks

The design of the building blocks is inspired by interlocking maths learning cubes such as Snap Cubes ®[3] and Edx Education Linking Cubes[4]. Each block has three different types of faces: 1 square stud, 3 square holes, and 2 regular faces (Figure 6.2). The

---

[3] https://www.learningresources.co.uk/snap-cubesr-set-of-100

[4] https://edxeducation.com/portfolio-item/2cm-linking-cubes-1000pcs-12012

goal of this design is to allow for enough freedom of the creation in 3D space – the set of different faces per block supports attachment in multiple directions – but also keep them simple and consistent in appearance. Each block is $2 \times 2 \times 2$ cm in size and is made of 3D printed plastic. The storage box contained 25 blocks of each out of 5 colors (red, orange, yellow, green, blue), making a total of 125 blocks.

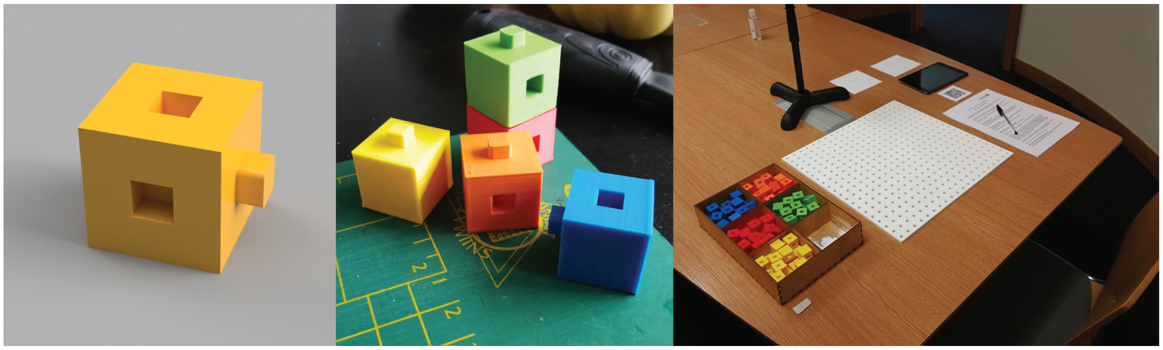


Figure 6.2: A 3D rendering of the block design, 3D-printed plastic blocks, and the study setup.

6.2.1.2 Data labels

The set of paper data labels included: a title label, a label for each categorical (i.e., seasons, countries) and sequential attribute (i.e., years), and a label for each single value attribute. We purposely provided a minimal set of data labels with no duplicates and no inclusion of axis labels (i.e., ‘X’, ‘Y’, ‘Country’, ‘Season’, ‘Year’) to reduce the possibility for redundancies. Lastly, we provided participants with some sticky tack to allow for freedom in placing labels, i.e., sideways on blocks or other midair placements.

6.2.1.3 Canvas

We designed a building area made of a white plastic 40×40 cm canvas with square holes at every 2cm so that the building blocks could be snapped in. Figure 6.2 shows the experimental setup for all tasks. The participant was seated in front of the white square canvas with the toolkit on their left.

6.2.2 Datasets

We used two datasets of similar structure and complexity as Huron et al. [100], which are included as supplementary material (Table A.1 and Table A.2). The first dataset[5]

---

[5] https://www.gapminder.org/data

represented CO_2 emissions in tons per person for five different countries, across three years. The second dataset[6] represented rainfall in the United Kingdom in millimeters for four seasons, across four years. All values are rounded derivatives from the raw data. The datasets were selected so that they are understandable, interpretable, and transferable for non-expert participants.

6.2.3 Participants

We recruited 16 participants (8 identified as male, 7 as female, and 1 as non-binary), of which 5 were 18-24 years, 4 were 25-34 years, 6 were 35-44 years, and 1 was between 45-54 years old. Participation was voluntary and without compensation. There were no particular requirements for participation other than that participants were (corrected to) fully sighted and physically able to construct a visualization with objects. Of all participants, 12 were familiar with the concept of data visualization, 13 were experienced in reading data visualizations, and 10 with creating data visualizations.

6.2.4 Procedure

At the start of the study, we introduced participants to the study, asked them to sign a consent form, and collected their demographics. We explained the goal of the study: to understand how people construct and label physical visualizations using an exemplar toolkit. We gave participants a set of general instructions and in total asked them to visualize two datasets using the toolkit. Participants were asked to think out loud during the creation process. If participants indicated to have finished but forgot to contextualize their physical constructs they were prompted by the researcher, for example about the topic *"how would someone else know what your visualization is about?"* or the created encoding *"how would they know what one block represents?"*. When finished with the first task (T1), the researcher would ask them to take two pictures of the end result and explain their visualization design. Afterward, the participant was asked to rotate the canvas either 90 degrees clockwise or counterclockwise, and indicate if they would like to make any changes to the labeling of the visualization and if so, they were requested to perform these changes, and take two pictures (from different angles) to capture the current state of the visualization. We repeated this process twice so eventually the participant had seen all 4 orientations of the square canvas. This whole process was repeated during task 2 (T2) with a second dataset. The mapping between the two datasets and two directions was counterbalanced across participants using a balanced Latin square (yielding 4 participant groups). The whole experiment lasted between approximately 60 to 90 minutes, depending on the participant's performance.

---

[6] https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-and-regional-series

6.2.5 Data Collection

During the study, we collected three different types of data:

6.2.5.1 Video

With participants' consent we took video and audio recordings of their interactions using two GoPros: from a top-down viewing angle and a view from the side. We used these videos to capture participants' actions during the creation process.

6.2.5.2 Pictures

After each task, and after the changes made upon each rotation of the canvas we asked participants to take two pictures from different viewing angles to capture the current state of the visualization. The first picture was a representation of their viewing angle while seated, and the second picture was from any angle they preferred to view their visualization most comfortably and/or effectively. We used these pictures to extract (i) the properties of their visualization design, and (ii) any changes to the labeling across different orientations.

6.2.5.3 Participant Observations

During the task, the researcher made notes of participant comments while thinking out loud. After each task we asked participants to (i) elaborate on the dataset using their visualization, (ii) explain the visualization they created, and (iii) if there was anything they struggled with while creating it. This was to understand participants' creation process and the properties of their visualization design. After both tasks, we asked them about their overall experience with the toolkit.

6.2.6 Method of Analysis

To be able to extract information on (i) the construction and contextualization process and (ii) the properties of the final visualization designs we developed coding schemes for the videos and pictures:

6.2.6.1 Analysis of the Creation Process

We analyzed the videos, using a qualitative and iterative approach, inspired by the approaches of Wun et al. [246] and Huron et al. [100]. We used the ethogram as created by Wun et al. [246] as a reference, but refined it to meet our apparatus (3D blocks instead of 2D tiles and the inclusion of labels) and study aim (role of labeling in the creation of physicalizations).

The first pass involved two researchers performing open coding to identify the behaviors of interest. Once the coding scheme was established, there was primarily one coder, with random checks to verify researcher agreement.

In total, we coded 13 types of actions across 3 activity categories (Table 6.1). Additionally, we captured when which out of 4 label types (title, sequential, categorical, and value) was interacted with.

Activity category	Action	Description
Data activities	Read	Read the data table.
	Verify	Verification of visualization, i.e. compare with data table and/or count blocks.
	Correct error	Correct an error.
Block activities	Collect	Collect (and count) blocks in hand, canvas or workspace.
	Organize	Organize (constructs of) blocks spatially in the canvas, without placing.
	Build in hand	Build block constructs in hand.
	Build in canvas	Build block constructs in the canvas, without placing.
	Place in canvas	Place block constructs in the canvas.
	Rearrange	Rearrange and place block(s) in the canvas.
	Placeholder	Place placeholder block(s) in canvas for labeling purposes.
Label activities	Order	Order labels in the workspace.
	Label	Place labels in canvas.
	Relabel	Rearrange label(s) in canvas.

Table 6.1: Ethogram of activity categories and actions identified in the video data.

6.2.6.2 Analysis of Visualization Design

We analyzed the pictures taken by participants after the completion of the physicalization creation process to identify (i) the visualization type; (ii) composition; (iii) color association; (iv) axis mapping; (v) data labeling position; and (vi) labels' reading direction. These codes emerged during an iterative process of analysis of the resulting physicalizations and aim to describe how the blocks and labels were mapped and distributed on the canvas to visualize the provided dataset.

Visualization type describes the distribution of blocks and the use of the multi-direction stacking affordance of the toolkit in the canvas. *3D visualizations* utilize multiple levels of stacked blocks to distribute data values using height (z-axis) within the 3D space. On the other hand, *planar visualizations* were constructed using a single level of blocks, thus distributing them only in the 2D space (flat surface, x, and y-axis). For instance, blocks organized in towers (stacked) are described as *3D*, whereas visualizations that do not stack more than one block in the canvas are *planar*.

Composition refers to visualization archetypes based on the distribution, dispersion, organization, and/or positioning (location) of blocks and groups of blocks within the canvas space. Composition archetypes emerged from the analysis of all the resulting physicalizations, grouping them by look-alike block distributions as new archetypes appeared. For instance, blocks organized equidistantly and dispersed across the canvas belong to a different archetype than those not organized equidistantly; or those clustered in one corner of the canvas.

Color association describes how participants use the color affordance of the toolkit. Generally, the color of blocks could be used to map *sequential* or *categorical* attributes from the dataset into the canvas space. In contrast, the number of stacked/grouped blocks is used to represent values.

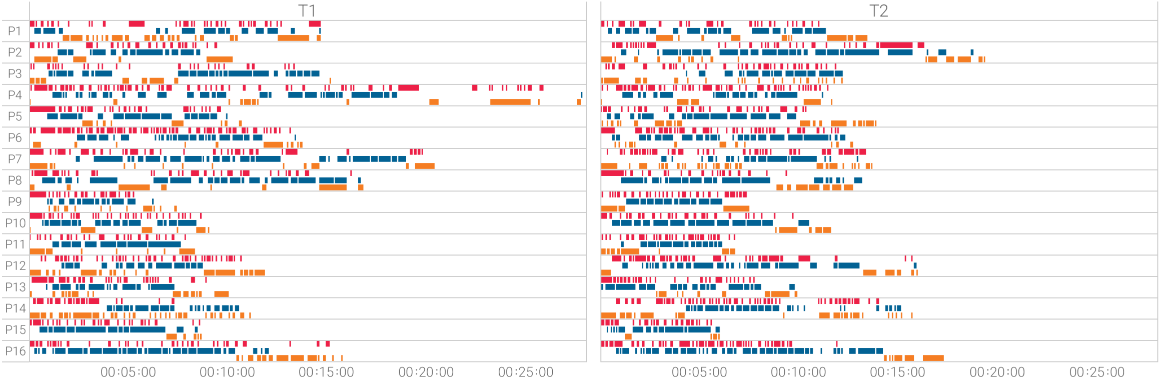


Figure 6.3: Activity categories over time for each participant for tasks 1 and 2: data (🟥), block (🟦), and label activities (🟧).

Axis mapping refers to the use of the canvas space to map sequential and categorical attributes into the x and y-axis (from the viewer's point). For instance, a physicalization that utilizes the horizontal direction (x-axis) to spread year values (sequence), whereas the canvas depth (y-axis) is used to map seasonal values (categories).

Data labeling position provides information about the *location* of each of the 4 label types: title, sequential, categorical, and value labels. For instance, whether a label is located on the canvas, next to a block, on top of a value block or a placeholder block, or onto one of its faces (in the z-axis).

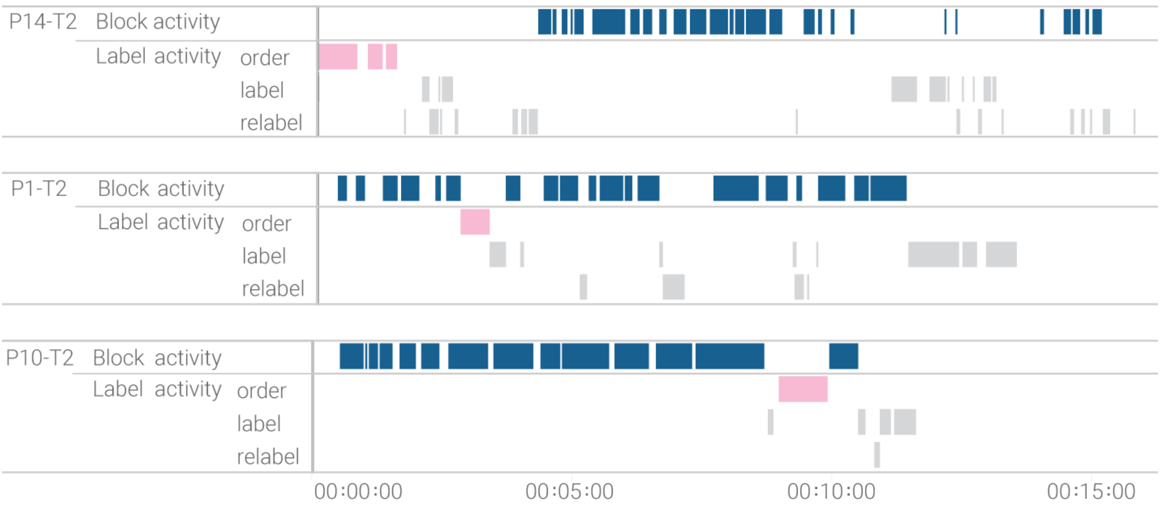


Figure 6.4: Different approaches to ordering labels (■): at the very beginning of the task (P14-T2), after block activity (■) took place (P1-T2), or at the very end of the task (P10-T2).

Labels' reading direction registers the orientation of each label type from the participant's point of view. This describes if the label can be read from their perspective (in a default direction), if it is upside down, or if it is rotated on an approximately 90 degrees angle; and whether all labels follow a consistent direction pattern or are in mixed directions.

6.2.6.3 Analysis of Influence of Orientation

We analyzed the changes participants made to the physicalization's labels after each shift in orientation (three instances) using the pictures they took at the end of each iteration. We followed the analysis of visualization design and registered the changes in *data labeling position* and *reading direction* for each of the 4 types of labels (title, sequential, categorical, and values). In addition, we compiled a list of actions as descriptors of the changes in position or tweaks and their occurrence per participant. For instance, a title label moved from the back of the canvas to the front, or value labels moved from the canvas to the top of towers of blocks were described as a "relocation". Similarly, changes in the orientation of labels or placeholders to preserve their reading direction were described as "rotations". Finally, we refined the list of actions as new ones emerged and organized the resulting dictionary in clusters when appropriate, e.g., grouping actions of low occurrence.

6.3 Findings

To answer our research question we structured the findings in three sections. The first section presents an overview of the construction and contextualization process when creating a physical visualization. The second section elaborates on the relationship between the physical and textual properties of the visualization design. The last section shows the influence of orientation on the changes to the textual properties of the physicalization.

Overall, we found that (i) the creation of physicalizations is an intertwined process of label and block activities and is unique per participant, (ii) the final visualization design is an integration of data labels and physical constructs, and (iii) the relations between these labels and constructs are influenced by orientation changes.

6.3.1 Construction & Contextualization Process

Herein, we discuss the role of labeling during the physicalization creation process. We first discuss the actions observed in general, after which we go into further detail on behavioral patterns observed within the label and block activities, and across activity categories.

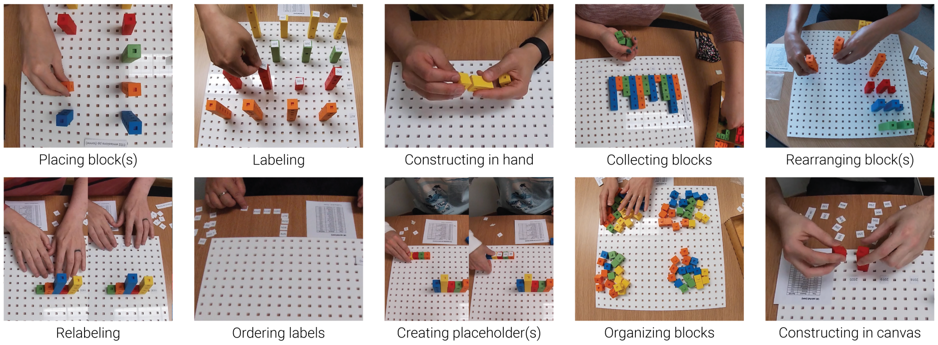
6.3.1.1 Overall creation process

Across all 32 tasks (16 participants $\times$ 2 tasks), participants spent on average 13 minutes to complete the task ($\sigma = 4.5$ minutes). 9 participants performed task 2 (T2) faster than task 1 (T1) on average by 4 minutes, whereas 7 participants performed T2 slower than T1, on average by 3.5 minutes.

Looking at the occurrence of activities over time, we observed that the construction and contextualization of physicalizations is an intertwined process, as illustrated in Figure 6.3. This means that labeling happens throughout the creation process rather than at the end. Across all participants and tasks, on average 53.5% of their time was spent on any type of block activities, 22.7% on any type of labeling activities, and 23.7% on any type of data activities.

Data activities such as looking at the data table generally happened throughout the process, as can be seen from the short time periods throughout the task (Figure 6.3). Block activities appear in longer periods of time clustered together. Lastly, label activities vary from short time periods throughout to clusters of longer time periods spread across the task, for example at the very beginning of a task to plan out the visualization design or at the end to complete the block constructs. Figure 6.5 provides a further detailing of the activities observed and the average time spent on each.

Following the overall process observations, we zoom in on the behavioral patterns within and between the different activity categories. For example, some participants built all constructs first (block activities), and then labeled the whole visualization (label activities), whereas others applied a more parallel process in which block and label activities alternated and/or intertwined. For an overview of the timelines per participant per task please refer to the supplementary material in Figure A.1.


Placing block(s) Labeling Constructing in hand Collecting blocks Rearranging block(s)
Relabeling Ordering labels Creating placeholder(s) Organizing blocks Constructing in canvas

Action	Time (%)
Placing block(s)	24.6
Reading	18.7
Labeling	15.7
Constructing in hand	11.1
Collecting blocks	7.9
Rearranging block(s)	6.4
Relabeling	4.6
Ordering labels	3.8
Creating placeholder(s)	2.6
Verifying	2.2
Organizing blocks	1.1
Correcting error	0.7
Constructing in canvas	0.5

Figure 6.5: Illustrations of the observed Block and Label actions, and the percentage of the average time spent on each action that appeared during the creation process.

6.3.1.2 Label activity patterns and label types over time

For each task, we extracted when which out of 4 label types was handled, and analyzed the relation between ordering, labeling, and relabeling.

Ordering. For 16 tasks (50%) we observed the ordering of labels at the beginning of the creation process (before any block activities). For example, P14-T2 in Figure 6.4 and as illustrated in Figure 6.5 by 'Ordering labels'. In contrast, we found that for 7 tasks (21.9%) ordering happened either along the creation process – such as P1-T2 in Figure 6.4 – or at the end (after block activities took place) – see P10-T2 in Figure 6.4. Lastly, the 9 remaining tasks (28.1%) did not involve any ordering of labels at all.

Labeling. Looking at the use of each label type over time we observed different strategies:

- *Title labels:* For more than half of the tasks the title label was placed at the very end ($f = 19$; 59.4%), whereas for 13 tasks (40.6%), the title label was placed at the beginning or first half of the task.

- *Sequential & Categorical labels:* We observed the placement of sequential labels was performed (i) throughout the task whilst building sequential block constructs ($f =$

12; 37.5%), or (ii) at the beginning or first half of the task (f = 12; 37.5%). For the remaining tasks, this happened at the end of the process (f = 8; 25%). For categorical labels, we observed that they are placed either at the beginning (f = 9; 28.1%) or first half of the task (f = 8; 25%); during the final half (f = 3; 9.4%) or at the end of the task (f = 9; 28.1%); or spread out during the task (f = 3; 9.4%).

When we cross-referenced the placing of sequential and categorical labels, we observed some participants placed both of them at the beginning of the task to plan the visualization (f = 9; 28.1%); whereas others preferred to place both at the end (f = 6; 18.8%). Moreover, some participants chose to place categorical labels at the beginning (f = 6; 18.8%) or the end of the task (f = 5; 15.6%) whilst sequential labeling was spread across the task, placing them either before or after a sequential construct was created.

- *Value labels:* For the majority of tasks, the labeling of values happened at the end of the task (f = 25; 78.1%), after the physical constructs were created. Of these tasks, 7 spent a longer period of time on placing all value labels, 5 spent a shorter period of time on creating a single key, and 2 involved the placement of value labels at first after which a key is created as well (P4, P9). For 2 tasks (6.3%) a longer period of time is spent on value labeling at the beginning or first half of the task. For instance, P14 spent time placing labels to plan out their visualization design, whereas P3 did the same to create a 'legend tower' (Figure 6.7). Lastly, for 5 tasks (15.6%) the value labeling happened throughout the task.

Relabeling. We observed that relabeling generally occurred for categorical and sequential labels rather than for value and title labels. To give an example, P8 placed categorical labels on the first bar charts they build, but as they got occluded by the subsequent constructs, they updated the categorical labeling after all physical constructs were finished. In contrast, P14-T1 relabeled each value label as they built physical constructs, after they had placed all labels at the beginning of the creation process to plan their visualization.

6.3.1.3 Block activity patterns

For each task, we extracted which block action(s) involved the largest percentage of time and whether or not they occurred in a chain of actions. To give an example, Figure 6.6 shows that for P6-T2 the most occurring chain of actions is *collect*, *build in hand*, and *place in canvas*. Overall, we observed four general strategies:

- *Collect – build in hand – place in canvas* (f = 10; 31.3%).
- *Place in canvas* (f = 9; 28.1%).

- *Collect – place in canvas* ($f = 8$; 25%).
- *Build in hand – place in canvas* ($f = 5$; 15.6%).

The occurrence of these different strategies to build and place constructs can be explained by the affordances of the apparatus. The physical blocks allow for the construction and 'clicking' together in multiple ways (in contrast to stackable tiles).

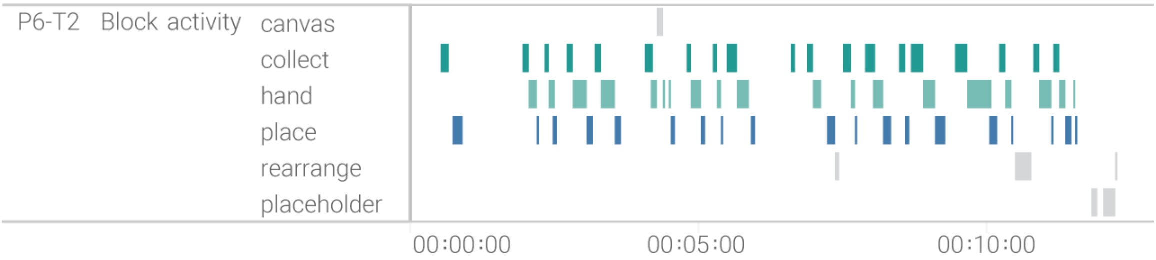


Figure 6.6: P6-T2 illustrates the block activity pattern *collect* (■) – *build in hand* (■) – *place in canvas* (■).

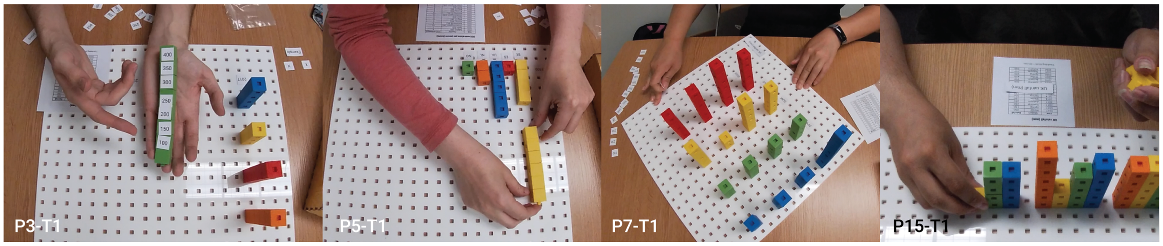


Figure 6.7: P3-T1 showing their 'legend tower', P5-T1 organizing block constructs on the canvas before placing them, P7-T1 simplifying construction through rotation of the canvas, and P15-T1 using a label to assist in reading the data table.

Organization. We observed different strategies in the organization of blocks. For instance, P5-T1 organized multiple block constructs on the canvas before placing them (see Figure 6.7). Moreover, P13-T2 first repeats the collection and organization of blocks within the canvas (Figure 6.5; 'Organizing blocks'), after which they start placing all of them.

Rearrangement. For 4 tasks (12.5%), we observed that a longer period of creation time was dedicated to the rearrangement of one or more blocks after their placement, for instance halfway through and/or at the end of the task.

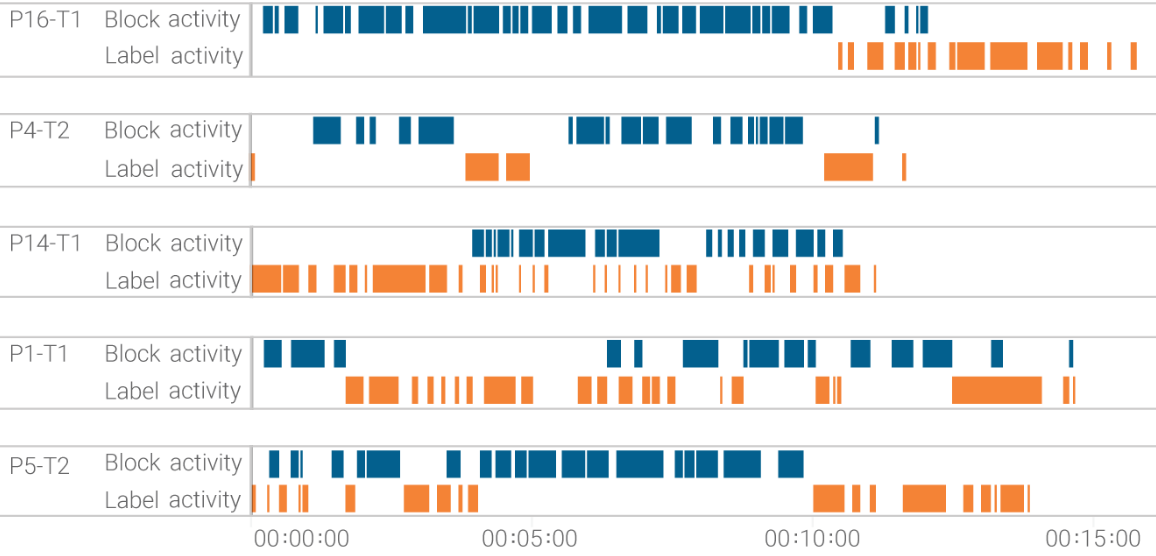


Figure 6.8: Different patterns across block (🟦) and label (🟧) activities: performed subsequently (P16-T1), in alternation (P4-T2), labeling after which block and label activities are intertwined (P14-T1), from alternation towards intertwined (P1-T1), and from intertwined towards alternation (P5-T2).

6.3.1.4 Patterns across block and label activities

If we look at the relation between block and label activities, generally, we observed that for 6 tasks (18.8%) all block activities were performed first, after which label activities were done (for example Figure 6.8; P16-T1). For the remaining 26 tasks (81.3%) we observed an alternating and/or intertwined process of block and label activities; meaning that participants were alternating between longer periods of time spent on label or block activities (Figure 6.8; P4-T2) or spent shorter periods of time on label and block activities subsequently, resulting in a more intertwined process (Figure 6.8; P14-T1).

Other examples show longer time periods of isolated label or block activities at first, that become shorter and more intertwined over time (Figure 6.8; P1-T1), or vice versa, planning out the visualization using an intertwined process, after which isolated block and label activities are performed (Figure 6.8; P5-T2).

An example of a fully intertwined process of block and label activities is P3-T2 (Figure 6.9). They mentioned first using the sequential and categorical labels to plan out the canvas, and placed each value label as they build constructs per data point.

Lastly, looking at the placement of placeholder blocks meant for labeling, we observed that this often occurs in parallel or in close proximity to label activities (Figure 6.9; P8-T1).

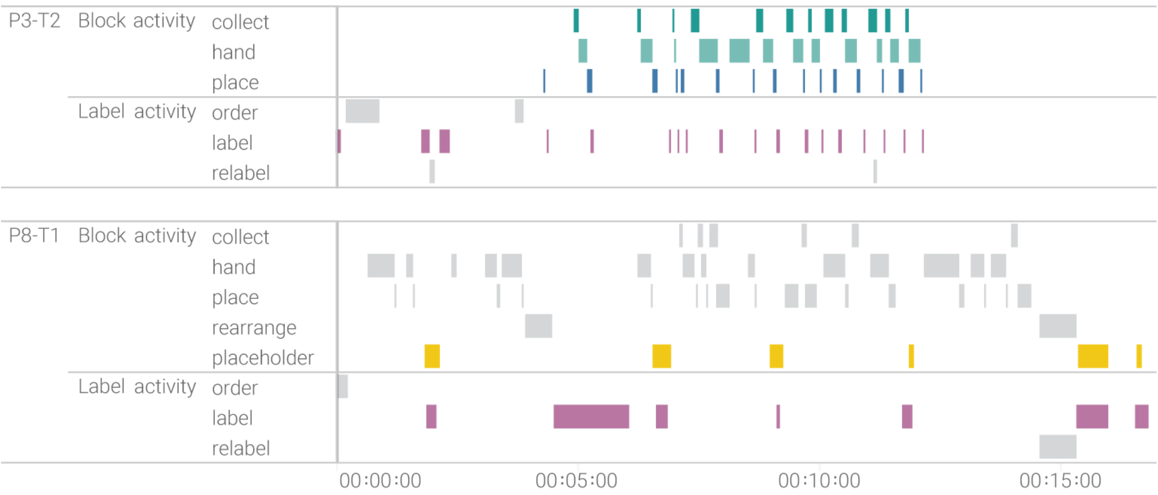


Figure 6.9: Examples of intertwined patterns across block and label activities: P3-T2 developed a pattern of collect (🟩), build in hand (🟩), place (🟦), and label (🟪). P8-T1 used placeholders (🟨) while labeling each sequence label.

6.3.1.5 Patterns across data and label activities

Looking at the relation between data and label activities, we observed that when block activities occur before label activities, this can influence the need for data activities, as physical constructs can be used as reference and/or means of verification.

For the 6 tasks that participants first performed all block activities and then labeling, we found that they did not look at the data table while labeling, as they could use their physical constructs as reference for extracting values. Similarly, we observed this for time periods throughout the alternating and/or intertwined processes, and especially at the end of a task when placing value labels. The placement of value labels at the end of a task was regularly accompanied by verification before, during, or after the labeling.

6.3.1.6 Other activities

We observed that participants sometimes used creative methods to support the creation process. For example, P7 rotated the canvas repeatedly to bring the area of interest closer to them and simplify construction (Figure 6.7; P7-T1), whereas other participants used the storage box or other attributes to cover up parts of the paper data table to guide reading (Figure 6.7; P15-T1).

Regarding the use of the different block faces, we observed that participants either cared much or not at all about the direction of the open and closed block faces. Participants that paid close attention to the order of block faces tended to build slower

Figure 6.10: Overview of all visualization designs created by participants. An enlargement is available in the supplementary material (Figure A.2).

and/or more carefully as precision was required. Lastly, P4 and P8 regularly clicked the wrong block faces together and had to correct themselves. They are the only two participants that showed some minor struggles when constructing the blocks in 3D space, due to their affordance of being attachable in multiple directions. Participants identified different advantages for the open and closed faces: they mentioned that closed faces could create more "neat" or "peaceful" visualizations, whereas the open faces could simplify comparison through counting. P16 mentioned the potential of the block faces (open and closed) to encode further information/detail, i.e., meaning ("to communicate a food item with or without sugar").

6.3.2 Visualization Design

In this section, we elaborate on the visualization type and composition, color association, axis mapping, and use of data labels as part of the final visualization designs created by the participants.

6.3.2.1 Visualization type and composition

Overall, we observed 5 different visualization archetypes across all 32 tasks. Figure 6.10 shows an overview of the visualization designs created by the participants and their corresponding archetypes, including:

- *Grid*: Equidistant blocks dispersed across the canvas ($f = 11$; 34.4%), for example, P2-T1.
- *Line*: Blocks placed subsequently in a single direction ($f = 8$; 25%), for example, P10-T1.
- *Clusters*: Blocks systematically organized in multiple graphs ($f = 6$; 18.8%), for example, P1-T1.
- *Collection*: Blocks randomly organized in multiple graphs ($f = 4$; 12.5%) for example, P6-T1.
- *Compact*: Blocks 'clumped together' with no dispersion across the canvas ($f = 3$; 9.4%), for example, P4-T1.

Out of all 32 physicalizations created, 27 physicalizations used the physical 3D space to visualize data in an upward direction (height). Only 5 physicalizations were created within the plane, by 4 different participants (Figure 6.10; indicated by 'planar'). 4 of these physicalizations were of the *line* archetype, either horizontal or vertical within the canvas, whereas outlier P13-T2 created a *collection* of waffle charts in the canvas (Figure 6.10; P13-T2).

We observed that for 6 physicalizations diagonal spacing was introduced into the x and/or the y-axis (Figure 6.10; indicated by 'diagonal'). P10-T2 created a complete diagonal line visualization, P6-T2 created a collection of diagonal graphs, P9-T2 and P14-T1 created a grid with a diagonal offset in the x-axis, and P16 created a line of diagonal graphs (T1) and diagonally spaced clusters (T2).

Lastly, P12-T2 created a special case of a *collection*, as the spatiality in the canvas was used to represent a geographical map of the countries, to create a more "impactful" visualization to represent carbon emissions (Figure 6.10; P12-T2).

6.3.2.2 Color association

For 28 tasks (87.5%) the color of blocks was associated with categorical attributes. Hence, participants used color to differentiate between countries or seasons. In the other 4 tasks (12.5%) color was used to differentiate between years (sequential attributes). Looking at the exact colors that were allocated to categories of the datasets, we observed more consistency in color association with seasons than with countries. Participants explained different approaches to the color mapping, which were either (i) as a utility to separate data ($f = 12$; 37.5%), or (ii) to create a conceptual mapping to familiar concepts ($f = 20$; 62.5%).

For the 16 tasks that involved the dataset on UK rainfall, the most common color allocations were green for spring (f = 13), blue for winter (f = 12), orange for autumn (f = 12), and yellow (f = 8) or red (f = 5) for summer. For 13 tasks participants consciously allocated color to seasons, based on associations between color and temperature (i.e. blue for a cold winter temperature), or seasonal landscape (i.e. yellow for a "dry climate" during summer). As an outlier, P14-T2 strategically kept the color red aside to highlight extremums in rainfall per year (see Figure 6.10; P14-T2).

For the 16 tasks that involved the dataset on CO_2 emissions, the most common color associations were orange for Netherlands (f = 7), red for Spain (f = 6), red (f = 4) or blue (f = 4) for the United Kingdom, yellow (f = 5) or green (f = 4) for Belgium, and blue (f = 5) or green (f = 4) for Norway. For 6 tasks participants tried to allocate color to countries, based on the colors of their flag (red for Spain) or other colors of national importance (orange for the Netherlands), followed by a process of elimination.

Overall, participants' strategy in the use of color association is dependent on the topic of the dataset. Accordingly, results suggest the adoption of a pragmatic approach to relate colors to familiar concepts first (e.g., color hue with the temperature of seasons, or flags), followed by the association or allocation of the remaining color resources by process of elimination.

6.3.2.3 Axis mapping

The most common mapping of axes we observed was that both sequential and categorical attributes were represented from left to right (f = 7; 21.9%). For instance, we observed 6 *line* and 1 *line (diagonal)* archetype displaying this pattern. Besides that, we observed equal occurrences of physicalizations that represented (i) sequential data from left to right, and categorical data from either front to back or back to front, and (ii) categorical data from left to right and sequential data from front to back or vice versa (f = 4; 12.5% for each occurrence). Lastly, we observed for 4 physicalizations that one data attribute was represented from left to right, while the other attribute was represented through spatiality. For example, for 3 physicalizations of the *collection* archetype, categorical data were represented from left to right and sequential data was represented using dispersed positioning in the plane.

Although participants generally followed the structure of the data table while constructing their physicalization, the only times randomization of categorical data took place was for the emissions dataset, for which participants randomized the order of countries, consciously or not (f = 6; 18.8%). This also happened a single time for the rainfall dataset, which was adapted by choosing a different season as the starting point for each year.

Hence, we conclude that generally for two data attributes (table top to bottom), if one attribute is represented left to right, the other is represented back to front or vice versa, with no particular preference for categorical or sequential data in either axis.

6.3.2.4 Data labeling position and reading direction

Overall, for the majority of tasks ($f = 28$; 87.5%) participants placed all labels in their default reading direction (left to right, labels legible from the viewing point). However, we observed different approaches in the positioning and orientation for each label type:

Title: For the majority of tasks the title label was placed on the canvas ($f = 28$; 87.5%) and for 4 (12.5%) on the side or top of placeholder blocks (Figure 6.10; P1 & P8). Looking at the relative location of the title, for 14 tasks it was placed in the front of the canvas (of which 6 were in the center), for 11 tasks in the back (of which 7 were in the center), and for 7 tasks in the middle area (of which 3 on the left). Lastly, we observed that 2 participants placed title labels in counterclockwise ($f = 3$; 9.4%, Figure 6.10; P1-T1, P11-T1/2) or clockwise reading direction ($f = 1$; 3.1%, Figure 6.10; P1-T2).

Sequential attribute: For the majority of tasks ($f = 28$; 87.5%) the sequence labels were placed on the canvas alongside the physicalization. For 2 tasks they were placed as a key in the back center of the canvas, either with (Figure 6.10; P11-T2) or without placeholder blocks to communicate the color mapping (Figure 6.10; P12-T2). P8-T1 placed the sequence labels on yellow placeholder blocks alongside the physicalization and P10-T2 placed them against the physical data points of the physicalization. Lastly, we observed that 1 participant placed sequential labels in a counterclockwise reading direction ($f = 2$; 6.3%, see Figure 6.10; P1-T1/2).

Categorical attribute: For 18 tasks (56.3%) the category labels were placed on the canvas alongside the physicalization. For 11 tasks they were placed as a key, either on the canvas alongside placeholder blocks ($f = 6$; 18.8%, for example, Figure 6.10 P2-T2), or on top of the placeholder blocks ($f = 5$; 15.6%, for example, Figure 6.10 P6-T1). Looking at the relative location of the category key within the canvas, the majority ($f = 7$; 21.9%) was placed in the front of the canvas (of which 4 were on the right). For 3 tasks the category labels were placed or attached against data points of the physicalization (Figure 6.10; P8-T1, P10-T1, and P13-T1). P13 mentioned that for each country bar chart, they placed the country label on the bar with the highest value for visibility. Lastly, we observed that 1 participant placed categorical labels in counterclockwise reading direction ($f = 2$; 6.3%, Figure 6.10; P1-T1/2).

Data values: For 15 tasks (46.9%) all value labels were used to indicate each individual data point, either by placing them on top of each bar chart ($f = 13$; for example Figure 6.10; P1-T1), or on the canvas in front of each bar chart ($f = 2$; for example Figure 6.10; P12-T1). For 11 tasks (34.4%) a single value label was used to create a key, either by placing it on the canvas by itself (Figure 6.10; P10-T1),

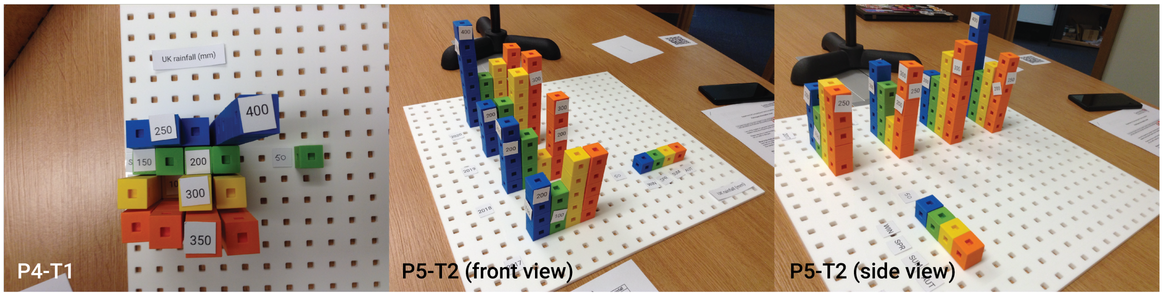


Figure 6.11: Different approaches to reference labels: P4-T1 placed labels for each distinct value on top of the physical bar charts, whereas P5-T2 placed labels on three different sides of the physical constructs to anticipate viewing from multiple orientations.

alongside a placeholder block (Figure 6.10; P5-T1), or on the top (Figure 6.10; P2-T2) or the side (Figure 6.10; P8-T1) of the placeholder. Lastly, there were 6 tasks in which multiple value labels were used to create reference points for data extraction. For example, P3-T1 created a 'legend tower' for sideways height comparison with the bar charts (Figure 6.7; P3-T1). Likewise, P4 included reference labels for each distinct value on top of the bar charts, as well as included a key on the right side of the physicalizations. However, they explained that when viewed from above, the reference labels allowed for value estimation of bars of similar height (Figure 6.11; P4-T1). P9-T1 placed reference labels on the canvas in front of the first row of data points (Figure 6.10; P9-T1), and P13-T1 placed them against the first row of data points (Figure 6.10; P13-T1). Lastly, in addition to a key, P5-T2 provided reference labels on 3 sides of the bar charts to anticipate viewing from different orientations (Figure 6.11; P5-T2). Moreover, we observed that 2 participants placed data value labels in mixed reading directions ($f = 1$; 3.1%, see Figure 6.10 P1-T1).

In sum, participants placed title labels in a central location on the canvas. Similarly, sequence labels were placed on the canvas, but then alongside one of the sides of the physicalization. In contrast, category labels were placed on the canvas alongside the physicalization, as well as a key separate from the physicalization to encode color mapping. Lastly, for almost half of the tasks all value labels were used to indicate each individual data point, whereas, for a third, a single value was used to create a key.

6.3.3 Influence of Orientation

Herein, we discuss the role of labeling when viewing physicalizations from different orientations. Participants were asked to rotate the canvas with 90 degrees increments and assess their labels (whether they wanted to change the labels to read them effectively and comfortably). We elaborate on the challenges encountered with the physical constructs within the canvas and the coping strategies participants adopted when manipulating labels to more effectively convey the information presented in their physicalizations.

6.3.3.1 Challenges of orientation

The rotation of the canvas introduces viewing perspective challenges that affect the digestion of the presented labels. Taking as the starting point the most common physicalization construction, we will unfold the potential issues encountered during the iterative change of orientation.

We take as a reference a 3D grid of data points with value labels on top of the bars; categorical and sequence labels placed on top of the canvas alongside the bars' rows/columns, and the title label located on the canvas at the front (all labels legible from the viewing point). For instance, after a 90 degrees rotation, all labels are read sideways and categorical/sequential labels are hidden behind stacked blocks. After a second 90 degrees change, labels are displayed upside down and the title label is pushed to the far end of the canvas. As such, each orientation change introduces (i) a change in viewing position affecting label legibility and salience, and (ii) a change in characters/numbers reading direction. These factors introduce the following challenges:

- *Reading Direction* occurs when text is not displayed in the default/legible orientation (characters displayed upwards for ease of reading), but is rotated clockwise, counterclockwise, or is presented upside down, thus introducing higher cognitive demand.

- *Occlusion* occurs when labels are hidden behind block constructs, making viewing from all directions more difficult.

- *Proximity and Organization* occurs when labels are relocated, increasing their distance from the viewing point, and therefore affecting the salience of information and the users' predefined mental model of the physicalization.

- *Ordering and Direction* occurs when the order of labels alters their meaning, hindering the digestion of the information displayed. For example, a sequence of year labels that loses chronological order upon multiple orientation changes.

6.3.3.2 Changes to data labeling as a coping strategy

In our study, participants were invited to modify (as they wished) the display of labels after each viewing orientation iteration. Herein, we elaborate on the changes participants made to the data labeling across the orientation conditions. In total, there were 96 conditions (16 participants × 2 tasks × 3 orientations). We did not find any significant differences between the orientation conditions (clockwise or counterclockwise). Overall, we observed 4 different types of changes made to the data labels (Table 6.2) listed in order of most occurrence:

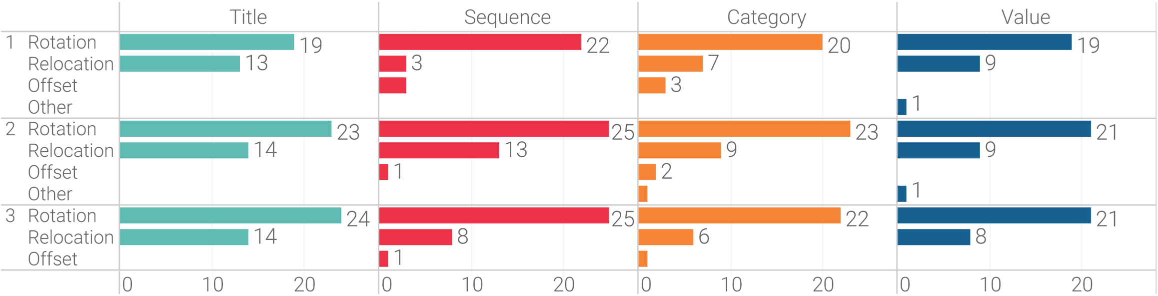


Table 6.2: Changes made to each label type – *title* (🟩), *sequence* (🟥), *category* (🟧), and *value* (🟦) – across the 3 orientations.

Rotation in a (counter)clockwise direction to set the reading direction back to the original default after the orientation change (f = 61-72; 63.5-75%). Although some participants changed the reading direction of all label types (P2, P3, P4), others prioritized changes to the orientation of categorical and sequential labels over title and value labels, specifically when these were upside down after the second orientation change (P6, P13). However, some participants reported not caring about reading direction at all (P1, P5).

Relocation of labels within the canvas to avoid occlusion, increase proximity, or preserve organization (f = 26-41; 27.1-42.7%). Generally, participants preferred to relocate title labels over the other types across orientation changes. This could be caused by a desire to maintain the original presentation of the title (P4, P10) or to place the label in a position that is salient and avoids occlusion.

Introduction of an *Offset* in relation to the physicalization to compensate for the occlusion of labels (f = 5-6; 5.2-6.25%). Offset strategies occur when modifying sequential and categorical labels (found alongside the block constructs) as they might get occluded after each change of orientation.

Other outlier changes (f = 1-2; 1-2%), such as the *Re-purposing* of blocks to use them as a key to two different data attributes (e.g., P5-T1 reused the block representing the scale to create a legend for categorical attributes). Moreover, we observed the *Addition* of new blocks to create a category legend and avoid occlusion (P5-T1), or of unused value labels to add detail (P13-T1).

6.3.3.3 Changes to physical constructs as a coping strategy

In addition to the changes to the data labeling during the different orientation iterations, we observed participants' strategies to try and anticipate orientation challenges during the creation process. These strategies emerged from the accumulation of participants' out-loud rationalization of "improvements" across tasks as a response to the changes of orientation experienced and/or anticipated.

The following strategies are a reflection of isolated instances of behaviors observed during the study to provide further evidence of coping mechanisms adopted at the creation level that we aim to be illustrative as much as they could be guiding for future work.

Space Dispersion and Organization: 7 participants played with the use of the canvas space (e.g., distancing blocks, centering the physicalization). This affected the organization of data blocks to facilitate the digestion of information and avoid occlusion. For instance, P1-T2 and P2-T2 reported increasing the space between bar charts (*dispersion*), whereas P4-T2 mentioned placing their data blocks in the middle (*centering*) of the canvas to make it "look good" and have space around them. Similarly, P6-T2 indicated they decided to add space between bar charts so the visualization looked less "messy", but they were concerned the use of space could convey meaning (e.g., separate different categories) when they aimed to solely improve readability. On the other hand, P9-T2 reported deciding to spread out bar charts so they do not visually block each other, whereas P13-T2 pushed groups of bars as far away as possible so they would not "distract" each other. Moreover, P16-T2 described organizing their bar charts so the smallest values (e.g., countries with lower CO_2 emissions) were placed on the outskirts of the canvas, whereas the highest values (e.g., countries with higher CO_2 emissions) were placed at the center so they would not be occluding.

Introducing Diagonal Offset: 3 participants experimented with the addition of a diagonal offset between data values. For instance, P10-T2 increased the separation in both the x and y-axis to create a "diagonal" line rather than mapping values on a single axis. Moreover, P9-T2 introduced a diagonal offset to display their grid as a rhomboid rather than a square, whereas P6-T2 introduced a diagonal offset for each bar chart in a collection archetype.

Addition of Key Placeholder: 5 participants introduced the use of blocks as key placeholders or legends. This was aimed to avoid the occlusion of labels behind blocks as legends were pulled away from the location of the physicalization structure. For instance, P8-T2 discussed their addition of a key aimed to facilitate looking at it from any possible angle. Additionally, P5-T2 mentioned placing a legend centered within the canvas to anticipate "hidden" labels after a 90 degrees turn, whereas P13-T2 wanted to use the free space available in the middle of the canvas to place all the information necessary to read their visualization (a legend for categories' color mapping and sequential labels to indicate organization).

Experimenting with Archetypes: 3 participants experimented with the use of the canvas space, thus changing the composition of their physicalization and creating a different archetype (e.g., moving from a 3D visualization to a planar one). For instance, P13-T2 mentioned "making it flat" and avoiding building different stories to facilitate understanding the data from every angle (and tackle occlusion). P2-T2 discussed the trade-off of using planar visualization as it introduces directionality (i.e., once rotated 90 degrees it looks "sideways"), which P15-T2 felt was limiting even though a planar visualization could remove occlusion problems.

Highlighting: 1 participant (P14-T2) decided to *highlight* the extremums of the data values with different colored blocks to improve the visualization of minimum and maximum values at a glance without necessitating to estimate height differences in the 3D space.

6.4 Discussion

We investigated the role of data labeling in the physicalization creation process, the visualization design, and the resilience of data labels across orientations. Our findings show that (i) label activities are alternated and/or intertwined with block activities during the creation process, (ii) labels are integrated with physical constructs in the final visualization design, and (iii) this relation between data labels and physical constructs is influenced by orientation changes. Overall, our results suggest that the use of data labels is fundamental to consider for future physicalization designs.

6.4.1 Towards A Principled Use of Data Labels in Physicalization Design

Although physicalizations embody data in their material and physical form [108], they still benefit from the inclusion of contextualizing elements (i.e. data labels, axes, legend, and annotations) to support the extraction of information from the physical representation. However, despite the evident importance of providing context to visualizations, most related work on physicalization is not labeled at all [e.g. 95, 187, 251]. Physicalizations that do use contextual elements are often inconsistent or specific to that individual design [e.g. 77, 107, 221]. As the current definition of physicalization [107] suggests, the focus is on *physicality* and not on 'data labeling' or other contextual elements of *the physicalization in use.* Moreover, the physical and spatial nature of physicalizations introduces additional challenges, as it remains unclear where to locate different kinds of labels and how they accommodate multi-user scenarios. Hence, there is currently no principled way of contextualizing physical representations of data.

The field of information visualization (infovis) has established ways to discuss and implement the contextualization of digital data representations [79, 170]. However, it remains unclear how this translates to the field of physicalization. Implementations of 2D visualizations in the field of infovis are more homogeneous than 3D representations of data. Hence, some variance will always exist in the data labeling of 3D physical constructs. Nonetheless, it would be useful to aim for the development of a collection of 'best practices', guidelines, or at least illustrative work to, as a research field, become more strategic at contextualizing physicalization design.

It is apparent that our specific apparatus aids in the creation of physicalizations of the 'bar chart aesthetic'. However, it still allowed participants to create a variety of visualization archetypes going beyond the traditional use of bar charts. We observed that across these different archetypes, the use of data labels was consistent: the majority of data labels were placed in the default reading direction and were paired and/or integrated with physical constructs (i.e. value labels on top of data points). Moreover, labeling was used in combination with other visualization components such as color encoding and axis mapping. As such, future work could investigate whether similar use of data labels, and similar integration of data labels with physical constructs will occur for a variety of physicalizations.

6.4.2 Utility of Labeling in the Physicalization Creation Process

Constructive visualization work [65] previously explored how the use of physical tokens can support the authoring of physical data representations. However, these approaches focus on the construction of visual mappings, and thus far did not actively include the use of data labels in the authoring process. Instead, the labeling or annotation of data is treated as a subsequent process to the construction process [100, 246], or their use is left up to participant preference [65]. As a result, it remains unclear what role data labeling can and/or should have in the creation process of physicalizations.

As the act of data labeling is part of a larger process of construction and contextualization, we decided to study it in the context of a constructive visualization process. Hence, we designed a toolkit that follows state-of-the-art methodology [100, 246], with the inclusion of both physical tokens as well as textual labels to investigate the use of data labels during the creation process. Our findings show that this allowed participants to alternate and/or intertwine label and block activities during the creation process. This illustrates the utility of the active inclusion of data labels for physicalization creation. Moreover, we observed that the use of data labels can serve different purposes: to plan the visualization before including physical constructs, to guide the creation of subsequent physical constructs, and to verify constructs afterward. Thus, the use of data labels allows for verifying physical constructs ad hoc, in particular when the label and block activities are heavily intertwined. Hence, the inclusion of data labels could provide people with more agency within the creation process of physicalizations.

The *extended infovis pipeline model* [106] describes the contextualization of physicalizations as *'decoration'* operations as part of *presentation mapping*. However, we observed that labeling activities can occur across different pipeline operations, such as the *loading* of data by ordering data labels in the workspace, or as part of *visual mapping* as they are organized as elements in the canvas alongside block constructs, before the final *presentation mapping* takes place.

To explain this, we take interest in the *interrelation principle*. Wun et al. [246] described this principle as the intertwined nature of operations due to the physical nature of the authoring tool. However, as they did not actively include data labels in the toolkits discussed, no reflections are provided on how labeling fits within this principle. We argue that similar interrelated processes occur for data labels as for physical tokens. To give an example, ordering data in the workspace outside the canvas is *loading data* [106]. However, the moment data labels are introduced in the canvas, relations are created between the data label and (i) other data labels, (ii) other block constructs, and (iii) relative position within the canvas. As such, data labels could be considered as building blocks in themselves, not just complementary to physical constructs.

Although Huron et al. [100] provide a conceptual flow diagram of common construction behaviors, this does not include the act of annotation as it happened as a secondary task after construction. Arguably, the act of appropriating data labels within the canvas and in relation to physical constructs can be described through those diagram elements as well (i.e. organize, arrange, merge, align) and should be considered alongside physical tokens in the process. Hence, it might be necessary to expand existing conceptual models and/or introduce new models as data labeling is an interrelated process within itself, and in relation to construction activities.

6.4.3 Data Label Resilience across Orientations

Chapter 4 [191] has demonstrated the influence of orientation, introducing ambiguity when extracting information from physical representations of data, and discusses the different types of occlusion that can occur due to user orientation. In line with this work, we observed challenges for the effective use of data labels due to orientation changes: the correction of reading direction, prevention of occlusion, and maintenance of proximity and organization.

We argue that the introduction of data labels can mitigate the challenges introduced by physical 3D space, such as directionality, occlusion, and user multiplicity. Whereas the use of duplicate data labels might seem a straightforward solution, the necessity for duplicates would ‘clutter’ the visualization. To simplify cognitive digestion, we argue for the use of *reactive* and *resilient data labels*.

Reactive data labels can accommodate the point of view of the user, and solve occlusions created through physical constructs. To acquire this, two parallel processes would need to happen: (i) data labels follow the point of view of the user to maintain reading direction and proximity (*user-label relation*), but are also reactive to (ii) the physical composition or layout of the physicalization, to prevent occlusion and maintain effective offsets (*label-layout relation*). If this is done successfully, it results in a *user-label-layout* relation that supports the effective extraction of information from physical data representations for any orientation. Our results on coping strategies through a change in data labels (and to some level physical constructs) are illustrative of ways in which future physicalization designs could counteract orientation influences (such as the rotation, relocation, and offset of labels). Depending on the system implementation, these strategies can be informative for the design of reactive data labels and/or adaptable physical constructs:

For static physicalizations [e.g. 107, 215] data label resilience needs to be high, as the physical construct is rigid and cannot adapt to viewing angle and/or perspective changes. Hence, accommodation for orientation influences is fully dependent on data label design and adaptability. This approach does not suggest a forced point of view but acknowledges the influence of user orientation on the perception of physicalizations. By incorporating reactive data labels, individuals can physically engage with static physicalizations while ensuring that the labels adapt to their viewing angles and maintain offsets. This supports the understanding of the represented data from any orientation. To give an example, data labels follow the viewer’s orientation to adapt the reading direction, and if a physical construct gets occluded in a particular orientation, the label can ‘float’ above or aside the construct to notify the viewer of its existence.

For dynamic and interactive physicalizations [e.g. 64, 69, 221] data label resilience can interplay with the specific actuation technologies implemented. While physically reorganizing the dataset through actuation can be beneficial, it may not completely resolve the issue of change in interpretation due to orientation. Simply reorganizing the data objects does not guarantee consistent perception across different orientations. However, by combining reactive data labels with potential physical reorganization, we can improve the interpretation of physicalizations. Hence, data label design along with adaptable physical constructs, can work in tandem to address the challenges of user orientation and enhance the comprehensibility of the physicalization. For instance, if a physical construct gets occluded, actuation can ‘move’ it aside to maintain the line of sight and the data label follows.

Moreover, on top of the interplay of data labels and actuation, the interaction could also play a role. For instance, users could indicate ad hoc what information they require and manipulate the data labels and/or physical constructs accordingly. The observation of isolated instances of strategies to cope with orientation through the change of physical constructs resonates with prior work on reconfiguration strategies in Chapter 5 [194]. Herein, we found that proximity change was generally the most used strategy to rearrange physical constructs, which relates to the organization and dispersion of physical constructs we observed in this chapter.

Lastly, the introduction of multiple users and/or a collaborative context creates new challenges for data labeling as well. For effective information extraction by collaborators, there is a necessity for either maintaining a shared view versus the introduction of individual viewports. For example, a shared view could be accomplished through top-down projection or display integration in each physical data point, whereas individual viewports could be accomplished through an AR overlay or VR environment.

To illustrate the concept of reactive data labels in more concrete terms, we can examine two case studies previously discussed in Section 3.1, and introduce the use of AR to realize reactive data labels. In the case of Econundrum (Section 3.1.2), while users provide data to their own disk using a mobile phone, a mobile AR overlay can accompany each disk height with numerical data, enabling them to reflect on the underlying data to the physical representation. Since Econundrum was suspended from the ceiling, complementary data labels can also assist in height comparison, compensating for potential distortions based on individuals' height. As the disks move up or down, the data label can dynamically highlight the changing value or follow the movement of the disk, facilitating users in perceiving changes in the data. Furthermore, when users approach their personal disk, the labeling adapts to provide more detailed information about their specific meals and portion sizes.

Similarly, in the case of EMERGE (discussed in Section 3.1.5), a head-mounted display (HMD) AR overlay could be used to enhance interaction with the bar charts. When users touch individual bars, additional information can be displayed above them. For example, when users pull specific bars in the center of the physicalization to highlight a particular set of graphs, a secondary set of data labels can appear above and around each highlighted bar, complementing the labels on the axes that may be obstructed by the user's hand during the interaction. After the user has finished their action, the highlighted set of bar graphs could disperse over the complete canvas, creating diagonal offsets to prevent occlusions. Meanwhile, the data labels follow each bar chart to maintain the salience of information.

6.4.4 Opportunities for Future Work

In our study, we focused on a subset of physicalizations – 3D bar charts – that are well-established in the field (i.e. [69, 221]). Hence, we can not make conclusive statements on the labeling of other types of physicalizations or even other implementations of 3D bar charts. Additionally, other label designs (i.e. curved, embossed, transparent, 3D), different ways of attaching labels and construction strategies, and/or more participants' agency in designing their own labels could generate diverse outcomes. Therefore, future work is needed to expand on our initial findings for these particular conditions, to further investigate the role of data labeling in the creation, design, and mitigation of physicalizations with orientation challenges.

First, in the present study, we did not record further demographics (i.e. occupation, cultural background, or native language) that could have been of influence on the observed labeling behaviors. Understanding the impact of these factors on the creation and interpretation of physicalizations would be valuable for future research.

Second, future work could further compare the different strategies for labeling we observed in the creation process. It could be valuable to compare the design outcomes of post hoc, a priori, and interrelated labeling activities. Moreover, we observed that data labeling can serve different purposes (i.e. to plan, guide, or verify a physicalization), hence, it could be further investigated what other purposes labeling can have beyond the creation process, such as self-reflection or as part of the presentation to others.

Third, although our apparatus allowed for the creation of different visualization archetypes, further investigation would be necessary to explore the data labeling of physicalizations beyond the bar chart aesthetic. Subsequently, our study is illustrative of coping strategies through a change in data labels (and to some level physical constructs), but is not an exhaustive list of how to contextualize physicalizations in general. Hence, future work could investigate the labeling of other types of physicalizations, and expand on coping strategies for challenges due to physical space.

Fourth, we acknowledge that our study had certain biases introduced by the characteristics of our apparatus and datasets. For instance, the structure of the data table could influence participants' order of creating constructs, and the use of an actual dataset introduces recognition bias for the ones familiar with the specific topics. Additionally, we recognize the potential benefits of incorporating some contextual elements (e.g. a map of Europe) to simplify the understanding of a dataset. While it is true that a map of Europe could eliminate the need for coding and labeling the countries in our specific study task, it is important to consider potential biases. Assuming that everyone knows the map of Europe by heart may introduce biases in the interpretation and understanding of the data, particularly for individuals who are less familiar with the region. Furthermore, for other types of data or values that do not have clear spatial associations, such as non-geographical or abstract concepts, labeling and coding would still be necessary to provide meaningful context. Therefore, we believe that striking a balance between providing contextual cues and ensuring accessibility and inclusivity for a diverse audience is crucial in the design and labeling of physicalizations. Moreover, the current dataset was two-dimensional (1 sequential and 1 categorical attribute), hence, we cannot postulate results for other datasets that are more or less complex, i.e. a more complex dataset with multi-dimensional data, requiring creation in multiple axes. Hence, future work would need to investigate how our findings translate for other datasets and toolkits.

Lastly, as our focus was on the use of data labels for contextualization, the methodology was designed to allow for data label alterations but not for changes to physical constructs. Hence, future work is needed to develop a further understanding of the interplay between label resilience and the adaptability of physical constructs.

6.5 Conclusion

In this chapter, we investigated the role of labeling in the creation process, final physicalization design, and when viewed from different orientations. We designed a custom toolkit including physical tokens and textual labels, and asked 16 participants to complete a total of 32 construction tasks. Our findings show that (i) the creation of physicalizations is an intertwined process of labeling and construction activities, (ii) resulting in an integrated visualization design of data labels and physical constructs, and (iii) these integrated labels and constructs are influenced by orientation changes. Hence, we argue for further development of contextualization methods for future physicalizations, and propose the introduction of *reactive data labels* to counteract challenges of orientation.

In the following chapter, we will synthesize the different pieces of work presented in this thesis, and discuss the key contributions, lessons learned, and future implications for physicalization research.

Chapter 7

Discussion

The previous chapters have individually explored the conceptual and empirical understanding of the implications of physical context and physicality on people's perception of and interaction with physicalizations. In this final chapter, we revisit the research questions posed in Chapter 1, reflect on key contributions and implications of the thesis work, and discuss future work and limitations.

7.1 Research Questions Revisited

This thesis explores how the physical context and physicality of physicalizations influence the interactions people have with physical information. In this section, we revisit the research questions formed in Chapter 1 and summarise the findings from corresponding studies for each question. The overarching research question addressed in this thesis is:

Main RQ: How do physicality and physical context influence people's interaction with physicalizations?

To help answer this question, we formed four sub-research questions, RQ1–RQ4. As a first step, to set the stage for the rest of the thesis work, we focused on a conceptual understanding of how state-of-the-art physicalizations are implemented in a real-world context. As physicalizations are fundamentally tangible, they are susceptible to interactions with their surrounding audience and context. However, these relations are currently not well captured in the working definition of physicalization, which mainly focuses on the direct physical and material properties of the system. Therefore, there is a need to conceptually understand how physicalizations coexist and interact with their physical context and audience, which led to the first sub-research question:

RQ1: How can physicalizations be understood in relation to their audience and real-world context?

In Chapter 3, we provided a meta-review of a representative sample of existing physicalization works and applied an interpretative approach [182] to develop a conceptual framework to describe physicalizations in relation to their surrounding audience and context: the *physecology*. We derived six design dimensions to describe the different physical and digital elements of a physicalization and how they interact with people and surroundings: (i) data type represented; (ii) method of information communication; (iii) interaction mechanisms; (iv) spatial coupling of input/output; (v) physical setup; and, (vi) type of audience. The physecology framework allows for the dissection of physicalizations into design components, showing how different physical and digital elements conceptually relate to each other and interact with people. Moreover, the design dimensions can be used to understand how state-of-the-art physicalizations position themselves within the design space and in relation to each other, and how the different design dimensions contribute to this.

With a better understanding of state-of-the-art physicalizations in their physical context, we shifted our attention to the inherent physicality of physicalizations, and how it might influence people's perceptions of physical information. As physicalizations represent data through their physical 3D shape, the orientation from which people are viewing it may affect the way this information is understood. Hence, the second sub-research question focused on investigating the influence of user orientation on the perception of physical information:

RQ2: What is the relation between user orientation and the perception of physicalizations?

In Chapter 4, we studied different low-level analysis tasks for abstract bar chart physicalizations, and introduced the term *orientation consistency* (OC) to systematically evaluate participants' consistency in these tasks across four orientations. We found that the perception of bar chart physicalizations is directly affected by user orientation, and can be explained through three types of occlusion: proximity, continuity, and atomic orientation occlusion. This study offers initial insights into the variability and complexity of the relationship between orientation and user perception.

Following the second research question, we investigated people's reconfiguration strategies with physicalizations. Currently, it is not well understood how people approach the direct manipulation of physical data points. Therefore, we applied the same methodology and apparatus from RQ2 to investigate the interaction possibilities of physicalizations. Hence, the third sub-research question was:

RQ3: What are people's reconfiguration strategies in relation to the physical structure of physicalizations?

In Chapter 5, we studied two clustering tasks with different levels of restriction for abstract bar chart physicalizations, and used common internal evaluations methods for cluster analysis [47] to systematically investigate participants' reconfigurations. We found that the two main reconfiguration strategies to reorganize bar chart physicalizations are proximity and atomic orientation changes to improve the cohesion and/or separation of clusters. Additionally, we provided a further dissection of reconfiguration characteristics for physicalizations of different physical structures.

Finally, having investigated the perception and reconfiguration of physicalizations, we moved one step beyond and looked at the contextualization of physical information, forming the last sub-research question:

RQ4: How do people construct and label physicalizations as part of a constructive visualization process?

In Chapter 6, we studied the construction and labeling of bar chart physicalizations using a custom-made toolkit. We analyzed our findings by developing a set of coding schemes and found that labeling plays an active role in the creation, visualization design, and when bar chart physicalizations are viewed from different orientations. More specifically, we found that the construction and labeling of physicalizations is a highly intertwined process, data labels are integrated with physical constructs in the final visualization design, and these are both influenced by orientation changes. Hence, our findings indicate that the use of data labels is crucial to take into account for future physicalization design.

Returning to the main RQ, the combined findings from the four sub-research questions in this thesis show how the influence of physical context and physicality can be understood through a conceptual framework and a series of empirical studies. In the next section, we will further unpack the contributions from answering the research questions and the implications for future work.

7.2 Key Contributions, Lessons Learned, and Future Implications

This thesis fundamentally suggests, based on a meta-review of state-of-the-art physicalizations and three empirical studies, that physicalization as a research area should work towards the design of *context-sensitive physicalizations* for them to become more informative, trustworthy, and effective physical translations of data. With context-sensitive physicalizations we refer to *physicalization design that accommodates for the challenges of physical space – such as user orientation, spatiality, and occlusion – and is designed with active consideration of the intended context of use (physecology).* The work conducted in this thesis provides a foundation for progressing on context-sensitive physicalization design and evaluation by contributing (i) a conceptual framework to discuss physicalizations in relation to their audience and real-world context, (ii) novel methods to evaluate the perception of and interaction with physicalizations, and (iii) a synthesis of empirical findings on the implications of physicality for people's interactions with physicalizations. Each contribution will be further detailed below:

7.2.1 A Conceptual Framework to Describe Physicalizations in Context

The first contribution of the thesis is a conceptual framework to describe physicalizations in relation to their surrounding audience and context. We contribute with a detailed analysis of a representative corpus of state-of-the-art physicalizations, as they were at the time of writing, and propose the physecology as a framework to describe a wide variety of physicalizations (Chapter 3). The physecology framework allows for the discussion of the relations between the digital and physical elements within and surrounding physicalizations, and how these elements couple different audiences to these systems. Moreover, it can be used to shift between low-level (e.g., the perception of different ways of information communication) and high-level challenges (e.g., specific domain applications) of physicalization research, so we can further unpack the different mechanisms that constitute a physicalization, as well as guide future physicalization design. In this way, physicalization research can become more strategic about the design of physicalizations for real-world use.

As discussed in Chapter 3, the six design dimensions serve as a foundation for understanding the properties of a physecology, however, we acknowledge that refinements of existing dimensions or the introduction of new ones may be necessary as we continue to build an understanding of physicalizations. For example, at the time of writing, multiple systematic reviews came out in an effort to understand physicalizations in light of other external factors [13, 55]. Similarly to the physecology, they discussed the variety of data topics, design purposes, locations, and audiences that physicalizations can have [13, 55]. Hence, by synthesizing the findings of various systematic reviews, future work can gain a more comprehensive understanding of physicalization research and its nuances.

7.2.2 A Novel Method to Investigate the Perception of and Interaction with Physicalizations

The second contribution of the thesis is a novel method to investigate the perception, reconfiguration, and labeling of physicalizations. The influence of user orientation has been a red thread through the empirical work in this thesis and we designed a novel setup across experiments introducing viewing from multiple orientations. In the first study, it was used to investigate the influence of user orientation on perception (Chapter 4), in the second study to reduce the previously found influence of orientation when studying reconfiguration (Chapter 5), and in the last study to investigate the resilience of data labeling across orientations (Chapter 6).

This thesis followed methodology as known from prior work; investigating perceptions of and interactions with static physicalizations [107, 109, 214, 215] as a proxy to inform the design of future computer-supported interactive physicalizations. Complementary, it applied concepts from related fields of visualization [6, 238, 239] and psychophysics [121] to inform the design of the apparatuses and tasks meant for a physical 3D space. This led to the design of tailored apparatuses, procedures, and methods of analysis for each of the studies to investigate physicalization components in isolation (perception in Chapter 4 and reconfiguration in Chapter 5) and as part of a larger sense-making process (labeling in Chapter 6). Finally, this thesis introduced new terminology and concepts to discuss and contextualize the empirical findings, such as 'orientation consistency' to systematically describe the influence of user orientation on performed tasks, and 'cohesion' and 'separation' to describe changes in clusters due to people's reconfigurations.

The methodology in this thesis primarily focused on investigating the visual perception of physical shapes. However, the insights gained from this methodology can serve as a foundation for exploring the perception of other material properties or other forms of perception, including multisensory experiences (e.g. haptic textures, density, inertia, sound, and temperature). For instance, beyond physical shapes, how can we systematically investigate people's (multisensory) perception of temperature and inertia as physical variables to represent data? Our methodology allowed for systematic investigation of the visual perception of shapes, which could be a foundation for the visual perception of other material properties (e.g. inertia), or other forms of perception (e.g. multisensory) of different physical properties (e.g. temperature).

Moreover, the way we formulated and introduced 'orientation consistency' as a metric to describe the influence of user orientation on the perception of different layouts of physical shapes could possibly be translated to systematic measurements to describe multi-sensory perceptions of other physical properties. Taking inertia as an example, it can be considered a characteristic that influences the physical behavior of objects. In the context of physicalizations, incorporating materials with different inertial properties could significantly impact users' interaction and manipulation of objects. Objects with higher inertia may feel more stable and resistant to movement, while objects with lower inertia may feel more responsive and easily set into motion. By systemically investigating the role of inertia in physicalizations, we can gain insights into how it affects users' perception, interaction, and overall experience with the physical representations of data. Similarly, by incorporating materials that can change temperature or provide varying thermal sensations, we can create a more immersive and engaging interaction between users and the physical representation of data. Temperature zones or gradients on a physical surface can convey information or guide users' exploration and understanding. Furthermore, just as colors and shapes are used to encode information in the majority of physicalization research, temperature can be utilized as an additional dimension for representing data. For instance, warmer areas could indicate higher values or levels of a certain variable, while cooler areas could represent lower values. By associating temperature with data attributes, users can interpret and make connections between the physical representation and the underlying information more intuitively.

Overall, the methodology employed in this thesis has the potential to extend beyond visual perception and facilitate the systematic investigation of other material properties and multisensory perceptions. By applying similar principles and techniques, we can gain valuable insights into how different properties, such as inertia and temperature, impact users' perception, interaction, and overall sense-making of physicalizations.

7.2.2.1 Methodological Limitations and Future Directions

Inevitably, the studies presented in this thesis have limitations, which were detailed in each chapter, but will be summarized here again.

First, as discussed in Chapter 4 and Chapter 5, we intentionally used abstract apparatuses to avoid recognition bias, therefore, participants could not use context to inform the task. Hence, future work would be necessary to investigate the influence of contextual information on similar perception and reconfiguration tasks. In contrast, the study in Chapter 6 on data labeling did involve exemplar datasets. However, the current dataset was two-dimensional so further studies are needed to be conclusive about the role of labeling for other more or less complex datasets.

Second, all three studies (Chapter 4, 5, 6) involved apparatuses of the bar chart archetype, therefore, further research is necessary to examine findings for other physicalization archetypes or even other implementations of 3D bar charts. It is worth noting that for our studies, we intentionally chose quadrilateral shapes as they posed interesting qualities for investigation across orientations. Quadrilateral shapes provided a clear and noticeable transformation as the viewer changed perspectives. In contrast, using alternative shapes such as cylinders or hexagons might introduce different challenges, as their transformations may not be as visually evident. Exploring the perception of alternative shapes and their placements will be valuable for understanding the impact of different physical forms on the information comprehension of physicalizations. Additionally, as noted in Chapter 6, future work could delve further into the impact of various label designs (e.g., curved, embossed, or transparent), different methods of attaching labels to physical constructs, and/or granting individuals the option to create their own labels on data labeling practices.

Third, for each study we only applied viewing from 4 orientations. Hence, limitations are that we cannot postulate about other or more orientations, nor the influence of angular view, body motion, or holistic exploration around the circumference of the physicalization on sense-making. Consequently, future work is necessary to investigate how any findings transfer to multi-user scenarios, and to what extent collaboration will amplify or reduce the effects observed. Collaborative settings introduce additional complexities, as individuals may have different perspectives and interpretations of the physicalization. Furthermore, cross-referencing shape and size variations of data objects and viewing from different orientations could create even more avenues for future work. Incorporating principles from Emmert's law [58, 60] and the *perceptual consistency* of properties such as shape and size [p. 188 in 32], we can explore how dissimilar shapes and sizes may be perceived as either similar or exponentially different depending on the viewer's orientation. For instance, consider a scenario where two individuals are viewing the same physicalization from opposite perspectives. One person sees two seemingly similar shapes with similar sizes, while the other observes two data objects exhibiting exponentially different shapes and/or sizes. This scenario can be utilized to represent a dataset that contains provocative or contrasting information, such as food groups consumed on one side of the physicalization and their corresponding climate impacts on the other side. In this way, the exponentially different climate impact values per group, where a portion of red meat has a significantly greater impact than an equal portion of chicken, can be visually highlighted. Explorations of this nature will contribute to a deeper understanding of the intricate relationships between collaborative dynamics, individual perceptions, and physical object properties.

Fourth, considering our methodology in light of the physecology raises questions about how to conduct empirical studies for each of the design dimensions. To give an example, in this thesis, we only studied the visual perception of physical shapes (Chapter 4), but as demonstrated in the meta-review from Chapter 3, physicalizations use numerous forms to communicate data, each of which presents its own perceptual challenges. Therefore, further research is required to understand the perception (and induced occlusion) for other communication means such as optical properties, material properties, and other modalities (sound, vibration, weight). Similarly, future work could investigate how people's reconfiguration strategies vary according to the level of directness in interaction, the use of implicit or explicit actions, and different implications (e.g., exploration versus the manipulation of data). Finally, in order to comprehend the elements that shape collaborative interactions with physicalizations, it is important to develop means of evaluating multi-user scenarios for a variety of contexts, across diverse physical setups, and for different spatial couplings with users.

To summarize, the way people perceive and interact with physicalizations is closely tied to context and should be studied as such. Further empirical research is needed to fully understand how different design elements interact, particularly when studying them in (partial) isolation. Therefore, future work should focus on developing systematic methods, apparatuses, and measurements to examine the influence of physicality and physical context on future physicalization design.

7.2.3 Empirical Evidence on the Perception of and Interactions with Physicalizations

The third contribution of the thesis is the presentation of empirical evidence and the extraction of new knowledge on the implications of physicality for people's interactions with physicalizations.

7.2.3.1 The perception of physicalizations is directly influenced by user orientation

While the influence of perspective on the perception of physical information might seem trivial, Chapter 4 provides a first characterization of *orientation consistency* and how people's sense-making is guided by different types of occlusion. More specifically, we found that *continuity occlusion* makes a set of objects seem to be intersected, which prevents the viewer to see the full continuity; *proximity occlusion* makes the perceived distance between objects appear either further or closer together, which prevents the viewer from seeing the true proximity; and *atomic orientation occlusion* makes objects of different forms appear similar or objects of similar form appear different, due to their atomic orientation.

To give an impression of the extent of this influence, we found that changes in user orientation created a systematic lack of consistency across tasks, participants, and physicalizations. Thus, the empirical findings show that for these study conditions, physicalizations cannot communicate information in all directions reliably, which abolishes one of the fundamental aims of physicalization. With our work, we aim to encourage researchers to design physicalizations that take perspective into account and use orientation consistency to measure how successful the physicalizations are in communicating information across perspectives.

7.2.3.2 Proximity and atomic orientation changes are two main strategies to reconfigure physicalizations

Chapter 5 contributes a first characterization of user strategies when reconfiguring physicalizations, illustrating the variety of approaches that people have when organizing physical data. We found that people use two main strategies when reorganizing exemplar physicalizations – change in proximity and change in atomic orientation – to create visual consistency and reduce ambiguities. Moreover, we identified further reconfiguration characteristics for different physical structures; exemplar physicalizations with a constant internal structure are likely to involve none or many changes; physicalizations representing overlapping clusters are likely to motivate a change of one or more centrally positioned objects; and physicalizations with objects in mixed orientations likely result in rotation changes, to either integrate or differentiate their atomic orientations.

In contrast to our findings, existing systems often allow for one type of interaction, which forces people to use it in one particular way. Moreover, there are also consequences for collaboration, because when people have different mental models of the physical layout, and therefore different strategies for reconfiguration, it can create misunderstandings between them. Therefore, it is important to reconsider the interaction design and actuation mechanisms of future physicalization systems, so they can accommodate all kinds of users.

7.2.3.3 Labeling plays a role in physicalization creation, design, and when viewed from different orientations

The findings from Chapter 6 show that (i) the construction and labeling of physicalizations is a highly intertwined process of block and label activities, (ii) data labels are integrated with physical constructs in the final visualization design, and (iii) these are both influenced by changes in user orientation. For each of the four label types – title, sequence, category, and value labels – we observed general behaviors. Title labels were most likely placed in a central location on the canvas. Similarly, sequence labels were placed on the canvas, but then alongside one of the sides of the physicalization. In contrast, category labels were placed alongside the physicalization, but also as a key separate from the physicalization to encode color mapping. Lastly, either all value labels were used to indicate each individual data point, or a single value was used to create a key. We found that change in user orientation introduced the following four challenges: the reading direction is no longer in a default orientation, occlusion occurs when labels get hidden behind blocks, the proximity and organization change (e.g. labels become more distant from the viewer, affecting the salience of information), and the ordering and direction get distorted (e.g. sequence labels lose their chronological order). Subsequently, we observed three coping mechanisms to counteract these challenges: rotation to set the reading direction back to the default position; relocation to avoid occlusion, increase proximity, or preserve the organization of the visualization; and the introduction of an offset in relation to the physicalization, to compensate for possible occlusion of labels.

Future work should evolve towards a more principled use of data labels in physicalization design, and aim for the development of a collection of best practices, guidelines, or at least illustrative work so physicalization research can become more strategic when designing contextual information for physicalizations. Moreover, there is the utility of labeling in the creation process (e.g., the inclusion of labels can increase agency). Hence, we should expand on existing conceptual models or introduce new models to describe data labeling in relation to the construction process. Finally, the introduction of data labels can mitigate challenges introduced by 3D physical space, such as directionality, occlusion, and user multiplicity, which should be explored further.

7.2.4 Empirical Findings in Light of the Physecology

We found that the perception of physicalizations is directly influenced by user orientation; Chapter 4 showed that changes in user orientation led to three types of occlusion of *physical constructs* (proximity, continuity, and atomic orientation occlusion) and Chapter 6 discussed four challenges of user orientation for the perception of *data labels* (such as reading direction, occlusion, change in proximity & organization, and distorted ordering & direction). Relating this back to the physecology framework, we can use the different design dimensions as lenses to illustrate what our findings on user orientation mean for the design space of physicalizations and how our work is only a starting point for context-sensitive physicalization design. The dimensions in which the challenges around the perception of physical constructs and data labels are most likely to manifest are Data Type, Information Communication, Physical Setup, and Spatial Coupling. Therefore, we will first elaborate on the influence of user orientation on these specific design dimensions. Furthermore, we will consider the implications of our empirical findings for designing interactions and addressing user multiplicity in physicalizations through the Interaction Mechanisms and Audience dimensions, respectively.

7.2.4.1 Representing Data Attributes in Physical Space

Looking at the Data Type dimension, the data attributes a physicalization is representing will likely counteract user orientation. The majority of samples of the meta-review in Chapter 3 involved the change of quantitative data ($f = 48$), followed by categorical data (f = 18). The studies in this thesis either involved abstract 'data' (Chapter 4 and 5) or a combination of categorical and quantitative data attributes (Chapter 6). Chapter 4 and 6 found that physical elements such as linear absolute size, but also spatiality of physical constructs (e.g., location on the canvas or atomic orientation) are a gauge for data relations (e.g., scale, extreme values, or sequential data) which will be susceptible to occlusion, and thus change in orientation. Regarding the availability of data, the perception of static datasets will likely be influenced by changes in user orientation, as the same physical structure will be perceived differently across perspectives due to occlusion. In contrast, the perception of dynamic datasets will be susceptible not only to occlusion created by user orientation, but also occlusion through changes in the data, as the physical structure will change even when viewed from the same perspective. Therefore, more research is needed to understand how different configurations of data attributes (e.g., quantitative, categorical, and/or ordinal data) and data availability (e.g., static and/or dynamic) can be effectively communicated in physical space, taking into account the influence of physicality, spatiality, and user orientation on the perception of this data.

7.2.4.2 Perception and Labeling of Information Communication Methods

Information Communication is concerned with how changes in data are realized, such as positioning in space and control over optical properties, which are all susceptible to occlusion. For example, user orientation will influence how people perceive positioning in space (e.g., movement from left to right or front to back is understood in relation to the user), and different forms of occlusion can occur. Positioning in space is the main form of communicating information in the sample of the meta-review ($f = 33$), followed by control over optical properties ($f = 25$). In this thesis, we only investigated the occlusion of intersecting objects – which resonates with positioning in space – however, occlusion can happen for each other form of information communication. To give some examples, future work could investigate occlusion that occurs for optical properties, material properties, sounds, haptics, etc. Moreover, in the Information Communication dimension, we investigated methods for communicating changes in data – mapping out changes beyond physical and material form – but did not actively consider the labeling of these changes. As a result, the physecology framework currently does not include data labeling as one of the design elements. However, as Chapter 6 showed, contextualizing physical information is important for the sense-making of it. Therefore, future work is needed to understand the influence of user orientation on different methods of information communication, as well as explore how data labeling can be integrated with these communication methods in physicalization design.

7.2.4.3 Physical Setup to Contextualize Physicalizations

Regarding Physical Setup, the meta-review showed that almost half of the samples were either a standalone physicalization ($f = 26$) or a physicalization with a logical distribution ($f = 27$), followed by only 7 systems with a spatial distribution. Introducing other digital and/or physical design elements alongside a physicalization makes them also susceptible to user orientation and occlusion. Moreover, the absence of data labeling in many existing physicalizations raises the question of how the physical setup and distribution of additional physical or digital components can counteract the effects of user orientation. Specifically, introducing a spatial distribution could be beneficial for the labeling of physicalizations (e.g., by using complementary displays or augmented reality to show data labels). Future work could explore how the physical setup of a physicalization can play a more active role in data labeling, and therefore contextualizing physical constructs.

7.2.4.4 Implications of Perspective for Spatial Coupling

Looking at Spatial Coupling, there are only 9 samples that show a full coupling, whereas 23 show a nearby coupling, and 19 no coupling at all. The spatial coupling dictates the relation between the user and the physecology in space and time, and therefore counteracts with user orientation (e.g., viewing from a greater distance increases occlusion). This is problematic for physicalizations with no coupling ($f = 19$), as it infers there is no established relation between user and physecology, hence there are no 'rules' on how the user should interact with it (e.g., people can freely roam around the physicalization without any information on how or when to view it). Hence, future work is needed to understand the implications of perspective (and occlusion) for different spatial couplings.

7.2.4.5 Expanding Interactions to utilize Physical 3D Space

The findings of this thesis highlight the significance of physicality and physical context when interacting with physical information. The Interaction Mechanisms dimension (Chapter 3) showed that more than half of the samples use indirect interaction with data ($f = 32$), followed by no interaction at all for almost a third of the samples ($f = 19$), and only a few samples involved direct interaction ($f = 9$). As a result, users often do not interact with the physicalization itself, but with another medium close to the system. This raises the question of why the inherent ability for physicalizations to be touched and interacted with is not utilized further.

From Chapter 5 we know that proximity and atomic orientation changes are effective means of reorganizing physicalizations. However, future research is needed to fully understand how these strategies transfer or change for different physicalization archetypes and with different datasets (rather than abstract ‘data’). For instance, cohesion and separation changes could facilitate the tweaking of cluster algorithms in an exploratory manner, or pushing objects closer together could result in the physicalization adapting its scale.

While our work focused on studying reconfiguration as a form of direct and explicit interaction, it is important to also examine how proximity and atomic orientation changes can inform other interaction mechanisms, such as indirect and/or implicit interactions. This is particularly relevant for physicalizations that combine both direct and indirect interaction. To give an example, when a bar chart can be manipulated through both touch and display interactions, it is necessary to ensure consistency in the interaction by updating both methods appropriately. Additionally, it could be further investigated how changes in proximity and atomic orientation can facilitate different interaction implications, such as the manipulation, exploration, and configuration of data. Therefore, future research should consider the transferability of present reconfiguration strategies to different physecologies and explore ways to expand interactions with physicalizations to further leverage physicality and physical context.

7.2.4.6 User-Multiplicity and Collaboration

Throughout the chapters, there has been a recurring challenge in how our work translates to multi-user scenarios, as well as the inclusion of multiple users for interactions with physicalizations. The meta-review (Chapter 3) discussed how physecologies can be viewed and used by audiences of varying sizes, from a single individual to thousands of passersby, and that these user groups may change over time, with spectators becoming users or user groups growing or shrinking. This demonstrates that physicalizations, due to their physicality and presence in real physical space, will often have multiple user roles and audiences. Even physicalizations designed for individual use may be observed and potentially used by others. Therefore, user multiplicity should be recognized as a fundamental aspect of physicalization design, and should be taken into consideration when determining the encoding, interactions, and data labeling of physicalizations. The three empirical studies raised different questions regarding user multiplicity, such as the effect of collaboration around physicalizations on the impact of user orientation (Chapter 4); the interpretation of one person’s interactions by others and the coexistence of reconfiguration in the case of multiple users (Chapter 5); and the accommodation of multiple users through data labels (Chapter 6).

Accommodating multiple users can be achieved through various means, such as providing multiple viewports or adapting data labels and physical constructs to suit the needs and preferences of the audience. This can involve different layers of adaptation, depending on the size and orientation of the audience. For example, when there is a single viewer, data labels and physical constructs may be tailored to that individual. However, with two or more viewers, different rules may be applied, such as averaging orientation between two people, adapting to the closest viewer, or allowing users to dictate orientation. Additionally, accommodations may be specific to users and spectators, with users requiring a position that allows for direct interaction with the system, while spectators may have a more secondary role in a less central position. Finally, users can be given different information depending on their perspective, which can facilitate or even dictate different collaborative settings and team roles. Future research can explore innovative ways to foster collaboration through physicalizations, such as by providing users with complementary but varying pieces of information.

To summarize, user orientation will likely influence people's perception of a physicalization in terms of the data attributes represented, the methods of information communication used, the physical setup, and spatial couplings. In response, we propose two strategies for context-sensitive physicalization design – to either minimize or leverage the impact of user orientation on people's interaction with physicalizations.

7.3 Towards Context-Sensitive Physicalization Design

The physicality of physicalizations makes them inherently susceptible to their surrounding audience and physical context. Moreover, the influence of user orientation on the perception of physicalizations is a central problem, which influences other fundamentals (e.g., reconfiguration and labeling) and counteracts with each of the design dimensions of the physecology (e.g., the perception of data changes through positioning in space is susceptible to user orientation). Therefore, there is a need to further explore design approaches for context-sensitive physicalizations, taking into consideration the facets of physicality and physical context. This thesis proposes two main approaches towards context-sensitive physicalizations: the *mitigation* or *utilization* of physical space and user orientation. In other words, we can either apply strategies to *mitigate* the influence of user orientation on the perception of physical information or *utilize* the influence of user orientation for novel ways to visualize data.

While movement can provide individuals with different perspectives, it does not guarantee that they will perceive the information accurately or consistently. By considering the following arguments, these approaches not only address the challenges posed by user orientation but also provide several benefits. Firstly, implementing mitigation strategies promotes accessibility, ensuring equal access to the physicalization for individuals with limited mobility or a preference for stationary positions. By accounting for different user orientations and providing methods to mitigate their impact, we promote inclusivity and equal access to the information presented. Secondly, mitigation strategies can help promote consistency in the interpretation of the physicalization across different users. While movement introduces variability in perspectives, having guidelines or techniques to minimize the influence of user orientation can aid in establishing a shared understanding of the represented data. Thirdly, offering mitigation strategies allows users to have control over their viewing experience. They can choose to explore the physicalization from different angles or opt for a static position, depending on their preferences or specific information needs. Mitigation strategies empower users to interact with the physicalization in a way that aligns with their cognitive processes and individual requirements. Finally, mitigation strategies can help align the perception of the physical constructs and data labels with the intended design. By considering the potential distortions caused by user orientation, designers can proactively address and compensate for these effects, ensuring that the displayed information accurately reflects their intended meaning and message. In this section, we will synthesize the findings of this thesis into strategies for context-sensitive physicalization design and elaborate on and provide examples of both approaches.

7.3.1 Mitigation

Mitigation refers to strategies to reduce the influence of user orientation on the perception of physical constructs and data labels. This can be achieved by accommodating user orientation (within the physecology) and/or adapting the physical structure (of the physicalization) to counterbalance different types of occlusion.

To postulate mitigation strategies, we will take from observed isolated instances of behaviors during our empirical studies; Chapter 5 showed that changes in proximity and atomic orientation are the most commonly used strategies to organize data in space and reduce occlusion, which can also be used to inform actuation of dynamic physicalizations (e.g., we observed an instance of separation increase to counterbalance occlusion); Chapter 6 discussed three coping strategies for data labels (rotation, relocation, and introducing an offset) and some indicative coping strategies for physical structures (space dispersion and organization; introduction of a diagonal offset; experimenting with archetypes (2D/3D); and highlighting). Together, these findings can help postulate how we mitigate perspective challenges.

Building further on these observations we propose the following strategies. As an example, we take a bar chart physicalization of a grid archetype and follow the most common label strategies as observed in Chapter 6. We will discuss how we can mitigate the influence of user orientation through (i) reactive physical constructs and/or (ii) reactive data labels. For simplicity, we will discuss them separately, but this subset is not exhaustive and can be used in combination with each other.

7.3.1.1 Reactive Physical Constructs

The findings on people's reconfiguration strategies (Chapter 5) and coping mechanisms for changes to physical constructs (Chapter 6) are illustrative of ways in which future physicalization design could counteract orientation influences. We propose the use of 'reactive physical constructs', which are physical constructs that follow the point of view of the user to maintain the visual consistency and organization of the composition and prevent occlusion. Reactive physical constructs can be realized through actuated positioning in space, as well as other information communication methods such as controlling optical or material properties. We will provide examples of how to realize reactive physical constructs through positioning in space (i) in relation to the canvas, (ii) per data point, and (iii) in terms of transformations (see Figure 7.1).

Taking the canvas as a whole, it can be actuated to rotate (in the z-axis) according to the viewer's movements to maintain the same exact organization of the physicalization across orientations (Figure 7.1A). Alternatively, the canvas could introduce diagonal offsets to accommodate for occlusion without having to alter the absolute organization (Figure 7.1B). This method would also work for a static physicalization without actuation. Finally, the canvas could 'morph' itself entirely to adapt its shape to the viewer's orientation and viewing angle, for example, it could heighten small data points (Figure 7.1C). In this way, it can maintain organization, prevent occlusion, and fully adapt to the user's point of view.

Individual data points could be altered in several ways to accommodate for user orientation. To give an example, they could individually relocate, rotate, and/or shape-change (e.g., bending) to prevent themselves from being occluded by other physical constructs (Figure 7.1D). Additionally, clusters of data points can work together to follow the viewer's movements and reorganize themselves in the canvas accordingly. For example, clusters can reorganize from small to large and close to far from the viewer to reduce occlusion (Figure 7.1E). Finally, the information on the physical constructs can be adapted to the viewing angle through rotation (e.g., lying flat when viewed from above; Figure 7.1F).

Physical constructs can change from one state to another in different ways. Hence, for the transformation of physical constructs we can draw from shape-changing interface literature on different types of transformations [183], as well as visualization work on animated transitions [86]. Especially when adapting a complete physicalization to user orientation, it is important to consider the steps of change, as the simultaneous movement of all elements may make it difficult for the user to perceive. For instance, Heer and Robertson [86] investigated the effectiveness of transitions for common visualizations (e.g., bar and pie charts) and found a preference for animated over static transitions (e.g., staggered movements to prevent occlusion). They discuss several principles originally developed by Tversky et al. [229], including *congruence* (e.g.,

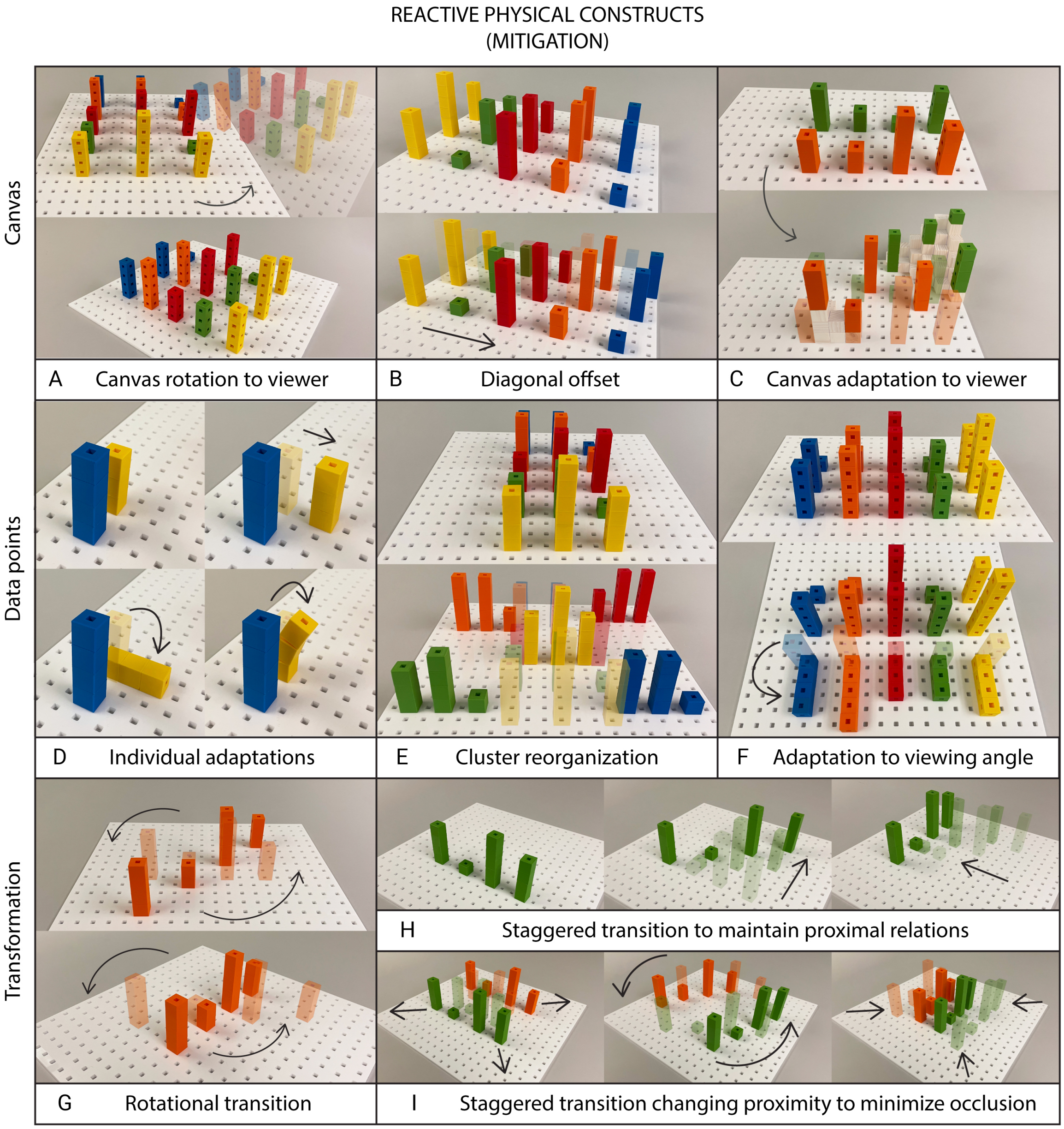


Figure 7.1: Overview of mitigation through reactive physical constructs.

respecting semantic correspondence by avoiding the reuse of specific data points to depict different data points across transitions) and *apprehension* (e.g., minimizing occlusion, maximizing predictability, and using staging for complex transitions). Whereas the insights from visualization are not directly transferable to physical 3D space, they can be a useful starting point when developing transformations of physical constructs. For example, in contrast to exemplar bar chart systems that tend to reuse the same physical constructs for different data points through linear bottom-up motions [69, 136, 220], physicalization transitions could adhere to semantic correspondence by rotation of the same physical constructs (see Figure 7.1G). Moreover, physical constructs could relocate while maintaining their proximal relations intact using a staggered transition (see Figure 7.1H). Lastly, physicalizations could minimize occlusion by, for example, decreasing the proximity of a cluster to increase the visibility of each data point, relocating the physical constructs according to the perspective of the viewer, and increasing proximity again to restore the original cluster (see Figure 7.1I).

7.3.1.2 Reactive Data Labels

The findings on coping strategies for changes to data labeling (Chapter 6) are illustrative of ways in which future label design could counteract orientation influences. We propose the use of 'reactive data labels', which means labels that follow the point of view of the user to maintain reading direction and proximity, but that are also reactive to the physical composition of the physicalization to prevent occlusion. In this way, the labels can maintain the relation with the viewer, but also with the physicalization. Reactive data labels can be realized by introducing a spatial distribution in the physical setup, for example through augmented reality (AR), such as head-mounted displays (HMDs) or mobile AR. We will provide examples of how labels can behave (i) when they are associated with a single data point, (ii) in relation to the entire canvas, and (iii) in terms of transformations (see Figure 7.2).

Individual data labels can be associated with single data points in several ways. For example, they can be placed on top or near each data point and follow the viewer's movements by rotating in the plane (z-axis) to support top-down viewing from different orientations. This can be implemented through multiple displays, a projection, or an AR overlay (see Figure 7.2A). Another option is to present individual data labels upright and floating above or near each data point, following the viewer's movement by rotating in the plane (z-axis). This solution would support viewing around the circumference of the physicalization and could be implemented using an AR overlay (see Figure 7.2B). Finally, individual data labels can be fully mapped to the position and angle of the viewer (in x, y, and z-axis) and float above or near each data point, implemented through an AR overlay (see Figure 7.2C). In this way, they support viewing from any angle around the circumference of the physicalization.

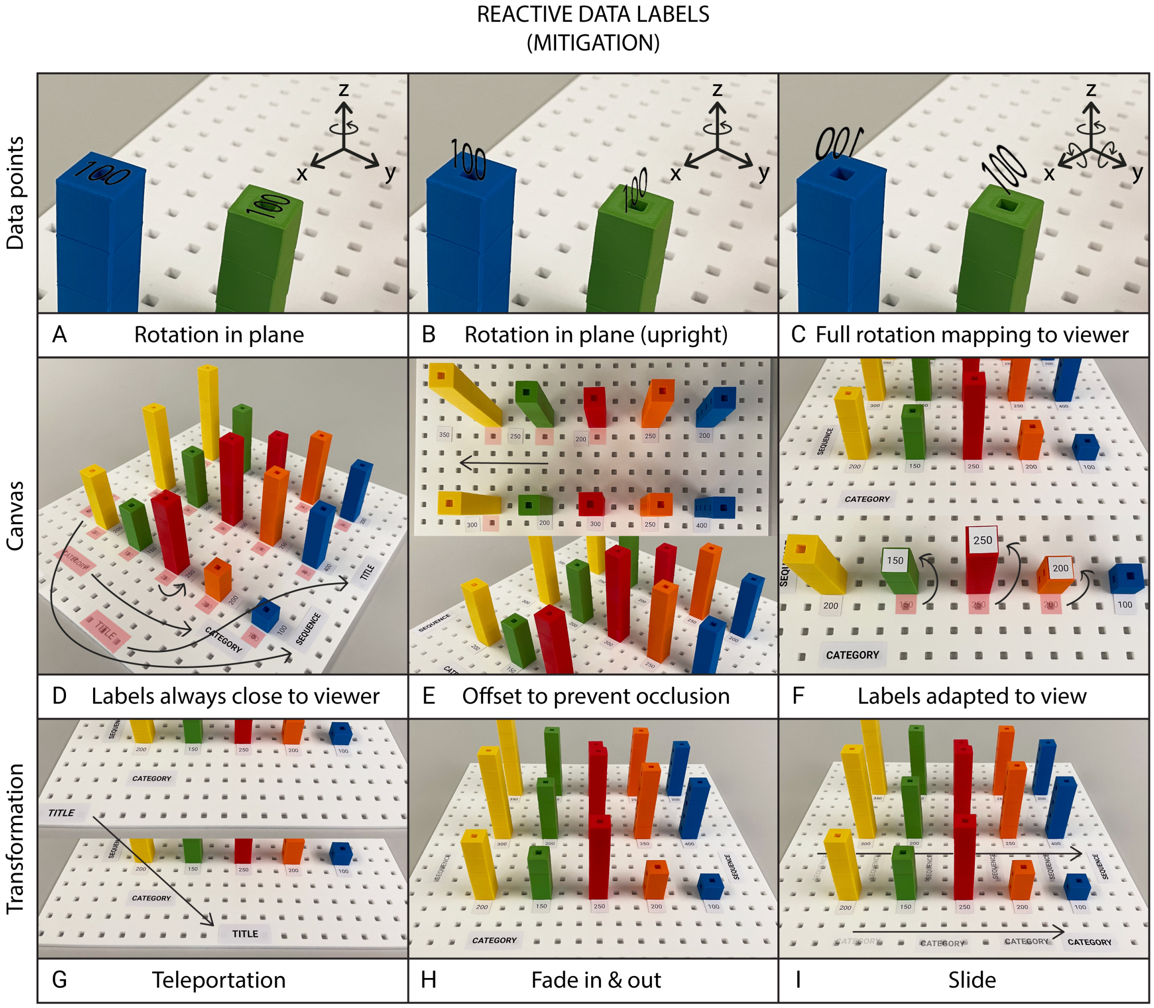


Figure 7.2: Overview of mitigation through reactive data labels.

In relation to the canvas, different scenarios can be applied to data labels. The adaptation of data labels to the orientation of the viewer can be more or less extensive. For example, data labels can always be as close to the viewer as possible, with the emphasis on maintaining proximity to the viewer and the intended organization of the composition through the relocation of data labels (see Figure 7.2D). Another scenario could be that data labels aim to prevent occlusion at all times, through relocation and offset (see Figure 7.2E). In this case, the emphasis is less on decreasing proximity to the viewer and more on making small adaptations to counteract occlusion. A third scenario could be that the information of data labels is adapted to viewing angle, through relocation, offset, and rotation. For example, when the viewer wants to get a close-up of a data point, the corresponding data label will relocate itself from the canvas to the top of the data point (see Figure 7.2F).

Similarly to reactive physical constructs, data labels can change from one state to another in different ways. For this, we can draw from the literature on shape-changing interfaces [183], which describes different types of transformation using varying speed, acceleration, tempo, frequency of movement, etc. Examples of transformations for data labels could be relocation through teleportation (Figure 7.2G), fading in and out (Figure 7.2H), or 'sliding' from one location to another (Figure 7.2I).

7.3.2 Utilization

Utilization refers to strategies that use the influence of user orientation on the perception of physical constructs and data labels in favor of novel physical representations of data. This can be achieved by dictating the vantage point of the viewer (e.g., the viewer is required to view the physicalization from a certain position within the physecology) and/or using special devices (e.g., including mirrors in the physicalization design) to create perspective experiences unique for physical 3D space. In this way, instead of preventing or reducing occlusion, we are actively using different forms of occlusion to support the viewing of the physicalization.

For the realization of physicalizations utilizing visual perception and perspective in physical 3D space, we can borrow from work on optical illusions. Optical illusions are visual phenomena that occur when the brain interprets information from the eyes in a way that does not match the physical reality of a situation [12]. In other words, optical illusions happen when the brain is tricked by the eyes into seeing something that is not really there or not seeing something that is actually there. Optical illusions come in many different forms [11] and have been previously used in HCI research. To give some examples, Yanagawa et al. [247] introduced Anamorphicons, a system using a touch-sensitive flat-panel display and cylindrical mirror. The display shows a distorted image, but when a user places the cylindrical mirror on top of the display, the original image can be viewed. Wang et al. [237] proposed a workflow to enable game designers to implement optical illusions in video games, including an illusion database[1] and six exemplar editors to facilitate implementation. Lastly, Flores and Araújo [68] investigated the application of anamorphosis and mixed reality in an educational context. Students were asked to create several anamorphic cubes, which then could be used as markers to trigger AR images from specific vantage points.

To introduce optical illusions in physicalization, one could use specific devices in the physecology (e.g., by introducing a spatial distribution in the physical setup to guide the viewer's vantage point through displays, projection, or AR) and through methods of information communication (e.g., by using actuated positioning in space to reveal different illusions). As an example, we will take a bar chart physicalization of a grid archetype and discuss how we can utilize the influence of user orientation through (i) physical construct illusions and/or (ii) data label illusions. For simplicity, we will discuss both elements separately, but this subset is not exhaustive and they can be used in combination with one another.

7.3.2.1 Physical Construct Illusions

Optical illusions can be implemented in different ways in physicalization design. For example, different variations of anamorphosis [7] – a distorted projection that can only be viewed 'correctly' from a specific vantage point and/or with special tools – can be used to alter physical constructs. Perspective (or oblique) anamorphosis [7] can make physical constructs (and data labels) accurately visible only from a specific vantage point (see Figure 7.3A). This can be used to dictate or provide cues for the desired user orientation before viewing the physicalization. Channel (or tabula scalata) anamorphosis [98] – which creates an illusion in which the vantage point from the left or right creates two different images – would allow for a single physical construct to visualize two or more different datasets (see Figure 7.3B). Mirror (or catoptric) anamorphosis [40] involves the use of specific mirror shapes (e.g., cylindrical or spherical) in combination with a distorted image to reveal the undistorted image. In contrast to perspective anamorphosis, the use of mirrors supports viewing from multiple vantage points around the circumference of a physicalization. Following the example of Yanagawa et al. [247], the principle of Anamorphicons could be used to create a set of interactive and dynamic physicalizations through the manipulation of cylindrical mirrors and a digital display (see Figure 7.3C). Additionally, more complex anamorphoses can be created by combining mirrors with deformed artifacts [245] to reveal two completely different images, instead of one distorted image.

Whereas anamorphosis involves the distortion of the image itself, POV (perspective of view) illusions can be used to manipulate the viewer's perception of the scene (e.g., through size, placement, or orientation). Following the work from Sugihara on

---

[1] http://hci.csie.ntu.edu.tw/illusiondb

ambiguous objects [217, 218], physical constructs can be designed to appear different when viewed from different perspectives. For example, viewing from aside or above reveals square versus cylindrical shapes, which could communicate highlights or outliers among the data points (see Figure 7.3D). When used in combination with actuation (e.g., rotation), one could use the distinction in shape to communicate different datasets, changes in data, outliers, and more.

Finally, multi-axes physicalization design could further utilize all three dimensions (x, y, and z-axis) to enable novel interactions with data in 3D space. For instance, multiple physical bar graphs could allow for different forms of comparison, such as side-by-side (e.g., number of steps taken today and yesterday), top-to-bottom (e.g., number of steps taken and hours of sleep), or in 3D space (e.g., number of steps taken, hours of sleep, and heart rate; see Figure 7.3E). Moreover, three dimensions could be used to visualize different levels of granularity in data. For example, the x-axis could show the total at different time intervals (e.g., total steps per day), whereas the y-axis could show how each total is constructed in further detail (e.g., total steps per hour for each day; see Figure 7.3F).

7.3.2.2 Data Label Illusions

Regarding data labels, we can create various illusions to provide clues for user orientation, guide viewing of more or less detailed information, or dictate specific vantage points. Similarly to physical constructs, perspective anamorphosis can be used to display data labels. For instance, an anamorphic illusion for data labels can initially guide the viewer to a desired vantage point, from which other interactions or actuations can occur (see Figure 7.3A). Furthermore, hybrid text illusions [173] could facilitate the presentation of general information versus details on demand [200] through different data labels from nearby or a distance (see Figure 7.3G). For example, when viewed from afar, general information such as titles and axes labels are communicated, whereas viewing a data point up close results in value labels. Finally, tilt-to-read illusions[2] could facilitate when the viewer is estimating bar chart heights from a close-up side view as the value labels only become visible when viewed from a strong angle (see Figure 7.3H).

---

[2] https://codepen.io/ninivert/full/JEPzxO

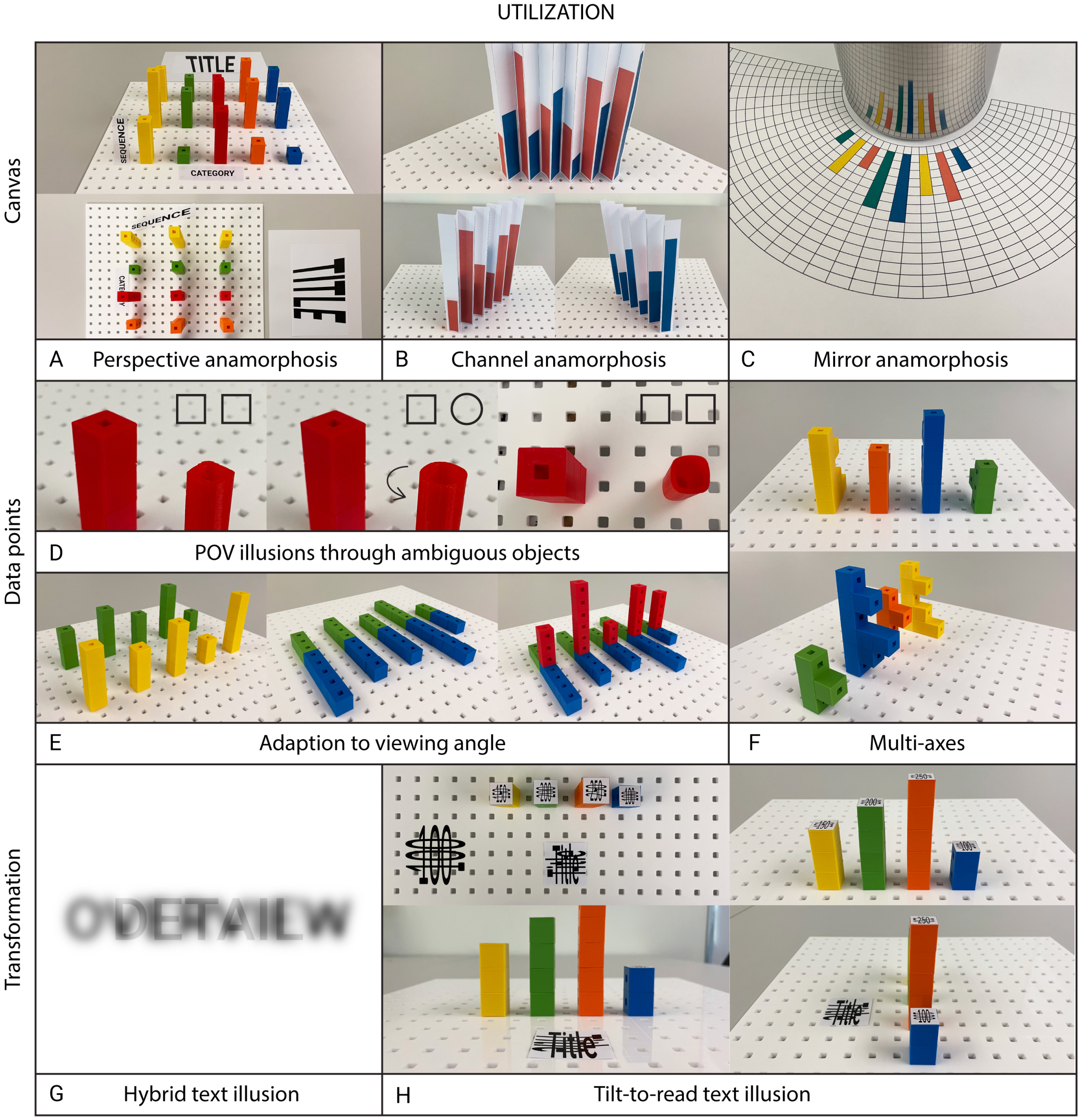


Figure 7.3: Overview of utilization approaches.

Chapter 8

Conclusion

In this thesis, we explore the implications of physicality and contextual factors on people's perception of and interaction with physicalizations. Using an inductive-deductive method, the thesis initially conducts a meta-review of state-of-the-art physicalizations in their real-world context, followed by three empirical studies on the perception, reconfiguration, and data labeling of bar chart physicalizations. As a result, we contribute (i) a conceptual framework – the physecology – which allows for the characterization of physicalizations in relation to their audience and context; (ii) a novel methodology to investigate the perception of and interactions with bar chart physicalizations across orientations; and (iii) new insights from empirical evidence providing an initial understanding of the direct influence of user orientation on perception, the strategies employed when reconfiguring physicalizations, and the role of data labeling in the creation and design of physicalizations, as well as their resilience across orientations.

Overall, the thesis emphasizes the importance of actively considering physicality and context in the design and evaluation of physicalizations intended for real-world use. The physecology framework can serve as a lens through which to view the empirical evidence and identify gaps in the current understanding of the perception, interaction, and contextualization of physicalization work.

Finally, the thesis advocates for 'context-sensitive physicalization design' as a way forward to create physicalizations that are reliable and effective means of communicating data, regardless of user orientation. Additionally, it presents two approaches that demonstrate various ways in which the influence of orientation can be minimized to eliminate ambiguities in information perception, or leveraged for novel visualization experiences. Future work can explore how these approaches for context-sensitive physicalization, in conjunction with the physecology framework, can facilitate the further implementation and evaluation of physicalizations for various application domains, audiences, and contexts.

Appendix A

Supplementary Materials (Chapter 6)

Year	**Season**	**Rainfall**
2017	Winter	200
2017	Spring	150
2017	Summer	250
2017	Autumn	250
2018	Winter	250
2018	Spring	200
2018	Summer	100
2018	Autumn	300
2019	Winter	200
2019	Spring	200
2019	Summer	300
2019	Autumn	350
2020	Winter	400
2020	Spring	200
2020	Summer	250
2020	Autumn	300

Table A.1: Dataset 1: UK rainfall (mm), 1 building block = 50 mm.

Year	**Country**	**CO2 emissions**
1900	Belgium (BE)	8
1900	Spain (ES)	2
1900	United Kingdom (UK)	10
1900	Netherlands (NL)	4
1900	Norway (NO)	2
2000	Belgium (BE)	12
2000	Spain (ES)	8
2000	United Kingdom (UK)	10
2000	Netherlands (NL)	10
2000	Norway (NO)	8
2018	Belgium (BE)	8
2018	Spain (ES)	6
2018	United Kingdom (UK)	6
2018	Netherlands (NL)	10
2018	Norway (NO)	8

Table A.2: Dataset 2: CO_2 emissions per person (tonne), 1 building block = 2 tonne.

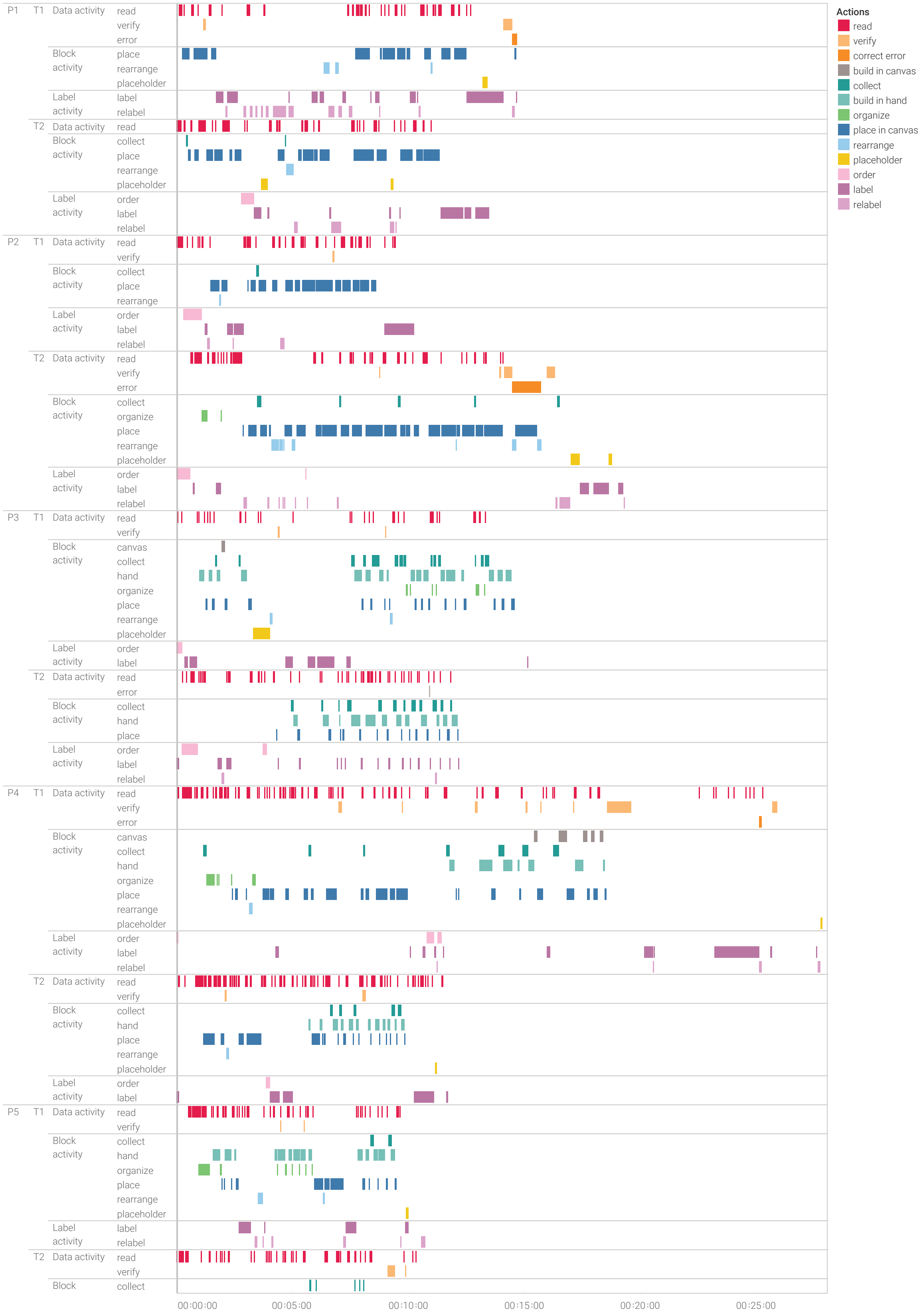
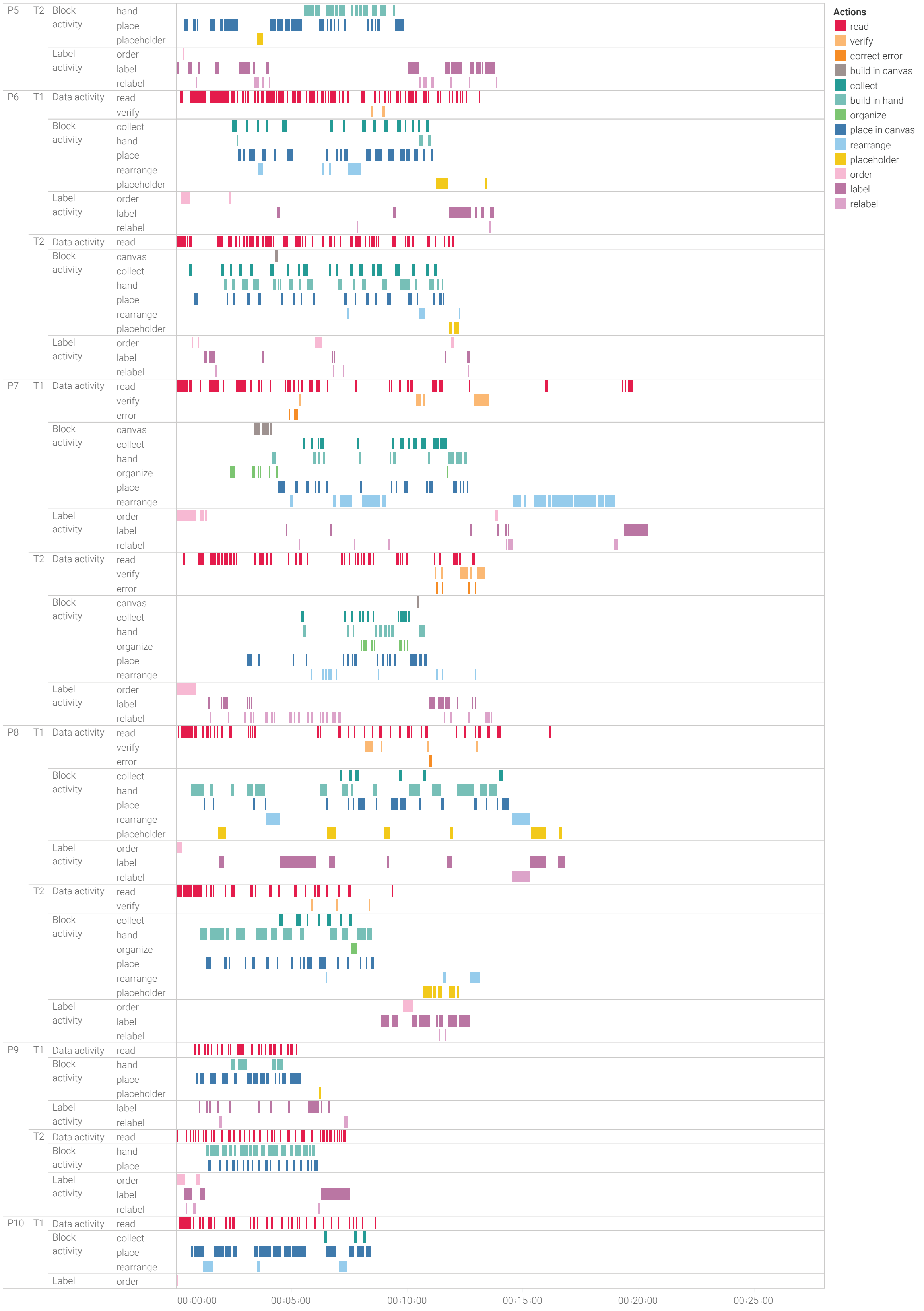
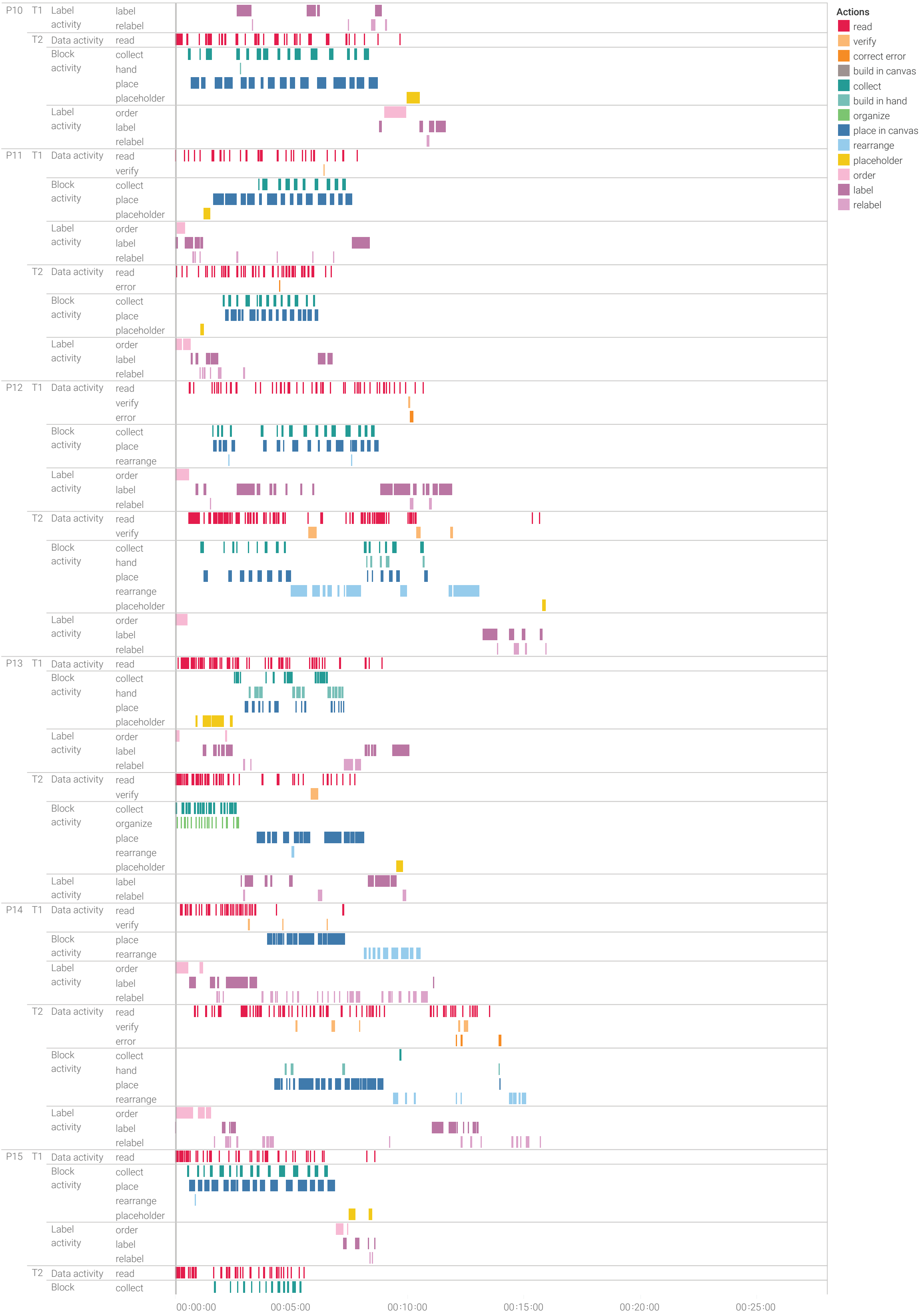
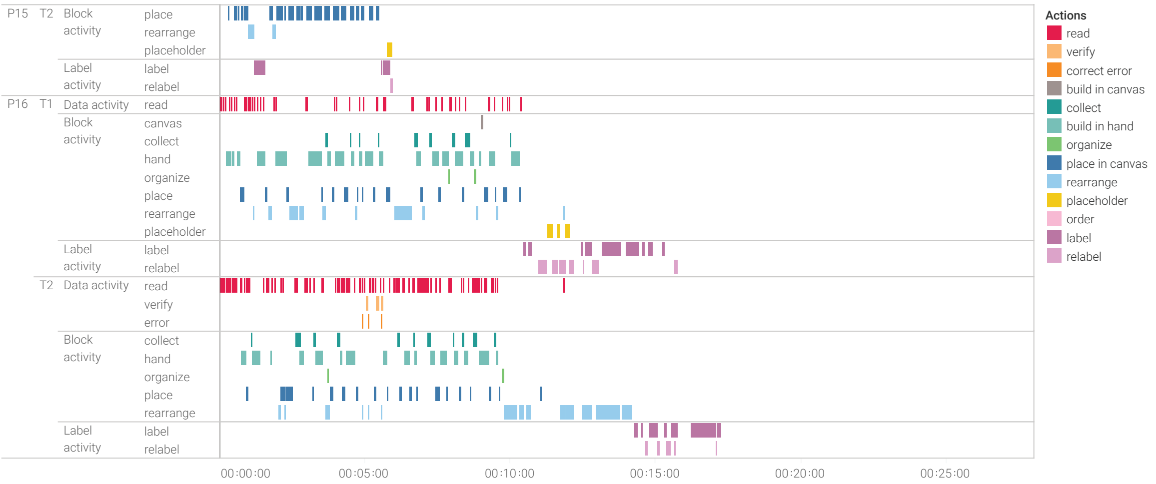


Figure A.1: Overview of the timelines per participant per task.


Actions
read
verify
correct error
build in canvas
collect
build in hand
organize
place in canvas
rearrange
placeholder
order
label
relabel
P5
T2
Block activity
hand
place
placeholder
Label activity
order
label
relabel
P6
T1
Data activity
read
verify
Block activity
collect
hand
place
rearrange
placeholder
Label activity
order
label
relabel
T2
Data activity
read
Block activity
canvas
collect
hand
place
rearrange
placeholder
Label activity
order
label
relabel
P7
T1
Data activity
read
verify
error
Block activity
canvas
collect
hand
organize
place
rearrange
Label activity
order
label
relabel
T2
Data activity
read
verify
error
Block activity
canvas
collect
hand
organize
place
rearrange
Label activity
order
label
relabel
P8
T1
Data activity
read
verify
error
Block activity
collect
hand
place
rearrange
placeholder
Label activity
order
label
relabel
T2
Data activity
read
verify
Block activity
collect
hand
organize
place
rearrange
placeholder
Label activity
order
label
relabel
P9
T1
Data activity
read
Block activity
hand
place
placeholder
Label activity
label
relabel
T2
Data activity
read
Block activity
hand
place
Label activity
order
label
relabel
P10
T1
Data activity
read
Block activity
collect
place
rearrange
Label
order
00:00:00
00:05:00
00:10:00
00:15:00
00:20:00
00:25:00


P10
T1
Label activity
label
relabel
T2
Data activity
read
Block activity
collect
hand
place
placeholder
Label activity
order
label
relabel
P11
T1
Data activity
read
verify
Block activity
collect
place
placeholder
Label activity
order
label
relabel
T2
Data activity
read
error
Block activity
collect
place
placeholder
Label activity
order
label
relabel
P12
T1
Data activity
read
verify
error
Block activity
collect
place
rearrange
Label activity
order
label
relabel
T2
Data activity
read
verify
Block activity
collect
hand
place
rearrange
placeholder
Label activity
order
label
relabel
P13
T1
Data activity
read
Block activity
collect
hand
place
placeholder
Label activity
order
label
relabel
T2
Data activity
read
verify
Block activity
collect
organize
place
rearrange
placeholder
Label activity
label
relabel
P14
T1
Data activity
read
verify
Block activity
place
rearrange
Label activity
order
label
relabel
T2
Data activity
read
verify
error
Block activity
collect
hand
place
rearrange
Label activity
order
label
relabel
P15
T1
Data activity
read
Block activity
collect
place
rearrange
placeholder
Label activity
order
label
relabel
T2
Data activity
read
Block
collect
00:00:00
00:05:00
00:10:00
00:15:00
00:20:00
00:25:00
Actions
read
verify
correct error
build in canvas
collect
build in hand
organize
place in canvas
rearrange
placeholder
order
label
relabel


P15
T2
Block activity
place
rearrange
placeholder
Label activity
label
relabel
P16
T1
Data activity
read
Block activity
canvas
collect
hand
organize
place
rearrange
placeholder
Label activity
label
relabel
T2
Data activity
read
verify
error
Block activity
collect
hand
organize
place
rearrange
Label activity
label
relabel
00:00:00
00:05:00
00:10:00
00:15:00
00:20:00
00:25:00
Actions
read
verify
correct error
build in canvas
collect
build in hand
organize
place in canvas
rearrange
placeholder
order
label
relabel

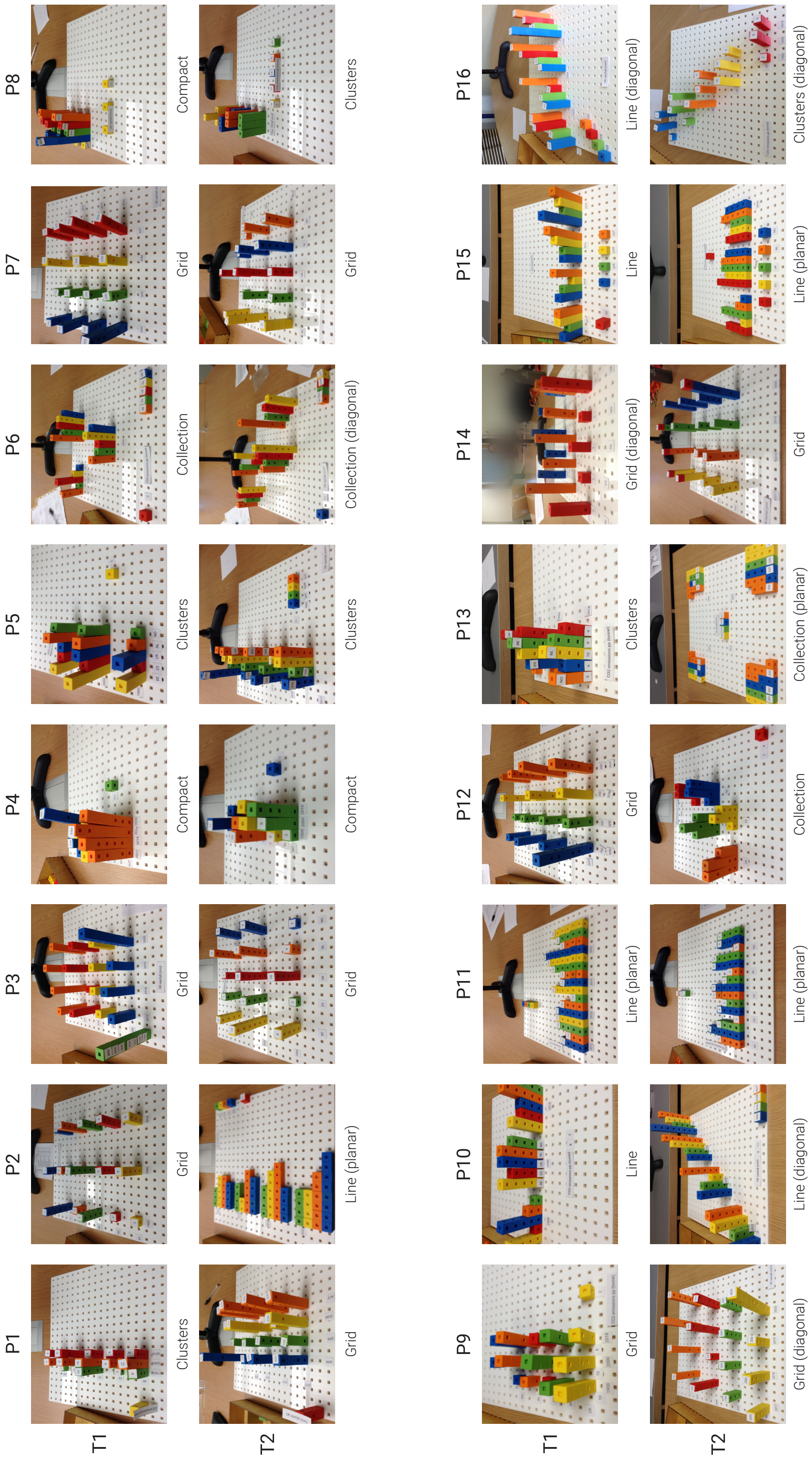


Figure A.2: Enlarged overview of all visualization designs created by participants.

Bibliography

[1] Gregory D Abowd, Anind K Dey, Peter J Brown, Nigel Davies, Mark Smith, and Pete Steggles. “Towards a Better Understanding of Context and Context-Awareness”. *Handheld and Ubiquitous Computing*. Springer. 1999, pp. 304–307.

[2] Pankaj K Agarwal, Marc Van Kreveld, and Subhash Suri. “Label placement by maximum independent set in rectangles”. *Computational Geometry* 11.3-4 (1998), pp. 209–218.

[3] Wolfgang Aigner, Silvia Miksch, Heidrun Schumann, and Christian Tominski. “Survey of Visualization Techniques”. *Visualization of Time-Oriented Data*. London: Springer London, 2011, pp. 147–254. ISBN: 978-0-85729-079-3. DOI: `10.1007/978-0-85729-079-3_7`.

[4] Jason Alexander, Anne Roudaut, Jürgen Steimle, Kasper Hornbæk, Miguel Bruns Alonso, Sean Follmer, and Timothy Merritt. “Grand Challenges in Shape-Changing Interface Research”. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI ’18)*. Montreal QC, Canada: ACM, 2018, pp. 1–14. ISBN: 9781450356206. DOI: `10.1145/3173574.3173873`.

[5] Kamran Ali, Knut Hartmann, and Thomas Strothotte. “Label layout for interactive 3D illustrations” (2005).

[6] Robert Amar, James Eagan, and John Stasko. “Low-level components of analytic activity in information visualization”. *IEEE Symposium on Information Visualization, 2005. INFOVIS 2005.* 2005, pp. 111–117. DOI: `10.1109/INFVIS.2005.1532136`.

[7] António B. Araújo. “Anamorphosis Reformed: From Optical Illusions to Immersive Perspectives”. *Handbook of the Mathematics of the Arts and Sciences*. Ed. by Bharath Sriraman. Cham: Springer International Publishing, 2021, pp. 175–242. ISBN: 978-3-319-57072-3. DOI: `10.1007/978-3-319-57072-3_101`.

[8] Laura Armstrong and Lawrence E. Marks. “Haptic perception of linear extent”. *Perception & Psychophysics* 61.6 (1999), pp. 1211–1226.

[9] Marcia Ascher and Robert Ascher. *Mathematics of the Incas: Code of the Quipu.* Courier Corporation, 2013.

[10] Fred Attneave and Malcolm D. Arnoult. "The quantitative study of shape and pattern perception." *Psychological bulletin* 53.6 (1956), p. 452.

[11] Michael Bach. *150 Illusions & Visual Phenomena with Explanations.* 2022. URL: `https://michaelbach.de/ot/`.

[12] Michael Bach and Charlotte M Poloschek. "Optical illusions". *Adv Clin Neurosci Rehabil* 6.2 (2006), pp. 20–21.

[13] S. Sandra Bae, Clement Zheng, Mary Etta West, Ellen Yi-Luen Do, Samuel Huron, and Danielle Albers Szafir. "Making Data Tangible: A Cross-Disciplinary Design Space for Data Physicalization". *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI '22).* New Orleans, LA, USA: ACM, 2022. ISBN: 9781450391573. DOI: `10.1145/3491102.3501939`.

[14] John C Baird. *Psychophysical analysis of visual space: international series of monographs in experimental psychology.* Vol. 9. Elsevier, 2013.

[15] Till Ballendat, Nicolai Marquardt, and Saul Greenberg. "Proxemic Interaction: Designing for a Proximity and Orientation-Aware Environment". *International Conference on Interactive Tabletops and Surfaces (ITS '10).* Saarbrücken, Germany: ACM, 2010, pp. 121–130. ISBN: 9781450303996. DOI: `10.1145/1936652.1936676`.

[16] Jakob E Bardram and Henrik B Christensen. "Pervasive Computing Support for Hospitals: An Overview of the Activity-Based Computing Project". *IEEE Pervasive Computing* 6.1 (2007), pp. 44–51.

[17] Niels van Berkel, Timothy Merritt, Anders Bruun, and Mikael B. Skov. "Tangible Self-Report Devices: Accuracy and Resolution of Participant Input". *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '22).* Daejeon, Republic of Korea: ACM, 2022. ISBN: 9781450391474. DOI: `10.1145/3490149.3501309`.

[18] Jacques Bertin. *Semiology of Graphics; Diagrams, Networks, Maps.* Tech. rep. 1983.

[19] Rahul Bhargava and Catherine D'Ignazio. "Data Sculptures as a Playful and Low-Tech Introduction to Working with Data" (2017). URL: `https://hdl.handle.net/1721.1/123453`.

[20] Jon Bird and Yvonne Rogers. "The Pulse of Tidy Street: Measuring and Publicly Displaying Domestic Electricity Consumption". *Workshop on Energy Awareness and Conservation through Pervasive Applications (Pervasive 2010).* 2010.

[21] Matthew Blackshaw, Anthony DeVincenzi, David Lakatos, Daniel Leithinger, and Hiroshi Ishii. “Recompose: Direct and Gestural Interaction with an Actuated Surface”. *Extended Abstracts of the 2011 CHI Conference on Human Factors in Computing Systems (CHI EA ’11)*. Vancouver, BC, Canada: ACM, 2011, pp. 1237–1242. ISBN: 9781450302685. DOI: `10.1145/1979742.1979754`.

[22] Susanne Bødker and Clemens Nylandsted Klokmose. “Dynamics in Artifact Ecologies”. *Proceedings of the 2012 Nordic Conference on Human-Computer Interaction: Making Sense Through Design (NordiCHI ’12)*. Copenhagen, Denmark: ACM, 2012, pp. 448–457. ISBN: 9781450314824. DOI: `10.1145/2399016.2399085`.

[23] Anna M. Borghi and Felice Cimatti. “Embodied cognition and beyond: Acting and sensing the body”. *Neuropsychologia* 48.3 (2010). The Sense of Body, pp. 763–773. ISSN: 0028-3932. DOI: `https://doi.org/10.1016/j.neuropsychologia.2009.10.029`.

[24] Richard Brath. “3D InfoVis is here to stay: Deal with it”. *2014 IEEE VIS International Workshop on 3DVis (3DVis)*. IEEE. 2014, pp. 25–31. DOI: `10.1109/3DVis.2014.7160096`.

[25] Nathalie Bressa, Henrik Korsgaard, Aurélien Tabard, Steven Houben, and Jo Vermeulen. “What’s the Situation with Situated Visualization? A Survey and Perspectives on Situatedness”. *IEEE Transactions on Visualization and Computer Graphics* 28.1 (2022), pp. 107–117. DOI: `10.1109/TVCG.2021.3114835`.

[26] Craig Brown and Amy Hurst. “VizTouch: Automatically Generated Tactile Visualizations of Coordinate Spaces”. *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction (TEI ’12)*. Kingston, Ontario, Canada: ACM, 2012, pp. 131–138. ISBN: 9781450311748. DOI: `10.1145/2148131.2148160`.

[27] Frederik Brudy, Christian Holz, Roman Rädle, Chi-Jui Wu, Steven Houben, Clemens Nylandsted Klokmose, and Nicolai Marquardt. “Cross-Device Taxonomy: Survey, Opportunities and Challenges of Interactions Spanning Across Multiple Devices”. *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI ’19)*. Glasgow, Scotland UK: ACM, 2019, pp. 1–28. ISBN: 9781450359702. DOI: `10.1145/3290605.3300792`.

[28] Grigore Burdea and Philippe Coiffet. *Virtual reality technology*. 2003.

[29] Tjeu van Bussel, Roy van den Heuvel, and Carine Lallemand. “Habilyzer: Empowering Office Workers to Investigate Their Working Habits Using an Open-Ended Sensor Kit”. *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems (CHI EA ’22)*. New Orleans, LA, USA: ACM, 2022. ISBN: 9781450391566. DOI: 10.1145/3491101.3519849.

[30] Nerea Calvillo. “Yellow Dust”. *Imminent Commons: The Expanded City*. Ed. by Alejandro Zaera-Polo and Jeffrey S. Anderson. Actar Publishers, 2017, pp. 46–52.

[31] Mackinlay Card. *Readings in information visualization: using vision to think*. Morgan Kaufmann, 1999.

[32] Neil R Carlson, Donald Heth, Harold Miller, John Donahoe, and G Neil Martin. *Psychology: The Science of Behavior*. Pearson, 2009.

[33] Robert Cercós, William Goddard, Adam Nash, and Jeremy Yuille. “Coupling Quantified Bodies”. *Digital Culture & Society* 2.1 (2016), pp. 177–182. DOI: 10.14361/dcs-2016-0114.

[34] Liwei Chan, Stefanie Müller, Anne Roudaut, and Patrick Baudisch. “CapStones and ZebraWidgets: Sensing Stacks of Building Blocks, Dials and Sliders on Capacitive Touch Screens”. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI ’12)*. Austin, Texas, USA: ACM, 2012, pp. 2189–2192. ISBN: 9781450310154. DOI: 10.1145/2207676.2208371.

[35] Chaomei Chen. *Information visualisation and virtual environments*. Springer Science & Business Media, 2013.

[36] Xuedi Chen. *x.pose*. 2014. URL: http://xc-xd.com/x-pose.

[37] Ed Huai-hsin Chi. “A taxonomy of visualization techniques using the data state reference model”. *IEEE Symposium on Information Visualization 2000. INFOVIS 2000. Proceedings*. IEEE. 2000, pp. 69–75.

[38] Jon Christensen, Joe Marks, and Stuart Shieber. “An empirical study of algorithms for point-feature label placement”. *ACM Transactions on Graphics (TOG)* 14.3 (1995), pp. 203–232.

[39] Antoine Clarinval, Anthony Simonofski, Benoît Vanderose, and Bruno Dumas. “Public Displays and Citizen Participation: A Systematic Literature Review and Research Agenda”. *Transforming Government: People, Process and Policy* (2020).

[40] Francesco de Comite and Laurent Grisoni. “Numerical Anamorphosis: An Artistic Exploration”. *SIGGRAPH ASIA 2015 Art Papers (SA ’15)*. Kobe, Japan: ACM, 2015. ISBN: 9781450339162. DOI: 10.1145/2835641.2835642.

[41] Patricia Costigan-Eaves and Michael Macdonald-Ross. “William Playfair (1759-1823)”. *Statistical Science* 5.3 (1990), pp. 318–326. DOI: 10.1214/ss/1177012100.

[42] Ida Damen, Daphne Menheere, Carine Lallemand, and Steven Vos. “Ivy: Reading a Critical Design for Sedentary Behavior in the Office Context”. *Companion Publication of the 2020 ACM Designing Interactive Systems Conference (DIS’ 20 Companion)*. Eindhoven, Netherlands: ACM, 2020, pp. 7–12. ISBN: 9781450379878. DOI: 10.1145/3393914.3395893.

[43] Evandro Damião. *The Dataphys Project*. 2017. URL: https://vimeo.com/228523280.

[44] Maxime Daniel and Guillaume Riviére. “Exploring Axisymmetric Shape-Change’s Purposes and Allure for Ambient Display: 16 Potential Use Cases and a Two-Month Preliminary Study on Daily Notifications”. *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI ’21)*. Salzburg, Austria: ACM, 2021. ISBN: 9781450382137. DOI: 10.1145/3430524.3442452.

[45] Maxime Daniel, Guillaume Riviére, and Nadine Couture. “CairnFORM: A Shape-Changing Ring Chart Notifying Renewable Energy Availability in Peripheral Locations”. *Proceedings of the 2019 International Conference on Tangible, Embedded, and Embodied Interaction (TEI ’19)*. Tempe, Arizona, USA: ACM, 2019, pp. 275–286. ISBN: 9781450361965. DOI: 10.1145/3294109.3295634.

[46] Kurtis Danyluk, Teoman Tomo Ulusoy, Wei Wei, and Wesley Willett. “Touch and Beyond: Comparing Physical and Virtual Reality Visualizations”. *IEEE Transactions on Visualization and Computer Graphics* (2020). DOI: 10.1109/TVCG.2020.3023336.

[47] David L. Davies and Donald W. Bouldin. “A Cluster Separation Measure”. *IEEE Transactions on Pattern Analysis and Machine Intelligence* ().

[48] A De Boer. “Label placement in 3D georeferenced and oriented digital photographs using GIS technology” (2007).

[49] Digit. *Poly*. 2009. URL: https://vimeo.com/9648429.

[50] Hessam Djavaherpour, Faramarz Samavati, Ali Mahdavi-Amiri, Fatemeh Yazdanbakhsh, Samuel Huron, Richard Levy, Yvonne Jansen, and Lora Oehlberg. “Data to Physicalization: A Survey of the Physical Rendering Process”. *Computer Graphics Forum* 40.3 (2021), pp. 569–598. DOI: https://doi.org/10.1111/cgf.14330.

[51] Tanja Döring, Axel Sylvester, and Albrecht Schmidt. “A Design Space for Ephemeral User Interfaces”. *Proceedings of the 2013 International Conference on Tangible, Embedded and Embodied Interaction (TEI ’13)*. Barcelona, Spain: ACM, 2013, pp. 75–82. ISBN: 9781450318983. DOI: 10.1145/2460625.2460637.

[52] Paul Dourish. *Where the action is: the foundations of embodied interaction*. MIT press, 2004.

[53] Pierre Dragicevic and Yvonne Jansen. *List of Physical Visualizations*. 2012. URL: http://www.dataphys.org/list.

[54] Pierre Dragicevic, Yvonne Jansen, and Andrew Vande Moere. “Data Physicalization”. *Handbook of Human Computer Interaction*. Ed. by Jean Vanderdonckt, Philippe Palanque, and Marco Winckler. Springer International Publishing, 2020, pp. 1–51. ISBN: 978-3-319-27648-9. DOI: 10.1007/978-3-319-27648-9_94-1.

[55] Žarko Dumičić, Katja Thoring, Hermann W Klöckner, and Gesche Joost. “Design elements in data physicalization: A systematic literature review” (2022). DOI: 10.21606/drs.2022.660.

[56] ECAL. *#Good vs. #Evil*. 2014. URL: https://vimeo.com/118477012.

[57] Shawn Edmondson, Jon Christensen, Joe Marks, and Stuart Shieber. “A general cartographic labelling algorithm”. *Cartographica: The International Journal for Geographic Information and Geovisualization* 33.4 (1996), pp. 13–24.

[58] Ward Edwards and Edwin G. Boring. “What Is Emmert’s Law?” *The American Journal of Psychology* 64.3 (1951), pp. 416–422. ISSN: 00029556. URL: http://www.jstor.org/stable/1419005 (visited on 06/26/2023).

[59] Madison A. Elliott, Christine Nothelfer, Cindy Xiong, and Danielle Albers Szafir. “A Design Space of Vision Science Methods for Visualization Research”. *IEEE Transactions on Visualization and Computer Graphics* 27.2 (2021), pp. 1117–1127. DOI: 10.1109/TVCG.2020.3029413.

[60] E. Emmert. “Grossenverhaltnisse der Nachbilder”. *Klinische Monatsblatter fur Augenheilkunde* 19 (1881), pp. 443–450. URL: https://cir.nii.ac.jp/crid/1572261549571172864.

[61] Severin Engert, Konstantin Klamka, Andreas Peetz, and Raimund Dachselt. “STRAIDE: A Research Platform for Shape-Changing Spatial Displays Based on Actuated Strings”. *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI ’22)*. New Orleans, LA, USA: ACM, 2022. ISBN: 9781450391573. DOI: 10.1145/3491102.3517462.

[62] Aluna Everitt and Jason Alexander. “PolySurface: A Design Approach for Rapid Prototyping of Shape-Changing Displays Using Semi-Solid Surfaces”. *Proceedings of the 2017 Conference on Designing Interactive Systems (DIS ’17)*. Edinburgh, United Kingdom: ACM, 2017, pp. 1283–1294. ISBN: 9781450349222. DOI: `10.1145/3064663.3064677`.

[63] Aluna Everitt, Anne Roudaut, Kasper Hornbæk, Mike Fraser, and Jason Alexander. “Investigating Pointing Performance for Tangible Surfaces with Physical 3D Targets”. *Proceedings of the ACM on Human-Computer Interaction (PACM HCI)* 6.ISS (2022). DOI: `10.1145/3567736`.

[64] Aluna Everitt, Faisal Taher, and Jason Alexander. “ShapeCanvas: An Exploration of Shape-Changing Content Generation by Members of the Public”. *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI ’16)*. San Jose, California, USA: ACM, 2016, pp. 2778–2782. ISBN: 9781450333627. DOI: `10.1145/2858036.2858316`.

[65] Danyang Fan, Alexa Fay Siu, Sile O’Modhrain, and Sean Follmer. “Constructive Visualization to Inform the Design and Exploration of Tactile Data Representations”. *The 22nd International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS ’20)*. Virtual Event, Greece: ACM, 2020. ISBN: 9781450371032. DOI: `10.1145/3373625.3418027`.

[66] Danyang Fan, Alexa Fay Siu, Sile O’Modhrain, and Sean Follmer. “Constructive Visualization to Inform the Design and Exploration of Tactile Data Representations”. *The 2020 International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS ’20)*. Virtual Event, Greece: ACM, 2020. ISBN: 9781450371032. DOI: `10.1145/3373625.3418027`.

[67] Kenneth P. Fishkin. “A Taxonomy for and Analysis of Tangible Interfaces”. *Personal Ubiquitous Computing* 8.5 (2004), pp. 347–358. ISSN: 1617-4909.

[68] Manuel Flores and António Araújo. “Applications of Anamorphosis and Mixed Reality in a Classroom Setting”. *10th International Conference on Digital and Interactive Arts (ARTECH ’21)*. Aveiro, Portugal, Portugal: ACM, 2022. ISBN: 9781450384209. DOI: `10.1145/3483529.3483532`.

[69] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. “InFORM: Dynamic Physical Affordances and Constraints through Shape and Object Actuation”. *Proceedings of the 2013 Annual Symposium on User Interface Software and Technology (UIST ’13)*. St. Andrews, Scotland, United Kingdom: ACM, 2013, pp. 417–426. ISBN: 9781450322683. DOI: `10.1145/2501988.2502032`.

[70] Joe Francica. *Interview with Xenotran Founder, Dr.Derrick Page*. 2004. URL: `https://www.directionsmag.com/article/3383`.

[71] Sarah Gallacher, Jenny O'Connor, Jon Bird, Yvonne Rogers, Licia Capra, Daniel Harrison, and Paul Marshall. "Mood Squeezer: Lightening up the Workplace through Playful and Lightweight Interactions". *Proceedings of the 2015 Conference on Computer Supported Cooperative Work & Social Computing (CSCW '15)*. Vancouver, BC, Canada: ACM, 2015, pp. 891–902. ISBN: 9781450329224. DOI: 10.1145/2675133.2675170.

[72] Helen Gibson, Joe Faith, and Paul Vickers. "A survey of two-dimensional graph layout techniques for information visualisation". *Information visualization* 12.3-4 (2013), pp. 324–357.

[73] James J Gibson. *The ecological approach to visual perception: classic edition*. Hillsdale, NJ, USA: Erlbaum, 1986.

[74] Silke M Göbel. "Up or down? Reading direction influences vertical counting direction in the horizontal plane–a cross-cultural comparison". *Frontiers in psychology* 6 (2015), p. 228.

[75] Connie Golsteijn, Sarah Gallacher, Lisa Koeman, Lorna Wall, Sami Andberg, Yvonne Rogers, and Licia Capra. "VoxBox: A Tangible Machine That Gathers Opinions from the Public at Events". *Proceedings of the 2015 International Conference on Tangible, Embedded, and Embodied Interaction (TEI '15)*. Stanford, California, USA: ACM, 2015, pp. 201–208. ISBN: 9781450333054. DOI: 10.1145/2677199.2680588.

[76] Dan Goods, Nik Hafermaas, and Aaron Koblin. *eCLOUD*. 2010. URL: http://www.ecloudproject.com.

[77] Pauline Gourlet and Thierry Dassé. "Cairn: A Tangible Apparatus for Situated Data Collection, Visualization and Analysis". *Proceedings of the 2017 Conference on Designing Interactive Systems (DIS '17)*. Edinburgh, United Kingdom: ACM, 2017, pp. 247–258. ISBN: 9781450349222. DOI: 10.1145/3064663.3064794.

[78] Rúben Gouveia, Fábio Pereira, Evangelos Karapanos, Sean A. Munson, and Marc Hassenzahl. "Exploring the Design Space of Glanceable Feedback for Physical Activity Trackers". *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp '16)*. Heidelberg, Germany: ACM, 2016, pp. 144–155. ISBN: 9781450344616. DOI: 10.1145/2971648.2971754.

[79] US Government. *Data Visualisation Standards*. 2021. URL: https://xdgov.github.io/data-design-standards/components/labels.

[80] Amy L. Griffin. "Feeling It Out: The Use of Haptic Visualization for Exploratory Geographic Analysis". *Cartographic Perspectives* 39 (2001), pp. 12–29. DOI: 10.14714/CP39.636.

[81] Tovi Grossman, Daniel Wigdor, and Ravin Balakrishnan. “Exploring and Reducing the Effects of Orientation on Text Readability in Volumetric Displays”. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. New York, NY, USA: ACM, 2007, pp. 483–492. ISBN: 9781595935939.

[82] Jianzhe Gu, Yuyu Lin, Qiang Cui, Xiaoqian Li, Jiaji Li, Lingyun Sun, Cheng Yao, Fangtian Ying, Guanyun Wang, and Lining Yao. “PneuMesh: Pneumatic-Driven Truss-Based Shape Changing System”. *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI ’22)*. New Orleans, LA, USA: ACM, 2022. ISBN: 9781450391573. DOI: 10.1145/3491102.3502099.

[83] Mark Hancock, Miguel Nacenta, Carl Gutwin, and Sheelagh Carpendale. “The Effects of Changing Projection Geometry on the Interpretation of 3D Orientation on Tabletops”. *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces (ITS ’09)*. Banff, Alberta, Canada: ACM, 2009, pp. 157–164. ISBN: 9781605587332. DOI: 10.1145/1731903.1731934.

[84] Jeffrey Heer and Michael Bostock. “Crowdsourcing Graphical Perception: Using Mechanical Turk to Assess Visualization Design”. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI ’10)*. Atlanta, Georgia, USA: ACM, 2010, pp. 203–212. ISBN: 9781605589299. DOI: 10.1145/1753326.1753357.

[85] Jeffrey Heer, Michael Bostock, and Vadim Ogievetsky. “A Tour through the Visualization Zoo: A Survey of Powerful Visualization Techniques, from the Obvious to the Obscure”. *Queue* 8.5 (May 2010), pp. 20–30. ISSN: 1542-7730. DOI: 10.1145/1794514.1805128.

[86] Jeffrey Heer and George Robertson. “Animated Transitions in Statistical Data Graphics”. *IEEE Transactions on Visualization and Computer Graphics* 13.6 (2007), pp. 1240–1247. DOI: 10.1109/TVCG.2007.70539.

[87] Paul Heinicker. *Passim*. 2015. URL: http://passim.paulheinicker.com/.

[88] Otmar Hilliges, David Kim, Shahram Izadi, Malte Weiss, and Andrew Wilson. “HoloDesk: Direct 3d Interactions with a Situated See-through Display”. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI ’12)*. Austin, Texas, USA: ACM, 2012, pp. 2421–2430. ISBN: 9781450310154. DOI: 10.1145/2207676.2208405.

[89] Silke Hilsing. *Virtual Gravity*. 2009. URL: https://vimeo.com/5641809.

[90] David Holstius, John Kembel, Amy Hurst, Peng-Hui Wan, and Jodi Forlizzi. “Infotropism: Living and Robotic Plants as Interactive Displays”. *Proceedings of the 5th Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques (DIS ’04)*. Cambridge, MA, USA: ACM, 2004, pp. 215–221. ISBN: 1581137877. DOI: 10.1145/1013115.1013145.

[91] Sarah Homewood, Harvey Bewley, and Laurens Boer. "Ovum: Designing for Fertility Tracking as a Shared and Domestic Experience". *Proceedings of the 2019 on Designing Interactive Systems Conference (DIS '19)*. San Diego, CA, USA: ACM, 2019, pp. 553–565. ISBN: 9781450358507. DOI: 10.1145/3322276.3323692.

[92] Eva Hornecker. "The Role of Physicality in Tangible and Embodied Interactions". *interactions* 18.2 (2011), [0–9]1, 4–[0-9]1, 4.

[93] Eva Hornecker and Jacob Buur. "Getting a Grip on Tangible Interaction: A Framework on Physical Space and Social Interaction". *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '06)*. Montréal, Québec, Canada: ACM, 2006, pp. 437–446. ISBN: 1595933727. DOI: 10.1145/1124772.1124838.

[94] Steven Houben, Ben Bengler, Daniel Gavrilov, Sarah Gallacher, Valentina Nisi, Nuno Jardim Nunes, Licia Capra, and Yvonne Rogers. "Roam-IO: Engaging with People Tracking Data through an Interactive Physical Data Installation". *Proceedings of the 2019 Conference on Designing Interactive Systems (DIS '19)*. San Diego, CA, USA: ACM, 2019, pp. 1157–1169. ISBN: 9781450358507. DOI: 10.1145/3322276.3322303.

[95] Steven Houben, Connie Golsteijn, Sarah Gallacher, Rose Johnson, Saskia Bakker, Nicolai Marquardt, Licia Capra, and Yvonne Rogers. "Physikit: Data Engagement Through Physical Ambient Visualizations in the Home". *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. San Jose, California, USA: ACM, 2016, pp. 1608–1619. ISBN: 9781450333627. DOI: 10.1145/2858036.2858059.

[96] Steven Houben, Nicolai Marquardt, Jo Vermeulen, Clemens Klokmose, Johannes Schöning, Harald Reiterer, and Christian Holz. "Opportunities and Challenges for Cross-Device Interactions in the Wild". *Interactions* 24.5 (2017), pp. 58–63.

[97] Meng-Ju Hsieh, Rong-Hao Liang, Da-Yuan Huang, Jheng-You Ke, and Bing-Yu Chen. "RFIBricks: Interactive Building Blocks Based on RFID". *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Montreal QC, Canada: ACM, 2018, pp. 1–10. ISBN: 9781450356206. DOI: 10.1145/3173574.3173763.

[98] James L. Hunt. "The Channel Anamorphosis". *Journal of Mathematics and the Arts* 3.1 (2009), pp. 19–31. DOI: 10.1080/17513470902869337.

[99] Samuel Huron, Sheelagh Carpendale, Alice Thudt, Anthony Tang, and Michael Mauerer. "Constructive Visualization". *Proceedings of the 2014 Conference on Designing Interactive Systems (DIS '14)*. Vancouver, BC, Canada: ACM, 2014, pp. 433–442. ISBN: 9781450329026. DOI: 10.1145/2598510.2598566.

[100] Samuel Huron, Yvonne Jansen, and Sheelagh Carpendale. "Constructing Visual Representations: Investigating the Use of Tangible Tokens". *IEEE Transactions on Visualization and Computer Graphics* 20.12 (2014), pp. 2102–2111. DOI: 10.1109/TVCG.2014.2346292.

[101] Samuel Huron, Till Nagel, Lora Oehlberg, and Wesley Willett, eds. *Making with Data: Physical Design and Craft in a Data-Driven World*. K Peters: CRC Press, 2023. ISBN: 9781032182223.

[102] Ekene Ijeoma. *Wage Islands*. 2015. URL: https://vimeo.com/138549946.

[103] Hiroshi Ishii and Brygg Ullmer. "Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms". *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI '97)*. Atlanta, Georgia, USA: ACM, 1997, pp. 234–241. ISBN: 0897918029. DOI: 10.1145/258549.258715.

[104] ISL. *Podium*. 2016. URL: https://vimeo.com/160130548.

[105] Nassim Jafarinaimi, Jodi Forlizzi, Amy Hurst, and John Zimmerman. "Breakaway: An Ambient Display Designed to Change Human Behavior". *CHI '05 Extended Abstracts on Human Factors in Computing Systems (CHI EA '05)*. Portland, OR, USA: ACM, 2005, pp. 1945–1948. ISBN: 1595930027. DOI: 10.1145/1056808.1057063.

[106] Yvonne Jansen and Pierre Dragicevic. "An Interaction Model for Visualizations Beyond The Desktop". *IEEE Transactions on Visualization and Computer Graphics* 19.12 (2013), pp. 2396–2405. DOI: 10.1109/TVCG.2013.134.

[107] Yvonne Jansen, Pierre Dragicevic, and Jean-Daniel Fekete. "Evaluating the Efficiency of Physical Visualizations". *Proceedings of the 2013 CHI Conference on Human Factors in Computing Systems (CHI '13)*. Paris, France: ACM, 2013, pp. 2593–2602. ISBN: 9781450318990. DOI: 10.1145/2470654.2481359.

[108] Yvonne Jansen, Pierre Dragicevic, Petra Isenberg, Jason Alexander, Abhijit Karnik, Johan Kildal, Sriram Subramanian, and Kasper Hornbæk. "Opportunities and Challenges for Data Physicalization". *Proceedings of the 2015 CHI Conference on Human Factors in Computing Systems (CHI '15)*. Seoul, Republic of Korea: ACM, 2015, pp. 3227–3236. ISBN: 9781450331456. DOI: 10.1145/2702123.2702180.

[109] Yvonne Jansen and Kasper Hornbæk. "A Psychophysical Investigation of Size as a Physical Variable". *IEEE Transactions on Visualization and Computer Graphics* 22.1 (2016), pp. 479–488. DOI: 10.1109/TVCG.2015.2467951.

[110] Charlene Jennett, Ioanna Iacovides, Anna L. Cox, Anastasia Vikhanova, Emily Weigold, Layla Mostaghimi, Geraint Jones, James Jenkins, Sarah Gallacher, and Yvonne Rogers. “Squeezy Green Balls: Promoting Environmental Awareness through Playful Interactions”. *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play (CHI PLAY ’16)*. Austin, Texas, USA: ACM, 2016, pp. 389–400. ISBN: 9781450344562. DOI: 10.1145/2967934.2968102.

[111] Sergi Jordá, G´unter Geiger, Marcos Alonso, and Martin Kaltenbrunner. “The ReacTable: Exploring the Synergy between Live Music Performance and Tabletop Tangible Interfaces”. *Proceedings of the 1st International Conference on Tangible and Embedded Interaction (TEI ’07)*. Baton Rouge, Louisiana: ACM, 2007, pp. 139–146. ISBN: 9781595936196. DOI: 10.1145/1226969.1226998.

[112] British Medical Journal. *The Long Run*. 2018. URL: https://www.youtube.com/watch?v=EsDpqNZpCvY.

[113] Heekyoung Jung, Erik Stolterman, Will Ryan, Tonya Thompson, and Marty Siegel. “Toward a Framework for Ecologies of Artifacts: How Are Digital Artifacts Interconnected within a Personal Life?” *Proceedings of the 2008 Nordic Conference on Human-Computer Interaction: Building Bridges (NordiCHI ’08)*. Lund, Sweden: ACM, 2008, pp. 201–210. ISBN: 9781595937049. DOI: 10.1145/1463160.1463182.

[114] Ken Kawamoto. *Tempescope*. 2015. URL: https://www.youtube.com/watch?v=aw0kWmMFv4g.

[115] Daniel F. Keefe, Seth Johnson, Ross Altheimer, Deuk-Geun Hong, Robert Hunter, Andrea J. Johnson, Maura Rockcastle, Mark Swackhamer, and Aaron Wittkamper. “Weather Report: A Site-Specific Artwork Interweaving Human Experiences and Scientific Data Physicalization”. *IEEE Computer Graphics and Applications* 38.4 (2018), pp. 10–16. DOI: 10.1109/MCG.2018.042731653.

[116] Christiane Keller. *dataMorphose*. 2009. URL: https://vimeo.com/4961482.

[117] Muzammil Khan and Sarwar Shah Khan. “Data and Information Visualization Methods, and Interactive Mechanisms: A Survey”. *International Journal of Computer Applications* 34.1 (2011), pp. 1–14.

[118] Rohit Ashok Khot, Deepti Aggarwal, Ryan Pennings, Larissa Hjorth, and Florian ’Floyd’ Mueller. “EdiPulse: Investigating a Playful Approach to Self-Monitoring through 3D Printed Chocolate Treats”. *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI ’17)*. Denver, Colorado, USA: ACM, 2017, pp. 6593–6607. ISBN: 9781450346559. DOI: 10.1145/3025453.3025980.

[119] Rohit Ashok Khot, Larissa Hjorth, and Florian 'Floyd' Mueller. "Understanding Physical Activity through 3D Printed Material Artifacts". *Proceedings of the 2014 CHI Conference on Human Factors in Computing Systems (CHI '14)*. Toronto, Ontario, Canada: ACM, 2014, pp. 3835–3844. ISBN: 9781450324731. DOI: `10.1145/2556288.2557144`.

[120] Mi Jeong Kim and Mary Lou Maher. "The Impact of Tangible User Interfaces on Designers' Spatial Cognition". *Human–Computer Interaction* 23.2 (2008), pp. 101–137. DOI: `10.1080/07370020802016415`.

[121] David Kirsh. "The Intelligent Use of Space". *Artificial Intelligence* 73.1–2 (1995), pp. 31–68. ISSN: 0004-3702. DOI: `10.1016/0004-3702(94)00017-U`.

[122] David Kirsh. "Interaction, External Representation and Sense Making". *Proceedings of the 31st Annual Conference of the Cognitive Science Society* (2009), pp. 1103–1108.

[123] David Kirsh and Paul Maglio. "On distinguishing epistemic from pragmatic action". *Cognitive Science* 18.4 (1994), pp. 513–549. ISSN: 0364–0213. DOI: `https://doi.org/10.1016/0364-0213(94)90007-8`.

[124] Nurit Kirshenbaum, James Hutchison, Ryan Theriot, Dylan Kobayashi, and Jason Leigh. "Data in Context: Engaging Audiences with 3D Physical Geo-Visualization". *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems (CHI EA '20)*. Honolulu, HI, USA: ACM, 2020, pp. 1–9. ISBN: 9781450368193. DOI: `10.1145/3334480.3382968`.

[125] Markus Kison. *Pulse*. 2009. URL: `http://www.markuskison.de/kinetic.html`.

[126] David Kjelkerud. *Wable*. 2007. URL: `https://www.youtube.com/watch?v=e6G5YlICVRg`.

[127] Lisa Koeman, Vaiva Kalnikaité, and Yvonne Rogers. "”Everyone Is Talking about It!”: A Distributed Approach to Urban Voting Technology and Visualisations". *Proceedings of the 2015 CHI Conference on Human Factors in Computing Systems (CHI '15)*. Seoul, Republic of Korea: ACM, 2015, pp. 3127–3136. ISBN: 9781450331456. DOI: `10.1145/2702123.2702263`.

[128] Lisa Koeman, Vaiva Kalnikaitundefined, Yvonne Rogers, and Jon Bird. "What Chalk and Tape Can Tell Us: Lessons Learnt for Next Generation Urban Displays". *Proceedings of The International Symposium on Pervasive Displays (PerDis '14)*. Copenhagen, Denmark: ACM, 2014, pp. 130–135. ISBN: 9781450329521. DOI: `10.1145/2611009.2611018`.

[129] Jan J Koenderink. "What Does the Occluding Contour Tell Us about Solid Shape?" *Perception* 13.3 (1984), pp. 321–330.

[130] Kurt Koffka. *Principles of Gestalt Psychology.* Vol. 44. The International Library of Psychology. Routledge, 2013.

[131] Janne van Kollenburg, Sander Bogers, Heleen Rutjes, Eva Deckers, Joep Frens, and Caroline Hummels. "Exploring the Value of Parent Tracked Baby Data in Interactions with Healthcare Professionals: A Data-Enabled Design Exploration". *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18).* Montreal QC, Canada: ACM, 2018, pp. 1–12. ISBN: 9781450356206. DOI: 10.1145/3173574.3173871.

[132] Teehan+Lax Labs. *Season in Review.* 2013. URL: https://vimeo.com/70821480.

[133] Mathieu Le Goc, Lawrence H. Kim, Ali Parsaei, Jean-Daniel Fekete, Pierre Dragicevic, and Sean Follmer. "Zooids: Building Blocks for Swarm User Interfaces". *Proceedings of the 2016 Symposium on User Interface Software and Technology (UIST '16).* Tokyo, Japan: ACM, 2016, pp. 97–109. ISBN: 9781450341899. DOI: 10.1145/2984511.2984547.

[134] Mathieu Le Goc, Charles Perin, Sean Follmer, Jean-Daniel Fekete, and Pierre Dragicevic. "Dynamic Composite Data Physicalization Using Wheeled Micro-Robots". *IEEE Transactions on Visualization and Computer Graphics* 25.1 (2019), pp. 737–747. DOI: 10.1109/TVCG.2018.2865159.

[135] Kyung-Ryong Lee, Somi Ju, Temirlan Dzhoroev, Geonil Goh, Moon-Hwan Lee, and Young-Woo Park. "DayClo: An Everyday Table Clock Providing Interaction with Personal Schedule Data for Self-Reflection". *Proceedings of the 2020 ACM Designing Interactive Systems Conference (DIS '20).* Eindhoven, Netherlands: ACM, 2020, pp. 1793–1806. ISBN: 9781450369749. DOI: 10.1145/3357236.3395439.

[136] Daniel Leithinger and Hiroshi Ishii. "Relief: A Scalable Actuated Shape Display". *Proceedings of the 2010 International Conference on Tangible, Embedded, and Embodied Interaction (TEI '10).* Cambridge, Massachusetts, USA: ACM, 2010, pp. 221–222. ISBN: 9781605588414. DOI: 10.1145/1709886.1709928.

[137] Daniel Leithinger, David Lakatos, Anthony DeVincenzi, Matthew Blackshaw, and Hiroshi Ishii. "Direct and Gestural Interaction with Relief: A 2.5D Shape Display". *Proceedings of the 2011 Annual Symposium on User Interface Software and Technology (UIST '11).* Santa Barbara, California, USA: ACM, 2011, pp. 541–548. ISBN: 9781450307161. DOI: 10.1145/2047196.2047268.

[138] James Leng. *Point Cloud.* 2012. URL: http://www.jamesleng.net/pointcloud.

[139] Jia Li, Catherine Plaisant, and Ben Shneiderman. “Data object and label placement for information abundant visualizations”. *Proceedings of the 1998 workshop on New paradigms in information visualization and manipulation*. 1998, pp. 41–48.

[140] Siân E Lindley, Anja Thieme, Alex S Taylor, Vasilis Vlachokyriakos, Tim Regan, and David Sweeney. “Surfacing Small Worlds through Data-In-Place”. *Computer Supported Cooperative Work (CSCW)* 26.1-2 (2017), pp. 135–163.

[141] Zhicheng Liu and John Stasko. “Mental Models, Visual Reasoning and Interaction in Information Visualization: A Top-down Perspective”. *IEEE Transactions on Visualization and Computer Graphics* 16.6 (2010), pp. 999–1008. DOI: `10.1109/TVCG.2010.177`.

[142] Simon Lok and Steven Feiner. “A survey of automated layout techniques for information presentations”. *Proceedings of SmartGraphics* 2001 (2001), pp. 61–68.

[143] Irene López García and Eva Hornecker. “Scaling Data Physicalization – How Does Size Influence Experience?” *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI ’21)*. New York, NY, USA: ACM, 2021. ISBN: 9781450382137. DOI: `10.1145/3430524.3440627`.

[144] John Losee. *A historical introduction to the philosophy of science*. OUP Oxford, 2001.

[145] Andrés Lucero. “Using Affinity Diagrams to Evaluate Interactive Prototypes”. *IFIP Conference on Human-Computer Interaction*. Springer. 2015, pp. 231–248.

[146] Tobias Lukassen, Halfdan Hauch Jensen, and Johan Bichel Lindegaard. *Chaotic Flow*. 2012. URL: `https://vimeo.com/56412526`.

[147] Yiyue Luo, Kui Wu, Andrew Spielberg, Michael Foshey, Daniela Rus, Tomás Palacios, and Wojciech Matusik. “Digital Fabrication of Pneumatic Actuators with Integrated Sensing by Machine Knitting”. *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI ’22)*. New Orleans, LA, USA: ACM, 2022. ISBN: 9781450391573. DOI: `10.1145/3491102.3517577`.

[148] Deborah Lupton. “Feeling your data: Touch and making sense of personal digital data”. *New Media & Society* 19.10 (2017), pp. 1599–1614.

[149] Peter Lyle, Henrik Korsgaard, and Susanne Bødker. “What’s in an Ecology? A Review of Artifact, Communicative, Device and Information Ecologies”. *Proceedings of the 11th Nordic Conference on Human-Computer Interaction: Shaping Experiences, Shaping Society (NordiCHI ’20)*. Tallinn, Estonia: ACM, 2020. ISBN: 9781450375795. DOI: `10.1145/3419249.3420185`.

[150] Wendy E. Mackay and Anne-Laure Fayard. "HCI, Natural Science and Design: A Framework for Triangulation across Disciplines". *Proceedings of the 2nd Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques (DIS '97)*. Amsterdam, The Netherlands: ACM, 1997, pp. 223–234. ISBN: 0897918630. DOI: 10.1145/263552.263612.

[151] Jennifer Mankoff, Anind K. Dey, Gary Hsieh, Julie Kientz, Scott Lederer, and Morgan Ames. "Heuristic Evaluation of Ambient Displays". *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '03)*. Ft. Lauderdale, Florida, USA: ACM, 2003, pp. 169–176. ISBN: 1581136307. DOI: 10.1145/642611.642642.

[152] Alessandro Masserdotti. *Actuated Prism Map of Italy*. 2016. URL: https://www.youtube.com/watch?v=DNzWbN3C7wU.

[153] Tara Matthews. "Designing and Evaluating Glanceable Peripheral Displays". *Proceedings of the 6th Conference on Designing Interactive Systems (DIS '06)*. University Park, PA, USA: ACM, 2006, pp. 343–345. ISBN: 1595933670. DOI: 10.1145/1142405.1142457.

[154] Jon McTaggart and Christian Ferrara. *Pulse*. 2012. URL: https://vimeo.com/45980795.

[155] Daphne Menheere, Evianne van Hartingsveldt, Mads Birkebæk, Steven Vos, and Carine Lallemand. "Laina: Dynamic Data Physicalization for Slow Exercising Feedback". *Designing Interactive Systems Conference 2021 (DIS '21)*. Virtual Event, USA: ACM, 2021, pp. 1015–1030. ISBN: 9781450384766. DOI: 10.1145/3461778.3462041.

[156] Miriah Meyer, Michael Sedlmair, and Tamara Munzner. "The Four-Level Nested Model Revisited: Blocks and Guidelines". *Proceedings of the 2012 BELIV Workshop: Beyond Time and Errors - Novel Evaluation Methods for Visualization (BELIV '12)*. Seattle, Washington, USA: ACM, 2012. ISBN: 9781450317917. DOI: 10.1145/2442576.2442587.

[157] Garrett C. Millar, Payam Tabrizian, Anna Petrasova, Vaclav Petras, Brendan Harmon, Helena Mitasova, and Ross K. Meentemeyer. "Tangible Landscape: A Hands-on Method for Teaching Terrain Analysis". *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Montreal QC, Canada: ACM, 2018, pp. 1–12. ISBN: 9781450356206. DOI: 10.1145/3173574.3173954.

[158] Andrew Vande Moere. "Beyond the Tyranny of the Pixel: Exploring the Physicality of Information Visualization". *2008 12th International Conference Information Visualisation*. 2008, pp. 469–474. DOI: 10.1109/IV.2008.84.

[159] Andrew Vande Moere and Dan Hill. “Designing for the Situated and Public Visualization of Urban Data”. *Journal of Urban Technology* 19.2 (2012), pp. 25–46. DOI: 10.1080/10630732.2012.698065.

[160] Andrew Vande Moere and Stephanie Patel. “The physical visualization of information: designing data sculptures in an educational context”. *Visual information communication*. Springer, 2009, pp. 1–23.

[161] Takafumi Morita, Yu Kuwajima, Ayato Minaminosono, Shingo Maeda, and Yasuaki Kakehi. “HydroMod: Constructive Modules for Prototyping Hydraulic Physical Interfaces”. *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI ’22)*. New Orleans, LA, USA: ACM, 2022. ISBN: 9781450391573. DOI: 10.1145/3491102.3502096.

[162] Tamara Munzner. “Process and Pitfalls in Writing Information Visualization Research Papers”. *Information Visualization*. Springer, 2008, pp. 134–153.

[163] Tamara Munzner. “A Nested Model for Visualization Design and Validation”. *IEEE Transactions on Visualization and Computer Graphics* 15.6 (2009), pp. 921–928. DOI: 10.1109/TVCG.2009.111.

[164] Tamara Munzner. *Visualization Analysis and Design*. Boca Raton, FL, USA: CRC Press, 2014.

[165] Miguel A. Nacenta, Mark Hancock, Carl Gutwin, and Sheelagh Carpendale. “The Effects of Changing Projection Geometry on Perception of 3D Objects on and Around Tabletops”. *ACM Transactions on Computer-Human Interaction (TOCHI)* 23.2 (May 2016). ISSN: 1073–0516. DOI: 10.1145/2845081.

[166] Henrik R Nagel. “Scientific Visualization versus Information Visualization”. *Workshop on state-of-the-art in scientific and parallel computing, Sweden*. Citeseer. 2006, pp. 8–9.

[167] Ken Nakagaki, Yingda (Roger) Liu, Chloe Nelson-Arzuaga, and Hiroshi Ishii. “TRANS-DOCK: Expanding the Interactivity of Pin-Based Shape Displays by Docking Mechanical Transducers”. *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI ’20)*. Sydney NSW, Australia: ACM, 2020, pp. 131–142. ISBN: 9781450361071. DOI: 10.1145/3374920.3374933.

[168] Ken Nakagaki, Jordan L Tappa, Yi Zheng, Jack Forman, Joanne Leong, Sven Koenig, and Hiroshi Ishii. “(Dis)Appearables: A Concept and Method for Actuated Tangible UIs to Appear and Disappear Based on Stages”. *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI ’22)*. New Orleans, LA, USA: ACM, 2022. ISBN: 9781450391573. DOI: 10.1145/3491102.3501906.

[169] Studio NAND. *Emoto*. 2012. URL: `https://vimeo.com/49679699`.

[170] Office for National Statistics (ONS). *Chart Titles and Text*. 2021. URL: `https://style.ons.gov.uk/category/data-visualisation/titles-and-text/`.

[171] Marie Neurath. “Isotype”. *Instructional science* (1974), pp. 127–150.

[172] Claire O’Malley and Danae Stanton Fraser. “Literature Review in Learning with Tangible Technologies” (2004).

[173] Aude Oliva and Philippe G Schyns. “Hybrid Image Illusions”. *The Oxford Compendium of Visual Illusions* (2017), pp. 763–766.

[174] Thomas Pederson, Lars-Erik Janlert, and Dipak Surie. “A Situative Space Model for Mobile Mixed-Reality Computing”. *IEEE Pervasive Computing* 10.4 (2010), pp. 73–83.

[175] Clément Pillias, Raphaël Robert-Bouchard, and Guillaume Levieux. “Designing Tangible Video Games: Lessons Learned from the Sifteo Cubes”. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI ’14)*. Toronto, Ontario, Canada: ACM, 2014, pp. 3163–3166. ISBN: 9781450324731. DOI: `10.1145/2556288.2556991`.

[176] Aura Pon, Eric Pattison, Lawrence Fyfe, Laurie Radford, and Sheelagh Carpendale. “Torrent: Integrating Embodiment, Physicalization and Musification in Music-Making”. *Proceedings of the 2017 International Conference on Tangible, Embedded, and Embodied Interaction (TEI ’17)*. Yokohama, Japan: ACM, 2017, pp. 209–216. ISBN: 9781450346764. DOI: `10.1145/3024969.3024974`.

[177] Kayleigh Porter and Gemma Arblaster. “How Does Vertical Reading Affect Reading Speed?” *The British and Irish orthoptic journal* 16.1 (2020), p. 38.

[178] Zachary Pousman and John Stasko. “A Taxonomy of Ambient Information Systems: Four Patterns of Design”. *Proceedings of the Working Conference on Advanced Visual Interfaces (AVI ’06)*. Venezia, Italy: ACM, 2006, pp. 67–74. ISBN: 1595933530. DOI: `10.1145/1133265.1133277`.

[179] Zachary Pousman, John Stasko, and Michael Mateas. “Casual Information Visualization: Depictions of Data in Everyday Life”. *IEEE Transactions on Visualization and Computer Graphics* 13.6 (2007), pp. 1145–1152. DOI: `10.1109/TVCG.2007.70541`.

[180] Gary Priestnall and Keith Cheverst. “Understanding Visitor Interaction with a Projection Augmented Relief Model Display: Insights from an In-the-Wild Study in the English Lake District”. *Personal and Ubiquitous Computing* (2019), pp. 1–15.

[181] Gary Priestnall, Jeremy Gardiner, Jake Durrant, and James Goulding. "Projection Augmented Relief Models (PARM): Tangible Displays for Geographic Information". *Electronic Visualisation and the Arts (EVA 2012)* (2012), pp. 180–187. DOI: `10.14236/ewic/EVA2012.28`.

[182] Linda L. Putnam and Scott Banghart. "Interpretive Approaches". *The International Encyclopedia of Organizational Communication* (2017), pp. 1–17. DOI: `https://doi.org/10.1002/9781118955567.wbieoc118`.

[183] Majken K. Rasmussen, Esben W. Pedersen, Marianne G. Petersen, and Kasper Hornbæk. "Shape-Changing Interfaces: A Review of the Design Space and Open Research Questions". *Proceedings of the 2012 CHI Conference on Human Factors in Computing Systems (CHI '12)*. Austin, Texas, USA: ACM, 2012, pp. 735–744. ISBN: 9781450310154. DOI: `10.1145/2207676.2207781`.

[184] He Ren and Eva Hornecker. "Comparing Understanding and Memorization in Physicalization and VR Visualization". *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '21)*. Salzburg, Austria: ACM, 2021. ISBN: 9781450382137. DOI: `10.1145/3430524.3442446`.

[185] Yvonne Rogers, William R. Hazlewood, Paul Marshall, Nick Dalton, and Susanna Hertrich. "Ambient Influence: Can Twinkly Lights Lure and Abstract Representations Trigger Behavioral Change?" *Proceedings of the 2010 International Conference on Ubiquitous Computing (UbiComp '10)*. Copenhagen, Denmark: ACM, 2010, pp. 261–270. ISBN: 9781605588438. DOI: `10.1145/1864349.1864372`.

[186] Kim Sauvé, Saskia Bakker, and Steven Houben. "Econundrum: Visualizing the Climate Impact of Dietary Choice through a Shared Data Sculpture". *Proceedings of the 2020 Conference on Designing Interactive Systems (DIS '20)*. Eindhoven, Netherlands: ACM, 2020, pp. 1287–1300. ISBN: 9781450369749. DOI: `10.1145/3357236.3395509`.

[187] Kim Sauvé, Saskia Bakker, Nicolai Marquardt, and Steven Houben. "LOOP: Exploring Physicalization of Activity Tracking Data". *Proceedings of the 2020 Nordic Conference on Human-Computer Interaction: Shaping Experiences, Shaping Society (NordiCHI '20)*. New York, NY, USA: ACM, 2020. ISBN: 9781450375795.

[188] Kim Sauvé, Pierre Dragicevic, and Yvonne Jansen. "Edo: A Participatory Data Physicalization on the Climate Impact of Dietary Choices". *Proceedings of the 2023 International Conference on Tangible, Embedded, and Embodied Interaction (TEI '23)*. Warsaw, Poland: ACM, 2023. ISBN: 9781450399777. DOI: `10.1145/3569009.3572807`.

[189] Kim Sauvé and Steven Houben. “Towards an Ecology of Interconnected Data Devices”. *CHI’21 Workshop Human-Data Interaction through Design*. 2021.

[190] Kim Sauvé, Steven Houben, Nicolai Marquardt, Saskia Bakker, Bart Hengeveld, Sarah Gallacher, and Yvonne Rogers. “*LOOP*: A Physical Artifact to Facilitate Seamless Interaction with Personal Data in Everyday Life”. *Proceedings of the 2017 ACM Conference Companion Publication on Designing Interactive Systems (DIS ’17 Companion)*. Edinburgh, United Kingdom: ACM, 2017, pp. 285–288. ISBN: 9781450349918. DOI: `10.1145/3064857.3079175`.

[191] Kim Sauvé, Dominic Potts, Jason Alexander, and Steven Houben. “A Change of Perspective: How User Orientation Influences the Perception of Physicalizations”. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI ’20)*. Honolulu, HI, USA: ACM, 2020, pp. 1–12. ISBN: 9781450367080. DOI: `10.1145/3313831.3376312`.

[192] Kim Sauvé, Argenis Ramirez Gomez, and Steven Houben. “Put a Label On It! Approaches for Constructing and Contextualizing Bar Chart Physicalizations”. *CHI Conference on Human Factors in Computing Systems (CHI ’22)*. New Orleans, LA, USA: ACM, 2022. ISBN: 9781450391573. DOI: `10.1145/3491102.3501952`.

[193] Kim Sauvé, Miriam Sturdee, and Steven Houben. “Physecology: A Conceptual Framework to Describe Data Physicalizations in Their Real-World Context”. *ACM Transactions on Computer-Human Interaction (TOCHI)* 29.3 (2022). ISSN: 1073-0516. DOI: `10.1145/3505590`.

[194] Kim Sauvé, David Verweij, Jason Alexander, and Steven Houben. “Reconfiguration Strategies with Composite Data Physicalizations”. *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI ’21)*. Yokohama, Japan: ACM, 2021. ISBN: 9781450380966. DOI: `10.1145/3411764.3445746`.

[195] Denise Schmandt-Besserat. *How writing came about*. University of Texas Press, 2010.

[196] Christian Schüller, Daniele Panozzo, Anselm Grundhöfer, Henning Zimmer, Evgeni Sorkine, and Olga Sorkine-Hornung. “Computational Thermoforming”. *ACM Transactions on Graphics* 35.4 (2016). ISSN: 0730-0301. DOI: `10.1145/2897824.2925914`.

[197] Sue Ann Seah, Diego Martinez Plasencia, Peter D. Bennett, Abhijit Karnik, Vlad Stefan Otrocol, Jarrod Knibbe, Andy Cockburn, and Sriram Subramanian. “SensaBubble: A Chrono-Sensory Mid-Air Display of Sight and Smell”. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI ’14)*. Toronto, Ontario, Canada: ACM, 2014, pp. 2863–2872. ISBN: 9781450324731. DOI: `10.1145/2556288.2557087`.

[198] Orit Shaer and Eva Hornecker. *Tangible user interfaces: past, present, and future directions*. Now Publishers Inc, 2010.

[199] William R Sherman and Alan B Craig. “Understanding virtual reality”. *San Francisco, CA: Morgan Kauffman* (2003).

[200] Ben Shneiderman. “The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations”. *The Craft of Information Visualization*. Ed. by Benjamin B. Bederson and Ben Shneiderman. Interactive Technologies. San Francisco: Morgan Kaufmann, 2003, pp. 364–371. ISBN: 978-1-55860-915-0. DOI: `https://doi.org/10.1016/B978-155860915-0/50046-9`.

[201] IoT Design Shop. *FizViz*. 2016. URL: `https://www.youtube.com/watch?v=xRHokuaM5Ms`.

[202] Gaurav Sinha, Rahul Shahi, and Mani Shankar. “Human Computer Interaction”. *2010 3rd International Conference on Emerging Trends in Engineering and Technology*. 2010, pp. 1–4. DOI: `10.1109/ICETET.2010.85`.

[203] Tobias Skog. “Activity Wallpaper: Ambient Visualization of Activity Information”. *Proceedings of the 5th Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques (DIS ’04)*. Cambridge, MA, USA: ACM, 2004, pp. 325–328. ISBN: 1581137877. DOI: `10.1145/1013115.1013171`.

[204] Stephen Smart and Danielle Albers Szafir. “Measuring the Separability of Shape, Size, and Color in Scatterplots”. *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI ’19)*. Glasgow, Scotland UK: ACM, 2019, pp. 1–14. ISBN: 9781450359702. DOI: `10.1145/3290605.3300899`.

[205] Charles Sowers. *Tidal Memory*. 2013. URL: `https://www.charlessowers.com/tidal-memory`.

[206] Ian Spence. “Visual psychophysics of simple graphical elements.” *Journal of Experimental Psychology: Human Perception and Performance* 16.4 (1990), p. 683.

[207] Ian Spence. “William Playfair and the Psychology of Graphs”. *Proceedings of the American Statistical Association, Section on Statistical Graphics*. 2006, pp. 2426–2436.

[208] Sjoerd Stamhuis, Hans Brombacher, Steven Vos, and Carine Lallemand. “Office Agents: Personal Office Vitality Sensors with Intent”. *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems (CHI EA ’21)*. Yokohama, Japan: ACM, 2021. ISBN: 9781450380959. DOI: `10.1145/3411763.3451559`.

[209] Brigitte Stegers, Kim Sauvé, and Steven Houben. "Ecorbis: A Data Sculpture of Environmental Behavior in the Home Context". *Designing Interactive Systems Conference (DIS '22)*. Virtual Event, Australia: ACM, 2022, pp. 1669–1683. ISBN: 9781450393584. DOI: `10.1145/3532106.3533508`.

[210] Domestic Data Streamers. *Drip-By-Tweet*. 2014. URL: `https://vimeo.com/221185107`.

[211] Dustin Stupp. *ON BRINK*. 2018. URL: `https://vimeo.com/281137843`.

[212] Miriam Sturdee and Jason Alexander. "Analysis and Classification of Shape-Changing Interfaces for Design and Application-Based Research". *ACM Computing Surveys* 51.1 (2018). ISSN: 0360-0300. DOI: `10.1145/3143559`.

[213] Miriam Sturdee, John Hardy, Nick Dunn, and Jason Alexander. "A Public Ideation of Shape-Changing Applications". *Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces (ITS '15)*. Madeira, Portugal: ACM, 2015, pp. 219–228. ISBN: 9781450338998. DOI: `10.1145/2817721.2817734`.

[214] Simon Stusak, Moritz Hobe, and Andreas Butz. "If Your Mind Can Grasp It, Your Hands Will Help". *Proceedings of the Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '16)*. Eindhoven, Netherlands: ACM, 2016, pp. 92–99. ISBN: 9781450335829. DOI: `10.1145/2839462.2839476`.

[215] Simon Stusak, Jeannette Schwarz, and Andreas Butz. "Evaluating the Memorability of Physical Visualizations". *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. Seoul, Republic of Korea: ACM, 2015, pp. 3247–3250. ISBN: 9781450331456. DOI: `10.1145/2702123.2702248`.

[216] Simon Stusak, Aurélien Tabard, Franziska Sauka, Rohit Ashok Khot, and Andreas Butz. "Activity Sculptures: Exploring the Impact of Physical Visualizations on Running Activity". *IEEE Transactions on Visualization and Computer Graphics* 20.12 (2014), pp. 2201–2210. DOI: `10.1109/TVCG.2014.2352953`.

[217] Kokichi Sugihara. "Joy of Ambiguous Solids: How to Make Anomalous Objects That Change Their Appearances in a Mirror". *Funabasi, Sugi Lab* (2015).

[218] Kokichi Sugihara. *Ambiguous Cylinder Illusion*. 2016. URL: `https://youtu.be/oWfFco7K9v8`.

[219] Ryo Suzuki, Jun Kato, Mark D. Gross, and Tom Yeh. "Reactile: Programming Swarm User Interfaces through Direct Physical Manipulation". *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Montreal QC, Canada: ACM, 2018, pp. 1–13. ISBN: 9781450356206. DOI: 10.1145/3173574.3173773.

[220] Faisal Taher, John Hardy, Abhijit Karnik, Christian Weichel, Yvonne Jansen, Kasper Hornbæk, and Jason Alexander. "Exploring Interactions with Physically Dynamic Bar Charts". *Proceedings of the 2015 CHI Conference on Human Factors in Computing Systems (CHI '15)*. Seoul, Republic of Korea: ACM, 2015, pp. 3237–3246. ISBN: 9781450331456. DOI: 10.1145/2702123.2702604.

[221] Faisal Taher, Yvonne Jansen, Jonathan Woodruff, John Hardy, Kasper Hornbæk, and Jason Alexander. "Investigating the Use of a Dynamic Physical Bar Chart for Data Exploration and Presentation". *IEEE Transactions on Visualization and Computer Graphics* 23.1 (2017), pp. 451–460. DOI: 10.1109/TVCG.2016.2598498.

[222] Faisal Taher, John Vidler, and Jason Alexander. "A Characterization of Actuation Techniques for Generating Movement in Shape-Changing Interfaces". *International Journal of Human–Computer Interaction* 33.5 (2017), pp. 385–398. DOI: 10.1080/10447318.2016.1250372.

[223] Ryan Theriot, James Hutchison, Nurit Kirshenbaum, and Jason Leigh. "Tailoring Data Visualization to Diversely Informed End Users". *Practice and Experience in Advanced Research Computing (PEARC '20)*. Portland, OR, USA: ACM, 2020, pp. 304–310. ISBN: 9781450366892. DOI: 10.1145/3311790.3396630.

[224] Edward Thompson, Dominic Potts, John Hardy, Barry Porter, and Steven Houben. "AmbiDots: An Ambient Interface to Mediate Casual Social Settings through Peripheral Interaction". *Proceedings of the 33rd Australian Conference on Human-Computer Interaction (OzCHI '21)*. Melbourne, VIC, Australia: ACM, 2022, pp. 99–110. ISBN: 9781450395984. DOI: 10.1145/3520495.3520504.

[225] Alice Thudt, Uta Hinrichs, Samuel Huron, and Sheelagh Carpendale. "Self-Reflection and Personal Physicalization Construction". *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Montreal QC, Canada: ACM, 2018, pp. 1–13. ISBN: 9781450356206. DOI: 10.1145/3173574.3173728.

[226] Alice Thudt, Uta Hinrichs, Samuel Huron, and Sheelagh Carpendale. “Self-Reflection and Personal Physicalization Construction”. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI ’18)*. Montreal QC, Canada: ACM, 2018, pp. 1–13. ISBN: 9781450356206. DOI: `10.1145/3173574.3173728`.

[227] Tinker. *Centograph*. 2009. URL: `https://vimeo.com/4961482`.

[228] James T. Todd. “The Visual Perception of 3D Shape”. *Trends in Cognitive Sciences* 8.3 (2004), pp. 115–121. ISSN: 1364-6613. DOI: `https://doi.org/10.1016/j.tics.2004.01.006`.

[229] Barbara Tversky, Julie Bauer Morrison, and Mireille Betrancourt. “Animation: can it facilitate?” *International Journal of Human-Computer Studies* 57.4 (2002), pp. 247–262. ISSN: 1071-5819. DOI: `https://doi.org/10.1006/ijhc.2002.1017`.

[230] B. Ullmer and H. Ishii. “Emerging frameworks for tangible user interfaces”. *IBM Systems Journal* 39.3.4 (2000), pp. 915–931. DOI: `10.1147/sj.393.0915`.

[231] Teoman Ulusoy, Kurtis Thorvald Danyluk, and Wesley J Willett. *Beyond the Physical: Examining Scale and Annotation in Virtual Reality Visualizations*. Tech. rep. Department of Computer Science, University of Calgary, 2018.

[232] Annemiek Veldhuis, Rong-Hao Liang, and Tilde Bekker. “CoDa: Collaborative Data Interpretation Through an Interactive Tangible Scatterplot”. *Proceedings of the 2020 International Conference on Tangible, Embedded, and Embodied Interaction (TEI ’20)*. Sydney NSW, Australia: ACM, 2020, pp. 323–336. ISBN: 9781450361071. DOI: `10.1145/3374920.3374934`.

[233] David Verweij, Saskia Bakker, and Berry Eggen. “FireFlies2: Interactive Tangible Pixels to Enable Distributed Cognition in Classroom Technologies”. *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces (ISS ’17)*. Brighton, United Kingdom: ACM, 2017, pp. 260–269. ISBN: 9781450346917. DOI: `10.1145/3132272.3134122`.

[234] Eliane Zambon Victorelli, Julio Cesar Dos Reis, Heiko Hornung, and Alysson Bolognesi Prado. “Understanding human-data interaction: Literature review and recommendations for design”. *International Journal of Human-Computer Studies* 134 (2020), pp. 13–32.

[235] Daniel Vogel and Ravin Balakrishnan. “Interactive Public Ambient Displays: Transitioning from Implicit to Explicit, Public to Personal, Interaction with Multiple Users”. *Proceedings of the 2004 Annual Symposium on User Interface Software and Technology (UIST ’04)*. Santa Fe, NM, USA: ACM, 2004, pp. 137–146. ISBN: 1581139578. DOI: `10.1145/1029632.1029656`.

[236] Frank Wagner, Alexander Wolff, Vikas Kapoor, and Tycho Strijk. "Three rules suffice for good label placement". *Algorithmica* 30.2 (2001), pp. 334–349.

[237] Po-Yao (Cosmos) Wang, Cong-He Xu, Ping-Yi Wang, Hsin-Yu Huang, Yu-Wei Chang, Jen-Hao Cheng, Yu-Hsin Lin, and Lung-Pan Cheng. "Game Illusionization: A Workflow for Applying Optical Illusions to Video Games". *The 34th Annual ACM Symposium on User Interface Software and Technology (UIST '21)*. Virtual Event, USA: ACM, 2021, pp. 1326–1344. ISBN: 9781450386357. DOI: `10.1145/3472749.3474824`.

[238] Colin Ware. *Information Visualization: Perception for Design*. Cambridge, MA, USA: Morgan Kaufmann, 2019.

[239] Stephen Wehrend and Clayton Lewis. "A problem-oriented classification of visualization techniques". *Proceedings of the First IEEE Conference on Visualization: Visualization '90*. 1990, pp. 139–143. DOI: `10.1109/VISUAL.1990.146375`.

[240] Mark Weiser. "The Computer for the 21st Century". *Scientific American* 265.3 (1991), pp. 94–105.

[241] Sean White and Steven Feiner. "SiteLens: Situated Visualization Techniques for Urban Site Visits". *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09)*. Boston, MA, USA: ACM, 2009, pp. 1117–1120. ISBN: 9781605582467. DOI: `10.1145/1518701.1518871`.

[242] Daniel Wigdor and Ravin Balakrishnan. "Empirical Investigation into the Effect of Orientation on Text Readability in Tabletop Displays". *ECSCW 2005*. Ed. by Hans Gellersen, Kjeld Schmidt, Michel Beaudouin-Lafon, and Wendy Mackay. Springer, 2005, pp. 205–224. ISBN: 978-1-4020-4023-8.

[243] Wesley Willett, Yvonne Jansen, and Pierre Dragicevic. "Embedded Data Representations". *IEEE Transactions on Visualization and Computer Graphics* 23.1 (2016), pp. 461–470. DOI: `10.1109/TVCG.2016.2598608`.

[244] Terri L Woods, Sarah Reed, Sherry Hsi, John A Woods, and Michael R Woods. "Pilot Study Using the Augmented Reality Sandbox to Teach Topographic Maps and Surficial Processes in Introductory Geology Labs". *Journal of Geoscience Education* 64.3 (2016), pp. 199–214. DOI: `10.5408/15-135.1`.

[245] Kang Wu, Renjie Chen, Xiao-Ming Fu, and Ligang Liu. "Computational Mirror Cup and Saucer Art". *ACM Transactions on Graphics* 41.5 (2022). ISSN: 0730-0301. DOI: `10.1145/3517120`.

[246] Tiffany Wun, Jennifer Payne, Samuel Huron, and Sheelagh Carpendale. "Comparing Bar Chart Authoring with Microsoft Excel and Tangible Tiles". *Computer Graphics Forum* 35.3 (2016), pp. 111–120. DOI: `https://doi.org/10.1111/cgf.12887`.

[247] Yuko Yanagawa, Kaori Ikematsu, Chihiro Suga, Mana Sasagawa, Yasushi Matoba, and Itiro Siio. "Anamorphicons: An Extended Display Utilizing a Cylindrical Mirror Widget". *Proceedings of the 29th Australian Conference on Computer-Human Interaction (OZCHI '17)*. Brisbane, Queensland, Australia: ACM, 2017, pp. 457–461. ISBN: 9781450353793. DOI: `10.1145/3152771.3156157`.

[248] Yangyang Yang and Kimiko Ryokai. "Exploring Laughter Sound Visualizations for Self Reflection". *Designing Interactive Systems Conference (DIS '22)*. Virtual Event, Australia: ACM, 2022, pp. 1472–1485. ISBN: 9781450393584. DOI: `10.1145/3532106.3533546`.

[249] Iddo Yehoshua Wald and Oren Zuckerman. "Magnetform: A Shape-Change Display Toolkit for Material-Oriented Designers". *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '21)*. Salzburg, Austria: ACM, 2021. ISBN: 9781450382137. DOI: `10.1145/3430524.3446066`.

[250] Deyue Yu, Heejung Park, David Gerold, and Gordon E Legge. "Comparing reading speed for horizontal and vertical English text". *Journal of vision* 10.2 (2010), pp. 21–21.

[251] Jack Zhao and Andrew Vande Moere. "Embodiment in Data Sculpture: A Model of the Physical Visualization of Information". *Proceedings of the 3rd International Conference on Digital Interactive Media in Entertainment and Arts (DIMEA '08)*. Athens, Greece: ACM, 2008, pp. 343–350. ISBN: 9781605582481. DOI: `10.1145/1413634.1413696`.

[252] Clement Zheng, Peter Gyory, and Ellen Yi-Luen Do. "Tangible Interfaces with Printed Paper Markers". *Proceedings of the 2020 ACM Designing Interactive Systems Conference (DIS '20)*. Eindhoven, Netherlands: ACM, 2020, pp. 909–923. ISBN: 9781450369749. DOI: `10.1145/3357236.3395578`.

[253] Andreas Zimmermann, Andreas Lorenz, and Reinhard Oppermann. "An operational Definition of Context". *International and Interdisciplinary Conference on Modeling and Using Context*. Springer. 2007, pp. 558–571.