Exploring the Potential of Physical Visualizations

Dissertation

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ABSTRACT

The goal of an external representation of abstract data is to provide insights and convey information about the structure of the underlying data, therefore helping people execute tasks and solve problems more effectively. Apart from the popular and well-studied digital visualization of abstract data there are other scarcely studied perceptual channels to represent data such as taste, sound or haptic. My thesis focuses on the latter and explores in which ways human knowledge and ability to sense and interact with the physical non-digital world can be used to enhance the way in which people analyze and explore abstract data. Emerging technological progress in digital fabrication allow an easy, fast and inexpensive production of physical objects. Machines such as laser cutters and 3D printers enable an accurate fabrication of physical visualizations with different form factors as well as materials. This creates, for the first time, the opportunity to study the potential of physical visualizations in a broad range.

The thesis starts with the description of six prototypes of physical visualizations from static examples to digitally augmented variations to interactive artifacts. Based on these explorations, three promising areas of potential for physical visualizations were identified and investigated in more detail: perception & memorability, communication & collaboration, and motivation & self-reflection.

The results of two studies in the area of information recall showed that participants who used a physical bar chart retained more information compared to the digital counterpart. Particularly facts about maximum and minimum values were be remembered more efficiently, when they were perceived from a physical visualization.

Two explorative studies dealt with the potential of physical visualizations regarding communication and collaboration. The observations revealed the importance on the design and aesthetic of physical visualizations and indicated a great potential for their utilization by audiences with less interest in technology. The results also exposed the current limitations of physical visualizations, especially in contrast to their well-researched digital counterparts.

In the area of motivation we present the design and evaluation of the *Activity Sculptures* project. We conducted a field study, in which we investigated physical visualizations of personal running activity. It was discovered that these sculptures generated curiosity and experimentation regarding the personal running behavior as well as evoked social dynamics such as discussions and competition.

Based on the findings of the aforementioned studies this thesis concludes with two theoretical contributions on the design and potential of physical visualizations. On the one hand, it proposes a conceptual framework for material representations of personal data by describing a production and consumption lens. The goal is to encourage artists and designers working in the field of personal informatics to harness the interactive capabilities afforded by digital fabrication and the potential of material representations. On the other hand we give a first classification and performance rating of physical variables including 14 dimensions grouped into four categories. This complements the undertaking of providing researchers and designers with guidance and inspiration to uncover alternative strategies for representing data physically and building effective physical visualizations.

ZUSAMMENFASSUNG

Um aus abstrakten Daten konkrete Aussagen, komplexe Zusammenhänge oder überraschende Einsichten gewinnen zu können, müssen diese oftmals in eine, für den Menschen, anschauliche Form gebracht werden. Eine weitverbreitete und gut erforschte Möglichkeiten ist die Darstellung von Daten in visueller Form. Weniger erforschte Varianten sind das Verkörpern von Daten durch Geräusche, Gerüche oder physisch ertastbare Objekte und Formen. Diese Arbeit konzentriert sich auf die letztgenannte Variante und untersucht wie die menschlichen Fähigkeiten mit der physischen Welt zu interagieren dafür genutzt werden können, das Analysieren und Explorieren von Daten zu unterstützen. Der technische Fortschritt in der digitalen Fertigung vereinfacht und beschleunigt die Produktion von physischen Objekten und reduziert dabei deren Kosten. Lasercutter und 3D Drucker ermöglichen beispielsweise eine maßgerechte Fertigung physischer Visualisierungen verschiedenster Ausprägungen hinsichtlich Größe und Material. Dadurch ergibt sich zum ersten Mal die Gelegenheit, das Potenzial von physischen Visualisierungen in größerem Umfang zu erforschen.

Der erste Teil der Arbeit skizziert insgesamt sechs Prototypen physischer Visualisierungen, wobei sowohl statische Beispiele beschrieben werden, als auch Exemplare die durch digital Inhalte erweitert werden oder dynamisch auf Interaktionen reagieren können. Basierend auf den Untersuchungen dieser Prototypen wurden drei vielversprechende Bereiche für das Potenzial physischer Visualisierungen ermittelt und genauer untersucht: Wahrnehmung & Einprägsamkeit, Kommunikation & Zusammenarbeit sowie Motivation & Selbstreflexion.

Die Ergebnisse zweier Studien zur Wahrnehmung und Einprägsamkeit von Informationen zeigten, dass sich Teilnehmer mit einem physischen Balkendiagramm an deutlich mehr Informationen erinnern konnten, als Teilnehmer, die eine digitale Visualisierung nutzten. Insbesondere Fakten über Maximal- und Minimalwerte konnten besser im Gedächtnis behalten werden, wenn diese mit Hilfe einer physischen Visualisierung wahrgenommen wurden.

Zwei explorative Studien untersuchten das Potenzial von physischen Visualisierungen im Bereich der Kommunikation mit Informationen sowie der Zusammenarbeit. Die Ergebnisse legten einerseits offen wie wichtig ein ausgereiftes Design und die Ästhetik von physischen Visualisierungen ist, deuteten anderseits aber auch darauf hin, dass Menschen mit geringem Interesse an neuen Technologien eine interessante Zielgruppe darstellen. Die Studien offenbarten allerdings auch die derzeitigen Grenzen von physischen Visualisierungen, insbesondere im Vergleich zu ihren gut erforschten digitalen Pendants.

Im Bereich der Motivation und Selbstreflexion präsentieren wir die Entwicklung und Auswertung des Projekts *Activity Sculptures*. In einer Feldstudie über drei Wochen erforschten wir physische Visualisierungen, die persönliche Laufdaten repräsentieren. Unsere Beobachtungen und die Aussagen der Teilnehmer ließen darauf schließen, dass die Skulpturen Neugierde weckten und zum Experimentieren mit dem eigenen Laufverhalten einluden. Zudem konnten soziale Dynamiken entdeckt werden, die beispielsweise durch Diskussion aber auch Wettbewerbsgedanken zum Ausdruck kamen.

Basierend auf den gewonnen Erkenntnissen durch die erwähnten Studien schließt diese Arbeit mit zwei theoretischen Beiträgen, hinsichtlich des Designs und des Potenzials von physischen Visualisierungen, ab. Zuerst wird ein konzeptionelles Framework vorgestellt, welches die Möglichkeiten und den Nutzen physischer Visualisierungen von persönlichen Daten veranschaulicht. Für Designer und Künstler kann dies zudem als Inspirationsquelle dienen, wie das Potenzial neuer Technologien, wie der digitalen Fabrikation, zur Darstellung persönlicher Daten in physischer Form genutzt werden kann. Des Weiteren wird eine initiale Klassifizierung von physischen Variablen vorgeschlagen mit insgesamt 14 Dimensionen, welche in vier Kategorien gruppiert sind. Damit vervollständigen wir unser Ziel, Forschern und Designern Inspiration und Orientierung zu bieten, um neuartige und effektvolle physische Visualisierungen zu erschaffen.

DISCLAIMER

Publications and Own Contribution

During the past four years of my time as Ph.D. student I worked together with many colleagues and students on various projects. To appreciate this collaboration, I decided to use the scientific plural in this thesis. The following sections will provide further information a clear overview of my personal contribution to each of the projects.

Chapter 5 - Beyond Physical Bar Charts
The content of this chapter is based on six main projects that, in turn, consist of six student's theses.

Subsection 5.1.1 - Threaded Bar-Star-Plot is based on the paper "Beyond Physical Bar Charts: An Exploration of Designing Physical Visualizations" by Stusak and Aslan [2014] and on a bachelor thesis by Ayfer Aslan [2013]. *Subsection 5.1.2 - Layered Physical Visualizations* is based on the paper "Can Physical Visualizations Support Analytical Tasks?" by Stusak, Tabard, and Butz [2013] and on a bachelor thesis by Lena Streppel [2014]. *Subsection 5.2.1 - Layered Physical Visualizations on Tabletops* based on the paper "Interacting with Layered Physical Visualizations on Tabletops" by Stusak [2014] and on a bachelor thesis by Maximilian Kreutzer [2014]. *Subsection 5.2.2 - Projection Augmented Physical Visualizations* is based on the paper "Projection Augmented Physical Visualizations" by Stusak and Teufel [2014] and on a master thesis by Markus Teufel [2014]. *Subsection 5.3.1 - Data Exploration Matrix* is based on a project thesis by Elisabeth Engel [2014]. *Subsection 5.3.2 - Swirlization* is based on a bachelor thesis by Barbara Schindler [2014].

The ideas for all theses were developed by me. The work was conducted in a collaborative manner with the students and each step in the project was jointly discussed in weekly meetings. However, all key decisions in which ways to proceed in the project, e.g., regarding the prototype design, study procedure and analysis of the results, were done by me. The main corpus of all papers were written by me and revised by the co-authors.

Chapter 6 - Potential for Perception & Memorability
The content of this chapter is based on two main projects, consisting of two student's theses, which were partly published at international peer-reviewed conferences.

Section 6.1 - Static Physical Bar Charts is based on the paper "Evaluating the Memorability of Physical Visualizations" by Stusak, Schwarz, and Butz [2015] and a master thesis by Jeannette Schwarz [2014]. *Section 6.2 - Modular Physical Bar Charts* is based on the paper "If Your Mind Can Grasp It, Your Hands Will Help" by Stusak, Hobe, and Butz [2016] and on a bachelor thesis by Moritz Hobe [2015].

The ideas for both projects were developed by me and I supervised the thesis and constantly provided input and feedback on the key decisions. We planned, conducted, and analyzed the evaluations in close collaboration. The main corpus of both publications were written by me and revised by the co-authors.

Chapter 7 - Potential for Communication & Collaboration
The content of this chapter is based on two main projects that, consisting of two student's theses.

Section 7.1 - PopUpData is partly based on a bachelor thesis by Arnold Schefner [2014]. The initial idea of the project was developed by Andreas Butz and me. I elaborated the concept and supervised the thesis, which resulted in the final design of the prototypes. The evaluation and analysis was done by me.

Section 7.2 - Collaborative Physicalizations is based on a project thesis by Xaver Loeffelholz and Peter Arnold [2015]. The initial idea of the project was developed by me and the project was supervised by Sarah Tausch and me. The work was conducted in a collaborative manner with the students and each step in the project was jointly discussed in weekly meetings. However, all key decisions in which ways to proceed in the project, e.g., regarding the prototype design, study procedure and analysis of the results, were done by me.

Chapter 8 - Potential for Motivation & Self-Reflection
The content of this chapter is based on the paper "Activity Sculptures: Exploring the Impact of Physical Visualizations on Running Activity" by Stusak, Tabard, Sauka, Khot, and Butz [2014] and a master thesis by Franziska Sauka [2014]. The idea of the project was developed by me and the thesis was supervised by me. The work was conducted in a collaborative manner with the student and each step in the project was jointly discussed in weekly meetings. We planned, conducted, and analyzed the evaluation in close collaboration. The main part of the publication was written by me, but in close collaboration with the co-author Aurélien Tabard.

Chapter 9 - Materialized Self
The content of this chapter is based on an intensive collocated collaboration with Rohit Ashok Khot for three months. We both contributed equally to the entire project, while Rohit Ashok Khot had a stronger focus on the "consumption lens" (see *Section 9.4 - Consumption Lens*) and my focus was on the "production lens" (see *Section 9.3 - Production Lens*).

Chapter 10 - Physical Variables
The content of this chapter is based on an intensive collaboration with Aurélien Tabard, consisting of discussions in biweekly meetings. However, the main part of the literature review and the proposition of the categories and variables was done by me.

Pictures and Illustrations

Due to the support by students, I did not create all images and illustrations of this thesis. In this case, I mention the name of the author in the corresponding caption. I created all pictures and illustrations that are not followed by such a statement.

Statistical Analysis

All statistical analyses in this thesis are based on estimation, i.e., effect sizes with confidence intervals. We decided to do this because of growing concerns regarding the limits of null hypothesis significance testing for reporting and interpreting study results in the field of HCI (e.g., Kaptein and Robertson [2012]; Dragicevic [2016]; Kay et al. [2016b,a]) as well as in other research fields (e.g., Kline [2004]; Cumming [2014]).

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First and foremost, I would like to thank my supervisor **Andreas Butz** for all the encouragement during my time as a doctoral student, especially when I was struggling with the entire undertaking. Thank you also for supporting lab visits abroad, trips to scientific conferences even in Hawaii and for dancing in the front row at one of my concerts. I also thank **Sheelagh Carpendale** for all her time and effort being my second supervisor and **Peer Kröger** for agreeing to be my committee chair. A big thank you in particular to **Aurélien Tabard** for helping me find a topic, building first prototypes and his assistance in writing my first scientific papers.

I will always look back at an incredible time working at the Media Informatics and Human-Computer Interaction Group, primarily because of all my great colleagues. I would like to thank **Emanuel von Zezschwitz** for your positive vibe, your DJ skills and endless parties, **Sarah Tausch** for being a beNUTS fan from the very beginning and always being friendly and happy even after "mean" jokes, **Alina Hang** for never being unforgiving and establishing the "Waffel-Gang", **Julie Wagner** for always thinking outside the box and organizing curious activities, **Henri Palleis** for your deadpan humor and assisting my students with 3D graphics, **Hanna Schneider** for your honesty and fun parties ending up at the "Shakira Bar", **Sebastian Löhmann** for your enthusiasm in sports and hip-hop and showing my students how to do hardware prototyping properly, **Bernhard Slawik** for the assistance in assembling the *Ultimaker* and always being helpful with tips and tricks for the best 3D print, **Axel Hösl** for showing me how to execute a proper high five and staying up all night at IDC Venice, **Tobias Seitz** for your high spirits and your enthusiasm in making music, **Alexander Wiethoff** for introducing me to the world of tangibles, **Alexander De Luca** for showing me how the world of research works, **Max Maurer** for introducing me to the art of being a student tutor and **Daniel Buschek** for taking over my duties. I also want to thank **Ronald Ecker** again for supervising my diploma thesis, where you proved that being a doctoral student and supervising students can be a lot of fun. Thanks as well to **Michael Sedlmair** for guidance and honest feedback at the very beginning of my time as a doctoral student and sorry that we never succeeded in writing a paper together. I also want to thank former and current colleagues as well as our external doctoral students **Hendrik Richter**, **Fabian Hennecke**, **Doris Hausen**, **Florian Alt**, **Renate Häuslschmid**, **Bastian Pfleging**, **Christian Mai**, **Maria Fysaraki**, **Malin Eiband**, **Ceenu George**, **Mariam Hassib**, **Mohamed Khamis**, **Daniel Ullrich**, **Felix Lauber**, **Sonja Rümelin**, **Martin Knobel**, and **Nora Broy**, for insightful presentations at our IDC, exciting discussions or amusing conversations at the one or the other coffee break.

Moreover, I want to thank **Heinrich Hussmann** for the helpful feedback during my IDC presentations and for always taking the time when I had questions as a student tutor. I want to give my special thanks to **Franziska Schwamb**; together we managed to answer even the most unusual requests by our students, and without you, I probably would have spent most of my vacation time in Cuba organizing a room for my thesis defense. Many thanks also go to **Rainer Fink**; I just hope that all sysadmins out there are as competent as you and share the same dry humor. I also want to thank **Florian "Floyd" Mueller** and **Rohit Ashok Khot** for inviting me to the Exertion Games Lab at the RMIT in Melbourne and the inspiring and very good time I had in your lab.

During my time I had the pleasure to work with many fantastic students, who all contributed to this thesis. I want to thank **Franziska Sauka** for 3D printing day and night, even on weekends, **Jeannette Schwarz** for keeping track of endless data source files, **Arnold Schefner** for the assistance in creating 400 pop-up cards, **Xaver Loeffelholz** and **Peter Arnold** for their great teamwork, **Moritz Hobe** for conducting a study that ended up in a best paper, **Ayfer Aslan** for your creativity and building the first physicalizations, **Lena Streppel** for combining old school visualization techniques and physicalizations, **Barbara Schindler** for bringing *Swirly* to life, **Elisabeth Engel** for moving LEDs, at least a little bit, **Maximilian Kreutzer** for bringing the *Surface* back to life and **Markus Teufel** for amazing coding skills and fascinating discussions far away from your thesis' topic.

Finally, a big thank you to all my **friends** and my band colleagues from **beNUTS** and **Rapid**, the rehearsals and concerts were always a perfect compensation to the research world. I am deeply grateful for all the support of my parents, **Erika Stusak** and **Hans Stusak**, my sister **Carolin Stusak**, and my brother **Steffen Stusak**. It helped a lot to know, that you are always there for me no matter what. Last but not least, I want to say thank you to **Tessa-Virginia Hannemann**. Thanks for all the proof-reading and discussions on study design or statistics, but also for philosophizing and listening to music night after night with a Cuba Libre in our hands and mostly for standing by my side even in tough times. Thank you very much for your love, support and optimism.

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List of Abbreviations

ACM Association for Computing Machinery

API Application Programming Interface

ASTM American Society for Testing and Materials

BC Before Christ

BELIV BEyond time and errors: novel evaLuation methods for Information Visualization

C&C Creativity & Cognition

CAD Computer-Aided Design

CBA Center for Bits and Atoms

CNC Computer-Numeric Controlled

CSCW Computer-Supported Cooperative Work

CSG Constructive Solid Geometry

CHI Human Factors in Computing Systems

DIS Designing Interactive Systems

DIY Do-It-Yourself

FabLab Fabrication Laboratory

FDM Fused Deposition Modeling

FFF Fused Filament Fabrication

GDP Gross Domestic Product

GPS Global Positioning System

GUI Graphical User Interface

HCI Human-Computer Interaction

HDR Human Development Report

IDC Interaction Design and Children

InfoVis Information Visualization

LED Light-Emitting Diode

LMU Munich Ludwig-Maximilians-Universität Munich

MIT Massachusetts Institute of Technology

MRI Magnetic Resonance Imaging

OECD Organisation for Economic Co-operation and Development

PLA PolyLactic Acid

PRIO Peace Research Institute Oslo

RGB Red Green Blue

SALW Small Arms and Light Weapons

SciVis Scientific Visualization

SDK Software Development Kit

SIGCHI Special Interest Group on Computer-Human Interaction

SMA Shape Memory Alloy

STL STereoLithography

TUI Tangible User Interface

TED Technology, Entertainment, Design

TEI Tangible, Embedded, and Embodied Interaction

UIST User Interface Software and Technology

USA United States of America

USB Universal Serial Bus

Chapter 1

Introduction

The goal of an external representation of data is to provide insights and convey information about the underlying data, therefore helping people execute tasks and solve problems more efficiently, comprehend contexts and relations or express emotion and provoke thought. However, the question in which ways data should be represented to be of value for humans is not easy to answer. Marr [1982] gives a simple but demonstrative example by means of the different formal systems for representing numbers, e.g., the Arabic, Roman, and binary numeral system. While all representations can encode the same number, the degree of accessibility for specific information, such as the powers of ten, varies considerably [Carpendale, 2003].

The visual representation of data on paper and digital screens has a long history and has proven its value to communicate abstract numbers in a simple and understandable form through bar and line graphs since the 18th century [Playfair, 1801]. Over time, especially through the adoption of the computer, visualizations have raised further attention and interest which led to the research field of Information Visualization (InfoVis). Amongst others, research in this area has investigated the efficiency of single visual variables as well as types of visualizations, developed novel interaction techniques for visualization systems and explored the value of visual representations for various audiences.

The findings have revealed, that an external representation can facilitate human capabilities, such as internal cognition and memory [Munzner, 2014]. Even though Munzner argues that external representations can take many forms, including physical objects, this opportunity has been mostly disregarded in the field of InfoVis. Therefore, this thesis aims to investigate the ways in which the experience and perception of data are influenced by representation modalities, and explores the benefits of encoding data physically.

Figure 1.1: Hans Rosling uses physical visualizations to explain the global population growth (left, image © TED) and the Syrian refugee situation in 2015 (right, image © Gapminder Foundation).

1.1 Motivation

Using physical objects and properties to represent data is not a new idea, as various examples built by artists and designers show [Dragicevic and Jansen, 2012]. Physical visualizations are often used as artistic artifacts to attract attention, convey meaning and messages beyond the data itself and provoke thought. Compared to their digital counterparts physical data representations have the advantage of being "*touched, explored, carried, or even possessed*" [Vande Moere, 2008]. Furthermore, Jansen et al. [2015] argue, that physicalizations can "*offer potential perceptual, cognitive, and communicative value that neither paper nor computer displays may be able to offer.*"

A vivid example of the ways in which physical representations can be used to explain data and emphasize messages are the presentations by the medical doctor and public speaker Hans Rosling. Figure 1.1-left shows an example of his Technology, Entertainment, Design (TED) talk on "religions and babies". By using card boxes, each representing one billion people, he illustrates what he calls "the big fill-up," which describes the prediction of the United Nations Population Division that the population growth will stop at 10 billion people. Another case is shown in Figure 1.1-right, in which he explains the Syrian refugee situation in 2015. Again he uses physical boxes, each representing one million people, to exemplify the migration of Syrians that have left their homes. As the boxes are placed on an interactive tabletop, he mixes analog and digital visualization techniques, resulting in a gripping story.

Those examples suggest that physical visualizations are useful and efficient to communicate and present information in a comprehensible form. However, data representations are not only used for communicating information but also for discovering new insights that were not previously known, for pure enjoyment and out of curiosity [Munzner, 2014]. It is still unclear and rarely studied which characteristics physical visualizations actually have, in which ways these can be used and for which purposes they are suitable.

Use All Our Senses

By approaching or touching objects, we can estimate its temperature, by lifting a milk carton we can draw conclusions about its fill level and by squeezing an avocado we can make inferences about its ripeness. Humans have learned for centuries the ways in which to sense and manipulate the physical world. Hiroshi Ishii has been fighting against the "pixel empire" for many years, as he argues that the Graphical User Interfaces (GUIs), commonly used for electronic devices, do not take full advantage of human capabilities [Ishii and Ullmer, 1997; Ishii et al., 2012]. Although multi-touch devices are considered more direct and physical, as they allow to "touch" interface elements and also support gestures, this is only a small subset of the expressive power of the human hand, not to mention the entire body. While a growing number of projects looked into interaction techniques beyond the desktop in the field of InfoVis [Lee et al., 2012], only little research has focused on the idea of encoding data into material and object properties [Jansen, 2014].

Emerging Technologies

With decreasing costs for digital fabrication technologies such as laser cutters or 3D printers, their distribution and adoption has increased greatly [Mota, 2011]. They allow an accurate fabrication of physical objects with different form factors and materials in a reasonable time frame and for a small budget. This creates the opportunity to study the potential of physical visualizations for various purposes in a broad range, for the first time. Also, the technical progress in research areas such as shape-changing interfaces lead to the questions in which ways such novel techniques can be integrated into everyday life and in which ways they can complement traditional 2D displays [Rasmussen et al., 2012]. While technologies for shape-changing interfaces are rapidly evolving, our understanding of their apparent benefits is still limited. Positive findings of the ways in which physically encoded data can influence individual's perception and experience can motivate further research in this area and can serve as an application scenario.

Physical Data Representations

Before the written word, humans used physical objects such as clay tokens as data representations, e.g., to organize and store economic data [Schmandt-Besserat, 1986]. With the invention of paper and much later on digital screens, data representations moved from three-dimensional physical objects to two-dimensional graphics on flat surfaces. Compared to physical data representations, which take time and material to build and are typically static, visualizations on digital screens are dynamic and support interactive exploration such as filtering or updating the dataset. Bearing in mind the costs and limitations of physicalizations, their adoption depends on providing clear benefits. Jansen et al. [2013] showed that moving a 3D bar chart from the digital into the physical world can improve efficiency at information retrieval tasks. Physicalizations may have many possible benefits, e.g., on perceptual or cognitive levels, but further research needs to provide evidence for or against these assumptions and address the multiple challenges and opportunities of this field.

1.2 Research Objectives & Research Questions

Most work in the area of physical data representations was done by designers and artists with a focus on aesthetic and impressive artistic installations. Data physicalization as a new and emerging field of research was proposed recently by Jansen et al.. Researchers are assured that physical data representations have the quality of evoking fascination and curiosity or even turn data exploration into an educational, enjoyable experience [Vande Moere, 2008]. However, those expectations are often not backed with research results. In addition, the creation of effective physical visualizations and their analytical value remain to be explored. Those considerations lead to two widespread research questions:

> *(RQ1) How do physicalizations influence the perception and experience of data exploration (compared to traditional data representations)?*
>
> *(RQ2) How can and should physicalizations be designed to fulfill specific purposes?*

To tackle these rather broad research questions in the yet open field of data physicalization we started with conducting an exploratory research through design. In several projects physical data representations were designed and built for a range of different datasets and in various form factors based on several materials. All had the common goal of exploring the ways in which physical visualization can be designed, to investigate in which ways people use and interact with them and to establish a basic understanding of their potential and limitations. The collected experiences and learned lessons in this exploration phase lead to three promising directions for physical visualizations and three related research questions:

> *(RQ3) How do physicalizations impact the recall of information?*
>
> *(RQ4) How do physicalizations impact communication and collaboration processes?*
>
> *(RQ5) How do physicalizations impact motivation and self-reflection?*

1.3 Research Approach

To find answers for the above formulated research objectives, I pursued the following approach:

Literature Review

To establish a theoretical basis for the design and evaluation of physical visualizations a literature review was performed covering three aspects: (1) background on psychological and physical human capabilities to gain a deeper understanding of the ways in which the sense of touch and physicality can be used for the representation of data; (2) overview of digital fabrication technologies such as laser cutters or 3D printers, which allow an easy, fast and precise creation of physical visualizations; and (3) an introduction into the history of physical data representations and examples of installations and systems that were created and developed in related fields.

Exploration

To explore the rather new research area of physical visualizations, various prototypes were created, based on tools and methods known from the field of Human-Computer Interaction (HCI), such as user-centered design or low-fidelity prototyping. This practical approach was inspired by the research through design method [Zimmerman et al., 2007], the intention and expected final output of which is a series of prototypes and a documentation of the design process, that can help to specify a context of use and set of target audiences. By designing and building a broad spectrum of physical data representations, from static to digitally augmented to dynamic prototypes, three promising directions for the value of physical visualizations could be identified.

Evaluation

To analyze the benefits of physical visualizations, several prototypes were evaluated for the three areas of perception & memorability, communication & collaboration and motivation & self-reflection. Controlled, lab-based studies were conducted and two in-the-wild studies [Rogers, 2011] to explore in which ways physical visualizations are used in day-to-day life. In these studies, participants used and interacted with the created physical visualizations and reported on their experiences through questionnaires and semi-structured interviews.

Retrospective

To recapitulate on the design, creation and evaluation of the built prototypes of physical visualizations, the collected experiences and learned lessons are discussed on an abstract level. The outcome is a conceptual framework for material representations of personal data and an initial characterization of physical variables.

1.4 Contributions

This thesis focuses on the investigation of ways in which information can be perceived through physical artifacts and material properties and thereby uncover its potential as well as highlight challenges and limitations. Based on the previously mentioned research questions this thesis offers two main contributions to the field of data physicalization.

Design of Physical Visualizations

In the course of this thesis, eleven prototypes of physical visualizations were built. A laser cutter, 3D printer, and classical workshop tools, as well as various materials such as paper, wood, acrylic glass and PolyLactic Acid (PLA), were used for their creation. While the focus was on static physical visualizations inspired by traditional 2D graphs, four projects explored digitally augmented and dynamic physical visualizations. This thesis provides details on the design process and the evaluation of all prototypes. Based on the findings and collected experiences through the creation and evaluation of these prototypes, two theoretical contributions to the design and potential of physical visualizations are proposed. On the one hand, it proposes a conceptual framework for material representations of personal data by describing a production and consumption lens. The goal is to inspire designers working in the field of personal informatics to harness the interactive capabilities afforded by digital fabrication and material representations. On the other hand, it gives a first classification of physical variables to guide designers and researchers in building effective physical visualizations.

Potential of Physical Visualizations

Based on the initial design and evaluation of six prototypes three promising areas of potential for physical visualizations were identified and investigated in more detail. The results of two studies in the area of perception & memorability showed that facts about maximum and minimum values were be remembered more efficiently when they were perceived from a physical visualization. Two explorative studies in the area of communication & collaboration highlighted the importance of the design and aesthetic of physical visualizations and revealed a polarization: Participants either strongly enjoyed working with the physicalizations or rejected them and described them as inconvenient compared to their digital counterparts. A field study in the area of motivation & self-reflection uncovered that physical visualizations of personal running activity generate curiosity and personal experimentation as well as social dynamics such as discussions or competition and therefore revealed additional benefits of physical visualizations compared to their digital counterparts.

1.5 Thesis Overview

This thesis is divided into three main parts. The first part provides an overview of the related work in the fields of haptic perception, digital fabrication and data physicalization. The second part describes several initial prototypes of physical visualizations and introduces three promising areas for physical visualization, which are investigated in more detail. The third part contains two theoretical considerations derived from the results and insights gathered in the evaluations of the prototypes. The thesis concludes with a statement about the limitations of the work and an outlook on future work. The three parts contain the following chapters.

Chapter 1 - Introduction
Chapter 1 grounds the thesis topic and provides details about the motivation for researching physical data representations. Furthermore research questions are formulated, the research approach is presented, and the contributions to the field are stated.

Part I: Background

The first part provides an overview of the related work relevant for the field of physical visualizations.

Chapter 2 - Embodied Interaction & Haptic Perception
Chapter 2 introduces the ideas of embodied interaction and the theory of embodied cognition. Moreover, research done in the field of haptic perception is discussed including object and material properties, their manual exploration and performance characteristics.

Chapter 3 - Digital Fabrication
Chapter 3 reviews projects regarding digital fabrication technologies. The section on personal fabrication describes application examples in a private or industrial setting. The second section focuses on research projects referring to digital fabrication and explains in which ways the research fields of digital fabrication and physical visualizations are associated with each other.

Chapter 4 - Data Physicalization
Chapter 4 offers an overview of work that is related to the physical representation of data. After a short introduction to its history, the focus of the chapter lies on the definition of the term physicalizations as well as the listing and categorization of research projects that experimented with physical data representations.

Part II: Prototyping Physical Visualizations

The second part describes several initial prototypes of physical visualizations and introduces three promising areas for physical visualization.

Chapter 5 - Beyond Physical Bar Charts
Chapter 5 presents initial prototypes of static, digitally augmented and dynamic physical visualizations. Based on the exploration and evaluation of these prototypes, three promising areas of potential for physical visualization were identified. Their investigation in more depth is the content of the following three chapters.

Chapter 6 - Potential for Perception & Memorability
Chapter 6 describes two projects studying the perception and recall of information. While the first project compared a digital bar chart to a physical one, the second project left out the digital counterpart and focused on the comparison of the dimensionality of physical visualizations.

Chapter 7 - Potential for Communication & Collaboration
Chapter 7 summarizes two explorative studies dealing with physical visualization used by

multiple individuals. The first study explored whether the act of assembling a personal visualization engages participants and leads to sharing and discussing the data. The second study investigated the collaboration of groups when solving information visualization tasks with physical and digital visualizations.

Chapter 8 - Potential for Motivation & Self-Reflection
Chapter 8 gives a summary of the *Activity Sculptures* project, where we 3D printed physicalizations based on personal running data. A three-week field study was conducted to explore the impact of such physicalizations on participant's behavior and their running activity.

Part III: Reflecting on the Design of Physical Visualizations

Chapter 9 - Materialized Self
Chapter 9 proposes the conceptual framework *materialized self*, which focuses on material representations of personal data. By looking into such artifacts from a production and consumption lens, it offers designers working in the field of personal informatics inspiration and guidance for creating personal physicalizations.

Chapter 10 - Physical Variables
Chapter 10 gives a preliminary categorization of physical variables, which is based on related work and the experiences collected during the design and evaluation of the prototypes. Going beyond the perception of material properties also emotional associative aspects are discussed.

Chapter 11 - Summary and Future Work
Chapter 11 concludes the thesis by providing a summary of the contents of the previous chapters. Besides the limitations of the work it also provides starting points for future work in the area of physical visualizations to encourage researcher to explore this fascinating and yet little-researched field.

I

BACKGROUND

Chapter 2

Embodied Interaction & Haptic Perception

This chapter first gives a short introduction to the design approach of "embodied interaction" and corresponding research areas such as tangible and ubiquitous computing and aims to illustrate the idea and vision of user interfaces and interactive experiences that go "beyond the desktop" (*Section 2.1*). The second part gives a brief overview of relevant research that was done in the area of haptic perception to emphasize human capabilities apart from the visual sense (*Section 2.2*). It further demonstrates the possibilities of physical objects to encode data that is perceivable by humans.

The purpose of this chapter is not an exhaustive account of all relevant work that was done in these areas of research but to present the broader motivation and inspiration behind the thesis' topic. The brief excursion into haptic perception illustrates first directions for possible benefits of physical visualizations.

2.1 Embodied Interaction

The term "embodied interaction" was introduced by Dourish [2001], as he proposed "embodiment" as a new design approach to HCI by drawing upon and bringing together the research areas of tangible and social computing. It focuses on everyday tasks and mundane experiences as well as the understanding of the world through practical activities. By gradually incorporating a wider range of human skills and abilities the interaction with computing devices can become easier and more widely accessible. Since its publication, the concept of embodied interaction is increasingly used for designing, analyzing and evaluating interactive systems [Marshall et al., 2013]. The Association for Computing Machinery (ACM) Conference on Tangible, Embedded, and Embodied Interaction (TEI), established in 2007 with a focus on tangible and embedded interaction, for example, integrated embodied interaction in its title with its fourth edition in 2010, in order to invite research on whole-body or gestural interaction more explicitly [Hornecker, 2010]. While it still seems unclear whether embodied interaction is as a single concept in HCI or rather a number of distinct perspectives, most work shares the reflection on the design possibilities offered by whole body interaction [Marshall et al., 2013].

The following section gives a brief overview of the field of embodied interaction, while focusing on the aspects that are most relevant to the thesis' topic. In particular it describes the visions of ubiquitous and tangible computing as one foundation behind the motivation and inspiration for investigating physical visualizations. Additionally, theories of embodied cognition are introduced that describe cognitive representations as *"less abstract and less brain-based and more embodied, embedded, extended, or enactive"* [Marshall et al., 2013].

2.1.1 Ubiquitous Computing & Tangible Interaction

Dourish's focus in his book "Where the Action is: The Foundations of Embodied Interaction" was on the area of tangible computing to describe one example of a phenomenologically inspired program of research. He later questions whether the use of the more general term of ubiquitous computing would have been a better choice than tangible computing [Dourish, 2013].

The term ubiquitous computing was introduced by Weiser in 1991 with his article "The computer for the 21st century". The distinction of ubiquitous computing to the traditional desktop computing is the concept that computing can occur everywhere at anytime, from the classical desktop or laptop, to various mobile devices to everyday objects. In following articles by Weiser and Brown [1996, 1997] they introduced, among other things, the "Dangling String", which was created by the artist Natalie Jeremijenko. The "Dangling String" can be seen as a physical visualization for network traffic as a physical string is rotated depending on the number of bits running through an Ethernet cable. They argue that while digital representations of network traffic are common, their symbols require interpretation and attention. In contrast, the Dangling String offers a peripheral perception to the formerly inaccessible network traffic and can be both seen and heard. This example illustrates the connection of the thesis' topic and the area of ubiquitous computing, in particular regarding the aspect of prototyping interactive systems that go beyond the desktop. It should be noted that the Dangling String was described as an example for calm technology and belongs to the area of ambient visualizations [Skog et al., 2003]. This thesis also explores more pragmatic visualizations [Kosara, 2007] that aim at actively analyzing and understanding abstract data.

Ubiquitous computing and tangible interaction share the common interest regarding the movement and configuration of computing devices and their carrier in the physical space, while tangible interaction in particular relies on tangibility and whole-body interaction [Shaer and Hornecker, 2010]. New developments in the area of ubiquitous computing, e.g., sensing techniques, also contribute through enabling technologies to the field of tangible interaction. The first prominent notion of tangible interaction in the area of HCI was the vision of "Tangible Bits" by Ishii and Ullmer [1997]. They argue that GUIs do not take advantage of the humans abilities to sense and manipulate the physical world. Their concept of Tangible User Interfaces (TUIs) expand the affordances of physical objects, surfaces, and spaces to support a direct interaction with the digital world. As TUIs are limited regarding the adjustment of the form or properties of physical objects in real time, Ishii et al. proposed their new vision of "Radical Atoms" in 2012. In their iceberg metaphor (see Figure 2.1) they describe GUIs as a submerged iceberg that is only controllable remotely, e.g., through a mouse, keyboard or a touchscreen. TUIs are described as the tip of iceberg, in which a part of the digital emerges beyond the surface of the water and allows a direct interaction. The vision of "Radical Atoms" finally assumes a material that "*can change form and appearance dynamically, so they are as reconfigurable as pixels on a screen*".

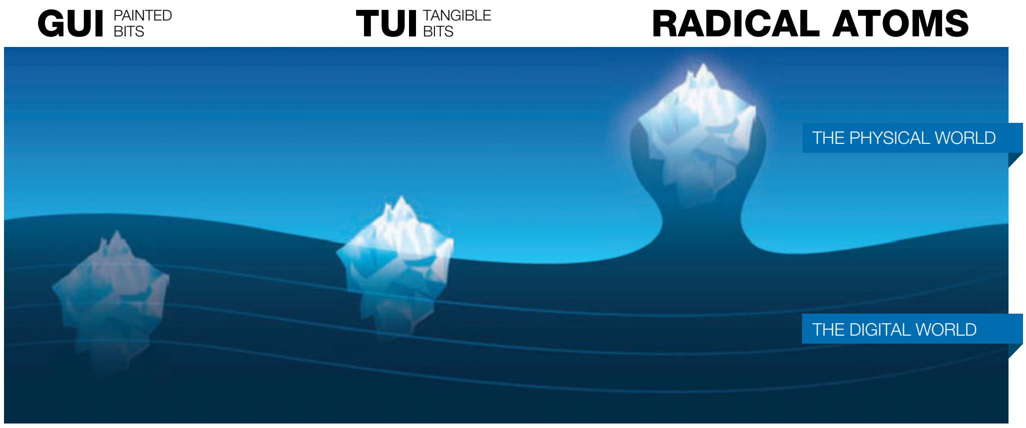

Figure 2.1: The iceberg metaphor by Ishii et al. [2012]: from GUIs to TUIs to Radical Atoms.

While physical visualizations could highly benefit from the realization of "Radical Atoms", this thesis fits into the area of tangible interaction. Hornecker and Buur [2006] broadly summarize tangible interaction as an approach to designing interactive systems that focus on tangibility and materiality of the interface, physical embodiment of data, whole-body interaction as well as the embedding of the interface and the individual's interaction in real spaces and contexts. All these points are relevant for the design of physical visualizations, especially the physical embodiment of data. It is worth mentioning that most prototypes in this area use physical objects for controlling a system (see also *Section 4.2 - Information Visualization & Tangible Interaction*) or displaying a specific state of a system, but not for visualizing abstract datasets.

2.1.2 Embodiment & Embodied Cognition

Dourish [2001] describes embodiment not as a physical reality but as a form of participative status and as all the things that are embedded in the world. This applies to a computer screen, a bookshelf but also to spoken conversations. Dourish specifies three ways in which embodiment is applicable to the design of interactive systems. First, by highlighting that interaction is intimately connected to the environment in which it occurs, e.g., to make certain kinds of activities easier or more difficult. Second, by considering the ways in which computation shapes the world we live in, e.g., is used in different ways for various activities in diverse physical environments. Third, by emphasizing observational techniques that focus on real people, in real settings, doing real tasks.

The latter show the link to the philosophical and psychology field of phenomenology, which is primarily concerned with "*how we perceive, experience, and act in the world around us*" [Dourish, 2001]. While phenomenology and related theories such as ethnomethodology and its observation methods are only mentioned in passing in this thesis, they motivated the evaluation of projects not only in lab studies but also "in the wild" through field studies [Rogers, 2011] (see for example the field studies within the *Activity Sculptures* project in *Chapter 8* or the *PopUpData* project in *Section 7.1*).

In the rather large and diverse set of perspectives on embodied interaction, the theories of embodied cognition (e.g., Wilson [2002]) sees particularly relevant for this thesis. Embodied cognition belongs to the theory of distributed cognition [Hollan et al., 2000] and assumes that thinking is not limited to the brain, but to the entire body and that body parts behave like cognitive components, that shape in which ways we think (Clark [1996]; Kirsh [1995, 1996, 2013]). Interesting for the area of physical visualizations is that besides body parts and body movements, the handling of physical objects and tools can also enhance cognitive processes. Moving an object around, for example, and attending to what that action reveals can encourage considering an idea from a new point of view. Under this assumption "thinking with things" or physical tools goes beyond off-loading working memory (e.g., Clark and Chalmers [1998]). Hollan et al. [2000] describes it as a coordination and cooperation of internal processes, such as memory, attention or executive function, and external resources, such as the objects, artifacts, and materials surrounding us.

Kirsh [2013] describes these "*cognitively gripped objects*" not as tools that simplify or speed up tasks but let us do things we cannot do without them. He further states that these objects change the ways in which we perceive the world as they affect the way we act and perform tasks. Kirsh illustrates his theory with an example of a person who smokes cigarettes and will, therefore, see most physical environments as filled with things that can act as an ashtray. Non-smokers are blind to them. Similarly, individual's skills and experiences will affect their perception and action in given situations.

By breaking down this theory to the area of physical visualizations, it seems valid to assume that their physical nature can extend or influence our perception and cognitive process and therefore, offer a new perspective on the exploration and analysis of data. It is neither the goal to replace traditional information visualizations on digital screens with physical visualization nor is there the assumption that physical visualizations are "better" than their digital counterpart. Physical visualizations are as an additional technique to represent data, and the purpose of this thesis is rather to explore their strengths and the ways in which physical and digital visualizations can complement each other. Kirsh [2013], for example, observed professional dancers and noticed their ability to engage their various senses. He concludes that kinesthetic perception reveals different properties than visual perception and that these kinesthetic properties "*make it easier to recognize the validity of inferences that would be near impossible to infer from vision alone if one did not also move the body*".

2.2 Haptic Perception

Terms and descriptions in the area of haptic perception vary between research areas. Most literature (e.g., Richter [2013]; Geldard [1972]; Loomis and Lederman [1986]) sub-divides haptic perception into three physiological concepts: *interoception* (feeling of internal organs, hunger, internal temperature), *proprioception* (movement and orientation of the body) and *exteroception* (tactile perception of surfaces, temperature, and pain on the skin). The "sense of touch" is based on proprioception as well as exteroception [Loomis and Lederman, 1986]. The *cutaneous* subsystem of touch uses sensory information derived from receptors embedded in the skin to sense characteristics such as roughness or compliance (*tactile perception*), thermal qualities (*thermoreception*) but also pain (*nociception*) [Richter, 2013]. The *kinesthetic* subsystem uses receptors embedded in muscles, tendons and joints and enables with limb movement and position the evaluation of geometric features such as orientation, shape, and size. In addition to these sensory mechanisms, it is important to consider in which ways the manual exploration of physical objects takes place and which object characteristics and material properties can be explored and identified [Lederman and Klatzky, 1987].

2.2.1 Object and Material Properties

The description and terms of material properties vary between researchers and research fields and show a lack of a defined classification, especially for the area of texture. The following gives a brief overview of the most common physical properties based on literature from psychophysical and neuroscientific research as well as areas such as architecture or product design.

In 1925 Katz (English translation by Katz and Krueger [2013]) already distinguished between two types of surface properties: "Modifikationen (qualities)" and "Spezifikationen (identifying characteristics)". "Qualities" are described as specific tactile surface features and "identifying characteristics" as the overall feel of the surface. Lederman and Klatzky [2009b] split the features of an object into material properties and geometric properties.

While the material properties (e.g., roughness or compliance) are independent of the particular object, the geometric properties describe the structure of the object (e.g., shape or size). In the area of physics, a general characterization is a distinction between *intensive* and *extensive* properties [Tolman, 1917; Redlich, 1970]. While extensive properties depend on the amount of material (e.g., mass, length, shape), intensive properties stay the same regardless of the quantity of matter (e.g., density, color, temperature). In contrast Zuo et al. [2001] differentiate on the one hand between objective and subjective properties and, on the other, hand propose physical-chemical attributes (perceived as e.g., warm, cold, soft, moist) and also geometric properties regarding the material (perceived as e.g., fine, granular, linear). In this section the initial focus will be on the objective properties, which can be controlled and measured for study purposes and, therefore, are most studied in the haptics research. Then less studied physical properties and the area of (perceived) textures will be described.

Roughness: *Roughness* received the most attention in the field of haptics research. In addition, it seems to be one the most important features for the distinction of haptically explored surfaces [Tiest, 2010]. As a physical concept, *roughness* is the amount of height and width differences on the surface. In manufacturing *roughness* is together with *lay* and *waviness* one of three main terms to describe a surface texture or surface finish [De Garmo et al., 2011]. While *lay* indicates the direction of the predominant surface pattern, *roughness* and *waviness* refer to surface irregularities. *Roughness* is the amount of fine height and width differences on the surface, expressed in micrometers, while *waviness* describes irregularity of greater spacing, partly referring to the shape.

Perceived *roughness* seems to be stronger affected by the height differences while the width has a smaller effect [Taylor and Lederman, 1975]. The perception of *roughness* is equal whether the surface is fixed and the hand moves or vice versa [Lederman and Klatzky, 2009b]. Perceived *roughness* can vary between static and dynamic touch [Hollins and Risner, 2000] and is associated with the spatial and temporal context. Surfaces can be perceived smoother or rougher depending on whether a smoother or rougher surface had been previously felt [Kahrimanovic et al., 2009].

Compliance: *Compliance* is as an umbrella term for physical properties such as elasticity, viscosity or softness, and hardness. Physically it can be expressed by the object's stiffness, which is defined as the ratio between a force that is on the object and the resulting displacement [Tiest, 2010]. This is also influenced by the object's dimensions, e.g., its shape. Studies found a relationship between perceived hardness and softness and physical stiffness and showed that softness and hardness are direct opposites [Harper and Stevens, 1964]. For softness perception and discrimination, cutaneous information is both necessary and sufficient [Srinivasan and LaMotte, 1996], but kinesthetic force information can influence it [Friedman et al., 2008].

Coldness: The *coldness* of an object at room temperature is distinct from the object's temperature, which has nothing to do with the material [Tiest, 2010]. Although materials are at room temperature, we can perceive them as "cold", because of the heat that is being extracted from our body when we touch them. Perceived *coldness* seems to be directly related to the amount of heat extraction [Sarda et al., 2004]. This depends not only on the material's thermal properties but also on the object's geometry [Tiest and Kappers, 2008]. While it is clear that *coldness* can be used to identify different materials, it is not yet possible to give a precise description of the processes that are involved in the perception of *coldness* [Tiest, 2010].

Slipperiness / Friction: When sliding a finger over a surface people can feel clear differences in resistance for different materials, therefore, perceived *slipperiness* can be used for haptic material identification [Tiest, 2010]. The perceived *slipperiness* has a correlation to the friction of a surface and depends on humidity, force, and speed of movement [Grierson and Carnahan, 2006]. *Slipperiness* is perceived through a combination of both kinesthetic (forces) and cutaneous (skin stretch) channels [Tiest, 2010]. Movement over the surface is essential for an accurate perception of *slipperiness*, whereas an action such as picking up an object can determine *slipperiness* statically [Grierson and Carnahan, 2006].

Weight: Physically the *weight* of an object is defined as the force of gravity. Weight can be perceived optimally when the object is actively explored, e.g., by lifting and handling the object [Lederman and Klatzky, 2009a]. There is an ongoing discussion about the processes involved regarding the perceived *weight*, such as cognitive expectations based on prior experience or the integration of sensory cues regarding the object's volume [Lederman and Klatzky, 2009b]. It has for example been demonstrated that a small object feels heavier than a large object of the same mass [Charpentier, 1891; Murray et al., 1999]. Similar illusions were shown for temperature and *weight* [Stevens, 1979] as well as material and *weight* [Ellis and Lederman, 1999]. These discrepancies show that the perceived *weight* depends on a wide variety of mechanisms [Lederman and Klatzky, 2009a].

Size and Shape: *Size* and *shape* of objects can be considered in various ways. Apart from the *exact shape* of an object, there is also a *global shape*, which related to the area or volume of an object. Furthermore, an object can fit within a grasp or extend beyond the grasp and, therefore, also uses kinesthetic input for exploration. Most research has focused on object length and width and showed excellent correspondence between the perceived and physical value when the object was held between two index fingers. Contrary research investigating the relationship between texture and length of an object, concluded that objects with a fine texture were perceived as being longer than coarse textured objects [Corsini and Pick, 1969].

Research in the area of *shape* focused most notably on curvature. Humans are capable of distinguishing angular differences while the performance depends on cutaneous and kinesthetic input, whose contribution varies with the scale of the curved surface [Lederman and Klatzky, 2009b]. Humans have problems haptically exploring and identifying the *shape* of large objects made of a single material. This is, amongst others, caused by the sequential nature of haptic manual exploration, which is slow and creates demands on memory and temporal integration. In general humans process an object not by its *global shape* but rather by its local features [Lederman and Klatzky, 2009b].

Orientation: There are a few works that studied the haptic perception of *orientation*. Experiments in which the participants had to position a test bar parallel to a reference bar presented simultaneously within a planar workspace showed that both vertical and horizontal lines are haptically perceived better than oblique lines [Lechelt et al., 1976; Lechelt and Verenka, 1980]. Furthermore the *orientation* is influenced by other factors, e.g., the location of the bars within the plane [Lederman and Klatzky, 2009b].

Subjective description of texture: *Texture* serves as a general term for the visual and tactile quality of a surface and its definition varies regarding research fields such as material science or cognitive psychology. Apart from the afore mentioned properties of *texture* (e.g., roughness, compliance, slipperiness) on the objective side, there is also the question in which ways people subjectively perceive textures, especially on a not easily quantifiable emotional level [Zuo et al., 2001].

Zuo et al. [2001] found four dimensions in their study about subjective *texture* perception: geometrical, physical-chemical, emotional, and associative. The first two dimensions stand in close relation to the previously listed properties studied in haptic perception. The geometrical dimension describes the geometrical configuration of a material surface with terms such as smooth/rough, plain/bumpy and regular/irregular. The physical-chemical dimension specifies the physical or chemical attributes of a surface with terms such as warm/cold, moist/dry or shining/unshining.

The last two dimensions are unrelated to the quantifiable properties and focus on the individual "feeling" of a *texture*. The emotional dimension describes the hedonic and affective sensations provoked by touching the surface. Most used words in this dimension were comfortable/uncomfortable, cheerful/dull and elegant/ugly. The associative dimension describes the most personal characteristics of a surface. This includes, for example, that the perceiver might compare a *texture* to other materials and existing experiences. Example terms are rubbery, plastic-like, metallic, leather-like or silky. The characteristic "feeling" of a surface or object seem to depend on the combination of various properties, rather than on one unique property [Hollins et al., 1993]. The findings by Zuo et al. [2001] are in line with the results of previous studies with similar objectives (e.g., Ohno [1979]; Ozawa et al. [1996]; Tanaka [1998]; Terauchi et al. [1997]; Aoki et al. [1985a,b]).

2.2.2 Manual Exploration

The last subsection described the properties that materials and objects can be made of. This subsection gives an introduction whether, and in which ways such properties can be distinguished by humans. In contrast to the visual sense, in which object recognition happens internal, and the external observation is restricted to eye fixations and movements, the haptic sense provides a rich domain of external observation [Lederman and Klatzky, 1987]. Humans use stereotypical hand-movement patterns to explore objects and surfaces that Lederman and Klatzky [1987] classified as exploratory procedures. They found eight exploratory procedures by focusing on generally observable movements that are related to the exploration of object properties and excluding object-specific actions, e.g., pencil-sharpening.

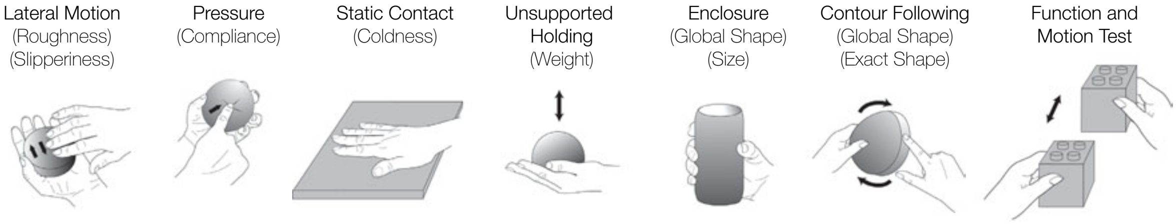

Figure 2.2: Illustrations of the exploratory procedures and their associated material and object properties, adapted and redrawn based on Lederman and Klatzky [2009a].

Lateral motion: Sideways movement, in which skin touches a surface, often a quick back-and-forth movement on a small area. This provides the most precise perception of the textural properties of a surface, including roughness.

Pressure: Applying normal pressure or torque to a surface or part of an object. Often the other hand stabilizes the object or applies opposing pressure. This provides the most precise perception of properties related to compliance.

Static contact: One hand passively rests on an object while this is supported externally, e.g., by a surface or the other hand. This provides the most precise perception of thermal qualities.

Unsupported Holding: An object is lifted away from a supporting surface and held in the hand without any pressure on the object but often combined with rotating and jiggling. This provides the most precise perception regarding weight.

Enclosure: Simultaneous contact with as much surface of the object as possible by grasping it with the entire hand. Often it is combined with the effort to mold the hand precisely to the object's contours or shift the object in the hand(s). This provides the most precise perception of an object's size and general shape.

Contour following: Involves the tracing around an object's contour. The movement is usually smooth and nonrepetitive and does not occur on a homogeneous surface. This provides the most precise perception of an object's size and exact shape.

Function and motion test: These two exploratory procedures are more object-specific than the afore mentioned as they describe movements that perform a particular function or the act of making a part of the object move. Both exploratory procedures are often excluded in following works as they seem very specific and only applicable when the object has a function or a moving part. It seems that these characteristics will gain importance for more sophisticated physicalizations, that are dynamic or interactive, as these exploratory procedures serve to examine in which ways a physicalization can be used and which functionality it provides.

While all these movements can be described in further detail, especially the area of enclosure or grasping, gained a lot of attention in research, including the field of human-computer interaction [Wimmer, 2015]. Various definitions and taxonomies have been proposed for describing grasps (e.g., Feix et al. [2009]; Napier [1956]; Cutkosky and Wright [1986]). A widely accepted classification of grasps discriminates between power/precision distinction (emphasis on stability or sensitivity), opposition type, thumb position, and involved fingers [Feix et al., 2009]. In the light of physical visualizations, it is worth mentioning that the choice of grasp in everyday tasks is effected to a greater extent by the task people want to accomplish than by the size or shape of an object [Cutkosky and Wright, 1986]. The same applies to other procedures, as specific movements are chosen for optimally extracting the desired information [Klatzky et al., 1987]. This leads to the assumption that physical visualizations can encode data in various ways, which will still be perceivable by humans if they know where and how to look for the underlying information.

2.2.3 Performance, Integration and Interaction

We summarized knowledge on the properties of materials and objects as well as the human capabilities to explore these characteristics. Physical visualizations are only adopted when the exploration and analysis of the underlying data are possible within a reasonable time span and with suitable precision. Furthermore, physical visualizations rarely consist of only one property and are seldom only explored via the sense of touch. They can be explored with all senses, predominantly the visual sense and they can consist of several physical properties to map multiple data variables. Therefore, it is important to consider how different physical but also visual or auditory properties integrate and interact with each other and influence the perception and performance.

Figure 2.3 shows an illustration by Lederman and Klatzky [2009a] in which they summarized exploratory procedures and the most common object properties with three performance characteristics:

- *Precision of information*: Each property has one exploratory procedure that leads to greater accuracy than any other and is therefore considered optimal. Half of the combinations of exploratory procedures and properties perform the task at above chance levels (sufficient). For one-third of the combinations the designated exploratory procedure results in only chance performance for providing any information about the target property. The contour following procedure is the only one that is classified as necessary, as it is the only one to produce above chance performance for the perception of the exact shape.

- *Breadth of object property information*: This performance characteristic describes the number of properties which can be perceived through a particular exploratory procedure at a rough level. While lateral motion or pressure only offer information about a few types of properties, enclosure and contour following provide information about both material and geometric object properties.

- *Average execution duration*: Most exploratory procedures are performed relatively quickly, on average in a few seconds. Contour following seems to be the exception, as it takes notably longer to perform. It should be noted that the performance, especially the execution duration, are dependent on particular physical objects and therefore, the results are limited by the tasks and objects that were used in the experiments [Lederman and Klatzky, 1987].

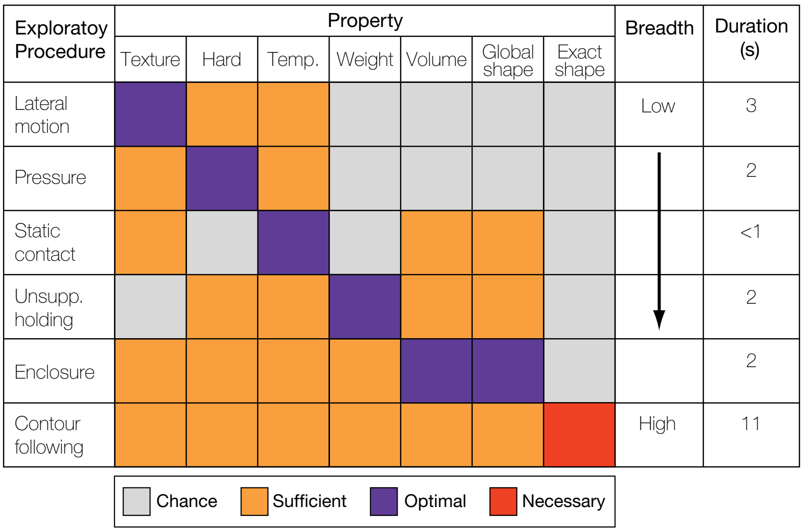

Figure 2.3: Illustration by Lederman and Klatzky [2009a] of three performance characteristics of haptic exploratory procedures: precision of information (chance, sufficient, optimal, or necessary), breadth of sufficiency or generality, and average execution time.

Another performance characteristic indicates to which extent exploratory procedures can be co-executed and properties perceived simultaneously [Lederman and Klatzky, 2009b]. Garner [1974] described the term of “dimensional integrality” and distinguished between “integral” and “separable” dimensions. Properties or dimensions are “integral” when it is difficult to attend to one dimension and ignore the other. For visual variables an example would be the dimensions brightness and saturation. When it is easy to attend to one dimension and ignore the other one, they are called “separable” dimensions. For visual variables an example would be the dimensions hue and shape [Ashby and Maddox, 1990].

Klatzky et al. [1987] showed that the parallel execution of exploratory procedures allows perceivers to integrate redundant properties, which speeds up the identification of multi-attribute objects. The classification by a single dimension was slower than by two, but a third redundant dimension did not improve performance [Klatzky et al., 1989]. This is not the case if the exploratory procedures, optimal for recognizing specific properties cannot be co-executed, for example, if the properties are located in different regions that cannot be explored simultaneously [Lederman and Klatzky, 2009b]. Subsequent experiments, limited to blindfolded participants, revealed that the combination of texture and hardness led to the fastest identification and that shape appears to be less important.

The availability and salience of object properties differ when haptic exploration is done with and without vision. The haptic and visual systems seem to have distinct encoding pathways, in which haptic exploration is oriented towards encoding information about an object's texture and material rather than its size or shape [Klatzky et al., 1991]. People's judgments of object similarity, for example, differed whether the instructions they were given were biased towards visual of haptic exploration, as the latter increased the importance of material properties [Lederman et al., 1996]. In contrast, vision-based instructions led to an emphasis on shape, which can result in an exclusion of almost every other perceived property of an object [Klatzky et al., 1987]. Katz [1925] also stressed the importance of the intention behind a haptic exploration, e.g., to perceive material properties or the global shape of an object. Klatzky et al. [1987] stated that vision does not work as a substitution for touch and that the two modalities are useful to perceive different aspects of an object. They concluded by describing the role of vision as "*providing a preview that is used to determine whether and when touch should be initiated.*"

2.2.4 Haptic Phenomena

In the area of information visualization, visual phenomena such as the very rapid detection of specific visual properties (pre-attentive processing) are used to build effective representations (e.g., Munzner [2014]). Designers of visualizations should also be aware of optical illusions, e.g., change blindness. In the area of haptic perception, similar effects relevant in creating effective physical visualizations can occur and will therefore, be briefly discussed in this chapter.

Although research in the area of haptic pop-out effects is not as comprehensive as in its visual counterpart, there are a few works in this field that have provided evidence for the existence of a haptic version of the pop-out effect. In information visualization, a pop-out effect usually describes the effect of that a target element producing a high level of activation with little influence of distractor elements. Plaisier et al. [2008a] showed that under specific conditions (target item is rough sandpaper, distractor item is fine sandpaper) blindfolded subjects only needed a single-hand sweep to detect if a target item was present, which they interpret as a haptic version of the pop-out effect. They further showed that search for a cube among spheres is more efficient than vice versa [Plaisier et al., 2008b]. A follow-up experiment looked into haptic search tasks for target and distractor items with various 3D shapes (cube, sphere, tetrahedron, cylinder, and ellipsoid) and led to the conclusion that such search tasks can be performed very efficiently and that edges and vertices are the most salient features [Plaisier et al., 2009].

Recent work furthermore indicated pop-out effects for properties that are unique to touch such as temperature and movable elements. An experiment by Plaisier and Kappers [2010] in which participants reported whether a cold sphere (22°C) was present among warmer ones (38°C) showed that cold objects pop out. They concluded that the high saliency of a cold item among warm items and the fact that variations in subjects hand temperature did not affect the result, which "make temperature differences useful as encoding variables in haptic interfaces." Van Polanen et al. [2012] argue that movability is a salient object feature, as their experiments showed that movable objects pop-out between anchored objects. If the target was a loose ball, the reaction times were independent of the number of distractors (anchored balls) but increased when the target was the anchored ball. They explain their results with shorter hand movement paths and narrower direction distribution as well as a higher average movement speed of the hand.

Similar to the pop-out effect perceptual illusions involving the haptic system have received less focus than its visual counterpart. A thorough overview can be found in a work by Lederman and Jones [2011], in which they organize tactile and haptic illusions in two categories: illusions related to the haptic space such as the observer's body and the external space, and illusions related to objects and their properties.

Haptic illusions that are related to the spatial representation of the body generally result from interactions between the perception of temporal and spatial properties [Lederman and Jones, 2011]. Most illusions involve distortions of the perceived distance between several stimuli or the location of tactile or thermal stimulation on the skin of the body. A popular example, which can also occur for visual and auditory stimuli, is the so-called "tau effect", which arises when observers have to judge the distance between three consecutive stimuli in a stimulus sequence. The perceived distance between three tactile stimuli is affected by the time interval of the stimuli and can lead to an overestimation of the spatial distance [Helson and King, 1931]. Furthermore, the perception of distance is also influenced by the part of the body that is stimulated [Anema et al., 2008]. Regarding the localization of stimuli haptic illusion can result in the perception of stimuli at body parts that received no stimulation. In general, it can be noted, that when "two events occur within certain spatial and temporal bounds, the localization of one event in space or time is influenced by the presence of the other" [Lederman and Jones, 2011].

Corsini and Pick [1969] found that the perceived length of different textures that were mounted on cardboard increased when it was of a smooth texture. Charpentier [1891] investigated that a smaller object is perceived heavier than a larger one, although they had an identical mass. Interestingly no such size-weight illusion occurred when no visual cues about the size of the object were available when it was lifted [Masin and Crestoni, 1988]. The so-called "golf-ball illusion" by Ellis and Lederman [1998] showed that previous knowledge and experiences can influence weight perception. Expert golfers perceived real golf balls to weigh less than practice golf balls that have been engineered to be of the same mass. This was not the case for novice golfers. Further illusions regarding the perception of weight have been found, e.g., that cold objects felt heavier than warm objects (e.g., Weber [1846]; Stevens [1979]) and that objects with a rough surface were perceived lighter than those with a smooth surface (e.g., Flanagan et al. [1995]; Rinkenauer et al. [1999]). These variations in the perception of physical properties "*reflect a wide variety of mechanisms, ranging from low-level receptor responses all the way to high-level cognitive expectations*" [Lederman and Klatzky, 2009a].

Chapter 3

Digital Fabrication

Digital fabrication enables the participation in the design and creation process of physical objects by directly interacting with the hardware and software used for producing these objects. In general, it can be described as the production of material artifacts using computer-controlled tools. Gershenfeld already predicted in 2007 that personal fabricators will become accessible to ordinary people and stressed their impact "*because what's being personalized is our physical world of atoms rather than the computer's digital world of bits.*" Chris Anderson [2010], the former chief editor of WIRED magazine and the reputable economic and social theorist Jeremy Rifkin [2011] called this progress the third industrial revolution, after the first typified by the steam-engine and the second embodied through the moving assembly line.

The relevance for this thesis lies in the rise and accessibility of digital fabrication technologies and the opportunity they create for building and studying the potential of physical visualizations in a broader range, for the first time. The following chapter is divided into the sections of personal fabrication (*Section 3.1*) and digital fabrication in the area of HCI (*Section 3.2*). The former confirms that it is reasonable to believe that private persons as well as companies will soon be able to create and use physical visualizations for various purposes if they provide clear benefits. The latter strengthens this assumption as the growing interest of research projects in the field of digital fabrication, especially in HCI, will simplify the use of digital fabrication machines and specialized software. Additionally, more advanced techniques will ease the creation of interactive physical visualizations, e.g., by enabling visual output or touch recognition.

3.1 Personal Fabrication

Gershenfeld coined the term "personal fabrication" with his work in 1999 and 2007 in which he specifies the coming revolution of "*personal computers to personal fabrication.*" This revolution brings the programmability of the digital world to the physical world. He, therefore, envisioned personal fabrication not as the production of three-dimensional mechanical structures, but as fully functioning systems with the integration of sensing, actuation, logic and display.

A paper by Mota [2011] described "the rise of personal fabrication" and highlighted that "*a growing number of individuals now has access to sophisticated production tools and the knowledge to manufacture objects for artistic, personal or commercial purposes.*" This widespread access to digital fabrication technologies will challenge and change traditional models of business, foreign aid, and education [Gershenfeld, 2012]. He argues that a driving inspiration for the profound human desire to create things is communication. When access to tools for technological development is achieved, a priority should be "*to apply them to accessing and exchanging information.*"

The following section will give an introduction into the currently most common tools and techniques in the area of digital fabrication, focusing on the tools that were extensively used in the thesis' projects. Thereafter relevant application areas that changed or arose through the opportunities of digital fabrication, will be discussed.

3.1.1 Tools & Techniques

The first machine in the field of digital fabrication was created at the Massachusetts Institute of Technology (MIT) in 1952 and was a Computer-Numeric Controlled (CNC) milling machine [Pease, 1952]. Subsequently, a variety of computer-controlled cutting tools have been developed, including plasma, lasers, mills (hot-)wires, waterjets or ice particles. These techniques are called subtractive manufacturing as they use a block of material and remove or subtract unnecessary parts until only the desired object remains. They can be further separated into techniques, in which an actual cutting tool is present, e.g., a CNC milling machine, or not, e.g., a laser cutter. The advantage of an cutting tool with an end, e.g., a mill, is the possibility of a carefully controlled depth [Gershenfeld, 2007]. In contrast to a beam of light or a jet of water, it allows to contour precise three-dimensional shapes, with a fine surface finish.

In addition to subtractive manufacturing a further principal method for rapid prototyping is called additive manufacturing. The first machine in this field was developed in 1981 by Kodama. In contrast to subtractive manufacturing, additive manufacturing fuses layers of material together to build the object. The machines commonality is a flexible part, e.g., the printing head in the case of a 3D printer. This part moves on a specific geometrical path to create the final object. Both methods have their own advantages and are appropriate for different circumstances. Therefore, they are also used in combination, which lead to the term of hybrid manufacturing. Gershenfeld [2012] also stresses that the revolution is not about additive versus subtractive manufacturing, but "*the ability to turn data into things and things into data.*"

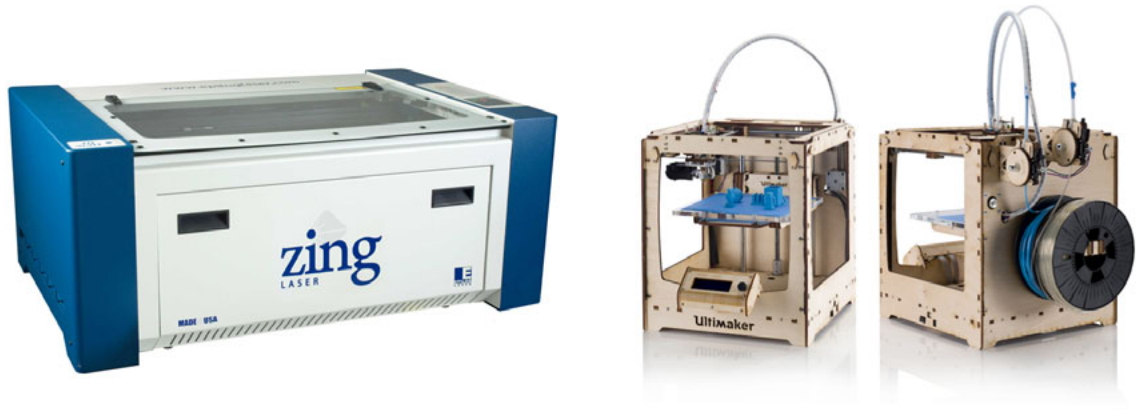

Figure 3.1: Left: the laser cutter Epilog Zing 6030 as an example for subtractive manufacturing. Right: the 3D printer Ultimaker Original as an example for additive manufacturing.

Currently the most common digital fabrication technologies are laser cutters and CNC mills for subtractive manufacturing and 3D printer for additive manufacturing. Figure 3.1 shows the laser cutter Epilog Zing 6030 and the 3D printer Ultimaker Original, both used for fabricating the prototypes in this thesis. The Epilog Zing 6030 is equipped with a laser wattage of 30 watts and enables cutting 2D shapes out of wood and acrylic glass with a thickness of up to one centimeter. Stronger lasers and other techniques can cut thicker and harder materials such as metal or granite and more complex models, e.g., through multi-axis cutting [Apro, 2008].

Regrading additive manufacturing the American Society for Testing and Materials (ASTM) group "ASTM F42 – Additive Manufacturing" developed seven categories as a standard terminology for additive manufacturing technologies [ASTM, 2012]. The Ultimaker Original uses the Fused Deposition Modeling (FDM) technology, also called Fused Filament Fabrication (FFF), which was invented by Crump [1991] and is categorized under "material extrusion." This technology creates an object by extruding melted material, such as plastic filament, through a nozzle to form layers as the material hardens immediately after extrusion, comparable to a glue gun.

All these machines have in common, that they create material objects from digital designs, i.e., "*turn bits into atoms*" [Mota, 2011]. The digital models can be created through the use of software for Computer-Aided Design (CAD) or through the help of 3D scanning (e.g., Levoy et al. [2000]). There are machines for 2D fabrication, e.g., a laser cutter and 3D fabrication, e.g., a 3D printer. Accordingly there is CAD software targeted for the design of 2D and 3D models. The complexity of professional CAD software is one of the challenges to overcome to reach a broader audience for personal fabrication [Mota, 2011]. Gershenfeld [2007] suggest to make a stronger use of humans' physical capabilities to interact with CAD software, i.e., "*two hands that work in three dimensions, with eyes to match [instead of] one hand that works in two dimensions.*"

Apart from the grade of the digital model, the machine's capabilities in handling it are the main factors determining the quality of the finished physical object. The individual size of the digital fabrication technologies limit the size of the final object. The Ultimaker Original, for example, can produce objects with a volume of up to 223 x 223 x 205 mm. Solutions for this restriction are a manual or automatic decomposition of the original object into a set of interlocking pieces (e.g., Vanek et al. [2014]; Alemanno et al. [2014]). Geometrical precision and freedom are further challenges, especially if the object is small and delicate. Although it is part of active research (see *Subsection 3.2 Digital Fabrication in HCI*), it is beyond most commercial machine's capabilities to create objects with various colors or combinations of material and surface properties. Similarly, fulfilling Gershenfeld's vision of fabricating an entirely functioning system, e.g., with one print, seem to be a long way ahead.

3.1.2 Maker Movement

Mota [2011] describes the period around 2007 as the starting point towards a democratization of manufacturing. She explains it with a cultural trend: "*a renaissance of the Do-It-Yourself (DIY) movement with a hi-tech facet*" [Mota, 2011]. Self-reliance and self-improvement through the acquisition of new knowledge and skills are at the basis of this movement. Amy Spencer [2005] summarizes that the "*enduring appeal of this movement is that anyone can be an artist or creator. The point is to get involved.*" The maker movement or community is a subset of the DIY community, whose members, in particular, create and modify soft- and hardware [Mota, 2011]. The term maker refers to the Make magazine and website[1], which is regarded as the point of when the DIY mindset was brought to technology in 2005.

Another development that helped the community's popularity was the growing distribution of digital fabrication technologies through the introduction and expansion of Fabrication Laboratories (FabLabs) and online fabrication services. The sinking prices of the machines, e.g., personal 3D printers, provided a furthering factor [Mota, 2011]. FabLabs are workshops equipped with essential fabrication tools such as 3D printers and laser cutters as well as analog tools such as saws and drills. Their goal is to provide communities around them with the tools for manufacturing new things, that cannot be found in commercial stores. The first FabLab was set up in 2003 in Boston by Sherry Lassiter and her team from the Center for Bits and Atoms (CBA) at MIT [Gershenfeld, 2012]. Towards the end of 2015, the Fab Foundation[2] already lists 593 FabLabs in 83 countries.

[1] `http://makezine.com/` (accessed 2015-12-15)

[2] `http://www.fabfoundation.org/` (accessed 2015-12-15)

Online services such as Shapeways[3] or Ponoko[4] provide on-demand 3D printing and laser cutting services to individuals and offer marketplaces for designers to sell their unique objects. An important feature of most of such web-based creators and configurators is the opportunity to customize and personalize the designs and objects. Design studios such as Nervous System[5] or Kwambio[6] use digital fabrication to realize products individualized by the user, such as jewelry, lighting or vases. The startups Meshu[7] and Flying[8] use personal data such as travel routes and turn them into sculpture and jewelry. As Gershenfeld [2012] described, personalization is the "killer app" in digital fabrication, i.e., "*producing products for a market of one person.*"

Online communities, and databases, in which designers and non-designers upload, modify and share models for digital fabrication play a significant role in the rise of the maker movement, in addition to the aforementioned online services. The most prominent of such platforms is Thingiverse[9], which in 2015 contained almost 450.000 models, ranging from kitchenware, toys and jewelry to machine parts and architectural models. Members are also interested in transforming their personal or abstract data into physical representations. Figure 3.2 shows three examples of physical visualizations, whose source code or data files were uploaded by members of the Thingiverse platform.

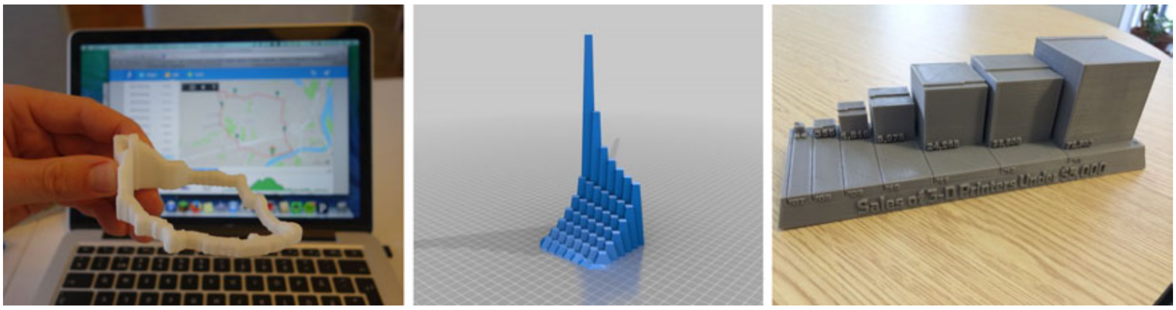

Figure 3.2: Examples for physical visualizations from Thingiverse. Left: Visualization of a run based on GPS tracking data by snrk [Thingiverse, 2014a]. Center: 3D bar chart of the income distribution by household in the USA by Griffin_Nicoll [Thingiverse, 2011]. Right: Volumetric visualization of 3D printer sales under 5000 from 2007 through 2013 by WSJ [Thingiverse, 2014b]

[3] `http://www.shapeways.com/` (accessed 2015-12-15)

[4] `https://www.ponoko.com/` (accessed 2015-12-15)

[5] `https://n-e-r-v-o-u-s.com/` (accessed 2015-12-15)

[6] `http://www.kwamb.io/` (accessed 2015-12-15)

[7] `http://meshu.io/` (accessed 2015-12-15)

[8] `http://flyingfrom.to/` (accessed 2015-12-15)

[9] `http://www.thingiverse.com/` (accessed 2015-12-15)

Although the maker movement "*challenge traditional conceptions of the technology user*" and lead to "*an explosion in both hobbyist and entrepreneurial experimentation*", there is also a growing awareness of the challenges and dangers regarding digital fabrication technologies [Tanenbaum et al., 2013]. Critical points are safety and quality regulations, e.g., who is responsible and liable if someone gets injured by objects individuals fabricate themselves [Mota, 2011]? Other serious questions are the legal implications related to these trends and technologies, e.g., theft of intellectual property, but also the controversy and threat of 3D printable gun files (e.g., Joy [2000]; Greenberg [2015]). Sustainability is another important aspect, as the simple and quick creation of physical objects may lead to increased waste, potentially creating an attitude that regards these objects as disposable and easily replaceable (see also *Chapter 8 - Potential for Motivation & Self-Reflection*).

3.2 Digital Fabrication in HCI

While the previous section focused on the manufacture of products at home and personal digital fabrication in general, this section investigates the adoption and distribution of digital fabrication in research, particularly in the field of HCI. It gives a compact overview of research related to HCI on the topic of digital fabrication and the complimentary technologies that was published at conferences of the ACM Special Interest Group on Computer-Human Interaction (SIGCHI) as of September 4^{th}, 2015. Three discrete research categories related to digital fabrication were identified using a process of open coding.

The workshop "FAB at CHI" [Mellis et al., 2013] in 2013 confirmed the growing interest and popularity of digital fabrication technology in the CHI community and aimed to explore new research directions and to reveal in which ways HCI can have a positive impact on the maker culture. The extended abstract surveys major topics on the relationship between digital fabrication and HCI and gives a brief overview of related work. However, this is the first specific, systematic and comprehensive literature review of digital fabrication in HCI, including 158 papers.

The following sections explain the method used to find and review relevant literature and describe the categories and corresponding subcategories which resulted from the analysis. We conclude with a reflection in which ways these findings can help identify and understand research trends regarding the interplay of HCI and digital fabrication, especially for the field of physical visualizations.

3.2.1 Method

To identify the relevant papers for this literature review, we used the search string "digital fabrication" in the ACM Digital Library. This search identified all publications at conferences of the ACM SIGCHI as of September 4^{th}, 2015 that have the associated term "digital fabrication" in any part of the paper. With this method, we were able to include articles that, despite not using the particular term "digital fabrication" in the content of the document, referenced corresponding work.

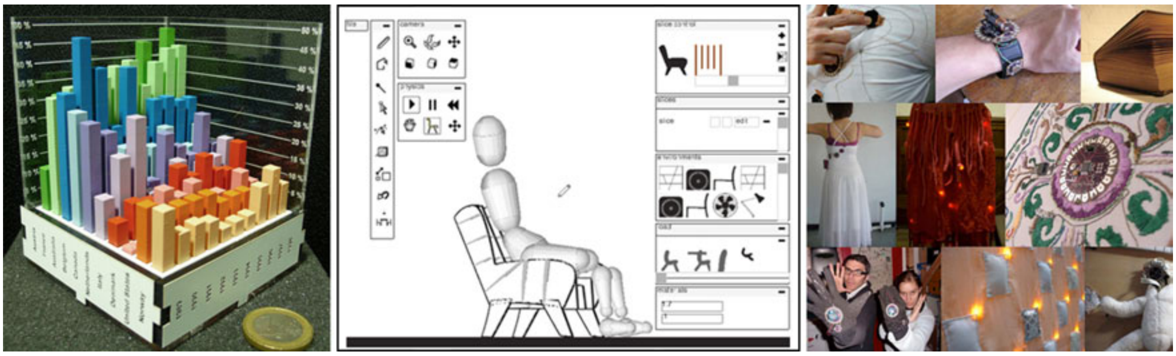

Figure 3.3: Representative photos of the most cited papers of each of the main categories from our analysis. Digital fabrication technologies are *used* as a tool, e.g., to create physical visualizations [Jansen et al., 2013] (left), being *enhanced* through software or hardware modifications, e.g., by building a user interface for sketching one's own chair [Saul et al., 2011a] (center) or *studied* in the wild, e.g., by investigating in which ways the technology is adopted [Buechley and Hill, 2010] (right).

As this single search term may have overlooked a number of relevant papers (e.g., papers that only mention a specific technology and not the broader term), we further searched for papers with a phrasing of "3D print", "laser cut" or "CNC mill" in the title or abstract. We limited the search for these terms to the title and abstract as we wanted to focus on papers in which the use of a digital fabrication technology played a significant role. It should be noted that this search method still excluded work that was published outside of the ACM Digital Library.

Our search resulted in 178 papers that were published between 2006 and 2015. In a first, manual analysis we removed 11% (19) of the papers that were not relevant to our literature review. Most of these papers were identified by the first full-text search for "digital fabrication" and referenced an article with the term in its title. Others mentioned the term briefly in the introduction or future work section. These papers were discarded whenever the actual topic of the work had no association to digital fabrication and did not use any corresponding technologies.

In the next step, we performed an iterative open coding [Anselm and Corbin, 1998] on the remaining 159 papers to identify different categories of research. We grouped papers based on a similar general topic and also looked at the paragraphs that included one of the search terms in more detail in order to identify the context in which the terms were used.

3.2.2 Quantitative Overview

Figure 3.4 shows the number of papers from 2009 to 2015 that used the term "digital fabrication" or named corresponding technologies, sorted by conferences. The main conferences were the ACM Conference on Human Factors in Computing Systems (CHI), ACM Conference on Tangible, Embedded, and Embodied Interaction (TEI), ACM Symposium on User Interface Software and Technology (UIST), ACM Conference on Designing Interactive Systems (DIS), ACM Conference on Creativity & Cognition (C&C) and ACM Conference on Interaction Design and Children (IDC), which in total accounted for 86% or 136 of the 158 papers (see also Figure 3.5-left). In "Other" we summarized papers published at DESIRE, ACE, OzCHI, NordiCHI, ICMI, UbiComp, LAK, BodyNets, ITS, CSCW, PerDis, ASSETS, and SUI. Please note that our search did not include the proceedings of UIST 2015 and that DIS was a biannual event until 2016.

We only found one paper before 2009 that mentioned desktop fabrication techniques such as 3D printing and laser cutting [Song et al., 2006] which was published at UIST 2006 (note that we excluded this paper in Figure 3.4 and 3.5 to enhance readability). A paper at the doctoral consortium at C&C [Mainstone, 2009] and a work-in-progress at CHI [Villalon et al., 2009] document the first use of the term "digital fabrication" in the field of HCI research in 2009.

The stacked area charts in Figure 3.4 show that TEI 2010 and 2011 seem to be the pioneering conferences for research in the field of digital fabrication while UIST started to pick up this trend in 2012. In 2013, the interest started in the CHI community, and 2014 can be seen as the year in which digital fabrication became a "mainstream" topic by almost tripling the amount of papers published at CHI compared to the year before (*2013:* 6; *2014:* 17). Also, the setback of publications at TEI 2014 (*2013:* 6; *2014:* 3; *2015:* 11) might be attributed to a rethinking phase, because this area of research was outgrowing its "niche existence". Given the small absolute numbers, this is speculative and might also simply be noise in the data.

Another minor trend can be recognized by the use of the generic term "digital fabrication" and specific fabrication technologies. In recent years more specific terms such as "personal fabrication" (e.g., Lau et al. [2013]; Mota [2011], see also *Section 3.1 - 3.1*) or "interactive fabrication" (e.g., Gardiner et al. [2011]; Mueller et al. [2012]; Willis et al. [2011]) arose and were used instead of the more generic term "digital fabrication". An interesting observation was that while these newer terms were defined and referenced in the papers, the term "digital fabrication" seemed to be considered general knowledge by then.

The growing popularity of digital fabrication and corresponding technologies becomes apparent through two keynotes [Gross, 2013; Blikstein, 2014] including the term as well as the ongoing increase of published papers in 2015. The CHI conference, for example, had an increase of 9 papers in digital fabrication alone (*2014:* 17; *2015:* 26), while the overall number of articles only increased by 21 (*2014:* 465; *2015:* 486). The high number of 13 workshop/tutorial/studio papers [Alexander et al., 2015; Cangiano and Fornari, 2014; Diez and Posada, 2013; Krannich et al., 2012; Lau et al., 2013; Leduc-Mills et al., 2013, 2012; Mellis et al., 2013; Mueller et al., 2014b; Sarik et al., 2012; Saul et al., 2011b, 2013; Young

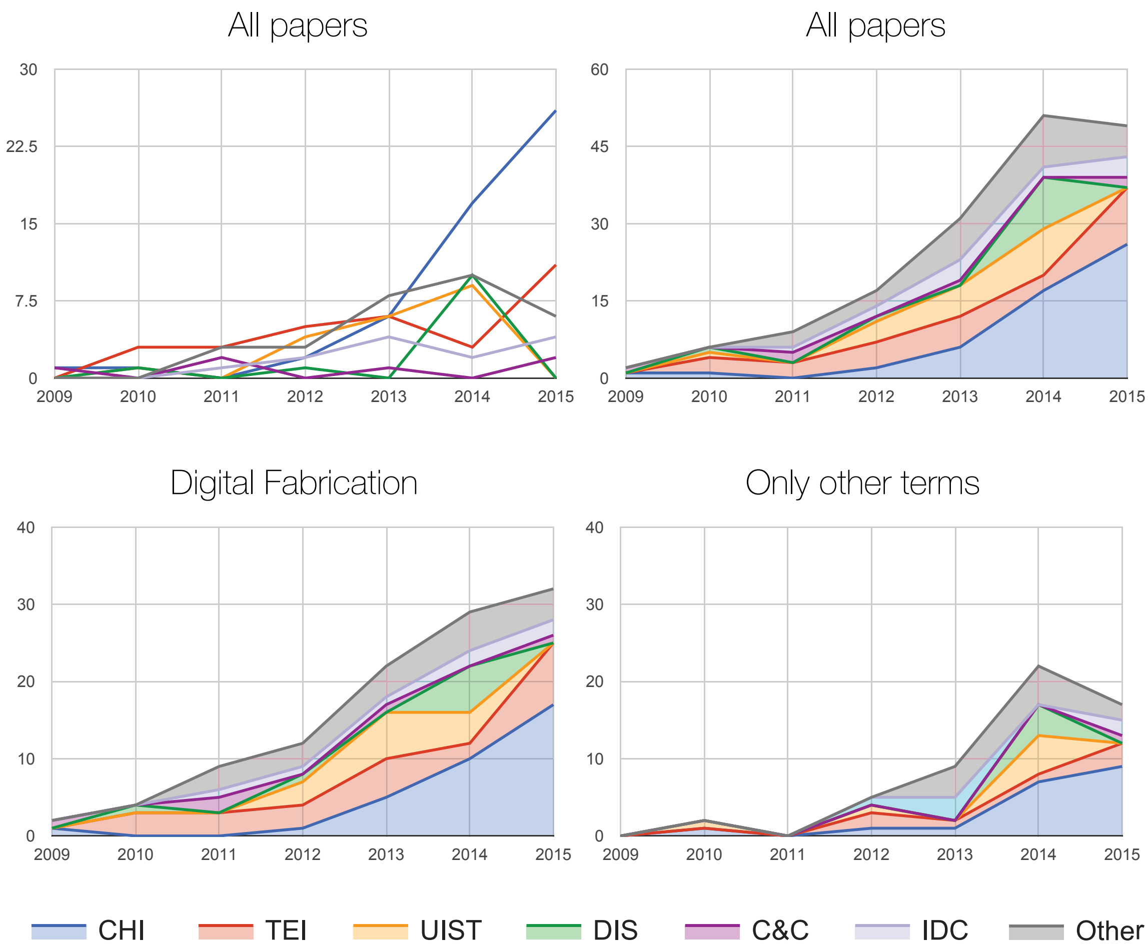

Figure 3.4: Number of relevant papers from 2009 to 2015 sorted by conferences. From top left to bottom right: line chart and stacked area chart of all papers found; stacked area chart of papers including the term "digital fabrication" and of papers including other search terms but not "digital fabrication".

et al., 2010] emphasizes that the research communities are trying to spread the knowledge on how digital fabrication machines work, what they can fabricate and in which ways they can be helpful for research purposes. The fact that digital fabrication techniques are fascinating for young academics is highlighted by the six papers that were published at doctoral consortia [Devendorf, 2014; Devendorf and Ryokai, 2014; Khot, 2014; Mainstone, 2009; Mellis, 2013; Stusak, 2015].

Figure 3.5: Left: Number of papers sorted by conference. Top right: Evolution of the resulted categories from 2009 to 2015. Bottom right: Number of papers in each resulted category sorted by conference.

3.2.3 Categories

Our analysis resulted in three main research categories: *use*, *enhance* and *study*. Each of these will be presented with an overview and their subcategories discussed in more detail. For the final analysis, the workshop and keynote publications were excluded and focus laid on the remaining 144 papers. It should be noted that several articles could have been classified in more than one category. In such cases, we focused on the main contribution of the paper in correlation to digital fabrication. Figure 3.5 shows the evolution of the categories and their distribution at the main conferences.

Use (n=50) One-third (34.8%) of the papers could be classified as the category *use*. The papers in this category used digital fabrication technologies "out of the box" without further modification, just as a means to an end.

Interactive Prototypes (n=22): The largest cluster of papers in this category used digital fabrication to support the creation of interactive physical prototypes. Most articles in this category only had a short mention of digital fabrication and the actual contribution and topic had a different focus. Examples are 3D-printed phone cases (e.g., Park et al. [2015]) or game controllers (e.g., Lin et al. [2014]; Varesano [2013]) as well as laser cut physical components (e.g., Vandermaesen et al. [2013]; Yao et al. [2013]).

Data-Driven Material Representations (n=17): In contrast to the previous subcategory the fabricated physical prototypes in these publications are based on abstract data. There is some work that focuses on the evaluation of efficient and effective physical visualizations (e.g., Brown and Hurst [2012]; Jansen et al. [2013]; Stusak et al. [2015]), as well as more exploratory approaches such as personalized souvenirs (e.g., Nissen and Bowers [2015]; Nissen et al. [2014]) or the visualizations of physical activity through engravings in leather [Lee et al., 2015], thermoplastics [Khot et al., 2014] or even chocolate [Khot et al., 2015a].

Explore Possibilities (n=11): Papers in this subcategory focused on digital fabrication, but used standard technology and aimed at exploring their possibilities and finding their limitations. Examples are fabricating do-it-yourself electronic products (e.g., Mellis [2013]; Mellis and Buechley [2014]; Mellis et al. [2011]), exploring design challenges with 3D printing technology [Vázquez et al., 2015] as well as analyzing the potential of digital fabrication technologies for crafting [Tsaknaki et al., 2014] and product development processes in general [Beaudette et al., 2014].

Enhance (n=63) The biggest group of papers found (43.75%) dealt with *enhancing* the way, individuals interact with digital fabrication technologies. Please note that several articles in this category could have been classified into more than one subcategory. In such cases, we tried to identify the primary focus of the project.

Graphical User Interfaces (n=14): This subcategory includes all papers that developed novel GUI to interact with digital fabrication machines. Most of them had the general goal to simplify the use of digital fabrication technologies for novice users (e.g., Agrawal et al. [2014]; Hurst and Kane [2013]; Jacobs and Buechley [2013]; Saul et al. [2011a]) while some had more concrete use cases such as the fabrication of physical visualizations [Swaminathan et al., 2014a], the construction of architectural models [Villalon et al., 2009] or enabling the design of expressive 3D models [Torres and Paulos, 2015]. Others tried to improve the actual fabrication process with suitable interfaces that helped to increase object fabrication speed [Beyer et al., 2015; Mueller et al., 2014] or assisted users in packing tasks for manufacturing [Saakes et al., 2013].

Non-Graphical User Interfaces (n=22): A large number of papers explored new ways of interacting with digital fabrication technologies that go beyond the classical graphical interface. The most popular direction is called *Interactive Fabrication* and allows real-time input to fabricate physical forms [Follmer et al., 2010; Mueller et al., 2013, 2012, 2013; Peng et al., 2015b; Shen et al., 2013; Willis et al., 2011; Zoran et al., 2013]. Tangible input devices were used to develop systems for children and novice users [Follmer and Ishii, 2012; Huang and Eisenberg, 2012; Leduc-Mills and Eisenberg, 2011; Leduc-Mills et al., 2012; Te, 2015] and also more experienced ones [Schneegass et al., 2014; Weichel et al., 2015; Yamamoto et al., 2014]. Others experimented with gestural [Johnson et al., 2012; Song et al., 2006; Willis et al., 2010] and bare hand input [Gannon et al., 2015; Zheng, 2015].

New Technology (n=17): This subcategory contains all papers that focus on the improvement or new development of digital fabrication technologies. Some work upgraded standard 3D printing processes to enable direct printing of interactive prototypes [Ishiguro and Poupyrev, 2014; Savage et al., 2013, 2014; Willis et al., 2012], the printing of wireframes [Mueller et al., 2014a] or the relocation of physical objects [Mueller et al., 2015]. Others built systems to simplify the documentation of the iterative process of fabricating objects [Tseng, 2015; Tseng and Tsai, 2015]. New contributions to digital fabrication approaches are made in the area of printing electronics [Kawahara et al., 2013; Olberding et al., 2013, 2014; Tsujii et al., 2014] as well as by systems which enable the printing of soft material [Hudson, 2014; Peng et al., 2015a] or machine-controlled knitting [Koutsomichalis et al., 2014].

Craft & Art (n=8): Papers in this subcategory explored digital fabrication technologies in alternative, creative and unusual ways or had designers and creative practitioners as the target audience. One area investigates the integration of craft and technology [Mellis et al., 2013; Zoran and Paradiso, 2013], another in which ways hybrid (physical-digital) fabrication systems can support meaningful experiences regarding the creation of things [Devendorf, 2014; Devendorf and Ryokai, 2014, 2015a,b] and one paper modified a 3D printer into an automated physical interface [Kim et al., 2014].

Study (n=31) The smallest category (21.5%) nevertheless represents an important perspective on digital fabrication as these papers *study* in which ways these technologies are used by a broader audience. In order to be classified into this category, the papers main contribution needed to be an observation on the ways people, other than the authors of the article, used digital fabrication.

Education (n=10): A large number of papers dealt with digital fabrication in the context of education, e.g., the ways it could be integrated and taught in school [Blikstein and Krannich, 2013; Buehler et al., 2014b; Krannich et al., 2012; Stager, 2013; Worsley and Blikstein, 2013; Wardrip and Brahms, 2015] and in which ways children, in general, can be engaged in learning [Fitton et al., 2015; Giannakos and Jaccheri, 2013; Leduc-Mills et al., 2013; Posch and Fitzpatrick, 2012].

Creative Practitioners (n=4): A couple of papers looked in detail at the user community of designers and investigated the impact of digital fabrication on product design [Cheatle and Jackson, 2015; Hermans, 2013] as well as craft and creativity [Devendorf and Rosner, 2015; Parraman and Adams-Foster, 2011].

Hackerspaces (n=4): Various papers conducted studies in maker- and hackerspaces to study maker ethics [Toombs et al., 2015], self-made tools [Bardzell et al., 2014], the design of infrastructures for 3D printing [Ludwig et al., 2014] and in which ways the process of creating worked for elderly DIY enthusiasts [Sun et al., 2015].

Particular Audiences (n=6): In addition to the previous areas there are various other audiences that were observed in relation to digital fabrication. Novices and designers [Buechley and Hill, 2010; Mellis and Buechley, 2012; Shewbridge et al., 2014], persons with disabilities [Buehler et al., 2014a], occupational therapists [Moraiti et al., 2015] and the Ju/'hoansi society living in Namibia and Botswana [Jacobs and Zoran, 2015] were watched and interviewed in order to unveil in which ways non-digital craft cultures can inform the design of digital fabrication tools.

Theoretical Propositions (n=4): Four papers took a more theoretical approach by linking digital fabrication with the theorization of form and materiality [Jung and Stolterman, 2012], questioning the maker movement [Jenkins and Bogost, 2015], exploring the ways in which experiences of expressivity, skill and value shift with the popularity of digital fabrication [Rosner et al., 2015] and arguing that the rise of personal fabrication will revolutionize the design, production, and distribution of physical artifacts [Mota, 2011].

Online Communities (n=3): Two papers studied Thingiverse, the largest online design community for digital fabrication. These examined in which ways hackers remix each others' design [Oehlberg et al., 2015] and investigated the designs and motivations for creating assistive technology [Buehler et al., 2015]. A further paper explored the potential of online customization in relation to digital fabrication [Nurkka and Jumisko-Pyykkö, 2014].

3.2.4 Conclusion & Reflection

The literature review provided a systematically derived basis for understanding the fascinating emerging field of research in digital fabrication. The analysis above certainly shows one thing: the area of digital fabrication is not only growing rapidly, it also unveils the signs of becoming a "mainstream" area of research, as opposed to the "niche" it was in its early years. While we could observe more papers, trying to tackle the fundamental technological problems of the field, in the beginning, we can now see more and more articles that merely use the technology for other purposes within HCI.

The example of data-driven material representations (see also next *Chapter 4 - Data Physicalization*) highlights the ways in which this emerging trend regarding digital fabrication can lead to entirely new research areas shows. In this case, digital fabrication enables an easy and rather cheap way to fabricate accurate physical visualizations and therefore, for the first time, create the opportunity for an appropriate evaluation of physical visualizations on a broad basis. The work categorized under "enhance" is also relevant, as the progress in this area will simplify the design and creation of interactive physical visualization, e.g., with built-in touch sensing. The category "study" confirms the adoption and distribution of digital fabrication technologies in private and public areas, e.g., education. In the future it is imaginable that schools will teach, for example, historical facts, with an hands-on approach, in which pupils build their own physical visualizations based on historical data.

Chapter 4

Data Physicalization

The term *Data Physicalization* was introduced by Jansen et al. [2015] in 2015. Hence, this type of data representation is rather new and cannot look back onto a huge scope of research and related work. Yet, related fields evolved in parallel inspiring the work in the area of data physicalization such as embodied and tangible interaction (see *Chapter 2 - Embodied Interaction & Haptic Perception*) or digital fabrication (see *Chapter 3 - Digital Fabrication*). Additionally data representations in material form have a long history and were used especially in the time before the desktop computer era. Examples of early artifacts that encode data are briefly described in *Section 4.1 - History of Physical Data Representations*.

Another important related area is the well-established research field of InfoVis, which shares the common goal of studying data representations of abstract data, while focusing on the visual sense. Physical visualizations have so far received little attention in the field of InfoVis. Relevant projects are at the interplay of InfoVis and tangible interaction, which mainly focus on the interaction with InfoVis systems through tangibles. Examples of such prototypes are presented in *Section 4.2 - Information Visualization & Tangible Interaction*.

Finally, the last and central section of this chapter describes physicalization as a new research field. Its strong connection and overlap to previous research done in InfoVis, especially regarding the process of creating a visualization, is demonstrated through the physicalization pipeline. Ultimately, we will give an overview of the related work in the field of data physicalization that has been done thus far.

4.1 History of Physical Data Representations

Before the invention of computational devices, even before the invention of paper, humans used physical artifacts such as stones, pebbles or clay tokens to externalize information. Jansen [2014] lists the Blombos ocher plaque dating 75,000 Before Christ (BC), as one of the oldest archaeological finds that might encode data, though she mentions that it is not clear whether the engravings are merely for ornamental purposes or actually represent information. A curated list of physical visualizations and related artifacts by Dragicevic and Jansen [2012], with over 200 entries in December of 2015, states Mesopotamian clay tokens from 5,500 BC as one of the earliest data visualizations.

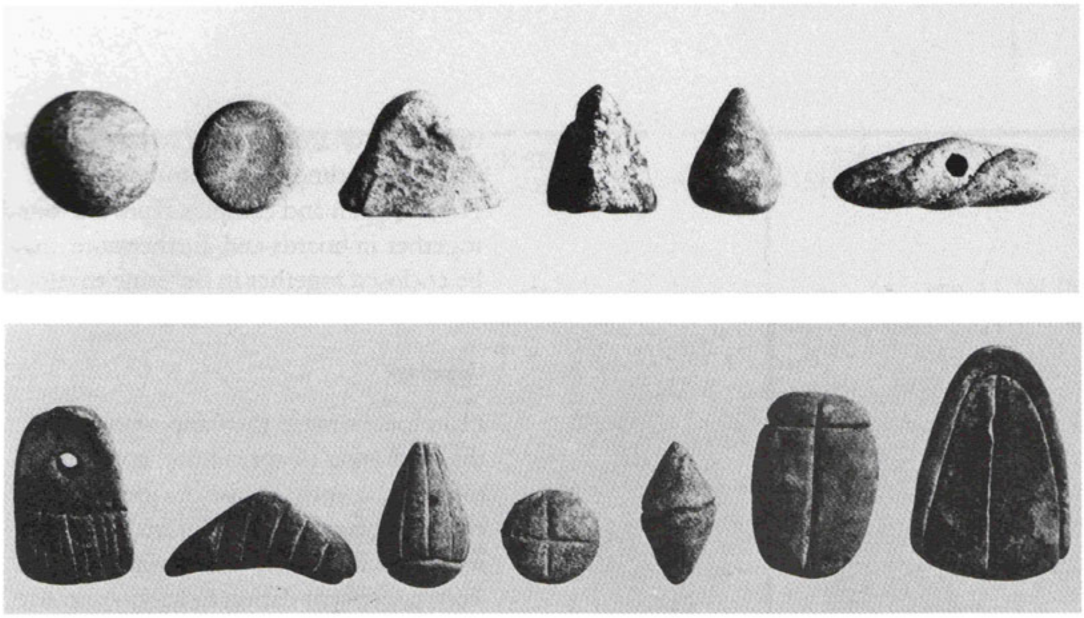

Figure 4.1: Top: examples for plain tokens. Bottom: examples for complex tokes. All tokens originated in Susa, Iran, late 4,000 BC; Courtesy Département des Antiquités Orientales, Musée du Louvre, Paris, France (image © Denise Schmandt-Besserat).

Small tokens modeled in clay in different shapes were probably used for accounting, i.e., to organize and store economic data [Schmandt-Besserat, 1986]. Figure 4.1 shows various examples of plain (top) and complex (bottom) tokens from Susa, Iran, dating from 4,000 BC. The plain tokens had a rather simple geometric form and a smooth surface. The complex ones were of a greater repertoire of forms and markings such as linear patterns, notches, and punctuations. These tokens were meant to help translate economic data into artifacts, that are easy to manipulate, e.g., can be lined up or arranged into visual patterns. Furthermore, they were used as a reliable storage of data, e.g., as a permanent record of transactions to be completed in the future [Schmandt-Besserat, 2010]. Both kinds of token were used for the same reckoning device, but the plain tokens represented products of a farm while the complex tokens referred to goods manufactured in workshops. Schmandt-Besserat [2010] summarizes that tokens "*translated concrete information into abstract markings, removed the data from their context, separated the knowledge from the knower, and increased objectivity.*"

Another example of an ancient recording and visualization system is the quipu also known as khipu, which was used by the Incas starting around 3,000 BC [Jansen, 2014]. A quipu consists of a collection of threads of varying length, knots and color (see Figure 4.2). It is still unclear whether quipu was a communication and information artifact or just a mnemonic device, which triggers the memory of a person. As an information tool, they were meant to encode signs in a defined way which was shared and known by a group of people [Beynon-Davies, 2009]. Research assumes that the Inka administrative system used quipus to synthesize, manipulate and transfer tribute and census data between different accounting levels [Urton and Brezine, 2005]. The encoding is based on the construction of the thread (e.g., material or color), the placement of threads upon other threads as well as the structure of the knots and their placement upon the threads [Beynon-Davies, 2009].

Figure 4.2: Example of quipus from the Inca Empire (image © Wikimedia Commons).

With the invention of paper around 100 BC, it became the favored medium to externalize information. In the mid-eighteenth and early nineteenth centuries, the first graphical methods for displaying data emerged. The work by Playfair [1786, 1801] is credited as the earliest statistical graphics, already including line graphs, bar charts, and pie graphs. Humans still used physical representations to externalize information. One example is the fabrication of physical models of atoms and molecules (see Figure 4.3). In the mid-1950s, one of the many challenges regarding protein structures was finding ways to represent these visually. Apart from drawing the structures, scientists carved structures out of balsa wood, engraved data onto transparent plastic sheets and used rulers and plumb lines for further exploration [Everts, 2013]. The picture at the center of Figure 4.3 is a nice example in which ways physical objects or in this case models, can enhance the thinking process (see also *Subsection 2.1.2 Embodiment & Embodied Cognition*). The complex structure of the molecule became more accessible to Perutz and his team as they were able to manipulate the model physically [Jansen, 2014].

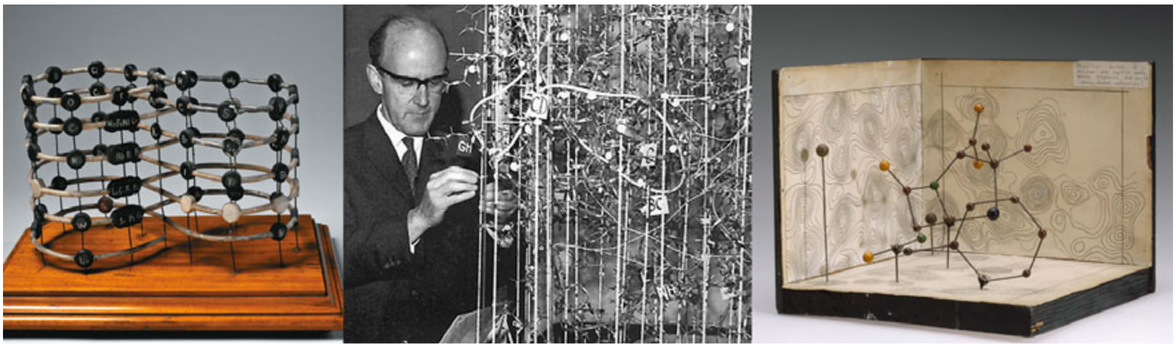

Figure 4.3: Examples of physical models of atoms and molecules structures. Left: Spiral periodic table designed by Sir William Crookes and constructed in 1898 by his assistant:, Gardiner (image © Museum of History of Science, Oxford). Center: Model of hemoglobin created by biochemist Max Perutz in 1968 (image © Life Sciences Foundation). Right: Electron density map and model of Penicillin fabricated by Dorothy Crowfoot Hodgkin in 1945 (image © Science Museum, London).

It is worth mentioning that the previous examples are *models*, i.e., reproductions of real objects, typically at a different scale or with a different level of abstraction [Jansen, 2014]. A *visualization* on the other hand includes the process of visual mapping (see also *Subsection 4.3.2 Physicalization Pipeline*), i.e., assigning visual variables such as color or position to data attributes [Chi, 2000]. Figure 4.4 shows three examples of historical physical visualizations that ran through the process of visual mapping. The left image shows a three-dimensional curve of the 1935 electricity load of the Detroit Edison Company. Each wooden slice represents one day and each day was split into 30 min intervals. The image in the center shows a physical flow chart created with a cosmograph consisting of one thousand strips of paper. By clamping strips of paper into position and inserting wedge and bar spacers between them, various data flows could be visualized. The right image visualizes the carried passengers on the street-car lines of Frankfurt am Main, Germany. Strips of wood, alternately black and white, are glued on top of each other along the streets having a car line. Each of the wooden strips represents 4.000 passengers carried on the lines in 24 hours.

4.2 Information Visualization & Tangible Interaction

The approaches and ideas of the tangible interaction research field (see *Subsection 2.1.1 Ubiquitous Computing & Tangible Interaction*) partially entered the area of InfoVis [Lee et al., 2012]. Jansen [2014] divides visualization systems using tangible elements roughly into the categories of tangible controllers and tangible displays. This section lists various projects of both groups to give an illustration in which ways tangible interaction was used in this domain.

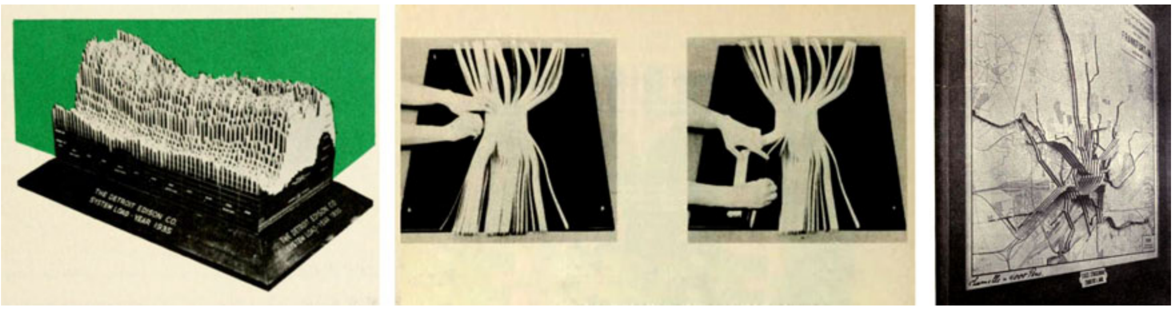

Figure 4.4: Examples of historic physical visualizations (image © Brinton [1939]). Left: Physical visualization of the electricity consumption for the year 1935 made by the Detroit Edison Company. Center: Physical flow chart by IBM from 1933. Right: Stacked strips of wood representing the number of passengers carried on street-car lines. Presented at the Internationale Baufach-Ausstellung, Leipzig, Germany in 1913.

The category of tangible controllers contains projects that use tangible controllers, beyond keyboard and mouse, for the input while the visual output is still on a flat digital display. A popular approach is to use physical models, e.g., 3D printed, and appropriate input devices, e.g., a stylus to simplify navigation and exploration of the data. The left image in Figure 4.5 shows the physical prop of a blood flow simulation. The prop and the pen are tracked in space, and as it is rotated or touched during exploration, the linked stereoscopic display is updated [Konchada et al., 2011]. The physical printouts enable a fast understanding of the shape, while the virtual reality visualization allows the exploration of the data inside the printed geometry. Similar projects used tangible artifacts to navigate through 3D Magnetic Resonance Imaging (MRI) data [Hinckley et al., 1994] or printed models of corals to navigate and annotate virtual models with a higher-resolution [Kruszyński and Liere, 2009].

A different approach is to use physical tokens as input devices to interact with data, e.g., by translating or rotating a token. Early examples are the tangible query interfaces by Ullmer et al. [2003, 2011], who implemented prototypes with physically constrained tokens to manipulate and visualize database queries. Other projects explored a novel physical input device for browsing, sorting and sharing digital photo collections displayed on a tabletop [Hilliges et al., 2007]. A more general approach was followed by the development of "SLAP Widgets", which are various silicone or acrylic widgets for tabletops, that aimed at combining the flexibility of virtual objects with physical affordances [Weiss et al., 2009]. Others compared tangible and direct-touch interfaces for 3D object manipulation tasks and 2D information visualization exploration tasks [Hancock et al., 2009]. Similarly, Al-Megren and Ruddle [2016] developed a tabletop system for interactive data visualization for biologists controllable through tangible or multi-touch interaction. Their evaluation showed that participants found patterns in the dataset faster with the tangible interface, as they developed more efficient strategies and performed fewer unnecessary analysis.

“Facet-Streams” by Jetter et al. [2011], which is shown in the right image in Figure 4.5, combined approaches of tangible controllers and tangible displays. While tangible controllers only expand the control of a visualization system into the physical world, tangible displays represent systems in which controls and displays are closely connected [Jansen, 2014], e.g., through projections and touch interaction. “Facet-Streams” used circular glass discs as tokens to materialize co-located collaborative search on an interactive tabletop. While the tokens primarily served as input devices, they were also used for data or settings storage and their transparent appearance allowed an augmentation with content and functionality. Their studies revealed that the prototype allowed a great variety of search strategies as well as collaboration styles and that the participants perceived the use as a fun and social experience.

Figure 4.5: Left: Interface that combines physical 3D prototypes with complementary virtual reality visualizations of the data inside the printed geometry [Konchada et al., 2011]. Center and Right: “Facet-Streams” uses tangible tokens to materialize collaborative search on interactive tabletops [Jetter et al., 2011].

The left image in Figure 4.6 shows the urban planning tool “Urp” by Underkoffler and Ishii [1999]. In this application physical, architectural models can be placed on a table surface and are augmented with projected forms, such as shadows or wind flow. By moving the tangibles, it is possible to explore different alternatives of urban planning and to simulate effects of changes in real-time. The center image of Figure 4.6 displays the project “Tangible Views” by Spindler et al. [2010]. With lightweight displays that can be moved through the physical space on or above a tabletop, this introduced new ways of visualizing and directly interacting with information by no longer restricting the interaction to the display surface alone. The authors concluded that their system enables a direct mapping of classical InfoVis techniques such as focus+context or overview+detail and that the bimanual interaction provides exciting alternatives to traditional desktop interfaces. Based on this Spindler et al. [2012] developed the concept of “Tangible Windows” which allows the interaction with 3D information spaces by combining tangible interaction, head tracking and multi-touch.

A fascinating area of research in which physical visualizations could serve as application scenario is the field of shape displays (e.g., Leithinger et al. [2011, 2015, 2014]; Rasmussen et al. [2012]). The right image in Figure 4.6 shows the “inFORM” by Follmer et al. [2013], a state-of-the-art shape display, which offers variable stiffness rendering and real-time user input through direct touch and tangible interaction. As the image demonstrates simple data

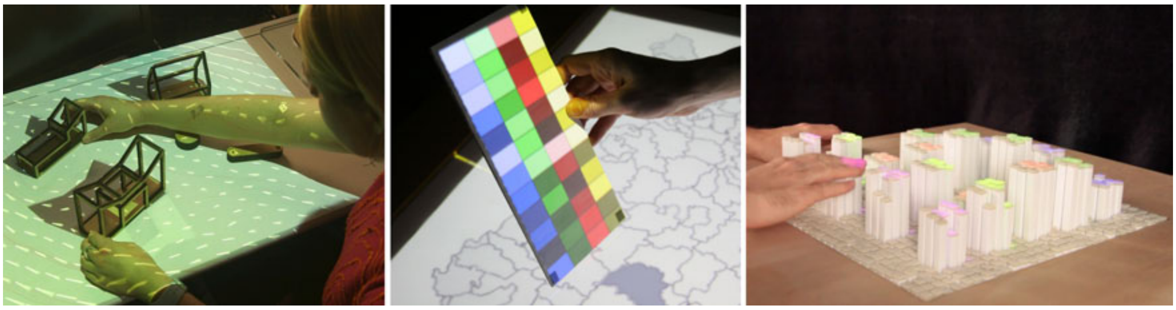

Figure 4.6: Left: The urban planning tool “Urp” by Underkoffler and Ishii [1999]. Center: “Tangible Views” for InfoVis by Spindler et al. [2010]. Right: The shape-changing display “inFORM” by Follmer et al. [2013]

representations such as dynamic bar charts are already realizable with such techniques. However, the exploration, implementation and evaluation of such systems with a focus on InfoVis applications are in its early stages.

4.3 Physicalization

The previous two sections gave an overview of early examples of physical visualizations as well as their history and presented examples of the ways tangible interaction was applied to InfoVis. This section, lastly introduces the rather new research field of *data physicalization*. First, different definitions regarding the physical representation of data are presented, and the abstract process of creating physicalizations is described. In final, current examples of physicalizations are briefly discussed and categorized.

4.3.1 Definitions

Jansen et al. [2015] proposed in their paper “Opportunities and Challenges for Data Physicalization” that:

> “*A data physicalization (or simply physicalization) is a physical artifact whose geometry or material properties encode data.*” [Jansen et al., 2015]

They also mention that this definition should be taken as a working definition and suggest to use the term as a synonym for physical visualization when one does not want to overemphasize the visual channel. In this thesis, both terms are used interchangeably. Furthermore, data representation is used as an umbrella term including physicalization and visualization. In 2013 Jansen et al. already distinguished physical visualizations from their digital counterpart as:

> "*Traditional visualizations map data to pixels or ink, whereas physical visualizations map data to physical form.*" [Jansen et al., 2013]

They argue that physicalization aligns with neologisms such as sonification and haptification but without favoring one particular sense. They further suggest to distinguish between data physicalization as a data-driven physical artifact, data physicalization as the process of producing physicalizations, i.e., *to physicalize* means to give data a physical shape and Data Physicalization as a research area (with capitalization to amplify when referencing to the research field). Jansen et al. [2015] propose to think of Data Physicalization:

> "*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.*" [Jansen et al., 2015]

It is worth mentioning that the use of a computer, either for the creation of the physicalization or their actuation, is explicitly referred to in this description. Jansen et al. [2015] highlight that new developments in digital fabrication, actuated tangible interfaces, and shape-changing displays (see also previous chapters) are a driving force behind the emerging research field of Data Physicalization. While research in these areas, from new theories to technological advancements, will be important both for the creation and design of physicalizations it is important to mention their focus distinctions, in particular regarding TUIs. TUIs focus on information input and manipulation tasks, whilst Data Physicalization focuses on information output and exploration tasks [Jansen et al., 2015].

In addition to the research field of TUI, Data Physicalization has a strong relation to the domain of InfoVis and SciVis. Common goals and approaches (see also next *Subsection 4.3.2 Physicalization Pipeline*) are the use of a computer-supported external representation to enhance humans' cognitive abilities to analyze and explore data [Card et al., 1999]. One key difference is that Data Physicalizations does not explicitly focus on the visual channel but also on haptic, audio, smell or taste [Jansen et al., 2015]. Another is that Data Physicalization excludes representations on flat visual displays if the geometry or material properties of the screen surface do not encode data. Jansen et al. [2015] stress that in Data Physicalization "*the focus is on the physicality of data representation, not on the physicality of interaction.*"

It is worth mentioning that Andrew Vande Moere started in 2008 with a thorough review of data sculptures (e.g., Vande Moere [2008]; Vande Moere and Offenhuber [2009]; Vande Moere and Patel [2010]), a sub-category of physicalizations. Jansen et al. [2015] describes such data sculptures as artifacts that are "*built by artists and designers who seek to elicit emotions and convey meaning beyond mere data.*" Zhao and Vande Moere [2008] define data sculptures 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.*" The left graphic in Figure 4.7 displays the a model developed by Zhao and Vande Moere [2008] for physical representation of data. They identified

InfoVis, TUIs, visualization art, and interactive art as relevant areas of research for data sculptures. The model is defined by the attributes “focus”, which spans between artistic and functional, and “manifestation”, which distinguishes between virtual and physical. To categorize types of data sculptures Zhao and Vande Moere [2008] further proposed a conceptual model of embodiment, in which they took into account both the “metaphorical distance from data” and the “metaphorical distance from reality” (see right graphic in Figure 4.7).

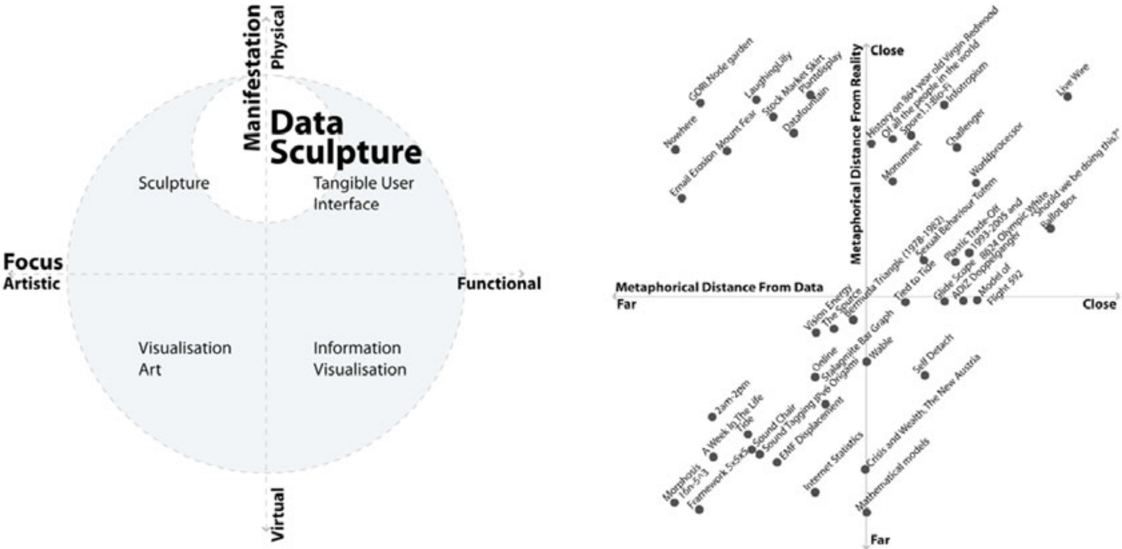

Figure 4.7: Model of physical representation of data (left) and embodiment in data sculptures (right) by Zhao and Vande Moere [2008].

Jansen et al. [2015] further proposed a research agenda for Data Physicalization and split open research questions in four main themes:

- *Designing Physical Data Representations:* To understand in which ways data can be conveyed effectively, it is necessary to develop a design space for physical data representations, to investigate the perceptual effectiveness of different approaches and to generate suitable processes to implement specific designs.
- *Supporting Animation and Interactivity:* Dynamic physicalizations could allow the reusability across datasets and support analytical and communication tasks. Again it is inevitable to explore the ways in which dynamic physicalizations can be realized and what designs are effective.
- *Application-Specific Challenges:* Identification of application areas in which physicalizations bring immediate benefit in relation to their creation costs and efforts.
- *Evaluation-Specific Challenges:* Development of evaluation methodologies that avoid experimental bias and allow a fair comparison, in particular against their intensively researched digital counterpart.

Apart from the challenges regarding dynamic physicalizations this thesis contributes insights to all of these themes and research questions by presenting various designs and evaluations of physicalizations, by identifying promising areas for physicalizations and by proposing an initial description for physical variables.

4.3.2 Physicalization Pipeline

A strong similarity between visualizations and physicalizations is the underlying process that transforms raw data into a final image, an interactive InfoVis system or a physical object. In InfoVis this process is known as the visualization reference model or the visualization pipeline. Figure 4.8 shows the visualization pipeline by Card et al. [1999], which has also been described by Chi and Riedl [1998] and refined e.g., by Carpendale [1999] or Tobiasz et al. [2009].

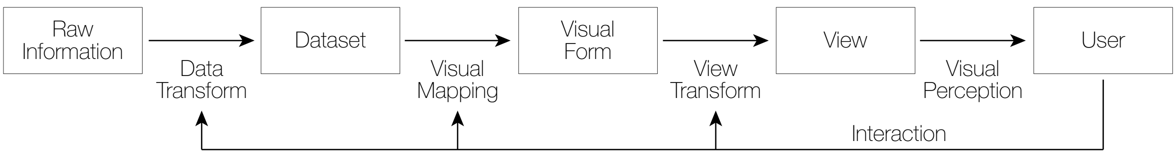

Figure 4.8: The visualization reference model or visualization pipeline by Card et al. [1999], transforming raw information into (interactive) visual representations.

As the visualization pipeline only focused on traditional InfoVis systems for desktop computers, Jansen and Dragicevic [2013] presented "*a conceptual interaction model and visual notation system that aims to facilitate the description, comparison and criticism of beyond-desktop visualization systems.*" Their major modification of the traditional pipeline was exchanging the view stage into the process of the physical rendering in which the visual presentation enters the real world. They furthermore expanded the pipeline with additional stages on the perception side, to define on what ways a visualization or physicalization is seen and read.

Figure 4.9 shows the extended pipeline in which stages are represented by rectangles and transformations by ellipses. The initial stage is the raw data, which is processed into a form that is suitable for representation by a data transformation (e.g., filtering or aggregating the data). The processed data is transformed into an initial visual form by mapping data entities to visual marks and data dimensions to visual variables [Card et al., 1999]. This stage is regarded as the core part of information visualization and is what differentiates one visualization technique from another [Jansen and Dragicevic, 2013]. For a visualization graphical primitives and attributes are used for the mapping, for a physicalization the geometry or material properties of the physical artifact can be used. The outcome of the visual mapping transformation is an abstract visual form, as the visual presentation is not yet fully defined.

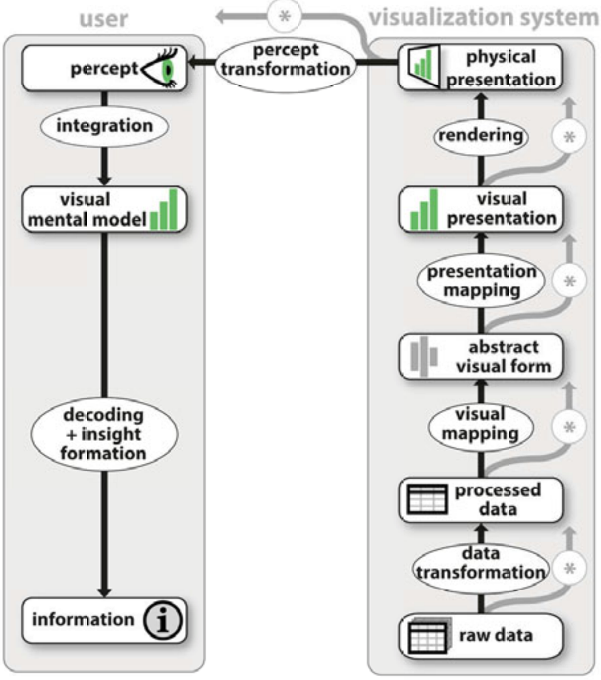

Figure 4.9: The extended visualization pipeline by Jansen and Dragicevic [2013].

A fully-specified visual presentation, which can be displayed, printed or fabricated, is reached after the presentation mapping. This transformation includes operations such as specialization (e.g., applying scaling functions), styling (e.g., assigning free visual variables), optimization (e.g., graph layout or matrix reordering), and decoration (e.g., gridlines, legends or captions). Jansen and Dragicevic [2013] describe the output of the presentation mapping as a complete visual specification which can be thought of as a bitmap image, an interactive visualization, or a 3D model in a computer implementation. The final transformation brings the visual presentation into existence in the physical world and therefore perceivable by humans. The physical presentation is defined as a physical object or apparatus that makes the visualization or physicalization observable, e.g., by displaying it on a digital screen, printing it on paper or presenting it on a shape display or as a 3D printed artifact.

The left side of Figure 4.9 shows the rough process of how physical presentations are read and used. The percept transformation defines the ways in which the physical presentation becomes a percept, i.e., what an observer sees at a specific point in time. This transformation is outside of the visualization pipeline control and is influenced by the observer and environmental factors, e.g., position of the observer or light conditions. The percept is transformed into a visual mental model by integrating previous percepts, e.g., different perspectives on the presentation. Finally, information is extracted from the visual mental model which is defined by the decoding and insight formation. Decoding requires an understanding of the visual mapping and refers to the extraction of data values. Combining the gathered information and putting it into context can eventually lead to new insights.

The importance of the visualization pipeline for this thesis becomes evident when looking at the descriptions of the single projects. All prototypes passed through the individual stages of the pipeline, starting from the raw data, determining the visual mapping and finally creating the physical artifact. By evaluating the various physicalizations, this thesis furthermore provides insights in which ways physicalizations are used and perceived.

4.3.3 Examples for Physicalizations

The previous sections described historic examples of physical data representations, in which ways TUIs were used for InfoVis systems and presented definitions for physicalizations as well as their creation process. This subsection lists current examples of physicalizations and associated projects, particularly those with a research background. A primary classification for physicalizations is to differ between static and dynamic data representations [Jansen et al., 2015]. As dynamic physicalizations are yet rather uncommon, the following projects are roughly categorized into pragmatic and aesthetic or artistic purposes [Kosara, 2007]. While the goal of a pragmatic physicalization is to explore, analyze, or present information in an efficient way, artistic physicalizations are often not recognizable as such, and the underlying data is not readable by an observer. Furthermore, artistic data physicalizations seek to elicit emotions and convey meaning beyond the pure data [Jansen et al., 2013] and have a strong relationship to Casual InfoVis [Pousman et al., 2007]. There is a smooth transition between these two categories, and various projects can be placed in between, as physicalization with an artistic intent can still be informative (e.g., Skog et al. [2003]; Holmquist and Skog [2003]). Therefore, the projects are further grouped inspired by approaches from InfoVis systems. Examples are a differentiation based on the underlying data (e.g., personal, scientific), the skills of the target audience (e.g., novice, savvy, expert) or their goals (e.g., exploration, analysis, communication) [Heer et al., 2008].

Likely, the most popular category of physicalizations is the field of data sculptures (see also subsection *4.3.1 Definitions*). Andrew Vande Moere studied these types of physicalizations thoroughly, e.g., by analyzing a large collection of prototypes developed by design students [Vande Moere and Patel, 2009]. They proposed a representational fidelity, to describe the works as symbolic, iconic or indexical. For symbolic representations (Figure 4.10-left) the data-mapping has to be learned, while indexical representations (Figure 4.10-right) have a direct relationship between the data and the physical artifact. Iconic representations (Figure 4.10-center) lie in between those two and often convey a metaphorical relationship.

A couple of recent projects with both aesthetic and pragmatic purposes focused on the representation of activity data. Khot et al. [2014] presented the “SweatAtoms” system which transformed physical activity data based on heart rate into 3D printed artifacts (see Figure 4.11-left). The data influenced the shape and size of the artifacts. A field study showed that

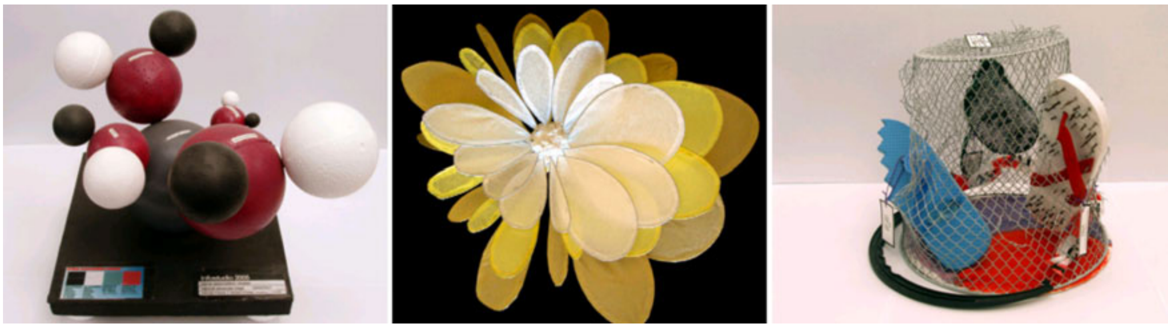

Figure 4.10: Examples of Data Sculptures: symbolic (left), iconic (center), and indexical (right) sculptures created by design students in a two-week assignment [Vande Moere and Patel, 2009].

Figure 4.11: Examples of physicalizations encoding activity data. Left: The "SweatAtoms" system transforms physical activity data into 3D printed artifacts [Khot et al., 2014]. Right: The "Patina Engraver" system engraves patina-like patterns on a wristband according to a participant's activity logs [Lee et al., 2015].

the artifacts made participants more conscious about their involvement in physical activity and revealed participants' different levels of engagemnt with the artifacts (see also Khot et al. [2013]; Khot [2014]; Khot and Mueller [2013]; Khot [2013]). Lee et al. [2015] developed the "Patina Engraver" system which engraves patina-like patterns on a wristband of an activity tracker according to a participant's activity logs (see Figure 4.11-right). More activity resulted in more aesthetic patterns with less noise. A field trial showed that the system had a motivational effect as participants increased their exercise effort to receive aesthetic patterns. It also triggered spontaneous social interactions in face-to-face situations.

While the previous two systems focused on the visual and haptic sense, the projects "TastyBeats" and "EdiPulse" had the approach to design palatable representations of physical activity. "TastyBeats" by Khot et al. [2015a,b] is a fountain-based interactive system that creates a sport drink based on the heart rate data of physical activity (see Figure 4.12-left). The heart rate values were mapped to water with different flavors, colors and electrolyte supplements. The palatable representation increased the awareness of participants regarding their physical activity, and the prepared drink served as a hedonic reward that motivated participants to

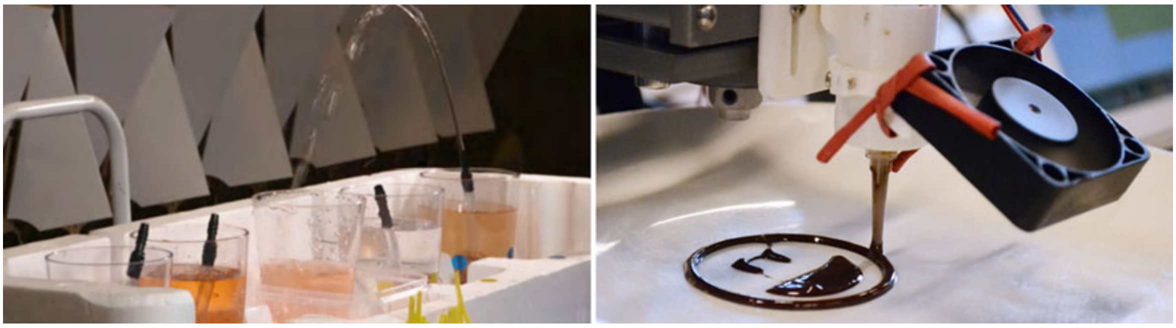

Figure 4.12: Examples of palatable physicalizations encoding activity data. Left: The "Tasty-Beats" system mixes a sport drink based on heart rate data of physical activity [Khot et al., 2015b]. Right: The "EdiPulse" system 3D prints personalized messages and emoticons according to physical activity data [Khot et al., 2015a].

exercise more. The "EdiPulse" system by Khot et al. [2015b,a] followed a similar approach, but instead of a drink produced 3D printed chocolates (see Figure 4.12-right). The data-mapping is rather abstract as the heart rate data only influences the thickness of the printed letters and emoticons. The system was not evaluated, but the authors believe it will motivate and inspire participants to exercise differently or try out new forms to receive various occurrences of 3D printed chocolates.

The following projects are still in the interplay of artistic and pragmatic physicalizations but follow a different approach as the previous described examples as they try to highlight the context between the data and how and where it is perceived. Zhu et al. [2015] argue that there is often a "*major disconnect between the medium of information representation and what the information is being represented about.*" In their "Data-Objects" project they evaluated the effect of providing information about an object's impact on an individual by physically embedding such information on that object itself. Figure 4.13-left shows two prototypes of Data-Objects phone cases which display data on the heart rate of the owner through height and roughness variations on the case surface. The authors argue that such a representation improves the understanding of the effects of using an object and that the physical presence ensures that people are more conscious of the data. Koeman [2014] proposes a similar idea with her domestic data sculptures that represent personal data in everyday artifacts for the home.

Nissen investigated the ways in which personalized souvenirs based on experience data can enrich an audience's encounter with cultural events [Nissen et al., 2014; Nissen and Bowers, 2015]. One example is a museum visitor's wristband (see Figure 4.13-center), the shape of which is mapped to the individual answers given in a questionnaire. Visitors also took an active part in the souvenir-making activity for an additional individualization. The studies showed that physical artifacts facilitate social interaction and reflection upon activities and experiences. Taylor et al. [2015] introduced the concept of "data-in-place" in which they explored the ways in which the production and use of data are connected to a place, both

Figure 4.13: Examples of Data-Objects. Left: "Data-Objects" phone cases which represent the heart rate data while a person used the phone through height and roughness variations on the case surface [Zhu et al., 2015]. Center: Personalized souvenir for a museum visitor as the shape of the wristband is mapped to the experience data of the visitor [Nissen et al., 2014]. Right: Physical bar graph displays community data in the environment where it was collected [Regan et al., 2015].

regarding physical and social geography. Physicalizations were used in a playful way of established representations such as pie charts and bar graphs (see Figure 4.13-right). They highlight the need to feed data back into the environment in which it was collected, into the existing social and communication infrastructures of a community. They also recommend that such physicalizations should be responsive to the environments in which they are installed [Regan et al., 2015].

Another category of projects focused on physicalizations that encode data through multiple or non-traditional modalities. The "Physikit" system by [Houben et al., 2016] represents environmental data through ambient physicalizations using various modalities such as light, vibration, movement, and air flow (see Figure 4.14-left). The results of a field study showed that participants developed an increased sense of the meaning of the data and customized the ambient physicalizations to fit their home decor. Barrass [2011, 2012] experimented with the idea of physical sonification by transforming acoustic dataforms into the shapes of bells. As the produced tones of the bells are perceptibly different from each other, he concluded that these could provide useful information about the underlying dataset. The right image in Figure 4.14 shows the usage of the crossmodal data-driven artifact "H^3" by Hogan and Hornecker [2013]. It represents live data streams of hydrogen levels in deep space using haptic-auditory feedback. Observations of visitors of a space observatory indicate that this kind of representation engaged visitors, and felt more real and less abstract than purely graphical representations. In a previous study, they had found clues that the modality and modality combinations used to represent data can influence the experience [Hogan and Hornecker, 2012].

Roberts and Walker [2010] encouraged the InfoVis community to develop a unified theory that covers all human senses and allows the integration of multiple modalities. They further foresee visualizations beyond the desktop, which use different modalities to both perceive and interact with information as "the next big thing" [Roberts et al., 2014]. Data representa-

Figure 4.14: Examples of physicalizations using multiple modalities. Left: The “Physikit” system represents data through ambient physicalizations using various modalities such as light, vibration, movement, and air flow [Houben et al., 2016]. Right: Visitor of a space observatory uses the “H^3” device to perceive live data streams of hydrogen levels in deep space through haptic-auditory feedback [Hogan and Hornecker, 2013].

tions that use additional senses to the visual one do not only influence the experience but can also be beneficial for the understanding and analysis of the underlying data as the following projects in the field of more pragmatic physicalizations demonstrate.

Data representations in a physical form found early applications as an affordable and accessible solution for the target audience of people with limited or no vision. Vasconcellos [1991, 1996], for example, explored the introduction of cartographic concepts through tactile maps and Griffin [2001] developed a haptic variable syntax for the representation of geographic information. Rowell and Ungar [2003a,b] did a thorough review of projects in this area. A broader analysis, that also included networks or images was done by Panëels and Roberts [2010]. Most of these systems used external haptic interfaces or devices, e.g., the PHANToM (e.g., Massie and Salisbury [1994]; McGookin and Brewster [2007]; Yu and Brewster [2003]). Apart from simpler approaches, such as the corkboard construction technique (see Figure 4.15-left), representing data for the visually impaired, researchers recently started to experiment with 3D printing technologies. Brown and Hurst [2012] developed the VizTouch software in a user-centered design, which allows the easy generation of 3D printable files of physical line graphs (see Figure 4.15-center). Visually impaired participants were able to read and understand the data being represented. Hu [2015] explored new paradigms for 3D printed physical bar graphs by including guidelines or invisible textures, to increase the accessibility of more complex charts (see Figure 4.15-right).

SciVis is another field in which various projects have been experimenting with physical representations. As in SciVis spatial representation is given [Munzner, 2008] and the focus lies on 3D phenomena [Friendly and Denis, 2001], e.g., medical or biological, the use of 3D artifacts seems nearby. Again the emergence of 3D printing motivated researchers to investigate the ways this technology can be used to represent and interact with scientific data (e.g., Bailey [2005]; Gillet et al. [2005]). Both pictures on the left of Figure 4.16 show a hemoglobin molecule with surface coloring to display electrical charges and a flex-

Figure 4.15: Examples of physicalizations for visually impaired. Left: Line graph constructed on a corkboard [McGookin et al., 2010]. Center: 3D printed line graph created with the VizTouch software [Brown and Hurst, 2012]. Right: 3D printed bar graphs with guidelines and textures [Hu, 2015].

ible model of DNA with magnets representing hydrogen bond donors and acceptors. The most common approach is to use such physical models to interact with computer models as tangible interfaces (see also *Section 4.2 Information Visualization & Tangible Interaction*). Similar approaches aimed at teaching school children about graph theory through a tangible construction kit [Schweikardt et al., 2009] or enhancing the understanding of statistical data through the creation of physical objects [Gwilt et al., 2012]. Physical models are also used to teach and illustrate geometry and mathematics (e.g., Segerman [2012]; Knill and Slavkovsky [2013a]). One example is the "drinkable Archimedes proof" (see Figure 4.16-right, for the digital and physical model). The spherical reservoir at the top can be filled with water, which then drips down into the complement of a cone in a cylinder at the bottom. By getting filled with water it demonstrates that both, the volume of the spherical reservoir and the cone in a cylinder, match [Knill and Slavkovsky, 2013b].

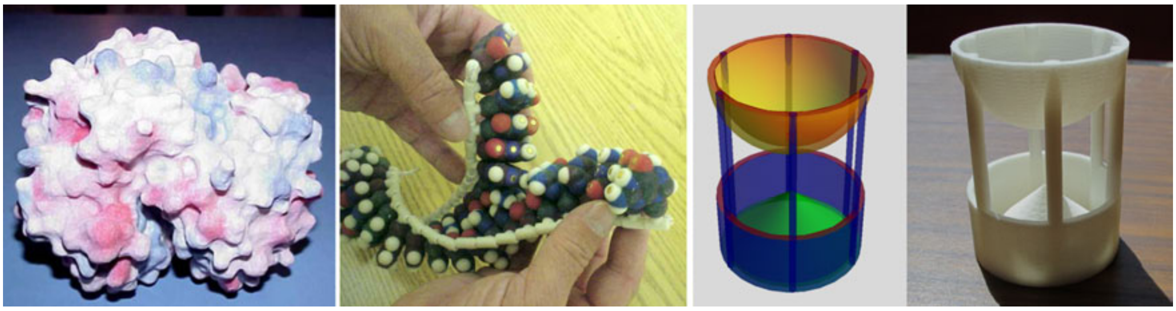

Figure 4.16: Examples of physicalizations for SciVis. Left: Hemoglobin molecule with surface coloring to display electrical charges [Bailey, 2005]. Center: Flexible model of DNA with magnets representing hydrogen bond donors and acceptors [Gillet et al., 2005]. Right: The "drinkable Archimedes proof" demonstrates the comparison of volumes [Knill and Slavkovsky, 2013b].

In the field of InfoVis Jansen et al. [2013, 2012] conducted the first study comparing physicalizations to their on-screen counterparts. They focused on bar charts and compared an on-screen 2D version, 3D visualizations in mono and stereo to a physical representation (see Figure 4.17). The results of two experiments revealed that the 2D version elicited better results than all 3D variations regarding low-level information retrieval tasks. However, the data also showed that the 3D physical bar charts outperformed the 3D on-screen bar charts. The authors list visual realism, which is hard to reproduce in a virtual setup, as one factor for the results and argue that physical touch seems to be a crucial cognitive aid. In a following experiment, Jansen and Hornbæk [2016] investigated size as a physical variable for bars and spheres. For the bars, the results were similar to 2D bars on a flat surface. For the spheres, the results show that data would be wrongly interpreted if it was encoded in the volume of the sphere, but the accuracy of sphere perception could be immensely improved if it was surface-based.

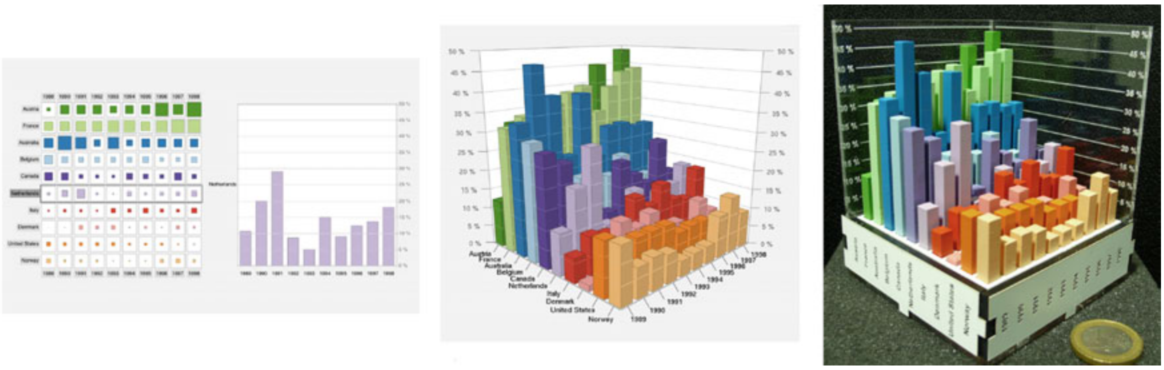

Figure 4.17: Representations that were used in an experiment regarding the efficiency of physicalizations: on-screen 2D bar chart; on-screen 3D bar chart; physical 3D bar chart [Jansen et al., 2013].

The MakerVis project by Swaminathan et al. [2014b,a] indicated the increasing interest and attention regarding physical representations of data. Their tool integrates the entire process of creating physicalizations to facilitate the otherwise laborious procedure, which requires expertise in both data representation and digital fabrication. Design sessions showed that participants could easily create their own physicalizations. That the use of physical tokens to represent data can lead to insights for the entire field of data representation is demonstrated in the work of Huron et al. [2014b] on constructive visualizations (see also Huron [2014]; Huron et al. [2014a]). By studying the ways in which people create, update and explain their own data representations using only tangible tokens they developed a model for a visual mapping process including several logical tasks such as loading data or computing new values.

While there are a couple of art installations (see Figure 4.18-left) experimenting with dynamic physicalizations (e.g., “pulse” by Markus Kison; “data morphose” by Christiane Keller; “emoto” by Moritz Stefaner, Drew Hemment and Studio NAND; “drip-by-tweet” by Domestic Data Streamers; “Datenreise” by Geiger et al. [2013]) research projects in this field are rather rare. Most work in this area can be categorized as ambient physicalizations that aim at changing human behavior in a positive way. Besides the “Dangling String” (see *Subsection 2.1.1 - Ubiquitous Computing & Tangible Interaction*) another early example of dynamic ambient physicalizations is “Breakaway” by Jafarinaimi et al. [2005]. The sensor-driven sculpture uses data from a people’s chair to suggest when it is time to take a break by encoding it into its shape and movement (see Figure 4.18-center). Similar projects used physical avatars in form of a puppet [Daian et al., 2007], a flower [Haller et al., 2011; Hong et al., 2015] or encoded data into the transparency of a lamp shape [Cha et al., 2016]. The first project that looked into the role of physically dynamic data representations for the exploration and analysis of datasets was EMERGE [Taher et al., 2015]: an interactive bar chart, equipped with plastic rods, RGB Light-Emitting Diodes (LEDs), a Microsoft Kinect® and a projector supported fundamental data representation tasks such as filtering or sorting (see Figure 4.18-right). Observations in a study revealed that physical interactions were intuitive, informative, and enjoyable but also unfolded the limitations of working with physical data.

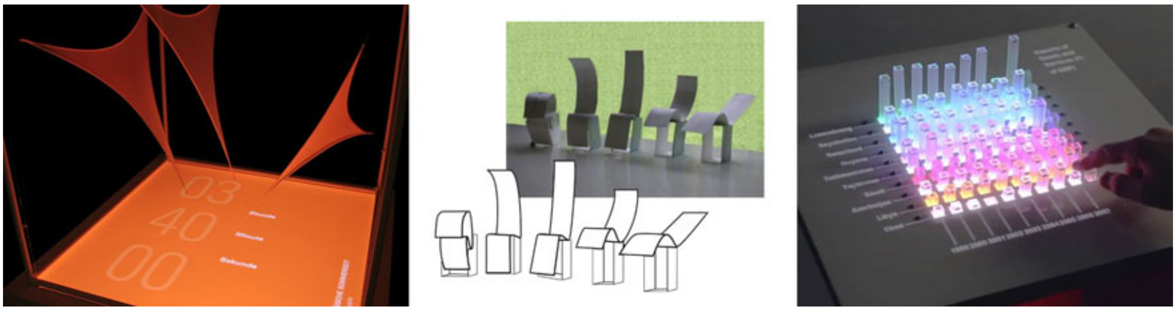

Figure 4.18: Examples of dynamic physicalizations. Left: The “data morphose” installation by Christiane Keller represents various data streams through spanned and moving sails. Center: “Breakaway” is an ambient sculpture that encodes data into its shape and movement based on sensors in a people’s chair [Jafarinaimi et al., 2005]. Right: The EMERGE project explored interactions with physically dynamic bar charts [Taher et al., 2015]

As the examples presented in this chapter illustrate, physicalizations have been created and used by various audiences for representing diverse datasets for several goals. Especially the rise of digital fabrication technologies simplified the creation of physicalizations and, therefore, increased the interest in studying their benefits, also regarding pragmatic purposes. Data physicalization research is still at its beginning, with many open research questions but also challenges regarding their design and evaluation [Jansen et al., 2015]. The projects presented in the following chapters seek to demonstrate in which ways physicalizations can enrich our thinking, learning, and communication.

II

PROTOTYPING PHYSICAL VISUALIZATIONS

Chapter 5

Beyond Physical Bar Charts

The previous chapters gave an overview of related research areas. We started with embodied interaction and haptic perception, which motivates the general idea of the thesis' topic (*Chapter 2 - Embodied Interaction & Haptic Perception*). The technical progress in digital fabrication technologies forms the basis for the simplified creation of physical visualizations (*Chapter 3 - Digital Fabrication*). The prior chapter gave an introduction into the new research area of data physicalization and outlined the multiple research challenges and opportunities (*Chapter 4 - Data Physicalization*).

Data physicalization is a new exciting research area as it combines various disciplines such as InfoVis, HCI, TUI, and psychology but also more technical-specific fields. This opens up a vast space to design for with almost uncountable questions to ask. But it also creates the difficulty to set a solid starting point for a discussion on why to investigate physicalizations and how to build them. Research in InfoVis demonstrated, that the design of visualizations is full of trade-offs and that many possibilities in the design space are ineffective for a particular purpose [Munzner, 2014]. Through the long history of research in InfoVis various guidelines regarding the design have been developed, and standards in which ways to evaluate them have been established. While data physicalization can use those as orientation and inspiration it is necessary to investigate if they are also suitable for the field of physicalization or if new guidelines and methodologies have to be developed.

This chapter introduces six prototypes of physical visualizations. The prototypes are categorized into the exploration of static, digitally augmented and dynamic physicalizations. All projects were inspired by traditional visualizations and followed a research through design

Personal contribution statement: The content of this chapter is based on six student's theses by *Ayfer Aslan [2013]*; *Lena Streppel [2014]*; *Maximilian Kreutzer [2014]*; *Markus Teufel [2014]*; *Elisabeth Engel [2014]*; *Barbara Schindler [2014]*. Part of it was published in articles by *Stusak and Aslan [2014]*; *Stusak, Tabard, and Butz [2013]*; *Stusak [2014]*; *Stusak and Teufel [2014]*. See *Disclaimer* for a detailed overview.

approach [Zimmerman et al., 2007]. One goal of the projects was to learn in which ways digital fabrication technologies can be used for designing and building physicalizations and therefore, exploring the design space. Another goal was to evaluate the prototypes to collect initial experiences and statements of people seeing and interacting with physicalizations and therefore, identifying promising directions for further research.

5.1 Static Physical Visualizations

The following section introduces two explorations of static physical visualizations. Inspired by traditional 2D visualizations such as bar graphs and matrices we built and experimented with novel physicalizations for a range of different form factors and datasets, made with acrylic glass and a laser cutter. First, we present the so-called threaded bar-star-plot, then prototypes of layered physical visualizations. We discuss the design process and the findings of our initial evaluations.

5.1.1 Threaded Bar-Star-Plot

The threaded bar-star-plot is the result of an iterative design process, which started with sketches on paper, which led to low-fidelity prototypes out of cardboard and eventually defined the final design built with acrylic glass and thread. The idea was to combine well-known 2D visualizations, in this case, a bar graph and a star plot, into one compact physical object. To enable reordering and filtering of the data, we also created a modular version of the threaded bar-star-plot. We compared the fixed and the modular physicalization to on-screen counterparts regarding information retrieval tasks.

Motivation & Background

As related work shows (see *Chapter 4 - Data Physicalization*), a large body aimed at conveying messages beyond the data itself and elicit emotions or provoke thought. They did not focus on the analytical value or the creation of effective physicalizations. As a starting point for an exploration into this direction, we investigated in which ways well-known 2D visualizations can be redesigned as physicalizations and in which ways the transformation from the digital into the physical world impacts basic information retrieval tasks. We further were interested in the question how the design process for physicalizations could look like, not only regarding the used tools and materials but also whether methods from HCI, such as low-fidelity prototyping or user-centered design are applicable.

Design Process

To reduce the possible design space, we focused on one dataset for the entire design process. We used the Better Life Index[1] dataset published by the Organisation for Economic Co-operation and Development (OECD). This index allows the comparison of well-being across countries, based on eleven dimensions such as health, income or education. The higher the values in each dimension, the better the country ranks on the scale. We chose this dataset as it is easy to understand and seemed an interesting topic for participants to analyze.

To discuss our initial ideas and to collect new ones, we conducted a focus group with six computer science students. To avoid concentrating too much on external influences such as material or size, participants sketched different ideas on paper and presented them. Figure 5.1-left shows one example sketch of a layered flower in which the countries are represented by flowers and the dimensions by petals. By laying flowers in a physical form on top of another, a comparison of the countries and dimensions is possible. Figure 5.1-center displays the idea of a rotary disk, which is inspired by traditional interactive visualizations and their controls to change e.g., the view. By rotating or sliding parts of the physicalization, it would be possible to change the displayed countries or dimensions.

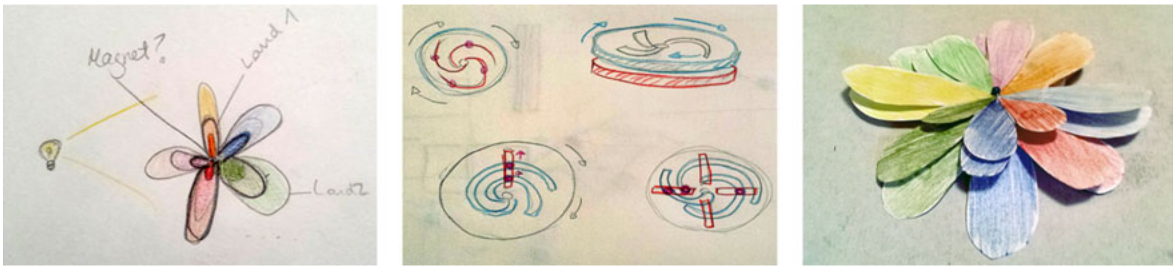

Figure 5.1: Sketches and low-fidelity prototypes of physicalizations. Left: Sketch of the layered flowers. Center: Sketches of the rotary disk. Right: Low-fidelity prototype of the layered flowers.

To get a first impression of the realization and handling of the prototypes we built various examples with basic materials such as paper and cardboard. The idea of the layered flowers, which was mentioned above is pictured in Figure 5.1-right. In this early stage of prototyping, the problem of occlusion from small petals by larger petals was already evident. We also did not pursue with the rotary disk prototype as even small datasets were difficult to display due to overlapping gaps on one disk.

Figure 5.2-left shows the first approaches of the threaded bar-star-plot. The idea was to use bar charts and star plots, both well-known 2D visualizations and combine them into one physicalization. Each of the four orthogonal arranged layers represents the values of a dimension of various countries by a bar chart. The four dimensions of the same country are connected by a thread, which forms a star plot for each. The 5.2-center shows further

[1] `http://www.oecdbetterlifeindex.org/` (accessed 2015-12-15)

developments of the threaded bar-star-plot built with a laser cutter and transparent acrylic glass, in which the bar charts and its labeling are engraved. We experimented with the thickness and the size of the acrylic glass to find a good compromise between stability and handling.

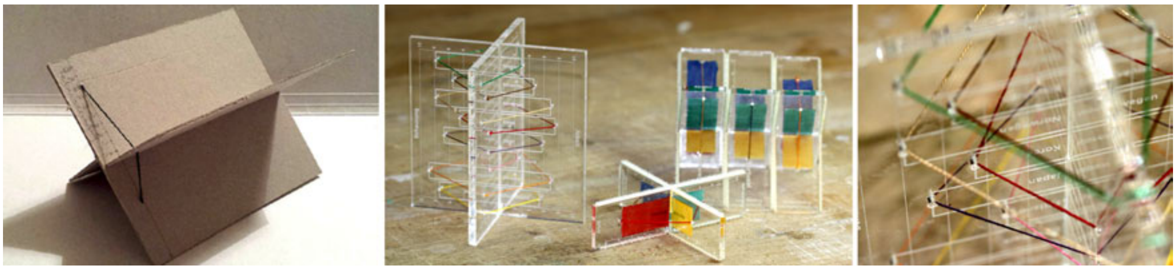

Figure 5.2: Pictures of the threaded bar-star-plot. Left: Low-fidelity prototype. Center: Final versions of the fixed and modular threaded bar-star-plot. Right: Close-up on on the fixed threaded bar-star-plot.

We explored the design of the threaded bar-star-plot further by experimenting with a modular version, as we wanted to enable basic analytical tasks such as filtering and ordering of the dataset, e.g., by adding or removing countries. Essential characteristics for the assembling are the stability once the different parts are connected but also easy handling in separating and joining the parts. The most promising solution was to attach hook-and-loop fastener at the edges of the acrylic glass. To facilitate the reassembling with the right orientation, we colored the bars according to their dimension (see Figure 5.2-right).

Study Design

We wanted to investigate in which ways people interact with our physicalization and in which ways basic information retrieval tasks can be accomplished. As a baseline, we compared the physicalizations to 2D on-screen visualizations displayed on a laptop. The design of the study and the digital data representations were inspired by Jansen et al. [2013]. In total, we had four different representations: the two variations of the threaded bar-star-plot (fixed and modular) and two digital visualizations. The digital visualizations displayed a matrix on the left, and a star plot or a bar chart view on the right, dependent on the selection made in the matrix view (see Figure 5.3). While the digital counterpart to the fixed threaded bar-star-plot always displayed the entire dataset, the counterpart to the modular version enabled filtering and reordering of the countries. This was done to achieve a fair comparison between the digital and physical modality. We call the two digital visualizations in the following also fixed and modular, to be consistent with the names of the physical visualizations.

The study had a duration of about one hour and took place in an isolated and quiet room equipped with the physicalizations, a laptop with a computer mouse and a separate touch tablet (see Figure 5.4-left). After a questionnaire about demographic data and previous experience with information visualization, subjects completed an initial training phase to get

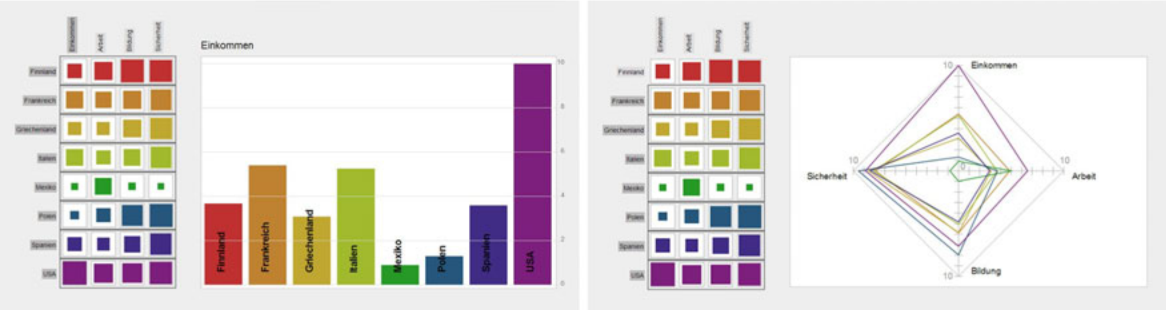

Figure 5.3: Screenshots of the digital counterparts of the threaded bar-star-plot. Left: matrix and bar charts. Right: matrix and star plot.

familiar with the data representations and the tasks. Next, the representations were handed over to the participants in a counterbalanced order, and they were asked to complete the following five tasks:

1. Which country has the highest value in [dimension]?
2. Order all countries descending by [dimension].
3. Order [four given countries] descending by [dimension].
4. Rank [four given countries] descending by all given dimensions.
5. Which are the countries with the highest and lowest values regarding all dimensions?

The input and output of the instructions, the tasks, and their responses were done on the separate touch tablet. Participants were instructed to be as accurate and as fast as possible. We measured the task completion time (interval between the press on "start" and the press on "done" on the tablet) as well as the error rate. The study ended with a questionnaire and a semi-structured interview about the data representations.

Out of the 16 participants, six were female. The average age was 25 years (range: 13-41). Eight participants were students of computer science, two pupils, and six employees. All were right-handed, and two had experience with data representations. Participants received a 10 Euro voucher for an online shop.

Results

Figure 5.4-right summarizes the average task completion time per data representation and task. Only task 1 shows a noticeable separation between the digital and the physical visualizations. The fixed digital visualizations had the fastest average completion time for all tasks. The fixed digital visualization seemed to be to most suitable to fulfill task 2 and 4, while the modular physicalization was clearly worse to accomplish task 2. The error rate was similar and very low for all representations.

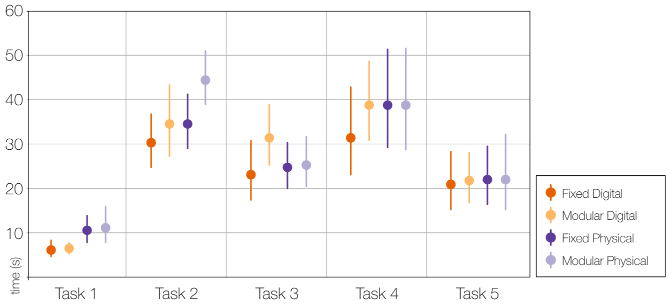

Figure 5.4: Left: Hardware setup that was used for the evaluation. Right: Results for the average task completion time in seconds per data representation and task (with 95% confidence intervals).

We collected subjective data through questionnaires using 5-point Likert scales ranging from 1=*strongly agree* to 5=*strongly disagree* (see Figure 5.5). Participants had the impression that the tasks were most easily fulfilled with the modular digital visualization. It was easier to interact with the digital variations than with the physical ones. This corresponds with participants' statements that the physicalizations were more complicated to understand than the digital visualizations. Also, the holding and rotating of the physicalizations were mentioned as laborious. The fixed physical visualization aided the completion of the tasks less than the other representations. The modular physical visualization was the most interesting one to interact with, while the fixed physical visualization was the less interesting one. Participants ranked the modular digital visualization 13 times at position one when asked to rank the techniques according to preference.

We observed differences between participants in the ways in which they used and interacted with the physicalizations. Seven participants constantly used one hand to interact with the fixed physical visualizations, but all participants used both hands to interact with the modular one. Four participants did not disassemble the modular physical visualization, two because it seemed impractical, two because of fear to break something. Often the participants were too cautious at the beginning to undo the hook-and-loop fastener. However, one participant broke several parts of the modular physical prototype while trying to demount it.

Discussion

Regarding the design process, it is worth to mention that the number of ideas generated during the focus group was rather low, especially compared to previous focus groups in a similar setting but about other topics, e.g., software interface design. One reason could be that the participants had only little experience with visualizations and none with physicalizations. While we decided against providing materials such as Lego® or pipe cleaners as we thought this could limit the creative output, the ideation process with pen and paper alone seemed to be a bit too abstract.

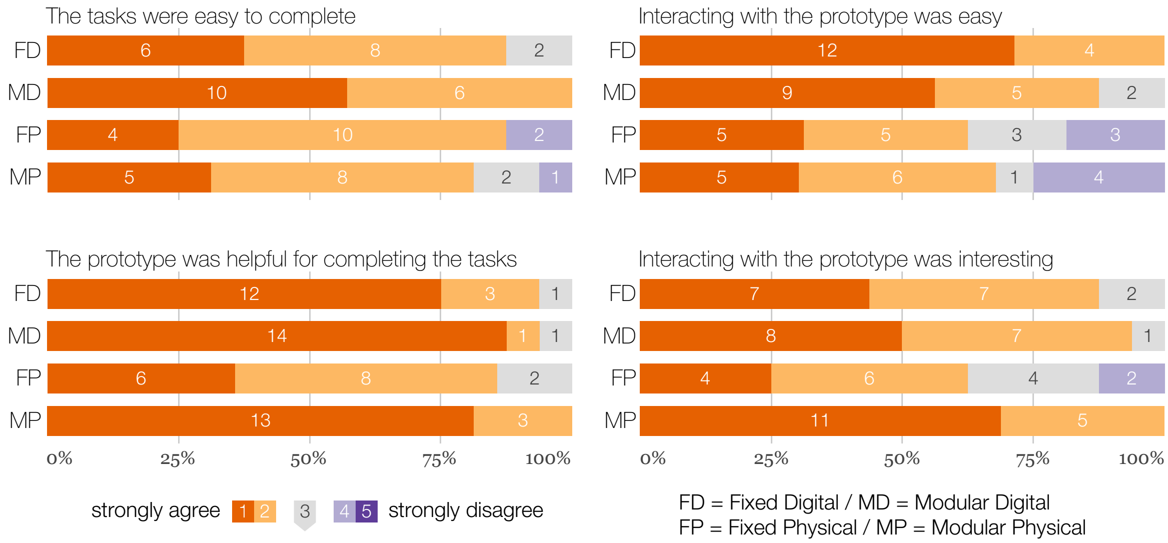

Figure 5.5: Results of the 5-point Likert scale questionnaires for all tested prototypes (FD = Fixed Digital; MD = Modular Digital; FP = Fixed Physical; MP = Modular Physical)

However, the design process with low-fidelity prototypes showed that the use of simple material such as paper or cardboard and common tools such as pencils and scissors to build physicalizations can have advantages. In an early stage, it was possible to identify problems regarding the design and get a good impression about the size and interaction possibilities. Limitations are stability and the general haptic characteristics, dependent on the material the final physicalization will be made of.

The study revealed that a sophisticated design is crucial if the physicalizations are aimed at supporting analytical tasks. Especially stability and "affordances" are essential properties, as participants stated the handling of our prototypes was sometimes challenging and laborious. In general, the study showed that our physicalizations were suitable to fulfill the five tasks, but participants were not convinced of their practicability. Interestingly we distinguished the trend that participants with a background in computer science found the physicalizations more interesting than the other participants. It was stated by five participants that they could not imagine using this type of physicalization for data analysis. However, they liked the design and suggested the encoding of personal data to serve as a souvenir or piece of scenery for the shelf.

5.1.2 Layered Physical Visualizations

While the prototype in the previous subsection combined two well-known 2D visualizations into one physicalization, the goal of the prototype described in this subsection was to move a 3D visualization, such as a 3D matrix or a 3D scatterplot, into the physical world. The outcome was a physicalization consisting of multiple acrylic glass layers, which were hold together but could be articulated in different ways. We evaluated two variations of such layered physical visualizations against a traditional representation in table form printed on paper.

Motivation & Background

While the observations and study results for the threaded bar-star-plot were promising concerning the analytic value of physicalizations, participants found the handling rather laborious and preferred the digital representations for fulfilling the tasks. As the threaded bar-star-plot was only a specific instance of a much larger design space the goal of this project was to design and evaluate another prototype to further explore the characteristics and possible benefits of physicalizations. We also wanted to investigate in which ways physical manipulation and simple mechanical movements can be integrated into physicalizations and distinguish unique physical characteristics.

As the combination of 2D visualizations into a physical object seemed less convincing to the participants, we focused on 3D visualizations for this project, as they have common problems on 2D digital screens, such as reduced depth perception and visual occlusion. During the survey of 3D visualizations we decided, that data and space-time cube representations would be an exciting and promising type to transform into a physicalization. In the case of the space-time cube, data is mapped onto two dimensions, while time is shown as a third spatial dimension. Such representations were, for example, used to explore relational databases [Stolte et al., 2003], geographic datasets [Kraak, 2003; Gatalsky et al., 2004] or dynamic networks [Bach et al., 2014].

Design Process

As underlying data, we used a dataset from the German Census Bureau[2] consisting of causes of death in Germany for various ages groups starting in 1980. Bearing in mind a later evaluation, we expected these topics to be interesting to a wide audience and easy to understand. Furthermore, the dataset was big enough to choose a suitable subset of values of high variances across years, age groups and causes of death.

The general idea behind the design of this physicalization was to stack multiple layers of transparent acrylic glass, inspired by the space-time cube metaphor. Each layer represented one year and contained a matrix visualization with the age groups and causes of death as axes. Each data point was represented by an engraved or cut circle in the respective layer. The area or radius of a circle represented the number of deaths in a respective age group for a given year.

We experimented with several possibilities to hold the single layers together and decided to use two different ways for the fixation. The first variation was to use a screw and a proper hole to enable an independent rotation of each layer about the time axis. The rotation allows

[2] `https://www-genesis.destatis.de/genesis/online` (accessed 2015-12-15)

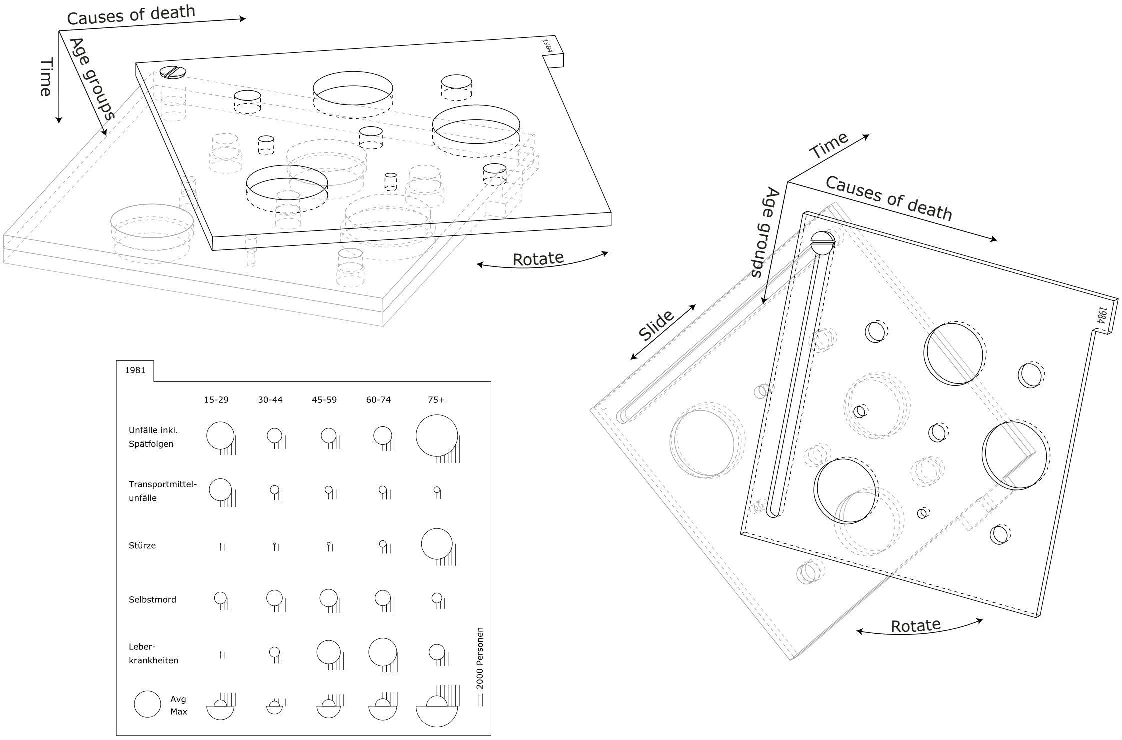

Figure 5.6: Top and right: Illustrations of the possibilities to articulate the final prototypes. Bottom: Laser stencil of the first layer.

a comparison of two layers but always twisted by a certain angle. Therefore, in the second variation, we changed the hole into a longish slot, which allowed a rotation and a vertical sliding of the layers (see Figure 5.6). Both simple mechanical movements can support the analytics tasks of filtering and sorting.

We tried various shapes to represent single data points, such as lines, circles and squares and used the laser cutter techniques of cutting and engraving. We also experimented with different types and weights of strokes, the thickness of the acrylic glass and the depth of the engravings. The final design consisted of holes cut as circles (see Figure 5.7) into 5 mm thick transparent acrylic glass layers. To improve the readability and comparison of single values we experimented with various techniques from classical 2D visualizations such as graphical overlays (e.g., Kong and Agrawala [2012]) and symbols inspired by cartography (e.g., Hake [1970]). The outcome was to augment each circle with small guides (see Figure 5.6-bottom), which seemed to be the best compromise between enhancing the readability of exact values and not reducing the possibility to see through the single layers. We further added a diagram with two semicircles encoding the maximum and average value for each age group (see Figure 5.6-bottom).

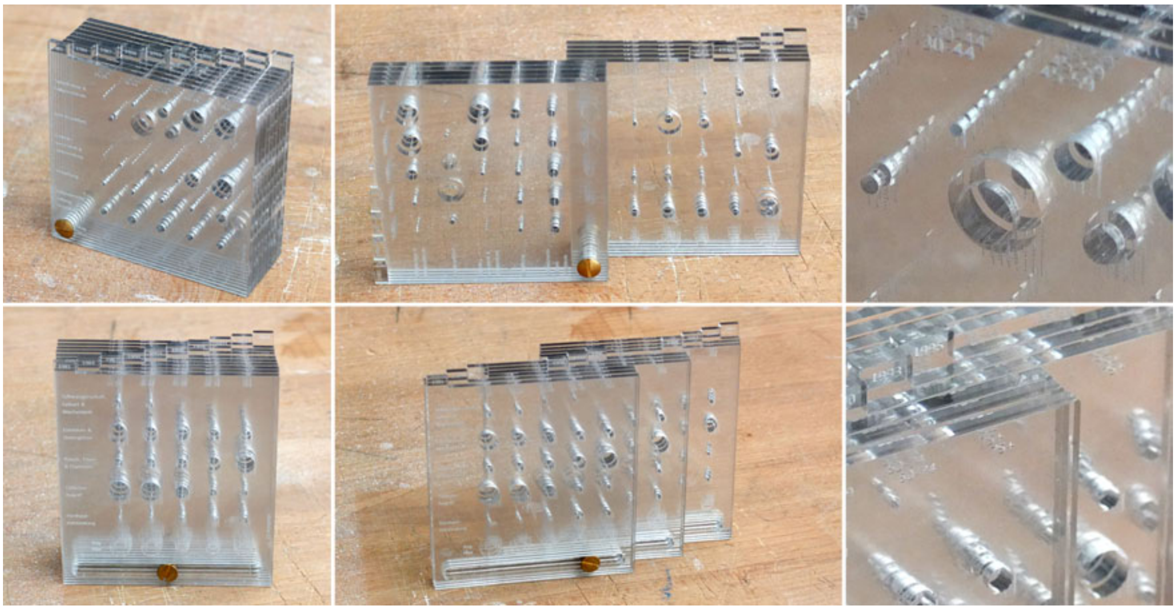

Figure 5.7: Final prototypes of the layered physicalizations that were used in the study.

Study Design

Similar to the study presented in the previous subsection the goal of this evaluation was to explore the ways in which the participants interact with our prototypes and for which analytical tasks they are suitable. We also wanted to investigate in which ways the two different mechanical movements influence the handling and experience. Our main interest in this explorative study was the observation of the participants and the collection of statements and experiences about the physicalizations.

In contrast to the previous study the baseline in this evaluation was an alphanumeric representation in table form printed on one piece of a DinA4 paper (see Figure 5.8-left). To focus on the physical modality we decided against a digital visualization and exclude possible influences, e.g., the interaction with a computer mouse. We used an alphanumeric representation in table form as an "extreme" counterpart to the physicalizations. In contrast to the physicalizations they allow an easy recognition of exact values but have a rather businesslike appearance through the use of numbers and tables. We thought it was suitable as a baseline to judge how well analytical tasks can be accomplished with our physicalizations.

The study had a duration of about one hour and took place in an isolated and quiet room equipped with the physicalizations, the data printed on paper and a separate touch tablet (see Figure 5.8-right). The procedure of the study was similar to the previous one and again inspired by Jansen et al. [2013]. We started with a demographic questionnaire and questions about previous experience with information visualization. Next, participants completed an initial training and exploration phase to get familiar with the data representations and the tasks. The representations were handed over in a counterbalanced order and participants had to fulfill six tasks with each of them:

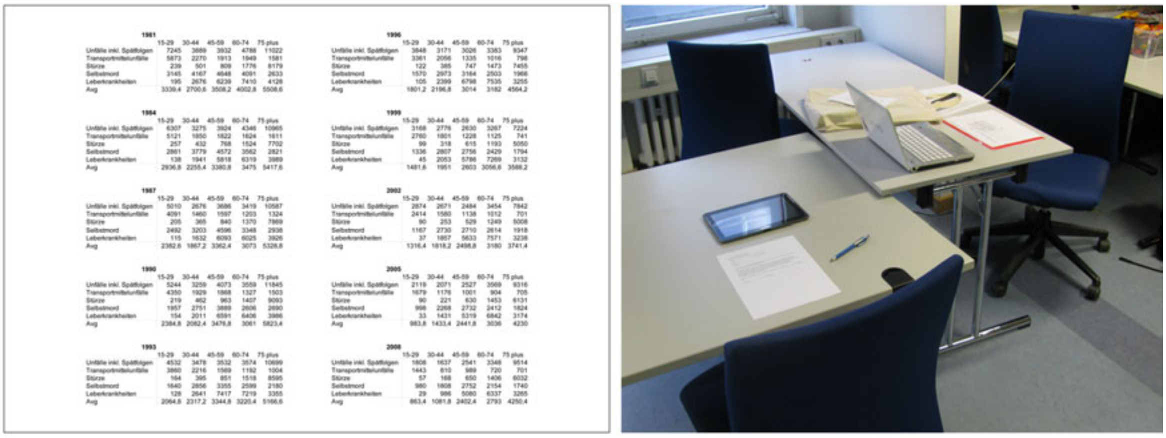

Figure 5.8: Left: Example of the paper representation that was used in our evaluation. Right: Hardware setup for the evaluation.

1. Enter maximum value for given [year] and [age group].
2. Order values of all causes descending for given [year] and [age group].
3. Order values of [four given years] descending for given [cause] and [age group].
4. Order values of [four given age groups] descending for given [cause] and [year].
5. Enter causes with above average values for given [year] and [age group].
6. Enter value range of all years for given [cause] and [age group].

All instructions and tasks were displayed on the touch tablet, in which participants also entered their responses. Participants were instructed to be as fast and as accurate as possible. We measure the task completion time and error rates. We videotaped the study and the experimenter observed the interactions of the participants with the data representations and took notes. To collect qualitative data we ended the study with a questionnaire and a semi-structured interview.

Out of the 18 participants, eight were female. The average age was 23 years (range: 20-30). All were computer science students and right handed, four had experience with data representations. Participants received a 10 Euro voucher for an online shop.

Results

Figure 5.9 shows the results for the total number of errors and the average task completion time per data representation and task. The number of errors show clearly that the representation on paper was better for giving the correct answer. About half of the participants could not fulfill task 3 or task 4 when interacting with one of the physicalizations and only one participant had the right answer for task 6. The results for the average completion time

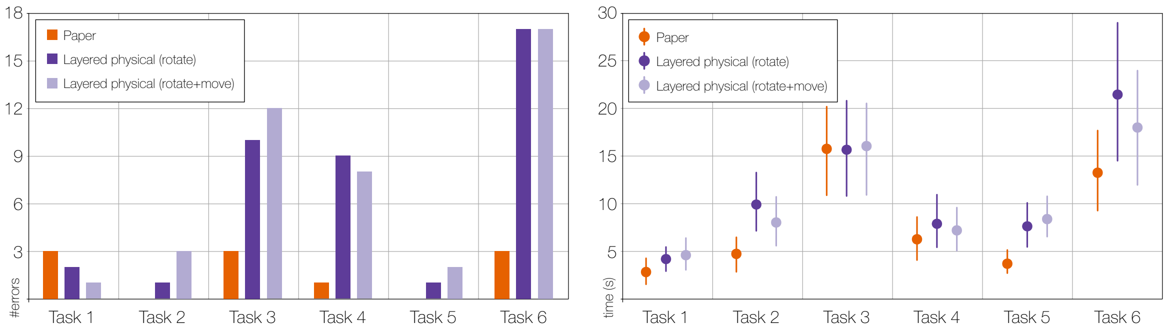

Figure 5.9: Left: Number of errors per data representation and task. Right: Average task completion time in seconds per data representation and task (with 95% confidence intervals).

show a similar pattern. Most tasks could be fulfilled faster with the representation on paper and only task 1, 3 and 4 could be completed in a similar time frame for all representations. However, with much less accuracy regarding the two physicalizations.

The questionnaires and semi-structure interviews revealed that participants rated the physicalizations as more playful and encouraging. They also had slightly more fun using them, as twelve and ten participants “strongly agreed” or “agreed” with the statement “I had fun completing the tasks” for the physicalizations and eight for the representation on paper. We also asked participants to rank the representations which lead to a polarized result: the physicalization which could be rotated and vertically slid was ranked first by seven participants, the other physicalization by six and the representation on paper by five.

During the exploration phase, we encouraged participants to think aloud about interesting facts in the data or discovered insights. We found the trend that participants stated more exact values and compared single values when using the representation on paper. When using one of the physicalizations they had a better overview of the data and focused more on trends over the years.

Figure 5.10 shows that participants interacted with the physicalizations in various ways and had different techniques to find or compare values. All participants used the table to arrange the layers back into a block. It was also common to look at the physicalizations from different angles and perspectives. They were examined from the back by nine participants, based on the statement that it is easier to detect a trend from small to big circles. They were also observed from the side by six participants which declared that this view eases the comparison of the outer circles. The physicalizations were held up to the light to improve the readability by four participants.

Participants stated that the physicalizations are something new and unfamiliar, which has to be learned first but are easy to use afterward. They pointed out that the physicalizations are most suitable for getting an overview of the data and spotting trends or outliers spread over time. The fun factor was often mentioned, as the physicalizations are something playful and nice, which encourages interaction. Most participants stated that sliding single layers is more useful for comparison than rotating, but that the combination of both led to confusion

Figure 5.10: Various examples of ways in which participants used and articulated our prototypes.

and disorganization of the layers. The factor of memorability was stated by seven participants. One statement was that “*the haptic prototypes generate a visual memory hook, which quickens and eases an observation later on.*” Another one was that “*the sizes of the holes are kept in good memory as they make use of the spatial imagination and visual thinking.*”

Discussion

The results of the study showed that our physicalization prototypes were suitable for accomplishing analytical tasks. However, the high amount of errors for some tasks highlighted the problems of our design. Participants had difficulties in retrieving exact values and comparing values with small differences. It is worth mentioning that one cause for this is that humans have a rather weak judgment comparing small changes in circle sizes or 2D shapes in general, which is independent of the physical or digital modality.

The study highlighted that the design of effective physical visualizations for data analysis is challenging. While stability was not a crucial factor, this time, participants often mentioned problems with reflections and perspective distortions. The study also pointed out, that physical visualizations have the potential to engage people in exploring the physical object and along with it the encoded data. It seemed natural for the participants to look at the physicalization from all sides and therefore, to perceive the data from different perspectives. In further designs, this could be used to show and highlight other aspects of a dataset.

We learned from the initial designs and evaluations of our static physical visualizations, that studies focusing too much on the performance seemed a bit fruitless and that evaluation methods “beyond time and error” could be more promising. Jansen et al. [2013] already mentioned that “*cost-benefit analyzes involving factors other than pure performance are needed to assess when physical 3D visualizations are most useful in practice.*” Novel evaluation methods are not only necessary for physicalizations but are also a heavily discussed topic in the field of InfoVis, which is highlighted by the bi-annual workshop entitled “BEyond time and errors: novel evaLuation methods for Information Visualization (BELIV)” [Bertini et al., 2006, 2008, 2010, 2012; Lam et al., 2014]. Examples of evaluation methods are insight based studies or other metrics adapted to the perceptual aspects of data representations as well as the exploratory nature of discovery. In our studies, participants stated, that they see a potential for physicalizations in displaying personal data, e.g., as kind of a data souvenir. They also mentioned the factor of memorability as they believe that data presented in a physical form could be remembered better or in different ways.

5.2 Digitally Augmented Physical Visualizations

The following section introduces two explorations of digitally augmented physical visualizations. Based on the findings of the evaluations of our static prototypes the idea was to augment physical visualizations with digital graphical overlays. The goal was to improve the readability of exact values and to enable the display of greater details as well as a deeper exploration of the data. First, we present our considerations in which ways the previous presented layered physical visualizations can be used for interactions on tabletops. Then we discuss our early approaches and experiences in combining physical visualizations with spatial augmented reality. We describe the design process of our initial prototypes and our observations during preliminary evaluations.

5.2.1 Layered Physical Visualizations on Tabletops

This subsection describes our considerations in which ways the layered physical visualizations, that were introduced in the previous subsection (see subsection *5.1.2 - Layered Physical Visualizations*) can be used for interactions on tabletops. As our prototypes can be articulated in various ways, we discuss novel interaction possibilities. We implemented an initial prototype, which we exhibited during an open lab day to students and other guests.

Motivation & Background

The evaluations of our static layered physical visualization showed that participants liked the design and stated that it is a playful approach for data analysis and encourages a deeper exploration. However, the study also showed, that participants had difficulties in fulfilling analytical tasks, especially retrieving and comparing exact values was error-prone. Also, our static prototypes were limited by their fixed visual appearance. Therefore, the combination of physical visualizations and interactive tabletops seemed to be a promising approach to data exploration. The idea is to use the physical visualizations to awake interest and to get a first overview of the data. Placing the physicalization on a tabletop with its large screen enables displaying greater details of the dataset and a deeper exploration. This follows the visual information seeking mantra by Shneiderman [1996]: the physicalization allows a first overview, and the tabletop is used to show further details.

In the field of InfoVis several system have been proposed using tabletops and tangible objects (see also section *4.2 - Information Visualization & Tangible Interaction*). The physical objects that were involved in such systems were only used as an input device or were models and not visualizations. Our goal was not to build a system for data analysis experts, but to focus on a broader audience, related to casual InfoVis [Pousman et al., 2007]. As we used transparent acrylic glass for our physicalizations, we were inspired by work that used tangibles entirely made of transparent or translucent materials. Such tangibles allow displaying content directly below them and enable dynamic illumination as well as glowing

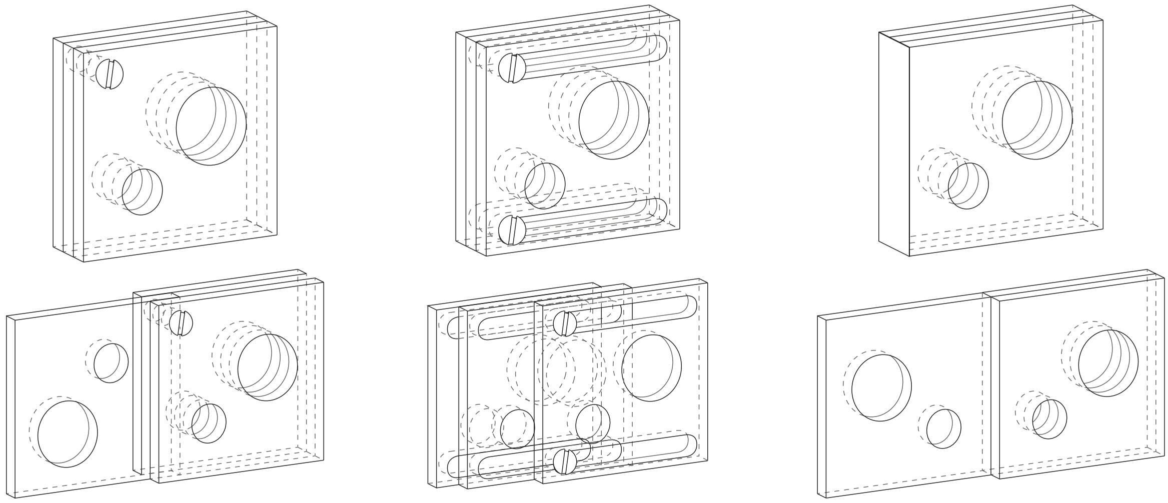

Figure 5.11: Fixations of the layered physical visualizations and possibilities to articulate them. Left: Fixation of the layers with one screw, which allows rotating. Center: Fixation of the layers with two screws, which allows sliding. Right: Fixation of the layers with tape on one side, which allows flipping.

effects [Büschel et al., 2014]. The tracking of tangibles can be realized by using transparent markers [Frisch et al., 2013]. Furthermore, transparent objects also facilitate direct touch interaction with the content below [Büschel et al., 2014] and even the acrylic carving could be used as an interactive surface [Mikubo et al., 2013].

Design Process

The design is based on the layered physical visualizations that were presented in the previous subsection. The principal design questions were how the physicalization and its possibility to be articulated can be used to interact with data and how and where the digital content should be displayed. While both, the physicalization and the tabletop can be used for input and output, in our example the physicalization needed the tabletop as an external light source.

As the combination of layers that can be slid and rotated led to confusion and disarrangement in our previous study, we refined the fixation and also added a new one. Figure 5.11 show three possible fixations. Already present in the last section is the fixation of the layers with one screw, which allows an independent rotation of each layer. As already mentioned, one problem of this variation is that the orientation of the representation changes with the rotation and comparisons of the single layers are difficult (see Figure 5.11-left). Instead of combining rotation and sliding it is possible to achieve a sliding mechanism alone, by using two screws (see Figure 5.11-center). It is also possible to fixate single layers with tape at one side, similar to bookbinding (see Figure 5.11-right). By turning over a layer, a horizontal or vertical flipped representation is attained. It is worth noting that a fixed construction is also possible, in which none of the layers can be articulated. The other extreme would be independent layers without any fixation.

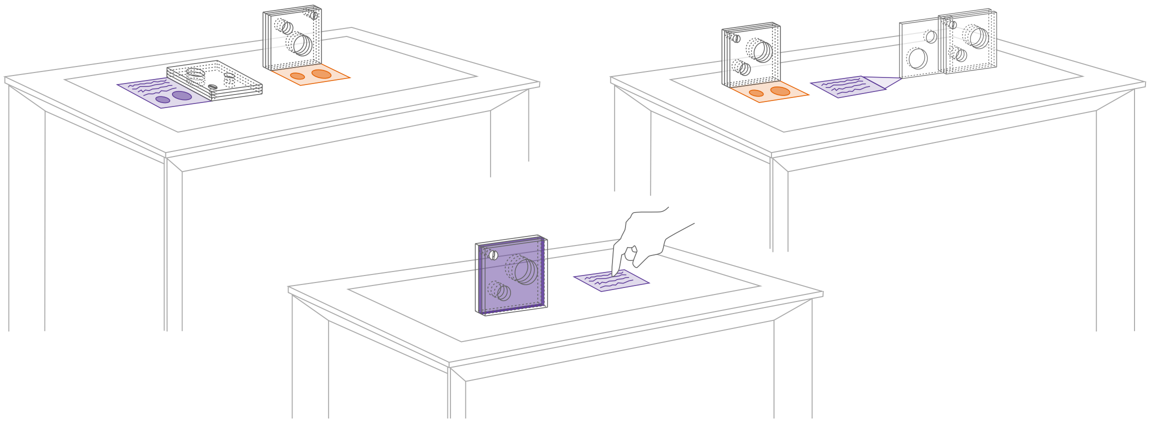

Figure 5.12: Interaction possibilities for layered physical visualizations on tabletops. Left: Displayed information is influenced by the side of the physicalizations that lies on the tabletop surface. Right: Rotating one layer out of the physical block can filter the data. Bottom: Tapping on a specific content on the tabletop highlights the associated layer(s) of the physicalization.

Similar to standard tangibles, our physicalizations support common interaction techniques for tabletops such as moving or rotating them across the surface. Figure 5.12 illustrates some novel interaction techniques based on the possibility of articulating the layered physicalization. Depending on the side of the physicalization that lies on the tabletop surface, different information, e.g., more details, about the complete dataset could be displayed. Turning the entire physicalization around could change the chronological order of the displayed data (see Figure 5.12-left). The possibility to articulate single layers allows a filtering of the dataset (see Figure 5.12-right). By rotating or sliding one layer out of the physical block, the digital information could be adapted according to that specific layer, e.g., displaying only one particular year. Also, more than one layer could be articulated. This enables a comparison of the data represented by the chosen layers, e.g., displaying their differences or the union. Taking the angle of rotation into account or how far a single layer is pulled out or turned over, could be used to realize more sophisticated interactions and results. It could also be imaginable to track touch input on the physicalization itself, e.g., by tapping on one specific layer. Digital content can be displayed around the physicalization, but the transparency of the acrylic glass makes it also possible to illuminate them with light from the display. By selecting specific content on the tabletop, associated layer(s) of the physicalization could be highlighted (see Figure 5.12-bottom).

Implementation

We implemented a rather simple prototype to test some of our ideas mentioned in the previous paragraph. As a dataset, we used the Application Programming Interface (API) of the online platform OutdoorActive[3], which offers data about hiking and mountain bike tours such as the type of tour, level of difficulty, duration or the difference in altitude. For our ap-

[3] `http://www.outdooractive.com/` (accessed 2015-12-15)

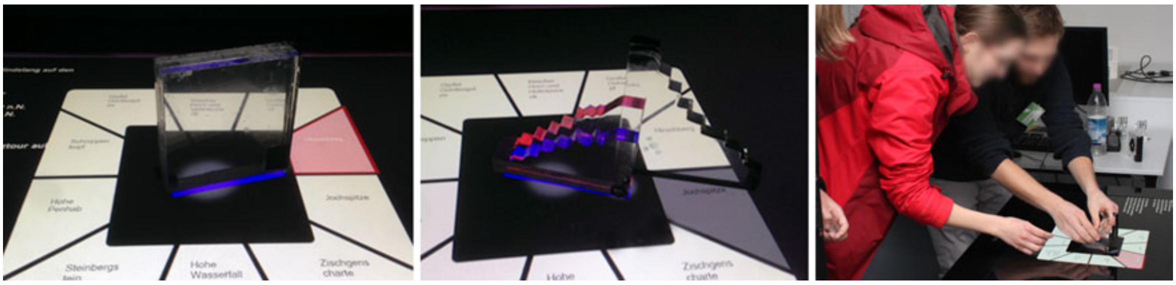

Figure 5.13: Implemented prototype for layered physical visualizations on a tabletop. Left: Initial physicalization placed on the tabletop. Center: Modified physical object to intensify the illumination effect on the top side of the object. Right: Through rotation of a layer the digital content can be filtered. Image © Maximilian Kreutzer.

plication scenario, we reduced the dataset to four main categories, each including ten tours. For the prototype, we used only three plain acrylic glass layers without any engraved data, as we wanted to focus on the interaction possibilities and the implementation of the tracking. As an interactive tabletop we used the Microsoft Pixelsense®.

The application started by placing the layered physicalization with a bigger side on the tabletop. Through rotation of the entire object, a category can be chosen, which are displayed around the tangible. By turning the object into an upright position the single tours of the chosen category are displayed on the tabletop (see Figure 5.13). By rotating the object a specific tour can be selected, and more detailed information about the tour will be displayed as text. Also, one layer will be illuminated in a color associated with the difficulty of the selected tour. By rotating a single layer out of the block, a filtering of the tours is possible based on the difficulty. As a result, all tours with a different difficulty will be colored in gray (see Figure 5.13-center).

We had to keep the prototype rather simple as we met a couple of problems during the implementation but wanted to present it to a broader audience in an informal setting at an open lab day (see next section). The biggest problem was the detection of single layers. On the one hand, we had to use rather thick acrylic glass layers ($\approx$ 1 cm) to attach tags that are large enough to be recognizable by the Microsoft Pixelsense®. On the other hand cutting such thick material with our laser cutter led to small deformations along the edges of the acrylic glass, as the top side is exposed to the laser for a longer time frame than the lower side. This resulted in the issue that the acrylic layers did not stand precisely plain on the tabletop surface which complicated the recognition of the tags. We also experimented with other tracking techniques such as image processing and object recognition algorithms, but could not achieve a satisfying tracking performance.

We modified the tangible as we were not convinced with the illumination effect on the top side of the object due to total reflection (see Figure 5.13-left). By exchanging the straight edges into jagged ones the illumination effect could be intensified (see Figure 5.13-center). This led to the idea to use the terrain profile of a mountain as inspiration for the out shape and therefore, adapt the tangible to the topic of the application. The flat layer represents the easier tours and the tallest one the most difficult ones (see Figure 5.13-center). It is worth mentioning that the physical object for this particular prototype cannot be called a physicalization as it does not encode any abstract data but symbolizes the category of tour difficulty. It corresponds rather to a tangible with the characteristic that it can be articulated.

Evaluation & Results

We presented our prototype at an open lab day of the Media Informatics and Human-Computer Interaction Groups of the Department of Informatics of the Ludwig-Maximilians-Universität Munich (LMU Munich). At the evening event around 100 visitors, mainly students of computer science or media informatics, interacted with our prototype or observed in which ways others used it (see Figure 5.13-right). Visitors shared their experience through verbal conversations while interacting with our system. We also had brief discussions with some visitors about possible application scenarios and what they liked and disliked about the concept.

Although the system had an early prototype status, the overall response from the visitors was positive. Participants appreciated the unusual and playful nature of the interaction with our system. This can be partly explained by a novelty effect as most visitors had no experience neither with interactive tabletops nor with tangibles. The lack of experience also led to an initial fear of contact, as most visitors only started to interact with the system after a short explanation and demonstration. The possibility of articulating the tangible fostered the curiosity of the visitors, as many of them tried various possibilities to place the tangible on the tabletop and were interested in the reaction of the system.

Often mentioned application scenarios were tourist information centers and museums with the explanation that the playful interaction encourages a deeper exploration of the underlying data. One visitor, a passionate mountain climber, had the idea to use the tangible as a souvenir representing personal data. Each acrylic glass layer would represent a reached summit of a mountain, and the layer could have the shape similar to the terrain profile of that specific mountain. By placing the object on the tabletop, he could retrieve more information, e.g., the date and duration of his tour or photographs he took.

The evaluation also revealed the limitations of the system. A few visitors stated that they found the interaction very cumbersome as the displayed content is rather little. We also had problems with the stability of the tangible with clear signs of use. The screw got loosened several times, and the fixed tags got out of place. Both resulted in problems of recognizing the tangible and its different states.

Discussion

Keeping in mind that we used an early prototype for an informal evaluation and rather a tangible than a physicalization for the interaction, we have to be careful in drawing strong conclusions. It was interesting to see that the visitors liked the prototype and that it led to a playful exploration of its capabilities. After explaining the concept behind the prototype, several visitors became quite creative regarding ways in which this could be used for further projects. We were excited by the notion of the souvenir that represents personal data, as similar ideas were already mentioned in our previous studies. Related concepts, such as personal objects for memory recollection and sharing, also had been investigated in the field of HCI (e.g., van den Hoven and Eggen [2005]; Mugellini et al. [2007]).

In summary, the theoretical considerations regarding the combination of physicalizations and interactive tabletops open up a large space for design and interaction possibilities. While we focused with our layered physicalizations on one specific instance, the general concept can be adopted to all kinds of physicalizations. Physicalizations can offer an overview of the data and engage people, the tabletop can be used to display further details on demand. One aspect that could be worth further investigation is the illumination of the physicalization through the tabletop. By using laser engravings inside a transparent glass object, e.g., with different densities, it could be possible to highlight specific aspects inside the physicalization on demand [Büschel et al., 2014]. We had the impression that the physicalization is degraded to a simple tangible once it is placed on the tabletop as its large digital screen attracts all the attention. Therefore, we had the idea to use projection augmentation as a digital overlay on the physicalization itself to keep the focus on the physicalization, which will be discussed in the following subsection.

5.2.2 Projection Augmented Physical Visualizations

This subsection describes the second project we made in the area of digitally augmented physicalizations. While in the previous subsection a tabletop was used to augment the physicalization in this project we experimented with spatial augmented reality through projections. The final prototype was a physical area chart, and the projections were used to provide guides and display additional information. A study revealed that projection augmentation can enhance otherwise static physicalizations and can help to overcome problems arising from perspective distortion.

Motivation & Background

Similar to the motivation in the previous subsection the goal of this project was to overcome the limitations of static physicalizations, e.g., their fixed visual appearance or perspective distortions. Our experiences and observations during the design and implementation of physicalizations on tabletops led to the impression that the digital layer should focus stronger on the physicalization itself. Instead of displaying most of the additional content around the physicalization it would be beneficial to present it on the actual physicalization.

Spatial augmented reality can be used to extend arbitrary physical objects with a digital layer. One popular example in which a projector is used to augment the look graphically as well as animate real world objects is “Shader Lamps” by Raskar et al. [2001]. The basic idea is to use a white object which is augmented with a texture by a projector. The quality of the augmentation is dependent on the light condition of the environment and limited by the brightness, dynamic range and pixel solution of the projector. A couple of projects related to the field of physicalizations used projections to augment their physical models and prototypes. Both, “PARM” [Gary et al., 2012] and “Illuminating Clay” [Piper et al., 2002] used projections to augment landscape models, e.g., with satellite or historical imagery. Research projects in the field on shape displays also often use projections to support visual feedback (e.g., Leithinger et al. [2011]; Follmer et al. [2013]).

Design Process

The design of projection augmented physical visualizations can be split into several dimensions. The physical visualization itself is the characteristic element, and its material (e.g., plastic, wood), fabrication (e.g., 3D printers, laser cutters), size and space for the projection should be taken into account. The projection can differ by its position (e.g., direct projection on the physicalization, projection near the physicalization) and its purpose (e.g., showing additional information, enabling interaction with the data or improving the readability). Furthermore, the input modality should be considered (e.g., touching, disassembling and reassembling the physicalization, control by a remote device).

Figure 5.14 shows various stages and prototypes from our design process. We started with sketching ideas for various types of data representations, such as map, area and bar charts (see Figure 5.14-top). We designed different digital 3D models for the projection mapping (see Figure 5.14-center) and experimented with physical models created with a 3D printer and a laser cutter (see Figure 5.14-bottom).

We used for all prototypes a dataset on the export of Small Arms and Light Weapons (SALW) from the Peace Research Institute Oslo (PRIO)[4], an organization which researches on the conditions for peaceful relations between states, groups and people. The dataset consisted of data about the exportation of SALW, e.g., the value in US$, for various countries for different years. The subject SALW was chosen because of the daunting role these weapons play in nowadays warfare. Bearing the later evaluation in mind, we thought it would be an important but also interesting topic to explore for the attendees.

Implementation

While the 3D printed models were more precise than the laser cut models, the printing process was very time-consuming and had constraints regarding the resulting models size. Therefore, we used a laser cutter to fabricate the final prototype consisting of an area chart, as this type offers a large surface for augmentation (see Figure 5.15). It was built out of birch wood, as this type of wood is easily processed with a laser cutter and its bright tint is well-suited for projection augmentation. The single area chart slices, each representing the annual value of sold weapons for one country from 1992 to 2010, were stuck into the slots of a wooden floor plate (30 cm x 60 cm).

[4] `http://www.prio.no` (accessed 2015-12-15)

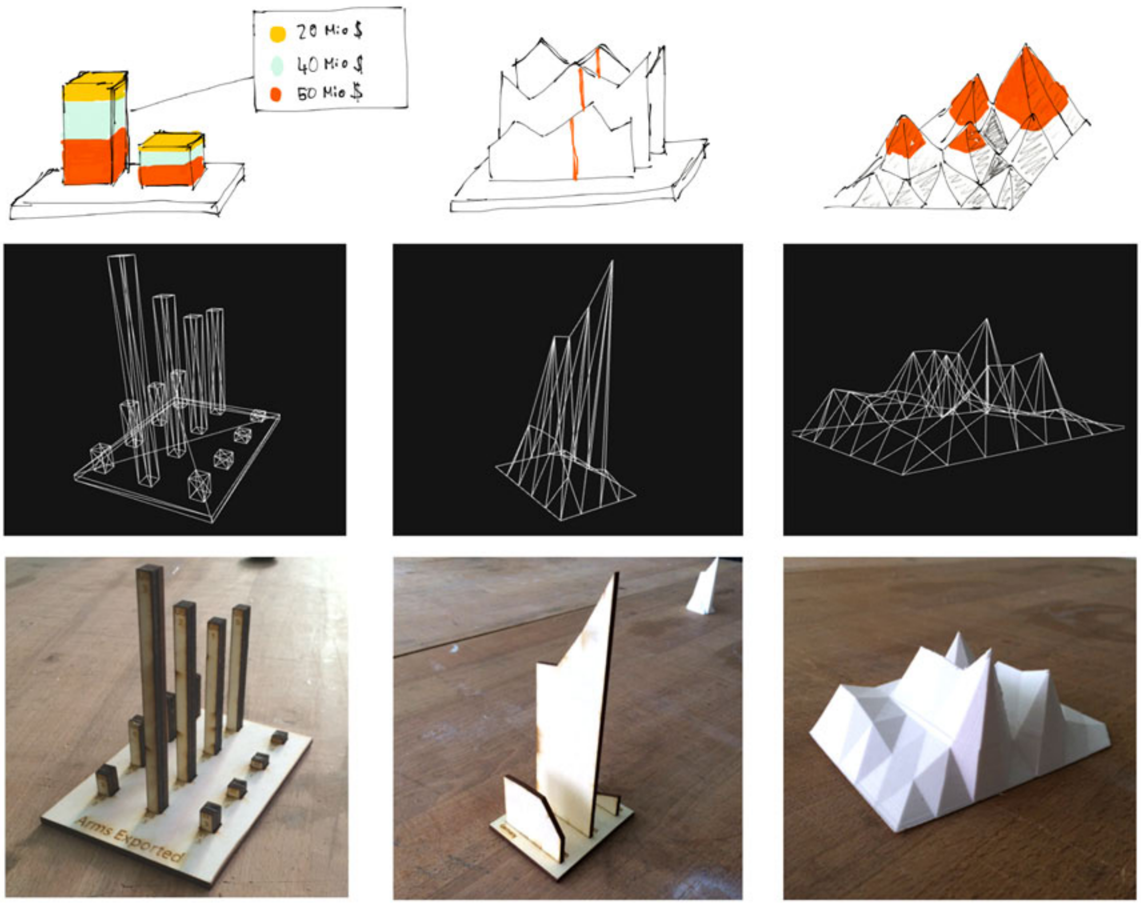

Figure 5.14: Sketches (top), 3D models (center) and early physical prototypes (bottom) from the design process for projection augmented physical visualizations. We experimented with map charts (left), area charts (center) and bar charts (right). Image © Markus Teufel.

The projection was used for various purposes, first of all for labeling the axis with the corresponding countries and years. The single slices could be augmented with additional details about the data in the form of stacked area charts, showing the split by the type of exported arms or buyer region (see Figure 5.15-top). To improve the comparison of different data items, we implemented vertical and horizontal guides (see Figure 5.15-bottom).

Interaction, e.g., moving the guides or changing the data for the stacked area chart, was realized through a remote tablet device. The gray colored touch areas at the bottom and on the right side of the tablet screen were used to activate and control the horizontal and vertical guides. The black square in the lower right corner was used to cycle through different stacked area charts. The size proportions of the different areas were chosen to facilitate eyes-free interaction. The remaining screen space was used to display exact values or relevant 2D visualizations (see Figure 5.15-bottom).

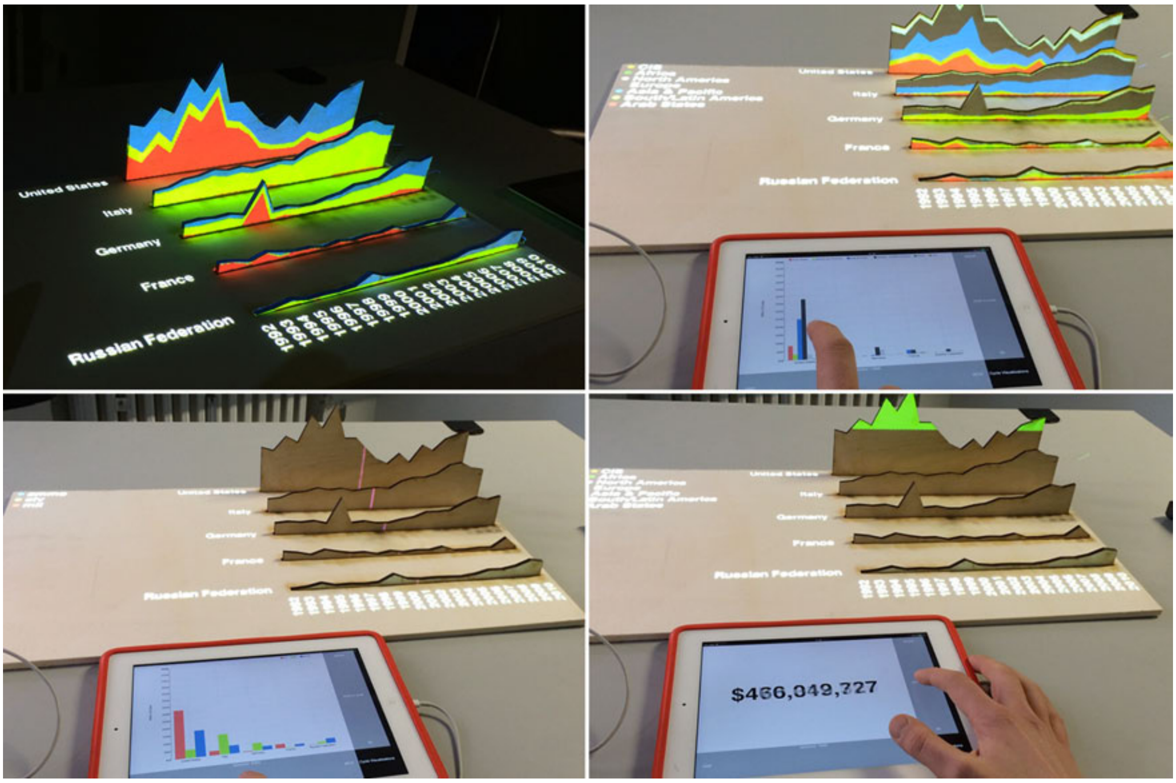

Figure 5.15: Final prototype for the projection augmented physical visualization. Additional information is projected (top-left) and can be controlled by an external tablet (top-right). To improve readability vertical and horizontal guides can be displayed (bottom). Image © Markus Teufel.

For the client and server applications we built on web technologies and JavaScript frameworks such as three.js[5], node.js[6] or raphael.js[7]. For the calibration process, which ensures the correct mapping of the 2D image, we used mapamok[8] by Kyle McDonald.

Study Design

The overall goal of the evaluation was to investigate in which ways participants would react and interact with the projection augmented area chart. We wanted to see what participants appreciated in particular when exploring data in unusual ways but also observe the limitations of our prototype. We further were interested in statements about possible usage scenarios and potential benefits of such types of data representation, but also in ideas for improvements and extensions of the system.

[5] `http://threejs.org/` (accessed 2015-12-15)

[6] `https://nodejs.org/` (accessed 2015-12-15)

[7] `http://raphaeljs.com/` (accessed 2015-12-15)

[8] `https://github.com/YCAMInterlab/ProCamToolkit/wiki/mapamok-(English)` (accessed 2015-12-15)

The study took place in an isolated, quiet and dim lighted room equipped with our prototype consisting of the physicalization, a projector (1366 x 768 pixel), a tablet device and a computer. It had a duration of about one hour and started with a demographic questionnaire and questions about previous experience with information visualization. The central part was an exploration phase, in which participants had to interact with the prototype without any further instructions. They were encouraged to think aloud about their experiences with the system and discovered insights in the dataset. After that, participants had to fulfill some basic information retrieval tasks, such as sorting and comparing values or specifying the range of values, to test if our system supports these tasks. The study ended with a semi-structured interview in which participants were asked about their opinion regarding the prototype.

We had 23 participants (nine female) with an average age of 27 years (range: 20-39). While 17 participants had a high level of experience with computers and digital visualizations, only eight were familiar with physical visualizations. The majority came from an academic environment (13 computer science students, four research assistants). Others reported to be barkeeper, geographer, media creator, project manager, software developer and social worker. Participants received a 10 Euro voucher for an online shop.

Results

Participants enjoyed using the prototype, as 22 participants stated they had fun using the augmented physicalization after the exploration phase. One statement was, "*I don't know why, but it is pure fun to use the guide tool.*" Interestingly only 16 participants repeated their initial statement after they had to fulfill the given tasks, which leads to the assumption that our physicalization is more suitable for an open and unforced exploration of data. Participants could accomplish basic information retrieval tasks with our prototype. Most wrong answers could be traced back to a general problem of stacked area charts, in which small values result in thin lines, which in turn hinders the readability or comparison of exact values.

Most participants found the visual feedback on the tablet device unnecessary or even confusing. By 18 participants it was only used for controlling the projection but not to receive further details, e.g., exact values. For eleven participants the separate touch tablet seemed to be too much, as they stated that they had difficulties to decide where to look at. Some stated that all information should be projected onto the physicalization and that the tablet should only be used as an input device. Surprisingly only two participants mentioned that they would like to touch the physicalization to trigger certain functions.

An unexpected finding was that only eleven participants found the horizontal guide as useful while 21 participants stated that the vertical guide is helpful to compare values as it overcomes the problem of perspective distortions. While exploring the data, three participants reported that they would appreciate a way to get background information regarding certain data points they discovered. One participant stated the interesting idea to apply a sorting algorithm, which would try to arrange small values in the center of the area chart. This would optimize their readability as they would not be distorted due to possible calibration errors at the models edges. However, only two participants noticed the problem of "pixel bleeding."

All participants stated that such a spatial augmented physicalization would be interesting for public spaces, e.g., a museum in order "*to bring an individual dataset closer to the visitors*", as one participant specified. Other ideas were meeting rooms, presentation stages, schools and waiting areas.

Discussion

Our exploration revealed that spatial augmented reality seems to be a promising way to overcome some limitations and problems of static physical visualizations. Guides, for example, help to overcome problems arising from perspective distortion. The augmentation of the physicalization with additional information can compensate its static nature without losing the advantages of physical objects, which can be touched and explored with all senses.

It is worth mentioning that our prototype did not support any direct-touch input but was controlled by an external tablet device. Our evaluation revealed that most participants were concentrated solely on the physicalization and stated that the additional device led to a confusing situation. Therefore, it could be worth considering the implementation of direct touch interaction on the physicalization or integrate interaction techniques such as rotating, moving or disassembling the physicalization.

While all our previous prototypes of physicalizations were rather small and could be easily held in one hand, this was the first larger prototype. It was interesting to see that this led to a full body exploration of the physicalization, as participants walked around the prototype, knelt down and changed the position of their heads. One participant mentioned that he liked the fact to move the entire body to explore data, in contrast to moving your hand and a mouse to control traditional digital visualizations. By providing multiple projections from different sides and by integrating the position of the onlookers and adapting the projections depending on their movements this could be further encouraged.

Another exciting direction for further investigations is the area of communicating and presenting data. Almost all participants named museums, schools and public places as promising places for projection augmented physicalizations or physicalizations in general. Others mentioned meeting rooms and presentation stages as application scenarios, which provides motivation for research on possible benefits of physical visualizations for communication and collaboration purposes.

5.3 Dynamic Physical Visualizations

The first section of this chapter introduced two static physicalizations and in the previous section, we explored in which ways various limitations of such static prototypes can be reduced through the augmentation with a digital layer. In the following section, we present two explorations in the area of dynamic or articulated physicalizations. The idea was to observe in which ways people interact with data representations in which not only the digital layers change but also the physical form. The first project investigates a physical data matrix that allows small height changes for each data point. The second project follows a rather artistic approach and explores in which ways a water swirl can be transformed into a data representation.

5.3.1 Data Exploration Matrix

This subsection describes our initial prototype in the area of dynamic physical visualizations. The outcome is a physical 5x5 LED data matrix equipped with various tangible interface elements and LEDs, which can be changed slightly in its height. We presented our prototype at an open lab day to collect early feedback and ideas for further developments.

Motivation & Background

After the investigation of static physicalizations and ways to digitally augment them, we wanted to explore and collect experiences of designing and building dynamic physicalizations. Bearing in mind that it was our first contact with hardware prototyping and electronics we wanted to keep the complexity and costs for the prototype on a low level. Therefore, the goal was to design and build a proof of concept and not a sophisticated system for data representation. We were inspired by early and rather simple shape displays, such as "Lumen" [Poupyrev et al., 2004] or "Glowbits" [Hirschmann, 2004], both focusing on an ambient and calm representation of information. In contrast, we wanted to investigate in which ways such systems can be used for the representation of abstract data. While articles about shape displays often focus on technical aspects, we wanted to evaluate in which ways people interact with our prototype and observe if it encourages the exploration of a dataset through a playful and unusual way.

Design Process

As mentioned earlier, we were inspired by first shape displays, which can encode multi-dimensional datasets, similar to 3D bar charts. For our prototype, we decided to use a country indicator dataset from Gapminder[9] about power generation. The dataset included the values of different types of electricity generation, such as wind energy or fossil fuels, for various countries in different years.

The final prototype of the *data exploration matrix* is displayed in Figure 5.16. The dataset can be displayed by a 5 x 5 matrix of RGB LEDs. Therefore, the color and brightness of the LEDs can be used to encode data. Furthermore, the LEDs have two different height positions, which can be used to highlight single data points, such as the maximum value (see Figure 5.16-center). Interaction possibilities were realized through tangible control elements (see Figure 5.16-right). The knob allowed switching between different years and

[9] `http://www.gapminder.com` (accessed 2015-12-15)

Figure 5.16: Final prototype of the *data exploration matrix* (left) with actuated LEDs (center) and tangible control elements (right). Image © Elisabeth Engel.

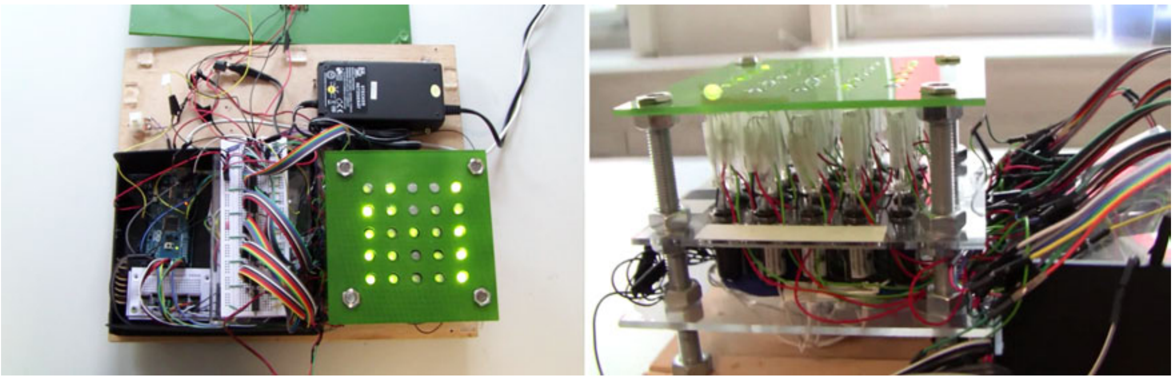

Figure 5.17: Used components and the setup of the *data exploration matrix* (image © Elisabeth Engel).

the switches enabled a view change between relative and absolute values as well as the representation of one year or its trend compared to five years before. We used tangible control elements instead of an external device, such as a mobile phone or tablet, to design the physicalization as one compact unit (30 cm x 26 cm x 15 cm).

The physicalization is composed of 25 LEDs, each mounted on a solenoid, which can move up and down a distance of 5 mm. The knob is realized through a potentiometer. An Arduino[10] Mega 2560 functions as a microcontroller that runs the program code and reacts on inputs through the tangibles by controlling the LEDs and solenoids. All components including an external power supply were assembled and hid in a colored laser cut box (see Figure 5.17).

[10] `https://www.arduino.cc/` (accessed 2015-12-15)

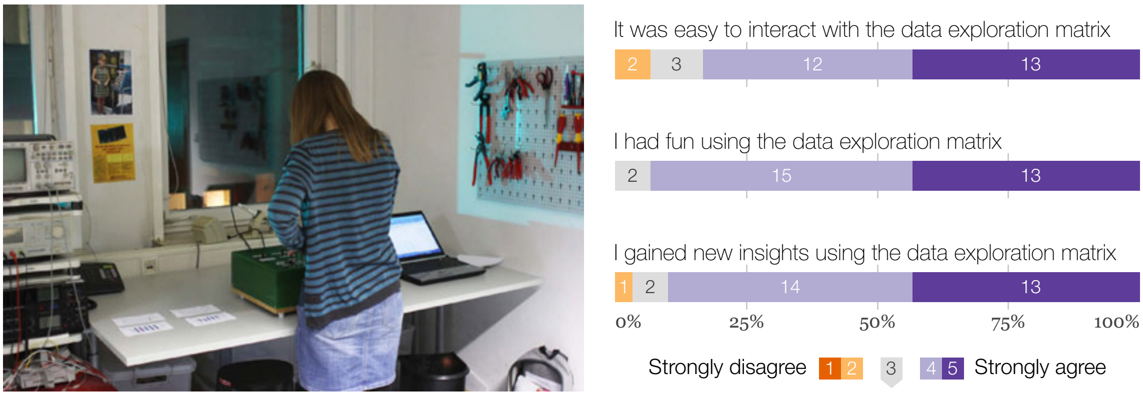

Figure 5.18: Left: The *data exploration matrix* was exhibited during an open lab day (image © Elisabeth Engel). Right: Results of the questionnaire answered by visitors.

Evaluation and Results

As we were curious in which ways people without any specific previous knowledge or interest in data representations would interact with our *data exploration matrix*, we exhibited it during an open lab day of the Media Informatics and Human-Computer Interaction Groups of the Department of Informatics of the LMU Munich. At the evening event around 100 visitors, mainly students of media informatics or computer science but also professors and the interested public, interacted with our prototype (see Figure 5.18-left). We observed the participants, took notes and had informal discussions with them. We also encouraged them to fill out a short questionnaire, which 30 of them did.

Most participants agreed that the *data exploration matrix* is fun to use (93.3%) and easy to interact with (83.3%). The results are illustrated in Figure 5.18-right. The main point of critic regarding the usability was the sparse labeling, especially of the tangible control elements. It was mentioned by three participants that the distance the LEDs can move up and down should be increased and allow intermediate stages. The request for a larger matrix with more LEDs and the possibility to touch them was made by two participants. The observations and discussions revealed that participants, in particular, liked the tangible control elements and the direct feedback. It was also intriguing to see that the prototype led to a discussion about the dataset and encouraged participants to collaborate and explore the data together.

The physicalization is suitable for exploring data and gaining new insights, as 27 participants agreed to this statement. It was encouraging to see that 15 of them could name specific facts they learned, e.g., that France generated less electricity with nuclear power in 2010 than in 2005. In summary, this leads to the assumption that the majority of people understood how to use and read the *data exploration matrix* to gain new insights, all joined with a playful and fun experience.

Discussion

The informal evaluation of our first prototype in the area of dynamic physical visualizations showed that they are a promising way of representing abstract data. Participants had fun exploring the data and could gain new insights. It was in particular interesting to see in which ways they enjoyed playing around with the tangible control elements. The positive feedback was only little related to the aspect that the physicalization was dynamic. Our setting seemed to encourage participants to explore both, the options and interaction possibilities of the *data exploration matrix* as well as the underlying dataset in a collaborative manner. This leads to the assumption that physicalizations, in general, have the potential to foster collaboration, similar to tangible user interfaces (e.g., Schneider et al. [2011, 2012]).

It is worth mentioning that our prototype of a shape display was kept rather simple, especially compared to state-of-the-art 2.5D shape displays (e.g., Leithinger et al. [2011]; Follmer et al. [2013]; Leithinger et al. [2015]). This could explain the moderate and little feedback participants gave related to the possibility of the LEDs to move up and down. The design and implementation of our prototype illustrated that the required technological complexity is high, closely related to the costs. Bearing this in mind it seemed more exciting and also important to focus on the investigation of human aspects related to physicalizations, e.g., in which ways the physical modality influences the perception and experience of data exploration. Therefore, concentrating less on tackling technical aspects. Findings in the area of perception can, in addition, provide motivation for further research on shape displays.

5.3.2 Swirlization

This subsection describes the second project we designed in the area of dynamic physicalizations. In the last subsection we introduced a prototype which was inspired by simple shape displays and a traditional matrix visualization. In this project we followed a more artistic approach. The final prototype explored in which ways a water swirl can be transformed into a data representation, e.g., by changing its depth. We were interested to see in which ways people would interact with our *Swirlization*, whether it supports the retrieval and exploration of the underlying data and which application scenarios seem suitable for such a data representation.

Motivation & Background

Our initial prototype of a dynamic physicalization was inspired by 2.5D shape displays and was based on changing the physical geometry, i.e., modifying the height position of single LEDs. As we tried to keep the technological complexity and general costs on a small level, the outcome seemed to be a bit unimpressive for our participants, especially compared to state-of-the-art 2.5D shape displays. Participants were rather fascinated by the tangible control elements and the LEDs matrix in general than by the possibility that the LEDs can move up and down. Therefore, the motivation for the second project was to turn away from

Figure 5.19: Final prototype of *Swirlization* with different coloring and swirl depths. Image © Barbara Schindler.

the classical actuation of LEDs or physical bars and to follow a rather artistic approach by experimenting with actuating unusual materials, e.g., liquids.

One source for inspiration for possible designs were ephemeral user interfaces defined by Döring et al. [2013]. They state the aspect that parts of the interface are not designed to last as one key characteristic. Others are the intrinsic qualities and aesthetics of the used materials, such as water, ice, fog or air. Furthermore, similar to physicalizations, they provide a rich and multi-sensory user experience. Ephemeral user interfaces can be used for novel playful and emotionally engaging interaction, e.g., as entertaining installations or learning applications [Sylvester et al., 2010]. Examples of ephemeral user interfaces for data representation are the "Drip-by-Tweet" and "Behance Reviews" installations by "Domestic Data Streamers"[11]. Both installations represent votes cast by transforming data into drops of colored liquid and funneling it into tubes or bottles.

Design Process

While we had various ideas in which ways to use water for representing data, such as water fountains or small waterfalls, we were most enthusiastic about the thought to transform a water swirl into a physicalization. We liked the concept as by changing the depth of the swirl, data can be encoded similar to a bar graph, but in an unusual form. As the water could be kept in a fixed tube it also seemed easier to handle than, for example, water pumps.

[11] `http://domesticstreamers.com/` (accessed 2015-12-15)

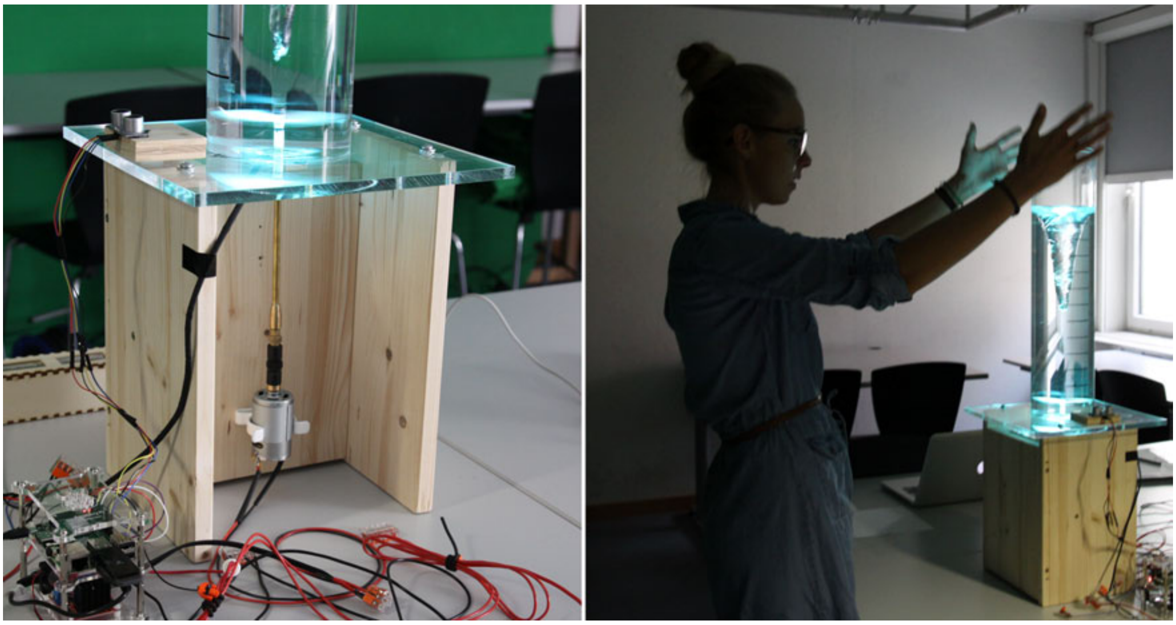

Figure 5.20: Left: Used hardware components and setup of *Swirlization*. Right: A participant uses the ultrasonic sensor to interact with our prototype. Image © Barbara Schindler.

As a container, we used a transparent acrylic glass tube with a height of 50 cm and a diameter of 11.4 cm, which was mounted on a wooden rack for stability. The swirl was generated by a rotor conjoined with a drive shaft which was powered by a motor (see Figure 5.20-left). By controlling the motor speed and therefore the number of revolutions the depth of the water swirl could be controlled (see Figure 5.19). We experimented with different motors and drive shafts to realize a quick and direct feedback of the swirl as well as a high depth. For aesthetic reasons and to add another dimension for data encoding we attached 16 RGB LEDs at the bottom side of the tube. Our final prototype with different coloring and swirl depths is displayed in Figure 5.19.

As underlying dataset, we used again the Better Life Index[12] published by the OECD, which we already used for the threaded bar-star-plot (see subsection *5.1.1 - Threaded Bar-Star-Plot*). The topic seemed interesting for participants to analyze and the dataset had normalized values ranging from 0 to 10 to rank the different countries. Bearing in mind that the depth of the swirl is not precisely controllable, one characteristic of ephemeral user interfaces [Döring et al., 2013], it seemed reasonable to limit the range of values to allow a bit of tolerance in the representation of the data. As a legend for the dataset, we used laser cut external displays (see Figure 5.21-left), which could easily be removed and therefore allow an experience of the *Swirlization* without a specific dataset.

[12] `http://www.oecdbetterlifeindex.org/` (accessed 2015-12-15)

We discussed various ideas on how to interact with the *Swirlization*. As we used a cylindrical tube as a container which easily can be circled by people, one idea was to use the position of a visitor as input. Other concepts included the use of tangible tokens, external touch devices or touch sensing on the tube itself. In the end, we decided to investigate during the evaluation whether and how participants would like to interact with our prototype and used easily to implement mid-air gestures as the basic interaction technique.

We used an ultrasonic sensor and a “Leap Motion”[13] for the tracking of the mid-air gestures. With the ultrasonic sensor, it was possible to control the depth of the swirl by varying the distance between the sensor and the hand. In this mode, the bottom of the swirl was on the same level than the hand. To navigate through the dataset, we used standard gestures provided by the API of the “Leap Motion” Software Development Kit (SDK). A circle gesture changed the category and a swipe gesture the selected country. The swirl was then colored analogous to the category color, and the country name was highlighted on the legend.

A “Raspberry Pi”[14] functioned as a microcontroller that ran the main program code, reacted on input by the ultrasonic sensor and controlled the LEDs and the speed of the motor. The “Leap Motion” was plugged into a laptop because of performance issues. Recognized gestures were then transferred via WiFi to the “Raspberry Pi”.

Study Design

Similar to the previous evaluations the primary goal was to observe in which ways participants experience the physicalization. We were also interested in participants ideas regarding possible interaction techniques for the *Swirlization*. We also wanted to know if such a system actually has a potential for representing abstract data and what participants consider as possible usage scenarios.

The study took place in an isolated, quiet and dim lighted room equipped with our prototype consisting of the physicalization and the legends, which were hidden at the beginning just as the laptop and the “Leap Motion”. It had a duration of about 30 minutes and begun with questions about demographics and previous experience with data representations. The main part of the study was a presentation phase, in which were ran an auto program that displayed the possibilities of the physicalization, such as changing the coloring and the depth of the swirl, but without any specific dataset. Participants were encouraged to think aloud about possible usage scenarios and interactions but also about the entire experience. In the second part, we added all external devices and gave participants a short explanation about the dataset and the interaction techniques. Participants were asked to explore the physicalization and to fulfill a few information retrieval tasks to evaluate if they understood the data representation. The study ended with a questionnaire and a semi-structured interview about participant’s opinions regarding the prototype.

[13] `https://www.leapmotion.com/` (accessed 2015-12-15)

[14] `https://www.raspberrypi.org/` (accessed 2015-12-15)

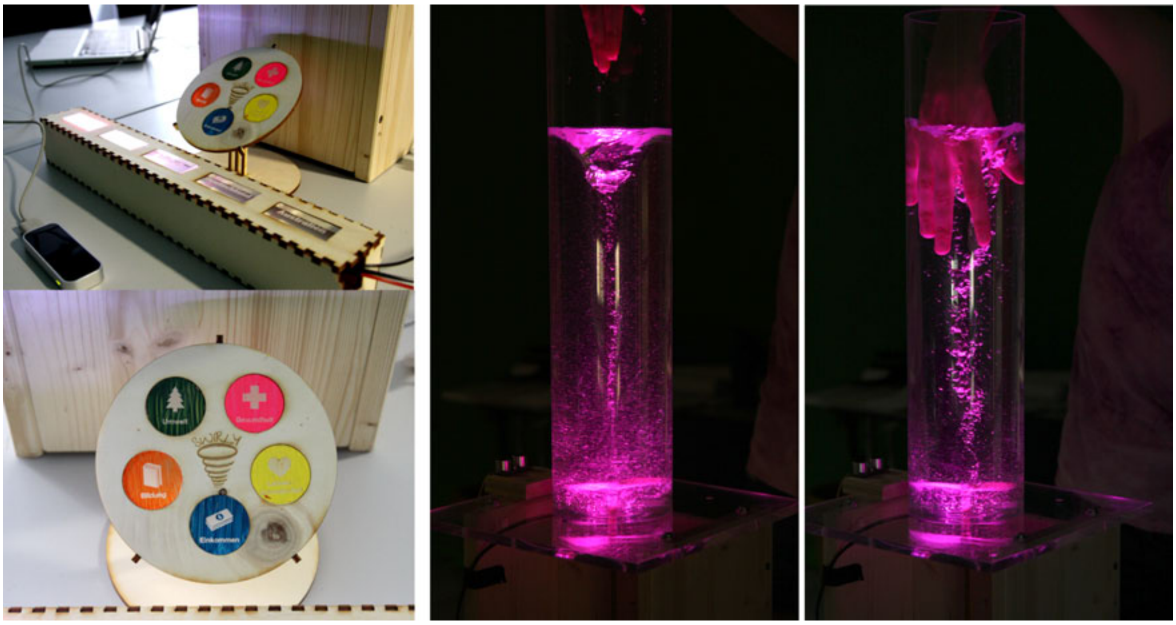

Figure 5.21: Left: Legends for the underlying dataset were presented on external displays. Right: Participants experimented with unusual interaction techniques. Image © Barbara Schindler.

We had ten participants (five female) with an average age of 27 years (range: 22-36). While four participants were students of media informatics, the remaining studied education, medicine, history of art, romance philology, experimental physics, and American history, culture and society. Therefore only three participants stated that they had experience with data representations. Participants received a 5 Euro voucher for an online shop.

Results

All participants found the *Swirlization* as visually pleasing as well as fun to use. One participant stated: "*It just looks cool. It is hard to look the other way.*" Another attributed "*some kind of hypnotic effect*" and a "*visual attraction.*" Participants also understood how to read the underlying dataset, as nine participants mentioned that the data representation was easy to understand, and 88% of the tasks were fulfilled correctly. They also rated the interaction techniques as comfortable and appropriate.

The most mentioned ideas regarding interaction possibilities were touching and rotating the tube or the water itself (see Figure 5.21-right). Some mentioned that the distance between a visitor and the physicalization could have an effect. Others preferred voice control and a few already noted mid-air gestures. Almost all participants mentioned the possibility to throw something into the tube, e.g., little plastic beads, to start a program or display a particular data point. One participant suggested physical tokens for each country and category and by throwing a combination of them into the tube, the particular data would be displayed.

It was rewarding to see that our physicalization stimulated participant's creativity as they listed various usage scenarios. Several participants associated the water swirl with the general area of weather and therefore proposed to display wind forces or the intensity of tornadoes or hurricanes. Because of its aesthetics, others thought of an informative piece of scenery, which could be used in a foyer, a yoga studio or a doctor's office to visualize the time or the waiting period. One participant even mentioned that it could be used as a fuel indicator in an electric car. The most mentioned application scenario was education, e.g., kindergarten, school, or museum, in which it could be used as a playful alternative to present and explore data.

The largest point of critique were the external laser cut legends. All participants mentioned that they would prefer a display more close to the physicalization, i.e., to the tube and the swirl. They also mentioned that the wood optic would not fit the acrylic glass tube. Some participants suggested using projections for the display of more detailed information.

Discussion

The design process and evaluation of *Swirlization* showed that moving from rigid materials to liquids for representing data is an exciting possibility for physicalizations. It demonstrated that a playful interaction with diverse materials is a promising way for representing abstract data. Our results strengthen the promises that physicalizations have the quality of evoking fascination and curiosity as well as turning data exploration into an enjoyable experience.

It is worth mentioning that such fascination is always generated by the novelty effect on some level. If those physicalizations as our *Swirlization* will be more common, e.g., as a classical installation in a museum, their power to provoke a memorable experience will probably decrease. In contrast to our previous prototype, our second prototype in the area of dynamic physical visualization illustrated the opportunities and possible benefits of actuating physical materials for the representation of data.

It also showed that such physicalizations benefit from their "uniqueness", which is hard to measure and therefore, challenging to compare to other data representations. Based on these findings and our general experiences with designing and evaluating physicalizations we decided to focus on static physicalizations instead of technological complex dynamic physicalizations. We also wanted to concentrate on physicalizations that are related to traditional types of 2D visualizations. This allowed a rather fair comparison of representation modalities and thereby seemed to offer the chance to draw stronger conclusions about the benefits of encoding data in a physical form.

Chapter 6

Potential for Perception & Memorability

The decision to focus on the question how the physical modality affects the perception and memorability of data were mainly based on the statements made by participants in our early evaluations as well as our collected experiences and observations (see *Chapter 5 - Beyond Physical Bar Charts*). Several participants mentioned memorability aspects when asked about possible benefits of physicalizations. During the evaluation of the layered physical visualizations (see *Subsection 5.1.2 - Layered Physical Visualizations* and textitSubsection refsubsec:LayeredPhysicalVisualizationsonTabletops - Layered Physical Visualizations on Tabletops) participants stated that they believe they could remember data better when it is encoded in a physical form. They motivated their assumptions with the natural third dimensionality which is provided by physicalizations as well as the direct haptic feedback and the fact that they make use of spatial imagination.

Our early evaluations focused on time and error or general observations on ways in which participants use and interact with novel physicalizations. While the results showed that physicalizations are suitable for analytical tasks, it usually took more time to fulfill tasks with the physicalizations compared to 2D visualizations. Therefore, it seemed a promising approach to explore areas that go "beyond time and error". We also learned about the challenges of evaluating physicalizations, especially to only manipulate the presentation modality to achieve a fair comparison and to avoid experimental bias [Jansen et al., 2015]. These experiences led to the decision to concentrate on traditional and well-known bar charts as visualization type.

Personal contribution statement: The content of this chapter is based on two student's theses by *Jeannette Schwarz [2014]* and *Moritz Hobe [2015]*. Part of it was published in two articles by *Stusak, Schwarz, and Butz [2015]* and *Stusak, Hobe, and Butz [2016]*. See *Disclaimer* for a detailed overview.

This chapter presents two studies, which are based on these considerations and evaluated the information recall of data perceived with physicalizations. The first study compared a static physical bar chart to a bar chart displayed on a tablet screen in a between-group design. The information recall of 40 participants was measured by a questionnaire about the representation's content, once immediately after exploration, and again after two weeks. The second study evaluated 2D and 3D modular physical bar charts, in particular, a paper-based representation and a version built with wooden blocks. In a repeated measures study with 16 participants, the memory performance was recorded immediately after the exploration and with a delay of one week.

6.1 Static Physical Bar Charts

Our first study that evaluated memorability aspects of physicalizations compared digital and physical static bar charts. The digital representation was displayed on a tablet screen, and the physicalization was built with colored laser cut acrylic glass (see Figure 6.1). Based on the experiences collected in a pre-study we conducted a study with 40 participants in a between-group design and measured the recall performance immediately after exploration and with a delay of two weeks. The questionnaires to test the recall performance consisted of three question categories: extreme values, numeric values, and general facts. The results revealed

Figure 6.1: The static bar charts in the digital and physical modality which were used in our study.

6.1.1 Motivation & Background

Our initial motivation to investigate in which ways the physical modality influences the perception and memorability of data are based on our early explorations with different prototypes of physicalizations. Multiple participants stated during the studies that they see a potential for physicalization in memorability aspects. In informal discussions with colleagues and on conferences at which we presented our early prototypes, this topic was mentioned consistently. Finally, Jansen et al. [2013] suggested, that future studies should investigate other factors than pure performance and named in a later article memorability as one relevant criterion [Jansen et al., 2015]. This subsection briefly motivates the decision to look into memorability aspects of data representations. It also gives further indications that there are justified expectations that the physical modality can influence the perception and memorability of information.

Perception & Data Representation

As it is not possible to cope the entire research area regarding the perception of data representations, we only briefly discuss related studies. Compared to a 2D bar chart on a digital screen, a physical bar chart has by nature a third dimension, which can be seen as a visual embellishment. The “data-ink ratio” by Tufte [1986] proposes that all ink that is not used to present data should be removed. Similarly, Cleveland [1985] recommends a minimalist approach, to reduce interpretation effort and to increase accuracy. However, study results in this area are undecided.

Studies found negative effects when adding a third dimension to a bar or pie chart, e.g., regarding the accuracy or evaluation time [Siegrist, 1996; Zacks, 1998; Schonlau and Peters, 2012]. Visual embellishments, e.g., rounded tops for bar charts, can impact absolute and relative judgments negatively [Skau et al., 2015]. While one study found a relation between a high data-ink ratio and faster response times as well as greater accuracy under specific conditions [Gillan and Richman, 1994], others could not confirm these results [Spence, 1990; Blasio and Bisantz, 2002; Kulla-Mader, 2007; Moere et al., 2012]. Other studies revealed that participants seemed to prefer non-minimalist graphs [Levy et al., 1996; Inbar et al., 2007], e.g., for showing information to others. They also found that adding “visual difficulties” might enhance comprehension of the data [Hullman et al., 2011; Borgo et al., 2012].

In our opinion, the third dimension in a physical bar chart is no visual embellishment, as physical objects have a third dimension by nature. For physicalizations this should not be rated as a distractor, although it encodes data in a redundant way. It should rather be assessed as “properly designed chart junk”. Therefore, we do not believe that the physical modality impacts the accuracy of data perception compared to the digital counterpart, assuming both have the same visual mapping.

Memorability & Data Representation

An ongoing debate in the InfoVis community about the role of visualization types regarding the perception, comprehension, and memorability of data, highlights the importance of this topic, not only for physicalizations. Ware [2012] specified "memory extension" as one quality of visualizations that extend human cognition. Studies in the area of psychology also support this conclusion, as results showed that pictures lead to better recall performance than words alone [Sampson, 1970; Cherry et al., 2003]. Furthermore the combination of pictorial and verbal stimuli could improve content recall [Hockley, 2008] and colored images could be recognized better than black-and-white images of natural scenes [Wichmann, 2002].

In the field of InfoVis various projects investigated aspects of memorability [Healey and Enns, 2012]. The impact on memorability was explored by studies focusing on visual embellishments [Bateman et al., 2010], visual features in network diagrams [Marriott et al., 2012], landscape visualizations [Tory et al., 2009] and pictographic representations [Haroz et al., 2015]. Others followed a more general approach and investigated which types of visualizations or specific characteristics support memorization [Borkin et al., 2013, 2016].

It is worth mentioning that a couple of these studies were criticized by Few [2011a,b, 2013, 2015, 2016], an author, consultant, and educator about data visualization. He questioned the study methodology, the number of participants and the design of the used visualizations. He also argued that "*Visualizations don't need to be designed for memorability—they need to be designed for comprehension.*" Other visualization researcher and practitioners disagreed in some points, e.g., by highlighting the conventions between fields in experimental design and analysis [Munzner, 2016]. Based on their experiences they also expressed, that memorability does matter in specific cases, e.g., when decisions do not have to be made immediately [Kosara, 2015; Jones, 2015].

We believe that schools and museums or education, in general, are a good example to motivate our study on physicalizations and memorability. In these examples, (1) the overall goal is to learn and remember information, (2) physical models are already being used (e.g., physical anatomy models in biology) and (3) the data is often static (e.g., historical data).

Memorability & Physical Objects

While, to the best of our knowledge, there are no studies regarding physicalizations and memorability, studies in the field of haptic perception indicate some promising results. Vision and haptics seem to share an abstract representation of the shape and structure of an object [Easton et al., 1997]. But this might be only true for implicit memory tests. Explicit memory tests implied that the recognition system keeps track of the modality through which an object is perceived. Research also suggests that the visual and haptic perception are processed dependently and transfer information, as the visual short-term memory is influenced by haptic perception [Kerzel, 2001]. Similarly the experiments by Kelly et al. [2011] proposed that locations that are learned with different senses are represented within a common reference frame: Haptic experiences could influence memories that were acquired visually.

It has also been shown that physical objects could be remembered better than pictures, and pictures better than words [Bevan and Steger, 1971].

Jones et al. [2005] compared the presentation of written content, such as advertising or consumer information, on printed paper and a digital screen. The results suggested that print outperforms the screen modality on recall but not on recognition. A study with a stronger relation to data representations, but focusing on spatial memory and item retrieval times, was conducted by Cockburn and McKenzie [2002]. They investigated the effectiveness of spatial memory for physical and digital arrangements of images in 2D and 3D. The participants found interfaces with more dimensions less efficient, but the physical modality performed better than the on-screen modality.

Therefore, we believe that the additional natural dimension of a physicalization and their unique characteristics can provide value as an aesthetic property, but also for comprehension and memorability. With their perfect visual realism and their opportunity to be touched or grasped, physicalizations could generate a more detailed representation in the subjects' memory, which could lead to a better memorability compared to their digital counterparts.

6.1.2 Design Process

Here we motivate our choices for the dataset and type of representation and describe the design of the digital and physical representations. We also present the procedure and results of a pre-study. The goal of the pre-study was to discover first tendencies, collect experiences about different study procedures and spot potential problems.

Datasets

We had two main decision criteria regarding the underlying dataset: (1) the topic should be interesting to a wide audience, but at the same time not too popular, to minimize the effect of previous knowledge and to allow a reception and memory of new information; (2) the complexity of the dataset should be on the one hand at a level at which the recall of the entire content is hardly possible. On the other hand, if the number of distinct pieces of information was too small, remembering the content might be too easy. Similarly, if the dataset was too complex, reading difficulties might distract from the actual content.

Therefore, we used country indicator data of two newsworthy topics from the Human Development Report (HDR)[1], an annual report about the development of the world's countries and their impact on individual lives. The first topic on *social integration* dealt with issues such as trust and perceived safety in individual countries. The second topic on *population trends* addressed problems in the demographic change of countries. For both topics we extracted a subset, consisting of the values for six countries and six different subtopics per country (2x36 values in total).

[1] `http://hdr.undp.org/` (accessed 2015-12-15)

Data Representation Type

We chose vertical 2D bar charts as the type of representation. They are well-known and conceptually easy to understand by people without experience in InfoVis. We decided to use 2D bar charts instead of 3D versions and static ones instead of dynamic or interactive prototypes to focus solely on effects of the modality of the representation. The experiment's results should therefore not be influenced by a novelty effect, a difficulty in interpretation or specific interactions. Furthermore, such bar charts can be made perceptually similar for the digital and physical modality using standard software and digital fabrication technology.

Data Representation Modalities

The general visual design was based on the visualizations that are available on the HDR website, which is generated by the visualization tool socrata[2]. This way we could exclude inherent biases through the design, as colors, guides and most of the labeling was predefined.

The final design of the digital bar chart for the *social integration* dataset is displayed in Figure 6.2-left. The only changes for the pre-study we made within the original visualization taken from the HDR website was an adaption of the legend. We switched the language from English to German, added little descriptions for each category and applied minor design changes (see Figure 6.2-right). The visualization was shown on an Apple iPad Air (2048*1536 px., 264 ppi) in full-screen display (see Figure 6.1). By choosing a tablet device instead of a classic desktop setting, we could enable similar conditions between the two modalities. Both had a similar size (physical: 28.5 cm x 17.0 cm; digital: 23.9 cm x 16.8 cm), weight (physical: ≈350 grams; digital: 454 grams) and could be held conveniently in one or both hands.

The single bars of the physical bar chart (see Figure 6.3) were built from 8 mm transparent acrylic glass using a laser cutter and were colored with acrylic paint. They were glued onto a base acrylic glass layer, which contained the labels for countries and the legend printed on self-adhesive foil. The colors and general layout of the physicalization matched those of the digital visualization. The single bars had engraved lines as a reading aid and numeric values which were also attached to the bars with self-adhesive foil. A transparent acrylic glass panel (28.5 cm x 17.0 cm x 0.2 cm) with engraved numeric values and lines served as a background.

Pre-Study

To discover first tendencies and test the study procedure, we conducted a pre-study with a between-groups design and three independent variables: modality (physical, digital), memorization (implicit, explicit) and time (immediately, delayed).

[2] `www.socrata.com` (accessed 2015-12-15)

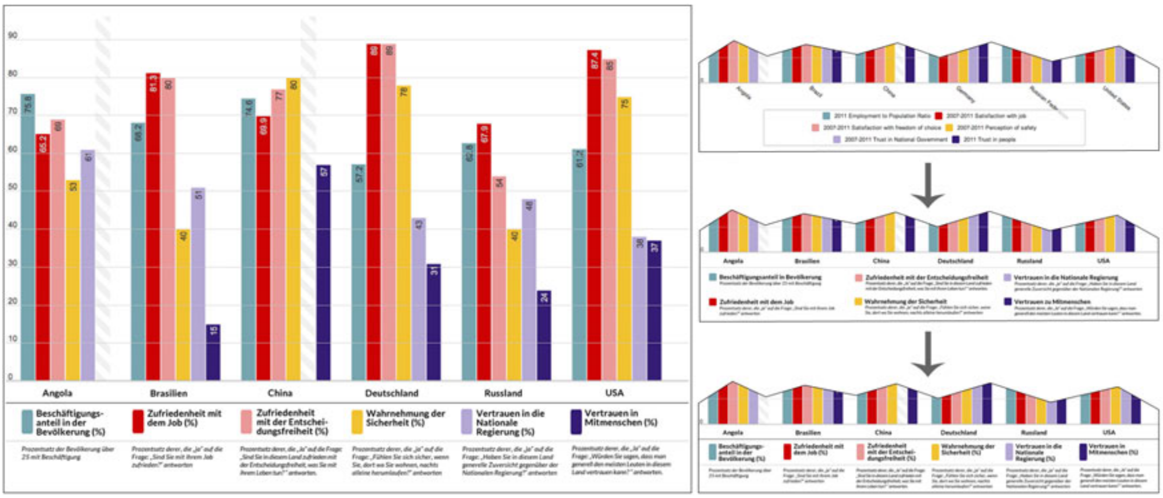

Figure 6.2: Left: The static digital bar chart for the *social integration* dataset. Right: The original labeling from the visualization on the HDR website for the *social integration* dataset (top) and our changes for the pre-study (center) and main study (bottom).

Method We chose a between-groups design instead of a between-subject design to avoid a potential novelty effect that might occur when participants are not familiarized with physicalizations. Our concern was that due to its novelty the physicalization could draw more attention and in the worst case influence or overrule the memory of the digital representation.

We looked at implicit and explicit memorization as we were interested in how large the difference of remembered information would be. While we preferred an evaluation of implicit memorization, as this seemed a more frequent use case, we worried that participants would only recall the most obvious facts about a dataset, when not told to explicit memorize the content.

For an equal reason, we wanted to have a look at the effect of the time when participants had to recall the information. In the immediate recall condition, the received information could be similarly “present” in both modalities and a potential benefit of the physical modality could become only noticeable after a period of time. We chose a delay of one day, to keep the total study period rather short. Also, research assumes that already after one day only 30% of received information can be remembered. However, this is based on memorizing nonsense syllables [Ebbinghaus, 1885]. We focused on (cued) recall instead of recognition as this type of memory retrieval seemed more related to our motivation example of education and museums.

Participants We had 24 participants (eight women) with an average age of 25 years (range: 23-27). All except one were students, of which 22 studied computer science or media informatics and one theater-science. One participant worked as a user-experience designer. Participants received a 10 Euro voucher for an online shop.

Procedure The pre-study took place in an isolated and quiet room equipped with a laptop and the two representations. It had a duration of about one hour and started with a demographic questionnaire and questions about previous experience with data representations. In the *reading phase*, one of the representations were presented to each participant in a counterbalanced order. The study leader encouraged the participants to explore the visualization and think aloud about all insights and content-related issues. The participants in the *explicit memorization* group were told to memorize as much as possible, as they had to answer questions about the content afterward. For the *implicit memorization* group, this ahead warning was not given.

While a participant was exploring the representation, the study leader checked a list of predefined facts (e.g., all country names and categories) which every participant was supposed to speak out loud during the *reading phase*. After the participant had finished reading, a fixed set of questions (e.g., which countries are shown in the representation?) were asked while the representation was still available to complete participant's knowledge, if necessary. After the *reading phase*, participants had to fill out a questionnaire collecting qualitative data.

The *recall phase* started either directly after the questionnaires or during a session on the following day. Participants were asked to recall freely everything they remembered about the representations. All answers were noted, and when the participants did not know any more facts, predefined questions were asked to support the recall phase. We videotaped the *recall phase*, which was transcribed by two researchers. We calculated a recall score which was inspired by Bateman et al. [2010], in which one point was given for each correct fact and 0.5 points if facts were not completely right or remembered after the predefined questions.

Results As we had three independent variables, a between-groups design, but a small group size, the results of the pre-study should be considered with caution and can only reveal first tendencies. Participants using the physicalization seemed to remember more facts in total (physical: M=29.58, SE=8.54; digital: M=22.25, SE=6.42), but the scores converged if only looking at the *delayed recall* (physical: M=22.58, SE=9.22; digital: M=19.5, SE=7.96). This was contrary to our assumption that the physical modality could have advantages for a postponed recall. The aspect of telling participants to remember the content did not seem to have any effect (explicit: M=25.95, SE=3.22; implicit: M=25.875, SE=2.49). This was also contrary to our assumption that subjects would recall fewer facts when not explicitly told to memorize them.

The pre-study also led to insightful observations and feedback from the participants. Participants did not frequently interact haptically with the physicalization, as most participants did not pick up the physicalization and neither used both hands for holding nor traced the bars with their fingers. Participants tended to tilt the physicalization to have a better perspective and to make use of the guides on the background panel. Two participants complained that readability for the physicalization was only granted when looking from the front and not from above. They suggested decreasing the space between the background panel and the bars. Three participants stated that the two-row design of the legend was confusing.

Figure 6.3: The static physical bar chart which was used in our study and a close-up on the bars' labeling and the background panel.

6.1.3 Study Design

The pre-study revealed first tendencies and gave us confidence in the general study design. Therefore, the main study was based on the procedure of the pre-study but was modified according to the observations from the pre-study. We also adapted the designs of the representations based on participants' suggestions. All modifications will be described in the following.

Method

We kept the between-groups design but focused only on one independent variable: representation modality (physical, digital). As we could not found any trends between *implicit* and *explicit memorization* and participants could remember enough information without explicitly being encouraged to do so, we only tested *implicit memorization*. As the pre-study revealed that the physicalization can have advantages for immediate recall, we kept the condition to test participants directly after the exploration. We added a long-term memory test for all participants with a delay of two weeks.

Recall Performance

One mayor change compared to the pre-study was done regarding testing the recall performance. While the study leader encouraged participants in the pre-study to tell all remembered facts verbally, in the main study, we used an online quiz. This was done to gain a more comparable memory score and to exclude possible influences by the study leader (e.g., differently phrased or leading questions).

The quiz contained a *free recall* and a *cued recall* test. In the *free recall*, participants had to fill out free text fields with all remembered information based on three questions for each representation:

- Which countries were shown?
- Which categories were included?
- What other facts do you remember about the representation?

The *cued recall* consisted of three question categories with 50 questions in total:

- *extreme values:* Questions related to minimum/maximum values of countries for various categories, in total 24 questions (e.g., "Which country has the most trust in its government?". Answers were chosen from a list of the six used countries, as well as "I don't know."
- *numeric values:* Questions related to specific numeric values, in total 12 question (e.g., "In Brazil, only 15% have trust in their government."). Answers were chosen from a dropdown list including "true", "false" and "I don't know."
- *facts:* Questions related to general facts of the underlying data, in total 14 questions (e.g., "Germany has more trust in its government than Brazil."). Answers were chosen from a dropdown list including "true", "false" and "I don't know."

The score for the *free recall* was calculated similarly to the pre-study. The given answers were analyzed by two researchers, and each correct answer gave one point, too vague answers 0.5 points. The calculation for the *cued recall* was easier, as there were only right or wrong answers. We decided for both scores to not subtract points for false statements. We further defined a *memorability score* as the ratio between the scores for the delayed and immediate recall. If, for example, a subject recalled 60% immediately and 45% after two weeks, this resulted in a memorability score of 0.75.

Representations

We used the same dataset as in the pre-study and made only little changes to the representations. The legend's layout was changed for both representations from a two-row design to a one-row design to better correspond to the order of the differently colored bars (see Figure 6.2-right). We also adapted the descriptions and added the unit in which each category was measured to the legend, to avoid any lack of clarity which we observed once in a while during the pre-study.

To minimize perspective distortion effects of the physicalization we moved the single bars closer to the background panel, as suggested by some participants. As we observed in the pre-study that participants did hardly interact haptically with the physical bar chart, we tried to improve the affordance of a haptic exploration. The massive base of the visualization was split into two parts: the legend and the bar graph (see Figure 6.3). Latter consisted out of a small base which contained all the bars as well as the labels and the background panel. It can be removed and held comfortably in one hand while using the other hand to explore the bars. Meanwhile, participants can still read the legend that remains on the table.

Participants

We had 40 participants (17 women) with an average age of 23.5 years (range: 18-32). The participants consisted of students only, of which 37 were Computer Science or Media Informatics students, three studied Economics. Participants received a 15 Euro voucher for an online shop.

Procedure

The study procedure was based on the pre-study. We shortened the qualitative questionnaires at the beginning and the end of the study to reduce the study duration. The *reading phase* was kept similar to the pre-study, but some of the predefined questions to complete participants' knowledge were rephrased. The *reading phase* was videotaped, and we also measured the total time participants were exploring the representations.

Before starting the *immediate recall* quiz, participants answered a qualitative and subjective memory questionnaire to clear the visual and linguistic memory. The online quiz was filled out on a laptop in the study room. Participants did not receive any feedback on their performance, nor were they told the correct answers to the quiz. They were informed that they would have to fill out another quiz in two weeks, but not that it would be the same. Some participants suspected there would be another memory test. For testing the *delayed recall*, participants received a link to the same quiz via e-mail two weeks later and had to complete it at home.

6.1.4 Results

This chapter summarizes our results concerning the evaluation of memorability aspects for static physical bar charts. In addition to the performance for *immediate* and *delayed recall*, we present qualitative data about participants' experience and memorization techniques as well as our observations regarding a haptic exploration of the representations.

Qualitative Questionnaires

After the *reading phase*, participants had to rate various characteristics of the representations on 5-point Likert scales, ranging from 1=*strongly agree* to 5=*strongly disagree* (see Figure 6.4). Participants who interacted with the physical bar charts rated the perceived information

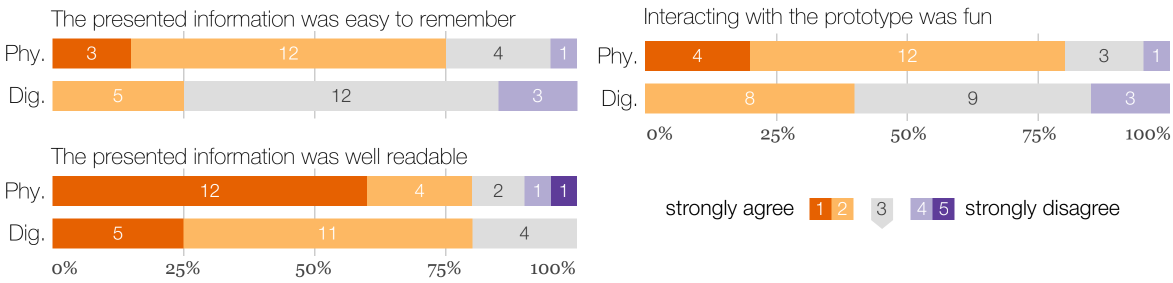

Figure 6.4: Results of the 5-point Likert scale questionnaires participants filled out after the *reading phase*, split into the two groups which either interacted with the physical or digital visualization.

as more *memorable* than those who used the digital version. Regarding the aspect of how *readable* they found the representations, the group of participants with the physicalization also gave higher ratings than the ones with the digital bar charts. Finally, participants with the physicalizations seemed to have more fun exploring the data than the participants with the tablet device.

Immediate Recall

For the *immediate recall*, the total results as the percentage of correct answers were for both, the *free recall* and the *cued recall*, slightly higher for the digital modality. A breakdown of the results of the *cued recall* into the three question categories revealed that the digital modality had little advantages for *extreme values* and the physical for *numeric values*. The highest percentage of correct answers had the digital modality for the category *facts*, which also led to the biggest difference between the modalities. In summary, the immediate recall performance showed no clear trends regarding one modality. The mean scores for the *immediate free recall*, and all results as the percentage of correct answers for the *immediate cued recall* are displayed in Figure 6.5.

Delayed Recall

For the *delayed recall* the total results as the percentage of correct answers were for both, the *free recall* and the *cued recall*, slightly better for the physical modality. A detailed look at the results of the each question category revealed that the digital modality had a higher percentage of correct answers for the *facts* category. The physical modality had slightly higher values for *numeric values* and reached a higher difference for *extreme values*. All results for the *delayed recall* are presented in Figure 6.5.

Memorability Score

We also looked at the *memorability score* for the *cued recall*, to put the results of the *immediate* and *delayed recall* in relation. In total, the score for the physicalizations was a bit higher. The score for the *facts* and *numeric values* categories were similar and did not identify any

Figure 6.5: Results of the main study. Top: Mean score for the *immediate* and *delayed free recall*. Bottom: The percentage of correct answers for *immediate* and *delayed cued recall* in total and for each question category (all with 95% CIs).

trend. The score for the category of *extreme values* showed a quite distinct difference in favor for the physical modality. All results of the calculated *memorability score* for the *cued recall* in total and for each question category are displayed in Figure 6.6.

Memorization Techniques

We asked participants after each quiz if they used any specific techniques to answer the questions and in which ways they tried to remember the content of the representations. Multiple answers could be typed into a free text field.

After the *immediate recall* the most often statements were "visual imagination of the representation" (24), "association with previous knowledge" (19), "facts that were surprising or differed from expectations" (16), "extreme values" (12), "association with newly acquired knowledge" (19), and "verbally expressed facts" (9). Two participants stated they recalled specific facts through the given options in the quiz and two others were able to recall facts through a personal connection with the country the fact was referring to. Regarding the statement of "visual imagination", the amount was split into 14 participants who used the digital representation and 10 participants who had the physical one.

The statements after the *delayed recall* were similar and included "visual imagination of the representation" (23), "association with newly acquired knowledge" (12), "facts that were surprising or differed from expectations" (11), "verbally expressed facts" (8), "association with previous knowledge" (7), and "extreme values" (6). Two participants stated that they

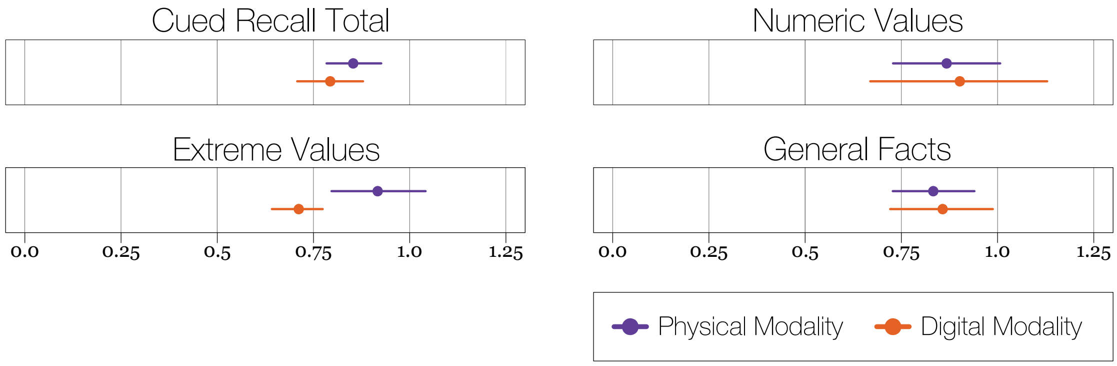

Figure 6.6: Results of the main study. Calculated *memorability score* (*delayed recall/immediate recall*) for the *cued recall* in total and for each question category (with 95% CIs).

memorized the answers they gave in the first quiz. Participants regarding the statement of "visual imagination" were again split into 13 participants who used the digital representation and 10 participants who had the physicalization.

Haptic Exploration

Although the physical visualization has been altered to encourage haptic exploration and the study leader suggested to the participants to hold either representation in their hands, only half of the participants followed this invitation. In the physicalizations group, twelve participants touched, held or pointed at the physicalization, while eight looked at it without haptic or manual involvement. For the digital modality, eight participants touched or held the tablet device and twelve only looked at the visualization while the tablet laid on the table. We could not find any trends in the recall performance between the participants who used haptic exploration and those who only looked at them. Participants spent slightly more time with the physicalization (M=19.27m, SE=1.50) than with the digital representation (M=17.62m, SE=1.00).

6.1.5 Discussion

Our results suggest that physicality alone was able to increase the memorability of data representations for a particular kind of information. Here we try to outline possible explanations but also discuss general observations and the limitations of our study.

Recall Performance

The percentage of correct answers for the *cued recall* did hardly differ between groups in each single comparison. These results are similar to the findings of related studies, which reported that physical and virtual instruction materials are equally effective for learning (e.g., Triona and Klahr [2003]; Marshall et al. [2010]; Zacharia and Olympiou [2011]). However, participants who used the physicalization forgot clearly fewer facts about maximum and minimum values within two weeks. It is worth mentioning that the digital visualization had a rather low memorability score for the category of *extreme values* compared to the other two question categories. While in the categories of *numeric values* and *facts* the modality with a higher value for the *immediate recall* also had a better value for the *delayed recall*, for *extreme values* the order swapped.

One explanation is that the visually recalled and imagined shape and position of very high and low bars can be remembered better in the physical modality. This is based on the assumption that spatial layouts can be memorized better in a physical setting [Kelly et al., 2011]. Scott [1967] argues that pictures of objects are better remembered than their names, as they are more distinctive. It could be argued, that a physicalization is in general more distinctive than their digital counterpart. We think this could particularly apply to the extreme values because of the vivid physical height of the bars. Similarly, physicalizations can provide a higher degree of detail and visual realism which is related to the aspect that physical objects can be remembered better than their pictures.

As we used a rather simple static bar graph built from acrylic glass, without any actuation or sophisticated interaction possibilities, we believe that a novelty effect hardly could impact the results. Also, in our opinion, it seems implausible that this caused such a large effect only for the memorability of extreme values. The same is true for the slightly longer reading times for the physicalizations. While we cannot exclude it as an explanation for the reduced decay, it seems unlikely that this only had an effect on the delayed recall. It is also worth mentioning that the results of the pre-study and main study did differ in some aspects. The results of the pre-study, for example, did suggest that physicalizations can have advantages for *immediate recall*, which could not be confirmed in the main study. While we believe that this can be explained by the lower number of participants and the higher number of independent variables, this should be investigated in further studies.

General Observations

Surprisingly, two cases in the physical modality group actually gained scores and overall became better over time. There are several explanations for this phenomenon. It might have been a matter of coincidence and participants have simply guessed wrong in the *immediate recall* but guessed right in the *delayed recall*. Another explanation could be that participants might have looked up the data out of interest since it was freely available on the internet. This seems unlikely as to display the exact combination of categories and countries, a relatively large search effort would have been required. Hypermnesia could also be an explanation, which leads to an increased performance for a repeated recall after a larger time interval. Hypermnesia seems to occur only with images and not with words and therefore, could be a phenomenon in the field of physicalizations.

Although the average rating for the readability of the physicalization was higher than for the digital visualization, three participants found the physical bar chart not readable at all. A circumstance that did not occur in the digital modality group. This indicates that physicality might be a problem for some people, who have, for example, a strong association with the digital domain. This could also be due to the novel experience and might vanish through familiarization.

It was intriguing to see, that the physicalization was experienced as more fun and more memorable although it had only been a physical replicate of a simple and plain bar graph. The statements that physical visualizations are more engaging and encourage people to explore an underlying dataset are often related to artistic installations with visual metaphors, which are commonly used in art exhibitions and museum presentations. However, participants' ratings indicate that physicality alone already has an effect on the user experience.

Limitations

The study also comes with limitations and aspects that should be considered when interpreting the results. All participants were students, and the majority had a technical background and experience with data representations. Therefore, the results can not be easily generalized. Further studies could involve an audience with a broader age range and participants with less anticipation for the digital domain. It should also be considered to change the study design from between-group into within-subject to collect more concrete comparative qualitative data about the representation modalities. This could lead to further insights which characteristics of a specific representation support the memorization of particular information.

Participants were allowed to fill out the second interrogation at home. This has lead to a variance of the time span between the completion of the first and second quiz, as some participants did not fill out the quiz before we sent a reminder two days later. Furthermore, it could not be prevented that participants either went to the previous page in the browser and corrected their results in the free recall part or that they got informed about the content of the representations by searching the Internet. Follow-up studies could require a second lab session in which participants have to fill out the quiz and also could be further interviewed about their experiences.

As another limiting factor, the study procedure involved optional predefined questions and the verbal expression of all facts the participants explored. The purpose was to ensure that each participant had the same knowledge before the interrogation. This process of verbal expression might have helped some participants more to remember the facts, than the data representation itself. This potentially confounding factor should be independent of the modality. A clearer approach for future studies could be to give the subjects certain tasks that induce the same knowledge implicitly.

Furthermore, most participants only held the physical bar chart in their hands but did hardly explore it haptically, e.g., by touching or tracing single bars. Tasks that more explicitly require haptic interaction could change this in further studies. The design of the physicalization could be adapted to invite further haptic exploration, e.g., by supporting the assembly and disassembly of single components of the physicalization.

It is noteworthy that there are many criteria other than memorability according to which the value of physical visualizations need to be judged (e.g., fabrication costs, interactive exploration, etc.). Furthermore, we evaluated two specific types of data representations, both without any sophisticated interaction possibilities. We believe this is a promising preliminary result for both casual and traditional InfoVis. Particularly for scenarios in which it is desirable to present memorable information, such as advertisement, journalism or education, the use of physicalizations might have benefits.

6.2 Modular Physical Bar Charts

Our second study regarding the perception and memorability of data perceived with physicalizations focused entirely on the physical modality. Similar to the previous study the type of representation was a bar chart, but in this case, we evaluated the difference between a paper-based representation and a version built with wooden blocks (see Figure 6.7).

Based on the results and our observations in the first study we designed and conducted a repeated measures study with 16 participants. We again measured the recall immediately after the exploration and with a delay of one week. Through the between-subject study design and semi-structured interviews, we could collect information about the process of recall and participants' opinions whether and how the representations differ in their potential for memorizing information. Through a modular design of the bar charts, in which each bar can be grasped and lifted, we tried to encourage a haptic exploration. The results confirmed our findings regarding the better memorization of extreme values perceived with a 3D physical bar chart compared to a 2D version. We discovered that the physical interaction techniques that we used in the study were not able to compensate lacking visual differentiation. The study also revealed that the two datasets had a strong influence on the recall performance.

6.2.1 Motivation & Background

Our primary motivation of the second study was to provide a better understanding of which characteristics of physical bar charts influence the perception and memorization of information. Based on the findings of our first study we had several research questions we wanted to address.

The results of the pre-study and the main study for the recall performance of information perceived with static bar charts did differ in some aspects. Therefore, we wanted to investigate if a second study can confirm our initial findings, especially regarding the better memorability of extreme values. The previous study did compare not only the modality but also the

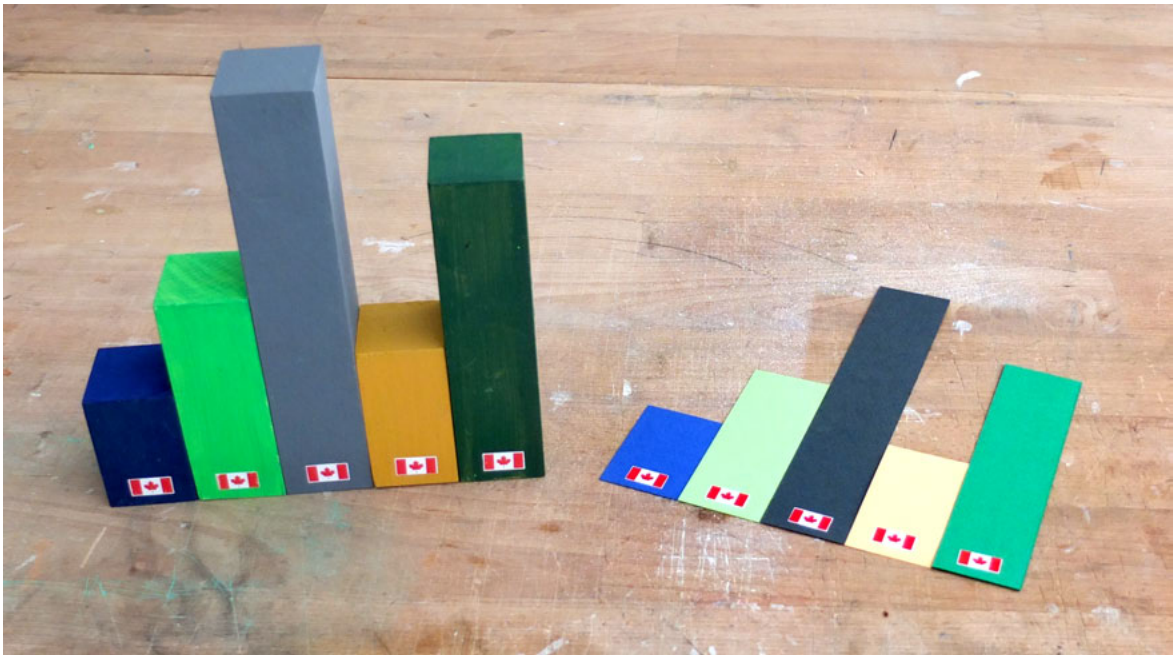

Figure 6.7: The modular bar charts which we used in our study, based on wooden blocks and paper strips.

dimensionality, as our physical bar charts had a third dimension by nature. We were interested in which ways the dimensionality of a physicalization and the related characteristics such as volume or weight influence the perception and recall of information.

As in the previous study only little haptic exploration of the physical bar charts occurred, we wanted a stronger focus on physical interactions to investigate in which ways, for example, disassembling, reassembling, grasping and lifting does influence the perception and recall performance. To further motivate our design decisions, we give a brief background of projects in the area of tangible interfaces that focused on aspects such as learning or problem solving.

Tangible Interfaces & Memorability

Section *4.2 - Information Visualization & Tangible Interaction* already gave an introduction to tangible interfaces and an overview of projects that combined data representation with tangibles. Here we want to focus on projects that investigated tangible interaction in the field of learning and problem-solving tasks.

O'Malley and Stanton Fraser [2004] argue that there can be real benefits for learning from tangible interfaces and that carefully designed physical interactions can simplify problem-solving tasks. Similarly, Zuckerman et al. [2005] state that the natural way to learn engages multiple senses in a constructive process. The use of tangible user interfaces in learning and education has received a lot of attention in recent years: they offer a playful approach to learning [Price et al., 2003], seem to encourage exploration and motivation [Rogers et al., 2002], and are believed as easily accessible to novices [Zacharia and Olympiou, 2011].

As a matter of fact, physical properties and haptic interaction have been used in education for a long time. In Mathematics tangible objects, such as the abacus or nowadays 3D printed artifacts [Knill and Slavkovsky, 2013a], are often used as an aid to teaching the numeral system or arithmetic. Another example is a technique to teach children how to write by Montessori [1964]. Children have to trace letters, which are cut out of sandpaper, with closed eyes. This leads to a perception of the letter's tactile sensation instead of its visual image and ought to result in a fixation of the letter's trace in the muscular memory. Bara et al. [2004] examined the effect of incorporating haptic exploration of foam letters on kindergarten children's understanding of the alphabetic principle. Results of the study showed that the haptic exploration can support the understanding of the alphabetic principle and is also likely to improve letter-decoding skills compared to a solely visual exploration.

Although studies often show positive effects in the use of physical materials in education, it is not clear whether this is due to their physicality or rather to the fact that learning with physical objects typically makes use of active learning and represents information in a more salient way [Triona and Klahr, 2003]. Also, several studies in the area of tangible interaction could not show a clear difference between the physical and virtual modality. Triona and Klahr [2003] found that physical and virtual instruction materials were equally effective for school students to design experiments. Marshall et al. [2010] did not find any effects on adults' discovery learning tasks using either physical or graphical materials. Zacharia and Olympiou [2011] argue that in the case of physics learning both, a virtual and physical setting support students' understanding of physical concepts equally. In summary, the impact of haptics and tangible interaction in education and whether it enhances the learning experience is still unclear [Minogue and Jones, 2006].

The results of our first study showed, that in the case of data representation, physicality alone could improve memorization. The results might differ as the previously stated studies in the area of TUIs have investigated the understanding of concepts, supposedly stored in the nondeclarative memory, but data representations convey factual information and correlations stored in the declarative memory. We furthermore focused on the difference between the 2D and 3D modality and explored whether the unique characteristics of physical objects that can be perceived haptically can enhance memorability.

6.2.2 Design Process

Based on the previous study and the related projects mentioned above, we determined a couple of aspects we wanted to attach importance regarding the design of the data representations. Here we motivate our decisions and describe the creation of the data representations.

Datasets

Our decision criteria regarding the underlying dataset were similar to the ones mentioned in the previous study. Therefore, we again used two topics from the HDR as the underlying dataset. The first topic on *economic* included, amongst others, values of imports and exports as the proportion of the national product for the individual countries. The second topic on *population* consisted of data such as the share of the population with a second or tertiary level of education. In total, we had two datasets, each composed of the values for six countries and five subtopics (2 x 30 values in total).

Data Representation Type

We chose a well-known vertical bar chart as the data representation type to minimize the influence of difficulties in reading or interpretation on the results, identical to the first study. We intended to encourage haptic interactions that go beyond touching single bars and include grasping or lifting single data points. The goal was to tap the potential of unique characteristics of physicalizations such as weight and volume. To achieve this, we kept the bars modular and followed a token-based approach [Huron et al., 2014b], in which each data point is represented by an independent physical token.

Data Representation Modalities

As the previous study showed, only manipulating the presentation modality and finding the right alternative to a physicalization for conducting a comparative study is challenging. A comparison between the digital and physical modality often inherits a comparison of the dimensionality. Therefore, we decided to concentrate on the dimensionality of physicalizations and exclude their digital counterparts.

Specifically, we compared paper-based 2D bar charts with a 3D version built from wooden blocks (see Figure 6.7). We categorized the paper-based representation because of their thinness as 2D in the following, although strictly speaking all physical artifacts, including paper strips, are 3D objects. To create the wooden blocks, we used a wood saw and colored them manually (see Figure 6.8-left). The paper-based representations were cut with a laser cutter out of colored drawing paper (160 g/m^2) (see Figure 6.8-center). The single bars of both physicalizations had the same size, similar colors for each category and small printed flags on them (see Figure 6.8-right). In contrast to the static bar charts in the previous study, we decided against labeling the bars with numeric values. This was done to encourage physical interaction with the single bars, as we provided a stand-alone scale instead for reading exact values (see Figure 6.9-right).

6.2.3 Study Design

The goal of our study was to learn more about the role of physical characteristics of physicalizations, such as volume and weight, regarding the perception and recall of the encoded

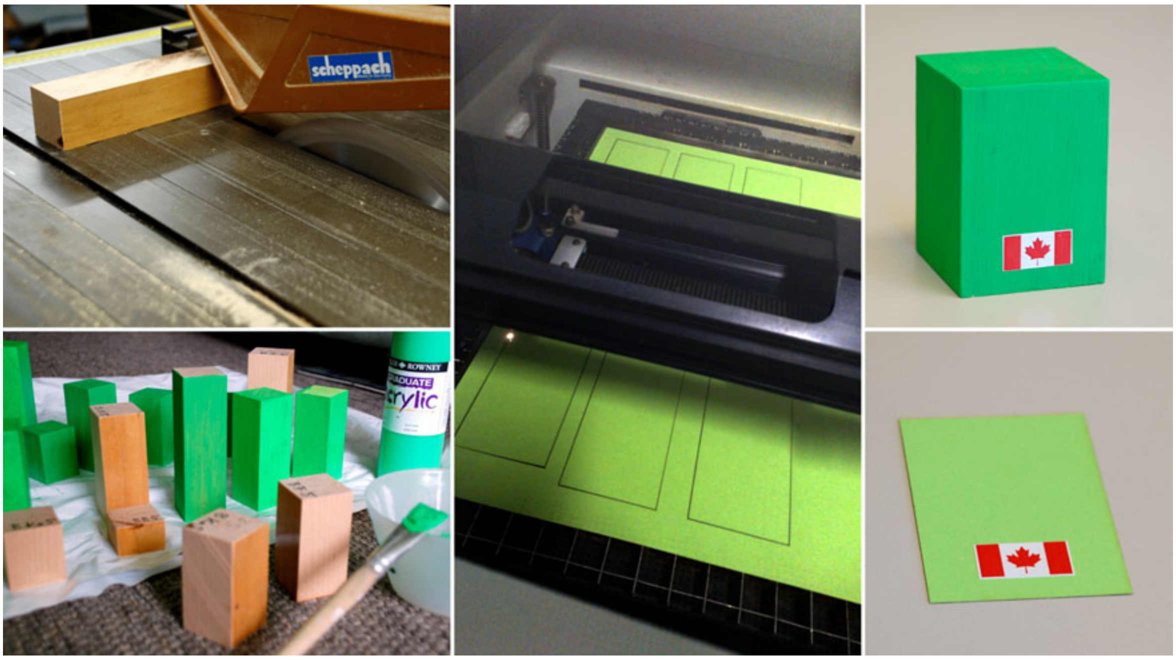

Figure 6.8: Creation of the physicalizations. Left: The wooden blocks were sawed and colored manually. Center: The paper strips were cut with a laser cutter. Right: Examples of one data point for the 3D and 2D modality. Image © Moritz Hobe.

data. We also wanted to gain some understanding whether and in which ways physical interactions influence this process. To investigate these questions, we conducted a study, in which we measured the recall performance once immediately after the exploration of the representations, and once with a delay of one week. To get insights about the subjects' judgments we used semi-structured interviews.

Participants

We had 16 participants (five women) with an average age of 22.8 years (range: 18-31 years). They were predominantly students of Media Informatics (14 out of 16). Participants received a 10 Euro voucher for an online shop.

Procedure

The study took place in an isolated and quiet room equipped with a table (100 cm x 160 cm), the physicalizations and a separate computer. We used a repeated measures design for the study with the independent variables *dataset* (*economic* and *population*) and *modality* (*2D* and *3D*). The resulting four conditions were counterbalanced using a Latin square. To measure the delayed recall we hold a second session after a gap of one week. The first session had a duration of about one hour, the second of about 30 minutes.

Participants first had to fill out a consent form and a demographic questionnaire. After that, the *exploration phase* started, in which one of the data representations encoding one of the datasets was presented to each participant and several tasks had to be fulfilled. Participants were also asked to rate different aspects such as memorability, fun and ease of use on 5-point Likert scales after each exploration. Similar to the previous study we focused on *implicit memorization*. Therefore, participants were not told about the recall phase or that they should try to memorize the encoded data.

Directly after exploring both physicalizations the *recall phase* started, in which participants had to complete two online quizzes about each dataset. The order was kept equal to order the physicalizations were presented. Participants did not receive any feedback on their performance, nor were they told the correct answers to the quiz. They also received no information about the procedure of the second session and that it contained a second quiz.

The second session started and ended with semi-structured interviews. First, we asked participants which data representation they could remember better after one week and whether they could give any details to substantiate their assumption. After filling out two online quizzes again, we wanted to know in which ways participants used the memorized physicalization to answer the questions. We were, in particular, interested in statements about physical characteristics and whether they had experienced any differences depending on the modality.

Tasks

As previously mentioned, participants had to fulfill several tasks during the *exploration phase*, which can be split into two main categories:

Assembling the physicalization The *exploration phase* started with a handover of a box containing all paper strips or wooden blocks to the participants. Participants sat in front of an empty table with geographically arranged flags and a legend with the order of the categories (see Figure 6.9-left). We gave participants no further instructions how to fulfill this task accurately.

However, the legend provided an order for the categories and the flags on the table a rough position where to place the bars. This was done as a compromise between the support of a fixed spatial frame of reference without limiting the possibilities of haptic interaction. The high level of flexibility in creating or manipulating physicalizations through haptic interactions might lead to a loss of a fixed spatial frame of reference, which implies the important visual variable of spatial position. If the spatial arrangement changes too often or lacks consistency, the data encoding might get more difficult, which could influence the perception and memorization, independent from the modality or type or data representation.

Retrieving and comparing single values After assembling the physicalization the study leader asked participants to name the countries with the highest and lowest values for each

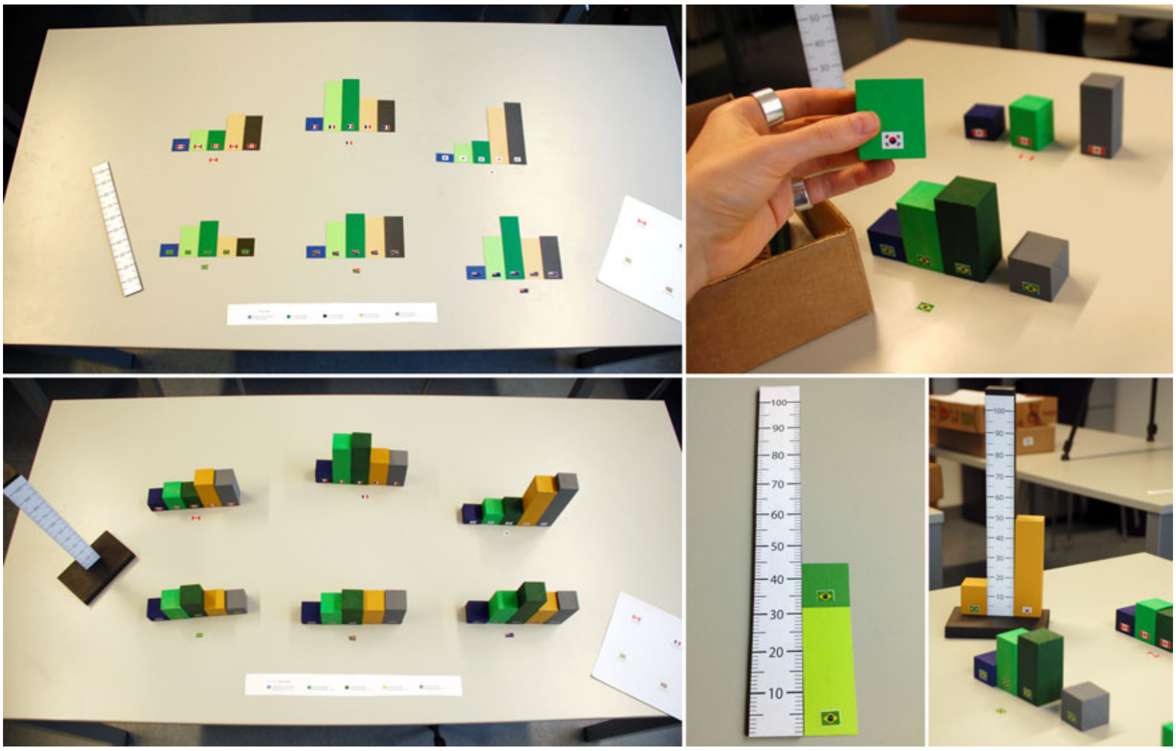

Figure 6.9: Participants had to assemble (top right) the wooden blocks or paper strips to create the final data representations (left). Stand-alone scales for both modalities were used in the study tasks to read and compare exact values (bottom right). Image © Moritz Hobe.

category. They also had to retrieve the exact values for specific data points, compare single bars or assess the outcome of summarized values (see Figure 6.9-right). Participants were encouraged to use the stand-alone scales to fulfill these tasks.

Data Collection & Analysis

We gathered several types of data to evaluate the memorability but also to further analyze and interpret the results. The study leader observed the participants during the study and took notes, e.g., of unexpected behavior. We also videotaped the *exploration phase* with two cameras from different viewing angles, to allow a recapitulation of such unexpected interactions or behavior if necessary. Through pen-and-paper questionnaires and semi-structured interviews in both sessions, we collected qualitative data. The goal was to obtain more information about the participants' process of recall and their opinions whether and in which ways the physicalizations differed in their potential for memorizing information.

Similar to our previous study, we used an online quiz to test the recall of information. Participants had to fill out the quiz directly after the two *exploration phases* and with a delay of one week. It contained different question categories:

- *extreme values:* Questions related to minimum and maximum values (e.g., “Which country had the highest Gross Domestic Product (GDP) growth rate?”). Answers were chosen from a drop-down list and consisted of either a specific country or a specific numeric value.
- *facts:* Questions related to general facts about the underlying data (e.g., “In which countries did the GDP increase between 2000 and 2010?”). Answers were chosen by selecting the corresponding checkboxes.
- *summations:* Questions that included the addition of values (e.g., “In which countries is the addition of secondary and tertiary education higher than 60%?”). Answers were chosen by selecting the corresponding checkboxes.

The questions about *extreme values* and *facts* were similar to the categories of the previous study. Instead of *numeric values* we used *summations* to encourage further physical interaction, e.g., placing the bars on top of each other. The list of answers did not include the choice of “I don’t know”, as this was hardly selected in the previous study. Based on the findings of the first study, we only focused on *cued recall*. The quiz after one week contained several additional questions that were not part of the first one:

- *image recognition:* Pictures of the assembled physical bars for one country were displayed but without the attached flags. Participants had to recognize the country and select the corresponding checkbox.
- *additional general questions:* General questions about the underlying data which were not asked in the first quiz.

The questions regarding *image recognition* aimed at evaluating not only the semantic knowledge received through the representation but also the recognition effect of the optical impression and corresponding physical characteristics. With the *additional general questions*, we wanted to investigate whether participants recalled information because they had to give the answers in the first quiz or if they actually remembered the information from the physicalization.

6.2.4 Results

This section presents the results of our study evaluating the recall performance of information perceived with modular physical bar charts. We also give a summary of participants’ opinions gathered through questionnaires and interviews.

Qualitative Questionnaires & Interviews

After each *exploration phase* with a physicalization, participants had to rate various characteristics of the representations on 5-point Likert scale questionnaires ranging from 1=*strongly agree* to 5=*strongly disagree* (see Figure 6.10). Participants rated both physicalizations as easy to use and inviting to interact with. This leads to the assumption that the results regarding the recall performance are not influenced by reading or interaction difficulties. Participants found the 3D physicalization more fun to interact with compared to 2D and considered the 3D modality as more memorable than the 2D version.

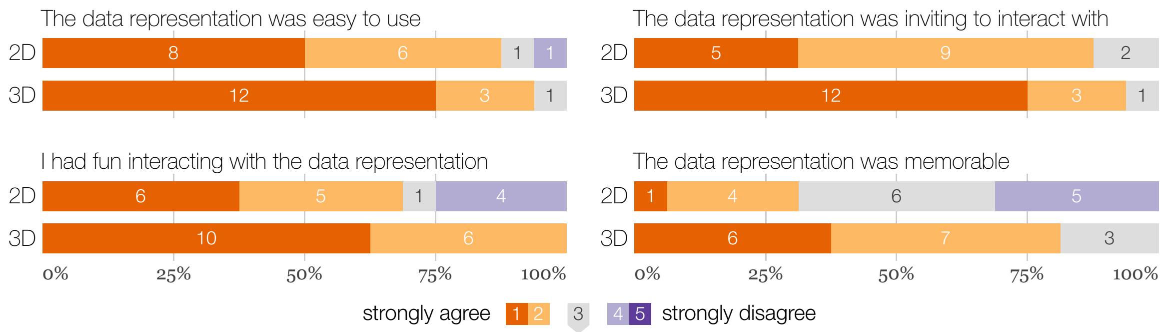

Figure 6.10: Results of the 5-point Likert scale questionnaires participants filled out after the each *exploration phase* of a physicalization.

We also asked participants to rank which modality they perceived as being more "present." The 3D modality was ranked better by the majority of participants both after the first session (*3D*=11, *2D*=3, *no difference*=2) and the second session a week later (*3D*=14, *2D*=0, *no difference*=2). However, participants had difficulties to support this assumption, e.g., by giving concrete details about the physicalization with wooden blocks.

Recall

As the overall recall performance for both datasets combined showed only a minor trend for the 3D modality, we had a deeper look into the results separately for each dataset. Figure 6.11 illustrates the percentage of correct answers for *immediate* and *delayed recall* for both datasets limited to the questions that were asked in both quizzes. The percentage of correct answers is higher for the 3D modality, both for immediate and delayed recall. This trend is much stronger for the *population* dataset. The percentage of correct answers for the *economic* dataset is quite low, independent of the modality.

As our previous study revealed that physical bar charts have advantages for remembering *extreme values*, we had a detailed look at the results of questions regarding *extreme values*. Figure 6.12 shows the percentage of correct answers about extreme values for the *population* dataset. It reveals that extreme values can be remembered better in the 3D modality, in particular for the *immediate recall*. The split into minima (lowest bars) and maxima (highest

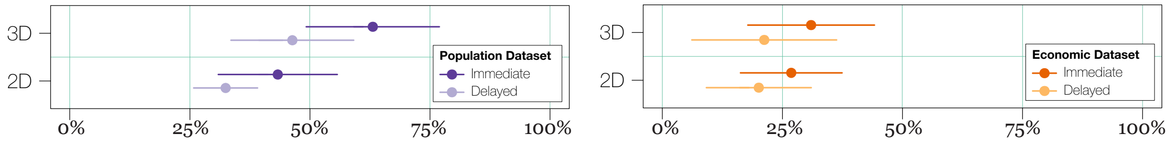

Figure 6.11: Percentage of correct answers for *immediate* and *delayed recall* for the *population* and *economic* dataset (with 95% CIs).

bars) uncovers that this result is mainly impacted by the better memorizations of maximum values in the 3D modality. While in our previous study the physicalizations only showed an advantage for the *delayed recall* for *extreme values*, this time, the difference between the modalities seemed higher for the *immediate recall*. The economic dataset showed a similar trend but much less distinct.

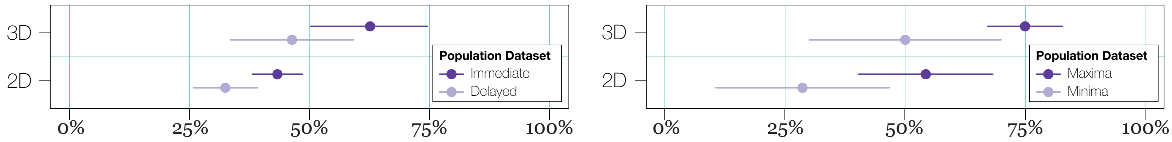

Figure 6.12: Left: Percentage of correct answers for *immediate* and *delayed recall* for the *population* dataset limited to questions about *extreme values*. Right: Percentage of correct answers for *immediate recall* for the *population* dataset, limited to questions about *extreme values* and divided into maxima and minima extrema (with 95% CIs).

A different view on the recall performance is presented in Figure 6.13. Here the results are grouped by the order the datasets were presented to the participants, independent of the modality. For the *population* dataset, a minor trend can be identified, that participants could remember the information better when it was encoded in the second physicalization. For the *economic* dataset a larger difference can be discovered. In particular, for the *immediate recall*, the order in which the physicalizations were handed out had a clear influence on the recall of information of the *economic* dataset.

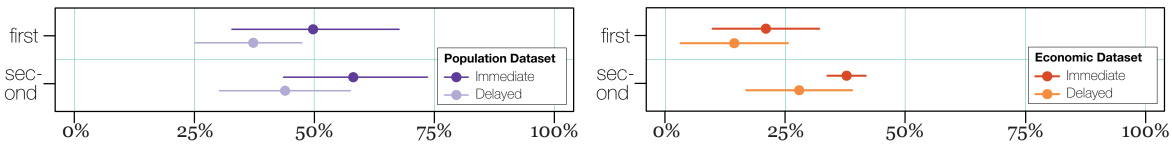

Figure 6.13: Percentage of correct answers for *immediate* and *delayed recall* for the *population* and *economic* dataset, depending on whether it was encoded in the first physicalization that was presented or the second (with 95% CIs).

Regarding the results for *facts*, *summations*, and *additional questions*, that were only asked in the second quiz, a small trend in favor for the 3D modality could be found. The same was true for the *image recognition* questions.

6.2.5 Discussion

While the results partially confirmed our findings from the previous study, they also revealed new observations, e.g., the strong influence of the dataset on the recall performance. In the following we discuss the results in the light of the dataset, the physical interactions, and the modality, but also, state the limitations of our study.

The Role of the Dataset

The results showed a clear difference in the recall results regarding the two datasets. The *population* dataset indicates a larger advantage for memorability for the 3D modality in both quizzes than the *economic* dataset. The recall performance for the *economic* dataset was in total quite low. The rather little differences between the *immediate* and *delayed recall* for the *economic* dataset can be explained through the aspect, that a small amount of facts, which were surprising or sticking out, can be remembered reliable, possibly independent from the type of data representation.

Participants also left questions unanswered much more often for the *economic* dataset than for the *population* dataset. While for the *population* dataset 85% of the questions were answered in the first quiz and 64% in the second, for the *economic* dataset it were only 62% and 49%. This suggests that participants did not remember the information wrong, but had difficulties in remembering it at all.

The semi-structured interviews revealed that most participants bore no relation to economic topics and stated that the data was too abstract and less interesting. This could be explained by the aspect that the majority of our participants were computer science students, with less interest or knowledge in economic topics. Jean Piaget's theory of constructivist learning, for example, assumes that the assimilation of external information is dominated by internal constructions and that learning is contextual, which means that humans learn in relationship to previous knowledge (e.g., Hein [1991]). A different view becomes apparent for the *population* dataset, as participants stated that the underlying data consisted of "*concrete and easily imaginable categories.*" These aspects seemed to have a relevant influence on the perception and memorization of the physicalization and its encoded data.

The quiz results further indicated that the gained information about the *economic* dataset was "overwritten" by the following information about the *population* dataset, but vice versa this effect was much lower. This can be partially explained by the interference theory, which states that an interaction between new and past learned knowledge can have an adverse influence on the speed of learning and memory performance. The two main kinds of interference are *proactive* and *retroactive interference*. The former explains the forgetting of new information because of memories and knowledge that was learned beforehand (e.g., Underwood [1957]). The latter describes the phenomenon when newly learned information is disrupting or hindering the recall of previously learned knowledge (e.g., Wohldmann et al. [2008]).

Another potential explanation for the differences appeared when we had a detailed look at the range of the values in the two datasets. For the *population* dataset, the distance between extreme values and their direct neighbors was higher compared to the *economic* dataset. This ends in more distinct visual differences, which probably increased the potential for memorization.

The Role of Physical Interaction

As previously mentioned, the visual difference between extremes and the neighboring values was higher in the *population* dataset. Therefore, the visual sense seemed sufficient to distinguish differences and detect extremes for the *population* dataset, as participants directly compared two bars only two times on average. In contrast, such comparisons, in which two bars were placed next to each other or measured with the help of the stand-alone scale to identify the higher or lower one, were made on average almost six times for the *economic* dataset. This leads to the assumption that the greater number of interactions could not compensate the lack of visual differentiation.

During the *exploration phase* participants had to assemble the overall physicalization from single bars and measure or compare single bars to retrieve values. Surprisingly, there were no larger differences in the ways in which the participants assembled the physicalization, e.g., all participants placed the wooden blocks upright. While our expectation was that these physical interactions, in which participants had to grasp and lift single bars could support the perception and memorization of information, only two participants stated that the manual assembly helped them to remember the categories and countries. An often used term by the participants to describe the interactions was “mechanical”. Participants reported also, that they tried to finish the initial assembly as fast as possible, as they assumed that a quick and unproblematic interaction with the bars was the focus of the study. This can also serve as an explanation for the low recall performance of the *economic* dataset as participants seemed to find the actual data not only uninteresting but also unimportant relating to the study.

During the semi-structured interviews in the second session, we learned that participants criticized the physical interactions as rather unnecessary. When asked about the study procedure four participants did not remember any use of the stand-alone scale until an explicit question about it. Similarly, one participant reported that she recognizes the scale, but declared that she used it very rarely. As a large part of the study consisted of comparing and measuring values, which necessitated the use of the scale, this statement is surprising. Grasping movements in the direction of the countries or single bars involving the kinesthetic sense also seemed no aid for the recall process, as only one participant remembered a specific grasping movement. It emphasized again that the physical interactions were performed almost automatically and that these interactions, based on participants' subjective opinions, could not support the process of memorization.

This shows that the design of effective and meaningful physical interactions for physicalizations is challenging and that the chosen approach to "enforce" specific interactions was not productive. The high repetition of the same, rather artificially encouraged, physical interaction of assembling and moving paper stripes or wooden blocks was probably too familiar, but also perceived as rather unnecessary, to generate actual benefits.

The Role of Modality

The results regarding the recall performance showed a trend that participants could remember information better when they perceived it with the 3D modality. Similar to the discussion of the results of the previous study we believe that the more vivid visual appearance of the wooden blocks compared to the paper strips are one possible explanation. The additional characteristics of the 3D wooden blocks such as the top and side faces or the volume contribute to the distinctiveness and might explain the benefits compared to the 2D paper strips. This is in line with the findings of Scott [1967] that object names are less memorable than pictures because they are less distinctive.

One participant furthermore stated that the 3D modality and the perceived information replaced the 2D modality completely in her impression. The weight of the single wooden blocks did not seem to support the perception or memorization of information, as none of the participants stated that they notably perceived the weight or could make use of the sensed information. This can be explained by the fact, that humans have evolved an expectation and "sensation" about the weight of everyday physical objects, therefore the weight differences of our standard wooden blocks were probably not perceived intentional.

One surprising statement by a participant referred to seriousness and credibility. She described the paper strips as "*flimsy*" and "*easy to manipulate*" and reported she took the wooden blocks more seriously. This could be an exciting area for future studies, e.g., by evaluating whether people trust data that is encoded in a physicalization more than data encoded in a digital visualization. A study by Ackerman et al. [2010] already investigated that the subconsciously perceived weight of an object can have an influence on cognitive processes. In this case, participants ranked job candidates better, when the application documents were attached to a heavy clipboard.

The better recall performance was especially the case for extreme values, which confirms to some extent the results of our previous study. As we do not believe that one of our two physicalizations is more novel or ordinary than the other, we assume that we can rule out a novelty effect, which was one possible explanation for the results of the first study. While in our first study the advantage for extreme values perceived through a physicalization was revealed in the *delayed recall*, in this study, a larger effect was found for immediate recall. Compared to the first study, participants also seemed to forget more information perceived with the modular physical bar chart within one week than with the static physical bar chart within two weeks. In addition to the different data representation, this could be influenced by the dataset, the study design, and the tasks.

In summary, it can be argued that a higher distinctiveness, when designed properly, may affect the perception and recall of abstract data in a positive way to a certain amount. The results of our the second study furthermore assume that the distinctiveness is based on the 3D modality and not mandatory for physical visualizations.

Limitations

Our study has various limitations and further aspects that should be considered when interpreting the results. Similar to the previous study we only investigated two specific types of data representations and only focused on the physical modality. Further visual mappings and other modalities should be tested to generalize our findings.

One aspect that seemed to influence the results noticeable was that our participants were mainly computer science students. Almost all participants stated that they had no relation to economic topics, which led to a quite low recall performance. This highlights two aspects, which are important to bear in mind, especially regarding studies about memorability. On the one hand, the choice of test datasets should be well-considered and on the other hand, preferences and previous knowledge of the participants should be interrogated. Similarly, the expectations of the participants regarding the study can have an influence as some stated that they focused on a fast and smooth interaction and not on the encoded data.

As another critical aspect, it should be mentioned that visualizations or physicalizations are often used to make complex data more accessible. It seems that the chosen physicalizations were not always able to fulfill this purpose. While for the *economic* dataset none of the physicalizations were successful, the 2D paper strips had also for the *population* dataset a rather low recall performance. This questions whether this type of data representation is actually suitable for representing abstract data.

The tasks and physical interactions of our study are further limiting factors, especially as participants stated that they often seemed unnecessary and were executed “mechanically.” Future studies could consider integrating the exploration and analysis of a data representation into a main problem-solving tasks, in which physical interactions are required and meaningful to comprehend the underlying data.

Chapter 7

Potential for Communication & Collaboration

The evaluations of our early physicalization prototypes (see *Chapter 5 - Beyond Physical Bar Charts*) revealed that physicalizations have a potential for presenting data in novel ways and also might benefit collaboration processes. When asked about application scenarios, for each prototype several participants mentioned museums and other public spaces, as physicalizations seem promising to encourage data exploration. Others mentioned meeting rooms and presentation stages, which strengthens the assumption that physicalizations have possible benefits for communicating and talking about data. When presenting our prototypes publicly (see *Subsection 5.2.1 - Layered Physical Visualizations on Tabletops* and *Subsection 5.3.1 - Data Exploration Matrix*), we observed that people did not only talk about the prototype but also discussed the underlying dataset and explored the data together.

This chapter presents two projects, which are based on these observations and investigated in which ways the aspect of presenting data physically impacts a joint data exploration. The first project describes our design process of paper-based pop-up physicalizations and the feedback from a hands-on evaluation, as we handed them out to more than 400 attendees of a scientific conference as part of the conference bags. In the second project, we compared the ways in which groups work together on data representation tasks, either using digital visualizations or physicalizations. We conducted an exploratory study with eight groups each consisting of three participants, to see whether physicalizations influence or even enhance group work. Both projects revealed the importance on the design and aesthetic

Personal contribution statement: The content of this chapter is based on two student's theses by *Arnold Schefner [2014]* as well as *Xaver Loeffelholz and Peter Arnold [2015]*. The latter was supervised by Sarah Tausch and the author. See *Disclaimer* for a detailed overview.

of physicalizations and exposed their limitations in contrast to their well-researched digital counterparts. The results also led to the assumption that physicalizations seem to polarize: Either participants strongly enjoyed working with them or rejected them as inconvenient and pointless toys.

7.1 PopUpData

Our first project that investigated the ways in which physicalizations can support the communication of data and encourage discussion about the underlying dataset focused on paper-based pop-up physicalizations. As pop-up cards are fun to create and receive, we wanted to take advantage of these characteristics by utilizing pop-up cards in the area of data representations (see Figure 7.1). We were especially interested in the question whether the act of assembling a personal pop-card, e.g., by folding and sticking, would engage participants, make them understand the underlying data, and lead to sharing and discussing the physicalizations. In this section, we report our design process and lessons learned from an initial study as well as the feedback from a hands-on evaluation, in which the attendees of the TEI 2014 conference received a pop-up card as part of their conference bag.

7.1.1 Motivation & Background

Our goal in this project was to introduce pop-up cards into the field of physical data representations. We believe that pop-up cards are an exciting addition to this field, as people can touch and interact with them, but also build their own pop-up physicalizations from scratch. They seem to provide a variety of possible benefits, such as leveraging human perceptual exploration skills, bringing data into the real world, or just engaging people in exploring data in new ways.

Paper-based pop-up cards and books fascinate people of all ages and cultures. It is intriguing to watch 3D shapes pop up out of nowhere just by opening an initially flat, folded piece of paper. The design and construction of great pop-ups is challenging and artists in this field are often titled paper engineers. To create functional and aesthetic pop-ups requires both artistic and technical skills [Glassner, 2002a]. The technique of pop-ups is most popularly used in children's books to enrich the storytelling but also for illustration purposes in areas such as geometry or medicine [Ruiz et al., 2014]. In the following we will give a brief overview of paper crafting in general and projects related to HCI.

Paper Crafting

Paper crafting has fascinated people probably since the invention of paper itself. Origami, the traditional Japanese art of paper folding is several hundred years old and still a popular type of paper craft that has been explored in literature (e.g., Demaine and O'Rourke [2008];

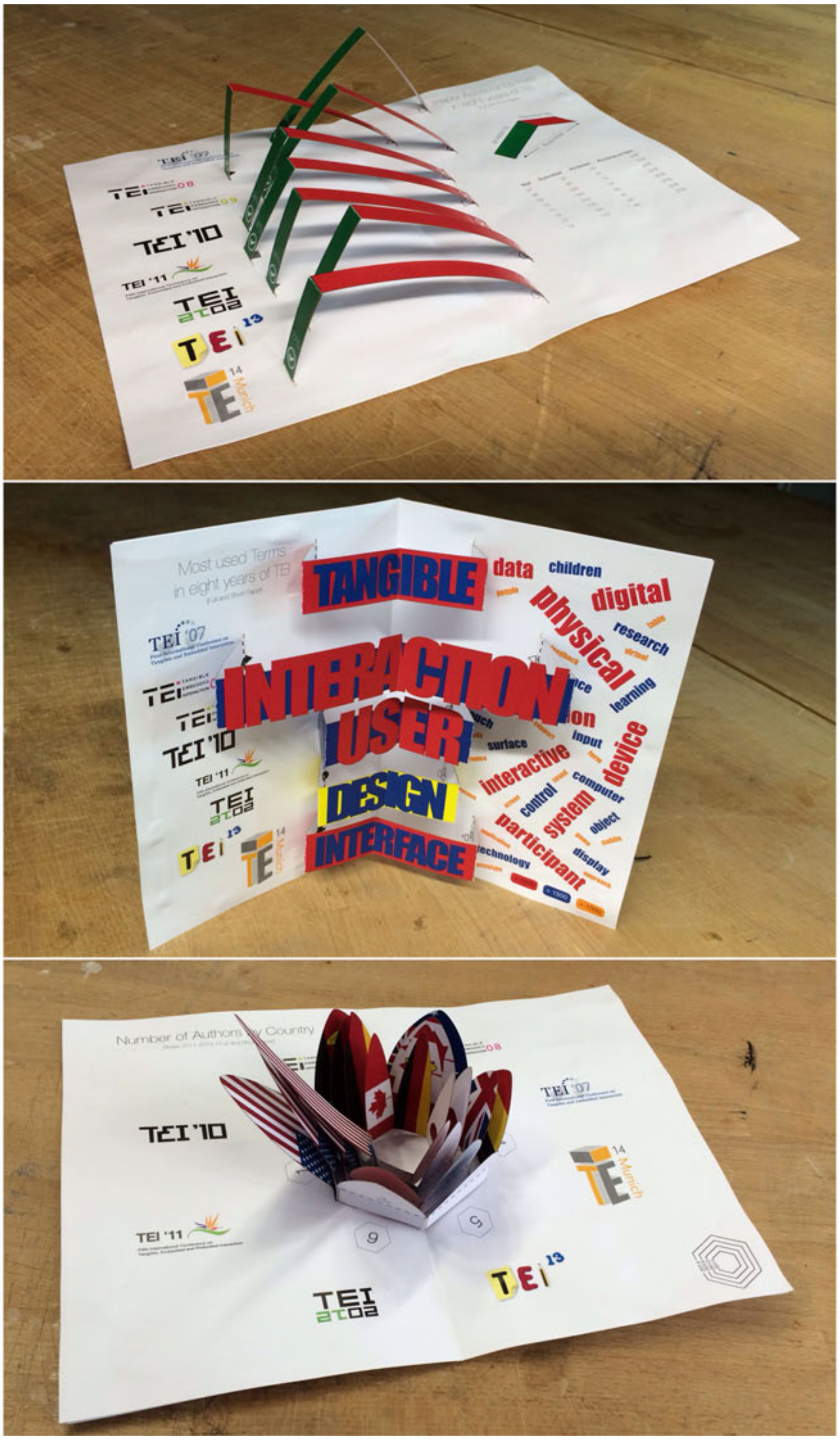

Figure 7.1: Final designs of the three pop-up physicalizations encoding data related to the TEI conference. Top: *summit* representing the acceptance rate. Center: *word cloud* representing the most used keywords. Bottom: *flower* representing the number of authors by country.

Hull [2012]). Origamic Architectures are a special type of paper pop-ups that involve cutting and folding of a single sheet of paper. Most scientific work in this area focused on methods to automatically generate pop-up cards that closely depict an input 3D model (e.g., Li et al. [2010]; Le et al. [2014]). As the design of pop-up cards can be difficult because of the various constraints required to make the card fold flat, a number of papers proposed interfaces for assisting the design and production of pop-up cards (e.g., Hendrix and Eisenberg [2006]; Okamura and Igarashi [2009]). In contrast to Origamic Architecture, pop-ups cannot only be created through folding and cutting but also by gluing pieces of paper together.

The work of Glassner [2002a,b] gives a thorough introduction to the design, creation and definition of simple pop-up mechanisms such as the "single-slit" or the "V-fold". Pop-up cards are called valid when they are both foldable and stable. When the structure can fold completely flat, a pop-up is said to be foldable. If the closing and opening of a pop-up does not need any extra external force besides holding the two outermost areas on each half of the ground paper, a pop-up is said to be stable [Ruiz et al., 2014].

These references provide a solid conceptual basis for the design of pop-up cards as well as its opportunities and limitations. Our literature review also confirmed that, apparently, pop-up cards have not been applied in the field of data representation so far. Recent work that integrated pop-up constructions in classrooms lead to strong student engagement and collaboration [Olsen et al., 2013]. This increased our expectations about the potential of representing data with pop-up cards.

7.1.2 Design Process

Our design process was mainly guided by the opportunity to place the final pop-up physicalizations in the conference bags for the attendees of the 8th international ACM conference on Tangible, Embedded and Embodied Interaction (TEI 2014). Informal discussions with colleagues lead to five key design goals:

- *Data:* the data that is represented through the pop-up physicalizations should be of interest to the attendees of the conference and potentially trigger discussions.
- *Data representation:* the pop-up physicalizations should be aesthetic, to motivate the conference attendees to assemble it and keep it as a souvenir. The underlying data should be easy to read from the final pop-up.
- *Assembly:* as the spare time at conferences is short, the assembly of the pop-up physicalizations should be easy and not take up too much time.
- *Fabrication:* the fabrication should be automated as far as possible and supported by digital fabrication machines (e.g., laser cutters) to enable production for the more than 400 attendees of the TEI conference in a reasonable time.
- *Valid pop-up:* The pop-up physicalizations should be foldable and stable (see above).

Datasets

We considered various datasets that might be interesting to the attendees and were especially inspired by the statistics that are shown during welcome presentations at conferences. We finally used five different datasets containing the following three data categories:

- *Acceptance rate:* the paper acceptance rate can be seen as a quality criterion for scientific conferences. Especially authors with accepted papers are often curious about it. We used the acceptance rate of all previous TEI conferences from 2007 to the current one in 2014 for our physicalizations.
- *Paper keywords:* the evolution of terms and keywords over the history of the TEI conferences seemed to be an exciting dataset that could evoke discussions (e.g., why a term was only popular in a specific year). We included two datasets, one with the most popular author keywords and one with the most used terms based on a full-text search on all accepted papers from 2007 to the current one in 2014.
- *Origin of authors:* For an international conference, not only the attendees' origin is of interest, but also which countries were most successful in having their papers accepted. We decided to focus on the number of authors by country, as including single affiliations seemed too complex for the limited resolution of a pop-up physicalization. We used two datasets for our physicalizations, one including only the first authors and one including all authors from 2011 to the current one in 2014.

Prototypes

For each data category, we iteratively developed an individual type of pop-up physicalization. The resulting final designs are shown in Figure 7.1. All physicalizations are built on a sheet of DIN A4 paper, which is folded in the center of the long edge and has slots into which different paper strips are inserted. The difficulty of assembly of the prototypes varies with the number of paper strips and the complexity of their folding.

Summit The *summit* pop-up physicalization (see Figure 7.1-top) consists of eight paper strips, each 15 cm long with three folds (1 summit fold, 2 for attachment). Each strip represents one conference year (2007 to 2014). The surface of the strip is proportionally colored either red (rejected) or green (accepted) according to the acceptance rate. The border between these areas determines the position of the summit fold and hence the summit shifts left or right according to the acceptance rate. The total number of submitted papers determines the relative distance between the two slots in the ground plate for each strip so that the folded strip will form a triangle of given height. More submissions yield a wider mountain. Finally, the absolute position of the slots in the ground plate is indirectly determined by the other restrictions, to receive a valid pop-up card. This is the reason why the mountains do not start on one line, and the summits are also not in one line (see Figure 7.1-top).

Word Cloud The *word cloud* pop-up physicalization (see Figure 7.1-center) consists of five differently sized paper strips with five folds each. Each strip represents one of the five most used author keywords or terms, which is printed on the strip. The size of the strip and its pop-up height represent the popularity of the word. On the left next to the word we printed graphs of the total count of the particular word for each year (2007 to 2014) and on the right its ranking position. The positions of the slots on the ground paper were chosen to receive an aesthetic arrangement of the words.

Flower The *flower* pop-up physicalization (see Figure 7.1-bottom) consists of four paper strips with fifteen folds each. Each strip represents one conference year (included are 2011 to 2014) and each of the six flower petals represents one of the six most successful countries regarding the number of (first) authors. The length of the petal is mapped to the total number of authors. The slots have a fixed position on the ground to transform the paper strips into a hexagonal form when the card is popped up.

Pre-Study

We showed and discussed preliminary designs with colleagues during the entire design process. We also conducted a pre-study with 6 participants to evaluate our final prototypes. Each participant had to assemble all three physicalization types in a random order and was asked to speak out loud, what she was thinking. The study showed that the successful assembly of each physicalization took about 10 to 15 minutes, which seemed like an adequate duration. We rephrased some parts of the assembly instructions and made some more design changes based on recommendations by the participants.

Fabrication

The actual fabrication was split up into two parts: the digital design and creation of the physicalizations and its analog production with the help of a laser printer, laser cutter, and handwork. We used Processing[1] to generate the shapes of the paper strips algorithmically based on the datasets. For the general layout and specific content, e.g., the assembly description, we used Adobe Illustrator.

The ground plate of each pop-up physicalization consisted of two pieces of paper glued together. The assembly description and a link to an online questionnaire were printed on the back, general information regarding the physicalization (e.g., the legend) on the front (see Figure 7.2). We used a laser cutter to cut out the various paper strips and their slots on the front paper (see Figure 7.3-left). It was possible to stack five pieces of paper on top of each other and cut them in one pass, which accelerated the fabrication process. We further placed as many shapes as possible on one single page to minimize the effort of switching papers during the cutting process. The final step was to collect all physicalization parts (ground paper and its associated paper strips) in a transparent envelope, which was then placed in the conference bags (see Figure 7.3-center and right).

[1] `https://processing.org/` (accessed 2015-12-15)

Figure 7.2: Final graphical design of the ground plates (clockwise from top-left): back plate with assembly description and a link to an online questionnaire. Example front plates for the *word cloud*, *flower* and *summit*. Bottom: Examples for the different paper strips.

Figure 7.3: Fabrication of the physicalizations. Left: The single paper strips were cut with a laser cutter. Center: Collection of cut paper strips and glued ground papers. Right: Final envelope that was placed in the conference bags including all physicalization parts.

7.1.3 Study Design & Results

We wanted to investigate in which ways the conference attendees would use and respond to our physicalizations, and we were curious to see whether possible benefits on a perceptual, cognitive or societal level would emerge. Since the pop-up cards had to be assembled by the attendees, we wanted to explore the ways in which this influenced their understanding and interest in the underlying data.

After the conference bags had been handed out to the more than 400 attendees of the TEI 2014 conference, we observed in which ways they used the physicalizations during the conference and had informal conversations with some of them during coffee breaks. We printed a hashtag (#teipaperviz) on the physicalizations to evoke reactions in social networks and added a link to an online questionnaire. Printouts of the questionnaires could also be found at the reception.

The feedback given personally by conference attendees during conversations was positive and encouraging. Most of them stated that the physicalizations looked nice and that the assembly was fun, although a bit complicated and sometimes unclear (see Figure 7.4). We observed that most physicalizations were assembled during the first two days of the conference when the workshops took place. We believe that the fact that the attendees were already manually active during the workshops increased the motivation to assemble the pop-up physicalizations. Also, the available spare time and suitable places for the assembly became less once the main conference started.

We received ten completed questionnaires, which was much less than expected, but still provided many interesting insights. In particular, a lot of comments were added to the different questions. All participants did succeed in assembling the physicalization. While eight of them rated the assembly as “easy” or “very easy”, two, who had found the flower in their conference bag, chose “very difficult.” All attendees stated that they did understand the physicalization and the underlying data, but rated it as rather difficult.

Figure 7.4: From left to right: An attendee struggling with the assembly. A wrongly assembled pop-up physicalization (missing summit fold). A pop-up physicalization which is kept as a souvenir and used as a wall decoration. Discussion about the physicalizations on a social network.

The answers why participants tried to assemble the pop-up physicalization varied, from “*I was bored and had waiting time*” to “*I was curious what it would look like.*” All participants agreed, that the instructions were still sometimes unclear and the assembly sometimes tedious. One subject wrote "*thankfully I love manual work and challenges*", another was less positive: "*I got it all to work, but it wasn't fun.*" The physicalizations were also part of conversations during the conference as seven of the ten participants specified. Some attendees also shared photos of the physicalizations on social networks (see Figure 7.4), but this was not as popular as we had expected.

Most participants liked the general idea of encoding data with pop-up cards. One stated, "*It makes one more happy to see the results, instead of looking at a table.*" Another emphasized, "*I actually memorize the acceptance rates better because I paid more attention to the numbers when assembling the visualization.*" A more critical comment was "*physical data visualization is a good idea. Assembling paper cut outs is a tedious way to do that, though.*" Regarding the question whether the attendees will keep the physicalization as a souvenir of the conference, the answers were split five to five. One comment was "*I don't know how long I will keep it, but for now, it's on my desk, and I like looking at it*", another stated "*I am excited how my colleagues who did not participate will respond to it*" and one was just enthusiastic: "*Of course! It's cool and original!*".

7.1.4 Discussion

The low participation of only ten completed questionnaires out of over 400 potential candidates was somewhat disappointing to us. After discussing potential ways to fix this, we consciously refrained from sending out more reminders or pushing for additional replies, as we were afraid this would introduce a positive bias (good-subject effect). The richness of the answers we did receive, including the written comments and discussions at the conference, still provides a sound basis for further investigation, as the general response was positive and intriguing.

The primary concern raised by most attendees was the rather unclear description how to assemble the pop-up physicalization. We explicitly decided against printing a picture of the final physicalization next to the description to maintain the excitement about what it would look like at the end. However, many attendees suggested this as an improvement. A comprehensible instruction seems to be a key point for motivating people to try the assembly. While we thought the assembly process could be an essential aspect to encourage attendees to explore the dataset and to get into a conversation with others, our observations could not confirm this assumption. In retrospect, the hand out of already assembled pop-up physicalizations might have been a better choice, as participants would have had more time to concentrate on the data. The aspect that the majority of the participants stated that they understood the physicalizations, but found the encoding process rather difficult, argues for the use of more classical data representations, such as bar charts or line graphs.

One other possible explanation for the small number of attendees, who assembled the physicalizations and gave feedback, is the particular subject group: TEI participants are used to exciting novel physical and interactive artifacts, mostly involving computers or electronics of some kind. The fact that our physicalizations were "only paper" could potentially make them even less attractive in this particular context. At the same time, this opens up an exciting area for future work. Actuated electronics such as Shape Memory Alloys (SMAs) or inflatable pouches are already used as creative crafting material in combination with paper [Qi and Buechley, 2012; Niiyama et al., 2015]. These techniques could be used to enhance pop-up physicalizations by enabling details on demand or highlighting specific data points and thereby make them even more fascinating than they already are.

We still believe that also purely paper-based pop-up physicalizations are an exciting way to bring data into the real world. One example could be pop-up Christmas cards of companies encoding the economic process of the last year. For this case, a prior assembly, as well as a sophisticated and aesthetic design, seem to be crucial points. We also see a potential at kindergarten or primary school, at which handicraft work with scissors and paper is common. By creating their own pop-up physicalizations representing personal or historical data, children could engage with data representation in a playful and novel way.

7.2 Collaborative Physicalizations

While the project in the previous section observed in which ways paper-based physicalizations are used in the setting of a scientific conference, in this section we present a study exploring the potential of physicalizations for collaboration. We studied the ways in which groups work together on data representation tasks, either using physical or digital visualizations. More specifically, we compared line graphs that were either made from laser cut acrylic glass or displayed on tablet devices (see Figure 7.5). We conducted an exploratory repeated measures study with eight groups each consisting of three participants, to see whether physicalizations could enhance group work.

In questionnaires and semi-structured interviews, participants rated physicalizations as slightly more fun to use and better for sharing information with other group members as well as more convenient for open-ended tasks. On the other hand, digital visualizations were considered as more professional and easier to understand, which is not surprising given their long history. In general, we found that they polarized: Participants either strongly enjoyed working with the physicalizations or entirely rejected them as inconvenient compared to the digital counterpart on a tablet.

7.2.1 Motivation & Background

Working together in small groups of people to achieve shared goals is common and natural. This can have various reasons such as getting a job done faster, sharing information or benefiting from the combined expertise of different people. For sharing knowledge and

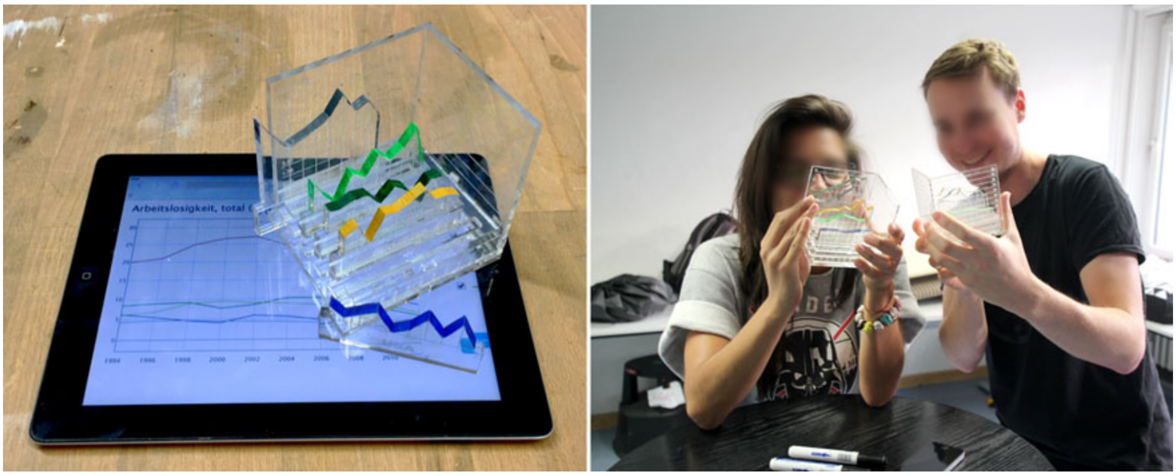

Figure 7.5: Left: The digital and physical visualizations used in the study. Right: Two participants using the physical visualizations.

understanding specific insights, a visual representation is often useful and necessary. Therefore, in the field of InfoVis an increasing number or projects are related to collaborative visualizations [Isenberg et al., 2011].

In our study, we wanted to explore whether physicalizations can be used for collaborative work. The unique characteristics of physicalizations, e.g., the fact that they are perceived with multiple senses and can easily be shared between collaborators, made it seem promising to explore in which ways people collaborate and communicate with physicalizations. In the following, we briefly discuss the area of collaborative visualizations and TUIs for collaboration, as findings suggest that tangibles can encourage collaboration.

Collaborative Visualization

The field of collaborative visualizations builds on findings from HCI, InfoVis and Computer-Supported Cooperative Work (CSCW). Isenberg et al. [2011] try to describe the entire scope of collaborative visualizations by defining it as "*the shared use of computer-supported, (interactive,) visual representations of data by more than one person with the common goal of contribution to joint information processing activities.*" While we agree with this definition and especially like the emphasis regarding "the shared use by more than one person" it is worth mentioning that the physical visualizations in our study were not computer-supported anymore, once manufactured.

There are various ways to categorize systems in the area of collaborative visualizations. The space-time matrix is borrowed from general collaboration scenarios and differentiates between space (distributed vs. co-located) and time (synchronous vs. asynchronous) [Baecker, 1994]. Another one is based on the level of engagement teams have with the data representation. This can vary from only viewing the information, actively exploring and interacting with the data or even creating new visualizations and sharing these with a larger community [Isenberg et al., 2011]. Other literature distinguishes between the underlying data (e.g., personal, scientific), the skills of the users (novice, savvy, expert) or their goals (exploration, analysis, communication) [Heer et al., 2008]. Based on these categorizations we see our work in the area of *co-located* data representations in which groups of *novice* and *savvy* users are *exploring* and *interacting* with a representation of data to *share knowledge* and *communicate* insights.

This rather new research area of collaborative visualizations poses many challenges in the intersection between collaborative work and visualization, such as the support and design of multiple in- and outputs [Isenberg et al., 2011]. However, the goal of our work was not to contribute in technology aspects, but rather in the field of social interaction and the observation and evaluation of the collaborative process itself.

Tangible Interfaces for Collaboration

Most projects in the area of collaborative TUIs combine tangible objects with interactive tabletops. Schneider et al. [2011] compared multi-touch and tangible interfaces for collaborative learning and found that the tangible interface fostered collaboration, helped exploring a larger part of the problem space and turned problem-solving in a more playful experience. A follow-up study showed that a tabletop system that enables tangible and digital exploration can support collaborative learning by engaging participants in the activity [Schneider et al., 2012].

Other studies showed that physical objects can increase engagement and exploration among children [Antle et al., 2009] and have great potential to encourage collaboration [Stanton et al., 2001]. Also, they are suitable for collaborative and situated learning [Klemmer et al., 2006; Marshall, 2007; Suzuki and Kato, 1995] as well as collaborative problem-solving activities [Xie et al., 2008]. Based on these studies, we believe that physicalizations can support people's engagement due to their aesthetics and affordances as physical objects.

7.2.2 Design Process

Our primary design goal was to find a visual representation that was suitable for group work and similarly well suited for both modalities to enable a fair comparison between them.

Datasets

As an abstract dataset, we used country indicator data from the world bank[2]. We created six subsets, each showing the development of one indicator for five countries (Germany, USA, China, South Africa and Brazil) over 18 years, from 1994 to 2012. To ultimately create tasks that involve collaboration we split the six sets into two triples that should be used by

[2] `http://www.worldbank.org/` (accessed 2015-12-15)

groups of three persons. The first triple of indicators was the GDP in US$, GDP growth (annual %) and the rate of Internet users per 100 people. The second triple consisted of total unemployment (% of total labor force), exports of goods and services (% of GDP) and imports of goods and services (% of GDP). Indicators, countries, and the time frame were chosen based on the availability of data, expected interest and with the goal to find highly visible developments over time and between countries.

Data Representation Type

Line charts are one of the most popular data representation types for time series data. They are also used on the world bank website to represent the chosen datasets graphically, beside tables and maps. They are well-known and commonly used in visualization or spreadsheet software and therefore should be easy to read and understand by our study participants. Furthermore they are suitable for both, an on-screen 2D visualization and a 3D physicalization.

Digital Modality

We chose a 2D layout similar to the one offered by the world bank for our six on-screen visualizations, which were created with the JavaScript library D^3 [Bostock et al., 2011]. Each visualization was shown on a tablet device (1280 x 800 pixels, 25.6 cm) in full-screen display. We chose tablet devices instead of laptops, computer screens or a projection in order to create conditions similar to the physicalization. In particular, this also ensured that each participant had his or her own visualization that could be held conveniently in one or both hands and easily be shown and handed over to the other group members. To enable a fair comparison between both modalities we kept the interaction possibilities rather simple, only allowing to show or hide specific countries via check boxes. Figure 7.6 shows our final design of the on-screen visualization.

Physical Modality

To create the six physicalizations we used transparent acrylic glass cut into shape with a laser cutter. The general design and physical size were inspired by the 3D bar charts used by Jansen et al. [2013]. It consisted of five country layers and five other layers for labeling and construction purposes. The final physicalization had a cube shape, with outer dimensions of 10 x 10 x 10 cm and matched the layout and colors of the digital visualization. To make distinction easier we painted only the top of every layer, so the colored lines would also be visible if occluded by other layers in front of it. Similar to the hide function in the on-screen visualization it was possible to take out each country layer. Two acrylic layers were used to show the vertical axes by engraved horizontal lines. Every country layer also had engraved vertical lines, which were lined up with the scale of years. Finally, we put little stickers on the side of every country layer to label the country, and one sticker on the back of the object to labeling the indicator. Figure 7.7 shows our final physical prototype.

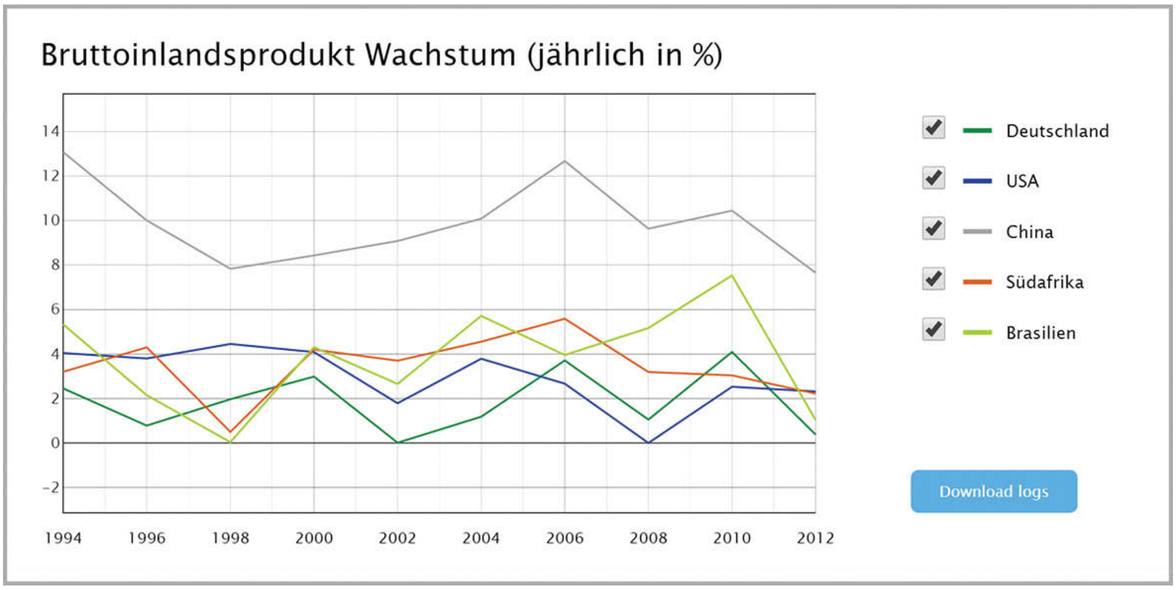

Figure 7.6: Final design of one of the line charts which were displayed in full-screen on tablet devices.

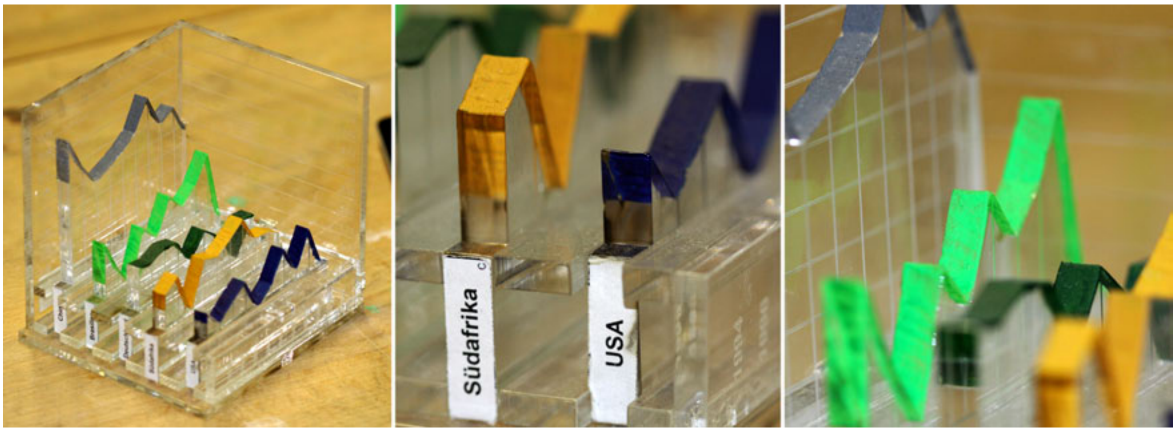

Figure 7.7: Final design of the physical line chart.

Dimensionality and Fair Comparison

It is worth highlighting that the data representations do not only differ in their modality (digital vs. physical) but also in their dimensionality (3D vs. 2D). While this decision introduces a larger difference between both representations, we argue that it still allows a fair comparison for several reasons. The previous study by Jansen et al. [2013] showed that physical 3D bar charts outperform their on-screen counterparts regarding information retrieval tasks, but that the digital 2D visualization performed best. Furthermore, on-screen 3D visualizations are generally considered problematic because of coverage and complex viewport control, as 2D inputs have to control a 3D visualization [Shneiderman, 2003]. In the physical world this is not the case as the person interacting with a 3D physical object can freely hold, rotate and move it in his or her hands. Therefore, we believe that our designs use the strengths of both modalities and do not impose artificial disadvantages on one of them.

7.2.3 Study Design

In contrast to our previous studies we did not focus on memorability aspects, task completion time or error rate. Instead, we were interested in i) learning more about social interaction in collaborative tasks when interacting with physical and digital visualizations, ii) gaining first insights in which ways physicalizations are used for collaboration and iii) exploring the potential of physicalizations for collaboration in general.

Participants

We collected participants through a social network and a mailing list of the university. To enhance group work, we asked for groups in which participants knew each other. We recruited eight groups with three participants each (in total 24 participants) who were between 20 and 31 years old (mean: 24.3 years; female: 11). Among the participants were 16 students (8 Media Informatics/HCI, 1 design in crafts, 1 magisterium, 1 medicine, 1 mechatronics, 1 bioinformatics, 1 graphic design, 1 engineering) and eight professionals (2 graphic designers, 2 consultants, 1 software developer, 1 business analyst, 1 store management assistant, 1 translator). Participants received a 10 Euro voucher for a well-known online store.

Tasks

We designed the tasks such that they made collaboration necessary. For each triplet of indicators we created six tasks (totally 12 tasks). The first four tasks were closed-ended, with certain countries, orders or numbers/values as correct answers. The first task always included all three indicators, while 2, 3 and 4 only included two indicators with all indicators appearing twice. Task 5 and 6 were open-ended tasks without a clearly right or wrong answer, involving all 3 indicators. These questions were designed to make participants explore the data more freely and focus on developments instead of exact numeric values. Some examples of the tasks are:

- Task 1: closed-ended question including all three indicators, e.g., “Did the country with the highest GDP-growth in the year 2008 also have a maximum in its GDP value and its rate of internet users in the same year?”
- Tasks 2-4: closed-ended question including two indicators, e.g., “Find the three countries with the highest GDP value in 2000. Order them by their GDP growth (from lowest to highest).”
- Task 5 and 6: open-ended questions, e.g., “Is there a correlation between the rate of internet users and the GDP value or GDP growth?”

Procedure

The study took place in an isolated and quiet room equipped with a bistro table and a whiteboard (see Figure 7.11). When participants arrived they were given an introduction to the study, and the upcoming order of events. After a first demographic questionnaire, they were introduced to the first modality, either the physicalization or the on-screen visualization. As an instruction, the study leader used one of the modalities and gave a short explanation on how to read the graphs as well as showing the interaction by taking a country layer out of the physicalization or hiding it with the checkbox in the digital visualization. Each participant was given one representation, and they were told to work together to solve the upcoming tasks. They were also told that they were allowed to exchange their representations with each other. Printed papers with tasks were placed on the whiteboard one at a time. The group was also equipped with whiteboard markers and should note down their answers on the whiteboard. Participants were encouraged to take as much time as necessary to find the answer but did not get any feedback if their answer was correct. The order of modalities and task sets was counterbalanced, and the study took one hour on average.

Data Collection

The experimenter observed the participants during the study and took notes. We also videotaped the entire process with two cameras in different viewing angles: a view from the top with a fisheye camera (see Figure 7.11) and one from the back. The videos were used to analyze the collaborative process, e.g., to see whether participants passed their visualizations on to each other. The whiteboard with the group's answers was photographed after each session to check correctness. Pen-and-paper questionnaires were used to gather demographic information and the participants' opinions on the data representations. A similar questionnaire was handed out after each modality and a third one in the end, in which participants had to compare the two modalities directly. We further conducted semi-structured interviews with each participant separately at the end of the study. These interviews aimed at obtaining more detailed insights about participants' positions whether and in which ways the data representations differed in their potential for collaboration.

7.2.4 Results

Our analysis and discussion is based on the data collected through questionnaires and interviews as well as the observations. The discussion is split into *Collaboration*, *Modalities*, and *Participants*. We will not focus on "time and error", as participants had marginal problems finding the correct answers for closed-ended tasks. Of an overall number of 48 tasks, four wrong answers in total were given with the physical modality and two wrong answers with the digital.

Collaboration

The collaboration was rated subjectively as perceived by the participants and also observed by the experimenters.

Perceived Quality The subjective perception of group work was equally positive for both, the digital and physical modality. Figure 7.8 shows the results of the 5-point Likert scale questionnaires (from 1=*strongly agree* to 5=*strongly disagree*), in which participants had to rate teamwork aspects after fulfilling the tasks with one of the data representations.

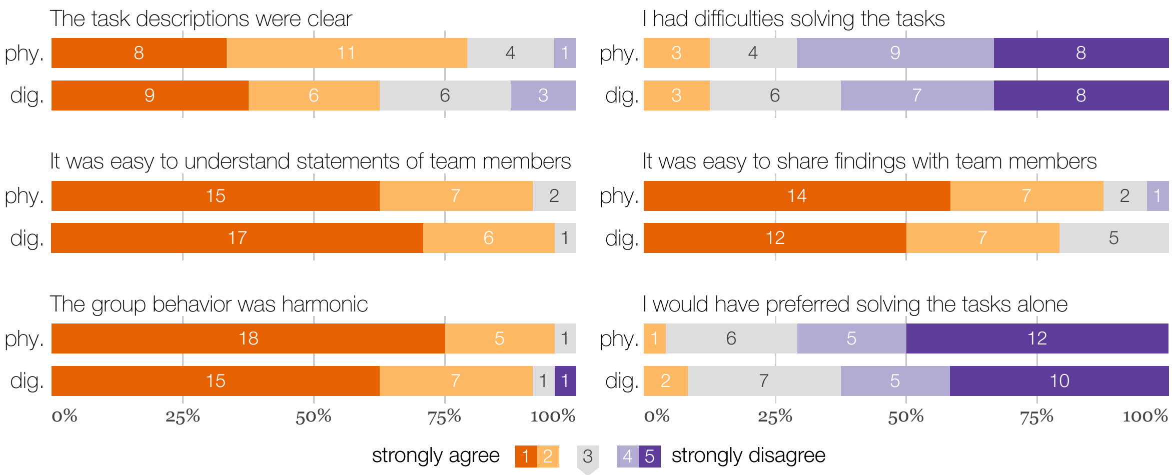

Figure 7.8: Participants' ratings for different teamwork aspects on 5-point Likert scales.

The majority of the participants understood the tasks and could fulfill them without bigger difficulties, independent from the modality. While participants found it a little easier to understand statements of team members using the digital visualizations, the rating to share information was slightly higher for the physicalizations. All participants rated the group behavior as harmonic, except of one, who strongly disagreed with this statement for the digital modality. The majority of the participants also reported that they liked solving the tasks together.

Participants mostly kept the representations they received in the beginning, even though we told them that exchanging representations was permitted. The ones with the relevant datasets for the specific tasks would then share the information gathered from their own representation. Whenever participants were not sure, they were inclined to show their representations to the others just to be sure. This review process differed among the two modalities. While with the on-screen visualizations, the person usually only pointed on their own tablet while other participants looked at their screen, the physical modality created more dynamic activity, such as handing over the object or walking around the table.

Observing the Open-Ended Tasks As desired, the open-ended tasks strongly triggered group work. Since there was no final correct answer to extract, participants gave much more thought to the questions. With the physicalizations, all teams decided to give up the order of "owning" one object and reporting findings to the other team members. Every team placed the three objects closely on the table to analyze them together. One very common approach was to arrange the physicalizations directly side by side (see images 4, 5, 6 in Figure 7.11) so everybody could have a look at all physicalizations at the same time. Some participants stated that the physicalization was more convenient for these open-ended tasks because they could arrange them close to each other and spot similar developments quicker. For the on-screen visualization only five of eight teams switched to a more open collaboration. These groups usually ordered the tablets in a way that all group members could view them together from a similar angle (see images 14, 16 in Figure 7.11).

Modalities

After completing both sets of tasks with the physical and digital visualization the participants received a last questionnaire in which they had to rate different modality aspects on 5-point Likert scales either favoring one or the other modality. Figure 7.9 shows that in general the digital visualization was rated slightly better than the physicalization.

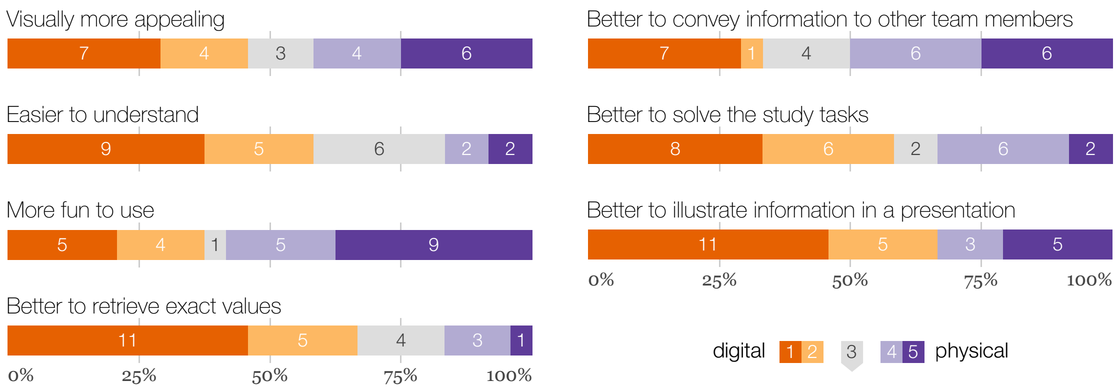

Figure 7.9: Participant's ratings for different modality aspects on 5-point Likert scales either favoring the digital or the physical modality.

Familiarity with On-Screen Visualization Many participants found the digital version easier to understand. This can easily be explained by previous experience with digital line charts, as participants stated that they were familiar with digital line charts as well as tablets and knew how to read and interact with them. The physical line chart was new for most of the participants and therefore they first had to learn how to read and use it. After a short exploration phase participants had no further problems in using the physicalization. No participant asked further questions to the instructor or other team members on how to read the visualizations or how to interact with them.

Accuracy of 3D Model Another benefit of the digital visualization was the fact that it was easier to retrieve exact values from it. This was because the digital visualization has a fixed viewpoint on the data at hand while participants had to create such a viewpoint themselves with the physicalization: "*It is just much easier to read data out of the visualization. With the physicalization, you always have to get the angle right before you can read the data and even then it might not be precise.*" (Participant ID: G5P2 = group 5, participant 2). Many participants would close one eye and hold the physicalization directly in front of their head to be able to read a exact numeric value. Figure 7.10 shows this problem of perspective distortion.

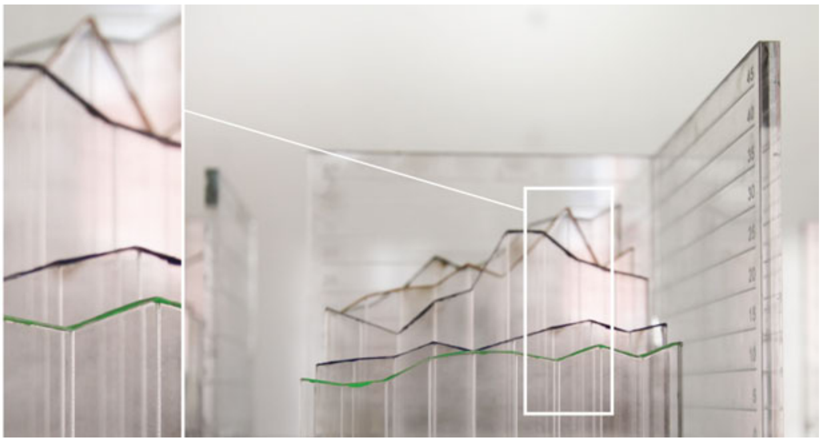

Figure 7.10: This picture illustrates the problem of perspective distortion. It is not possible to align all vertical lines of the physical modality.

Furthermore two participants (G2P3, G7P1) explicitly questioned the precision and reliability of the physical modality because of its production process. The accuracy of the digital version on the other hand was never questioned by them as it was not assumed to suffer from production issues, and infinite zooming was possible. In retrospect these drawbacks of the physicalization can also explain why the on-screen visualization was rated as better for solving the study tasks, as the number of closed-ended tasks requiring exact comparisons was higher than the number of open-ended tasks.

Usage for Presentation Two-thirds of the participants favored the digital visualization for a presentation. As we found out in the semi-structured interviews, most people thought it was also a matter of the audience's size. While many would use a physicalization for small groups, the digital version was favored in the general case with typical statements such as "*it's just way easier to show other people data on a projector during a presentation*" (G1P2). To emphasize the importance of professionalism in a presentation participants stated "*you just have to go with the time*" (G1P2) as a digital presentation is still perceived more modern and "*a digital visualization on a tablet is just more professional*" (G2P2). People that would rather use a physicalization stated, that it is a matter of personality which data representation suits the purpose better: "*I am more of a spatial person who likes to see things* *in 3D to get a better grasp of the information, and I would feel more comfortable using a big 3D visualization for my presentation*" (G3P3). Some of them also think the audience would remember statements better when they had this "*haptic sensation*" (G8P2) with a physicalization.

Perceived Fun A majority of the study participants considered the physicalization as more fun to use. As the perception of fun is very subjective, we tried to gain a deeper understanding of this within the semi-structured interviews. The participants who reported they had more fun with the on-screen visualization explained this mainly by complaining about the tediousness of the physicalization. As they had fewer problems with the tablet, they also gave it a better fun rating: "*It didn't take so much time to complete the tasks, so it was more fun*" (G4P2). On the other hand, the 58%, who had more fun with the physicalization, did not choose it because of shortcomings of the other modality. Most of these participants stated that they liked it better because they "*could touch it*" (G2P2, G7P1) and had "*something to play with*" (G7P1). Although a tablet also offers the option to touch it, this advantage was only mentioned for the physicalization. This shows in which ways a fabricated 3D model is still thought of being something more "real" and "concrete" than the digital counterpart displayed on a physical device. Some participants stated it reminded them of their childhood. One participant stated it was similar to be "*playing with a box of bricks*" (G1P1). This raises the questions how younger people or children would interact with the two modalities.

Figure 7.11: Pictures from our study illustrate in which ways participants worked with the two modalities.

Sharing Findings with Group Members Half of the participants rated the physical modality as better for conveying information to the other group members (16% no difference and 33% for the digital visualization). The semi-structured interviews revealed that this can be partly explained through interaction techniques that were only possible with the physicalization. With the physicalizations participants could draw direct comparisons between different datasets in an unforeseen way: Many groups appropriated the physical objects by pulling out the layers of a specific country from all physicalizations and spatially arranging them next to each other. They even overlaid them to compare different sets of data of the same country (see images 7, 8, 9, 10 in Figure 7.11). This is a good example of how the richer physical modality supports appropriation. It was not possible with the digital visualization because there was no way to transfer datasets from one visualization to the other. If someone wanted to show certain information to the others, they had to pass along the whole tablet, as opposed to only the relevant layers with the 3D models. Showing one or two country layers with one finger on a position of interest was perceived as a good way to share findings with multiple participants. The physicalization allowed also to sort the countries differently. Some participants stated that this gave them a "*better general overview*" (G2P3) of the datasets.

Physical Activity Apart from the questionnaire we made the general observation, that groups were physically much more active while solving tasks with the 3D models. When using the digital visualization, most of the time the tablets were just lying on the table, and information was exchanged mainly verbally. With the physicalizations, on the other hand, there was much more movement. The 3D models were grasped, lifted up and passed around, probably because of the more comfortable shape. The participants were more inclined to move around the table, look at the visualizations from different angles and change positions more frequently, especially during the open-ended tasks (see images 1, 2, 3 in Figure 7.11). The increase in movement could also partially be explained by the mentioned perspective problem, as participants needed to rotate the model or move to a certain position.

Participants

To see whether the findings of this study can be generalized, the influence within groups as well as the influence of the background and nature of the participants have to be discussed.

Group Dynamics and Opinions The rather split results of the 5-point Likert scales (see Figure 7.9) show that roughly half of all participants clearly favored for the digital modality. Even though the questionnaires were answered alone and without discussing them with the other team members, most groups showed similar preferences. Three groups completely preferred the digital modality, two groups the physical modality. One group had no clear preference. For two groups, one participant differed strongly from the other team members: In both groups, this participant preferred the physical modality while the rest of the group preferred the digital visualization. The tiny number of "no preference" ratings and our interviews show that people either really liked working with the physicalizations or rejected them.

Background of Participants A total of 75% of the participants were enrolled in technical university programs or have technical occupations and 33% were studying HCI. This could lead to two speculations: Participants with a technical background might rather reject the physical modality for practicability reasons. In contrast, HCI students might show more interest and acceptance for the new modality. However, we could neither detect a higher rejection from participants with technical backgrounds, nor a significantly higher acceptance from HCI students. The first group that completely favored the physicalizations consisted of three HCI students, the second of three graphic designers. However, another group entirely consisting of HCI students fully rejected the new modality. This shows that although a strong influence of the participant's personality or background is highly likely, this background can not be fully captured by the person's job or study subject.

The two participants who clearly favored the physical modality while their team members had contrary opinions could serve as good directions for possible interest groups of physicalizations in the future. One of them is a consultant working in finance (G8P2). She stated that the on-screen visualization did not provide any special advantages for the given task while she highly praised the fun factor of the physical modality as well as its haptic quality. Most participants who enjoyed the physicalization gave similar arguments as an explanation. They were familiar with the digital visualization but still preferred the physical counterpart because of its unique advantages and specialties.

The other participant with a strongly different attitude from the rest of the group had no technical background and studied dance while currently working as a translator. In the interview she stated that she felt uncomfortable with the tablet and could not engage in the collaboration as much as she wanted because of the technical barrier: "*I couldn't really handle the first visualization because it was pretty complicated and so I stayed rather quiet*" (G2P1). She was even relieved when they switched to the physicalization and stated that she felt much more at ease with it. Although this is only one participant, it indicates another possible interest group. Some people are not comfortable with using computers or can not work with regular displays, e.g., visually impaired people. These people could show stronger interest in physical representations.

7.2.5 Discussion

Although in general the perceived quality of the collaborative work did not change on a large scale, our study gave first insights in the way in which physicalizations can be used for group work and enhance collaboration. We saw an increase in physical activity and group dynamics and found that the physical modality was perceived as more suitable to share findings with the other team members. Regarding the general acceptance of the physical modality we collected strong opinions with most participants either fully accepting or rejecting the physical modality. Supporters of the physicalization enjoyed the haptic quality and as a result of it the greater fun factor. The other part preferred the on-screen visualization because it was familiar, faster to understand and more professional. Only very few participants were neutral. It raises the question if physicalizations can be "too much fun" and therefore unsuitable for work places or whether they should be designed less playful, to avoid bringing back childhood memories.

The initial knowledge gained from this study implies several fields that should be explored in the future. First, the general design of physicalizations needs to be questioned. The perspective distortion of physical 3D visualizations is a problem and there is no final answer how to overcome this issue. One possible approach could be the use of projection augmentation (see also *Subsection 5.2.2 - Projection Augmented Physical Visualizations*). Certain information or guides could be displayed on top of the 3D model while preserving its haptic quality. Furthermore, with the developments in shape changing surfaces, physicalizations could become less static. In contrast to our previous study, in which participants stated to took the modular wooden bar chart more seriously, in this study participants questioned the precision and reliability of the physicalization because of the fabrication process. This further highlights the question regarding the confidence that people have in data that is encoded physically and which characteristics influence this trustworthiness.

While physicalizations need improvements to become on-par with on-screen visualizations in certain domains it should also be possible to apply findings of this study in the research field of CSCW. Many participants explicitly stated that they enjoyed the easy sharing of findings with the physical modality. This raises the question in which ways similar intuitive sharing options could be created in digital systems.

This finding also reveals again, how challenging it is to conduct a study with a fair comparison between a digital and physical modality, in which only the presentation modality is manipulated. Our two data representations did differ in the modality and dimensionality, but also in the form factor and, rather unforeseen, in their interaction possibilities and functionality. This shows the strengths of tangible interactions and physical objects, as humans do not have to learn such interactions, but apply them intuitively. Therefore, it is not only necessary to ask, in which ways similar intuitive interactions could be created in digital systems, but also in which ways physical and digital systems could act jointly. In the future it could be imaginable to switch back and forth between a digital and physical data representation, dependent on the underlying dataset, the particular task or the number of team members.

Finally, the influence of the participants' background and personality should be further studied. A possible way would be to conduct similar studies with different target groups, such as children, teenagers or visually impaired people. Furthermore, studies with people having a lighter or stronger aversion to new technology could be conducted to gain further knowledge on how to design intuitive physicalizations for them. We also discovered that the interest in physicalizations can not be clearly linked to just a technical or non-technical background.

Further studies will have to explore what exactly makes some people show high interest in a physicalization while others seem to see no value in it. Interestingly, none of the participants gave statements related to a “novelty effect,” as a feature of the physicalizations. Another question is, whether physicalizations should be designed in a way to be accepted also by those who currently reject them or whether research should rather focus on those who already show interest.

Chapter 8

Potential for Motivation & Self-Reflection

Most of our physicalizations in the last two chapters encoded abstract data and can be categorized as pragmatic data representations. Apart from the PopUpData project, all studies had the task to perceive and explore data in an efficient way, aiming at memorizing information or solving tasks collaboratively. Apart from such pragmatic physicalizations, data representations can also have an artistic or aesthetic purpose to convey meaning beyond the data itself and allow a stronger personal connection. In the evaluations of our initial prototypes (see *Chapter 5 - Beyond Physical Bar Charts*) it was frequently mentioned by participants, that they would like to encode their personal data in such physicalizations. They described this as a personalized or data-driven souvenir, which they could use as an aesthetic piece of scenery for the shelf.

This chapter presents the *Activity Sculptures* project, which is based on these statements and investigated in which ways personal activity data can be encoded in physical artifacts and explored their potential for motivation and self-reflection. Activity Sculptures are 3D printed physical tokens encoding data of physical activity. In our work, the data from a run is processed to create a unique piece, which becomes part of a larger sculpture (see Figure 8.1). We conducted a three-week field study with 14 participants to observe the ways in which such sculptures impact participants' experiences and their running activity. The study revealed that participants liked the general idea of receiving personal physical rewards for their physical activity. The sculptures generated a playful experimentation, e.g., by changing running habits, and social dynamics, e.g., discussions on runs or envy and competition.

Personal contribution statement: The content of this chapter is based on a master thesis by Franziska Sauka [2014] and was published as an article by Stusak, Tabard, Sauka, Khot, and Butz [2014]. See *Disclaimer* for a detailed overview.

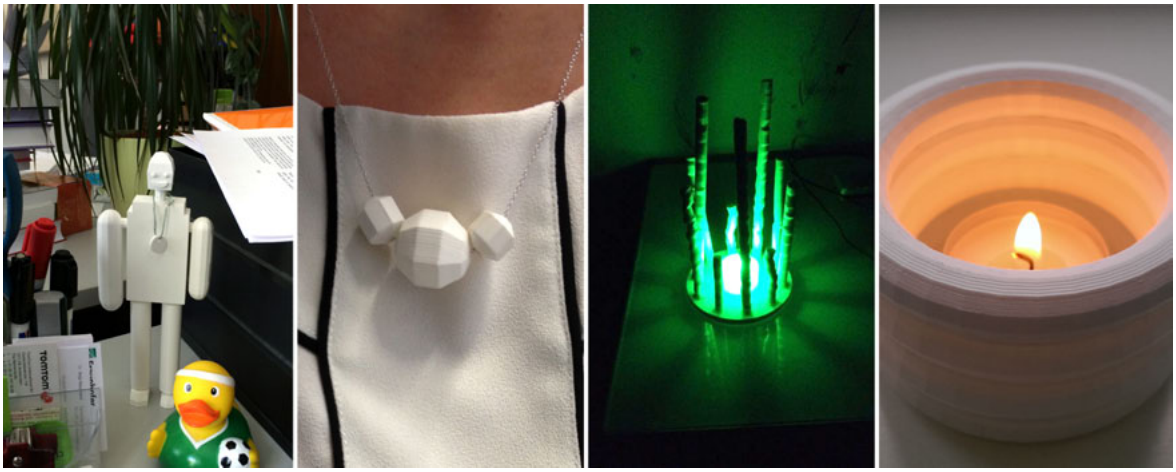

Figure 8.1: Four Activity Sculptures encoding running activity data: a figure, a necklace, a lamp and a jar.

Our findings suggest that physicalizations of personal data can provide additional benefits such as strengthening emotional connections and complement persuasion mechanisms with a more playful and reflective look at ones' activity. Therefore, they seem a promising complement to their digital counterparts. The project demonstrates a promising way of how physicalizations can be used for displaying personal data and reveals exciting further directions.

8.1 Motivation & Background

Our primary motivation to explore the potential of physicalizations representing personal data is based on the statements participants made in our early explorations. The decision to focus on running activity data had several reasons. One was that sport is a domain in which physical tokens such as medals or cups are already widely used as material rewards. Furthermore, existing research in technology-supported behavioral change shows that feedback and (digital) visualizations of past activity can increase current physical activity. Therefore, we were interested whether the same effects would come into play with physicalizations, or which other dynamics would emerge. Finally the tracking of physical activity, especially of running activity, became much easier recently. This is especially the case for running activity, provoked through advances of sensing technology in wearable fitness trackers (e.g., Fitbit Charge, Garmin Vivosmart, Jawbone, Misfit Shine) and smartphones with their corresponding mobile tracking applications (e.g., RunKeeper, Nike+ Running, Endomondo, Runtastic).

Khot et al. [2014] followed a similar approach with their *SweatAtoms* system, which transformed physical activity data based on heart rate into five different 3D printed material artifacts. The field study in six households for two weeks revealed that participants' relationship to physical activity can be affected by physical representations and strengthen emotional connections. Our work complements/differs from their project in the following ways:

- *Broader study:* Both studies were conducted "in-the-wild", but we had twice as many participants (14 vs. 7) and a longer duration (three vs. two weeks).
- *Different data:* Instead of everyday physical activity we focused on running activity. We used various variables related to running activity (running time, distance, speed, duration, elevation gain), while Khot et al. [2014] concentrated on heart rate data.
- *Different design strategies:* Besides the various models of the sculptures, we also followed a modular approach in which physical objects add to each other, leading to bigger artifacts.
- *Off-site printing:* In the *SweatAtoms* system participants had to print the artifacts themselves. Therefore, the printing process had an observable influence on participants' experience with the data representations. As participants directly received the artifacts in our case, we had a stronger focus on the physicalizations and the encoded data.

Also related to our project are works in the area of "quantified self" and research on behavioral change. In the following, we briefly discuss in which ways technological solutions have been proposed to track people's activity and to foster change in their behavior.

8.1.1 From Lifelogging to Quantified Self

Before the invention of computers and digital tracking devices, artists and scientist have used tools such as notebooks to track and reflect on their daily activity. With the raise of personal informatics at the end of 1990's, a number of self-tracking projects emerged. One prominent example of these experiments is the MyLifeBits project [Gemmell et al., 2003]: Large amounts of personal data were recorded and organized, first focusing on computer based data [Freeman and Gelernter, 1996], later also based on lifelogging prototypes incorporating an increasing number of sensor data [Bell and Gemmell, 2009]. The primary goal of this collection of various types of data was to augment personal memory. Those experiments showed that collecting and reflecting on personal activity data can have a clear impact on areas of health and well-being [Li et al., 2010]. This led to the recent emergence of the "quantified self" movement [Wolf, 2009], an "*international collaboration of users and makers of self-tracking tools*" with the goal to gain "*self-knowledge through self-tracking with technology*"[1]. This self-knowledge based on personal data can range from detecting spending habits, to stress or advancements in physical activity, often with the underlying goal of self-improvement and a change of undesired behavior.

[1] `http://quantifiedself.com/` (accessed 2015-12-15)

8.1.2 Motivating Physical Activity

The design of tracking and motivational applications are often based on behavioral psychology [Consolvo et al., 2009; Froehlich et al., 2010], with the hypothesis that immediate contextual feedback can promote behavioral change [Li et al., 2011]. Tracking of activity and providing of contextual feedback has become much easier recently, due to progress in sensing technology and wearable devices. Therefore, it seems that the primary challenges to behavioral change are not technological but human ones, such as helping people reach their goals and retain the changes over time [Bacon et al., 2002]. Strategies to support behavior change can be found in social theory and include the promotion of gradual changes in individuals' behavior [Grimley et al., 1994] or mechanisms for sustaining the changes over time. A thorough literature review by Consolvo et al. [2009] identified the following strategies:

1. *use abstraction*, rather than raw sensor data to foster reflection;
2. *be controllable*, by letting people set their own goals [Locke, 2002];
3. *show trends*, for people to relate past efforts to the goals they set;
4. *be positive*, positive reinforcement encourages change [Consolvo et al., 2008]; negative feedback or punishment are not effective motivators [Lin et al., 2006];
5. *be comprehensive*, by not limiting feedback and rewards to what can be sensed, but account for other positive behaviors that were not captured by the system [Consolvo et al., 2006];
6. *be aesthetic*, by displaying information in a comfortable and attractive manner; this can increase enjoyment and engagement [Fan et al., 2012];
7. *be unobtrusive*, by collecting data without interrupting users and presenting it when needed;
8. *be public*, allow sharing [Munson and Consolvo, 2012] as well as social influences through family participation [McLean, 2003].

Although these strategies are mainly based on observations and experiences with digital systems and visualizations, we used them as guidelines and inspiration for the design of our physicalizations. They provided powerful motivators and demonstrated approaches of ways in which behavior can be influenced without people noticing. The field study of twinkly lights [Rogers et al., 2010], for example, showed that ambient information could transform the way people behave without them being aware of it, in this case, taking stairs rather than the elevator.

Nonetheless, many other factors apart from psychological elements contribute to lifestyle improvements. For instance, Munson and Consolvo [2012] showed that digital rewards do not motivate inherently which raises questions about how such rewards should be designed.

Furthermore, the design of behavioral change systems is often based on inherent norms and visions of ideal behaviors [Rogers and Marsden, 2013]. Rather than persuading people into a specific behavior, more positive strategies might aim at changing attitudes instead of behaviors. Examples for such positive strategies are designs or systems that leave room for stories [Purpura et al., 2011] or move beyond the individual [Brynjarsdottir et al., 2012; Dourish, 2010]. Yetim [2013] sees persuasion as a communicative act which enables designers to promote discussion "*on the intent of persuasion and the strategies chosen to achieve the desired attitude and/or behavior change.*" This approach might avoid an overly rational model of human behavior, which is often criticized [Brynjarsdottir et al., 2012; Purpura et al., 2011]. We think that encoding personal activity data in a physical form can foster reflection and communication on physical activity, similar to their digital counterparts. We believe, that physicalizations can provide additional benefits, such as generating a playful rather than functional relationship to one's physical activity.

8.2 Design Process of Activity Sculptures

This section describes the design and the fabrication process of the Activity Sculptures. Based on a literature review, a brainstorming session and an online survey we explored various concepts (see Figure 8.2), which we then refined into four types of sculptures. We developed a fabrication process leveraging web technologies to fetch running data, and generated 3D models which could then be 3D printed.

8.2.1 Initial Concepts

Similar to digital visualizations, physical data representations can display data in various types and for different purposes. Our first step was to limit the space within which we would design Activity Sculptures and gain initial insights which characteristics they should meet. We organized a Brainstorming Webs [Hyerle, 2008] session with five colleagues (graduate students) to discuss ideas in which ways such Activity Sculptures could look like. The most promising concepts were later refined through a review of the literature presented above and rated by a wider public through an online survey (47 participants).

Initial Design Directions

The brainstorming session had two outcomes: concrete concepts for the sculptures and general design trends and characteristics, that the sculptures should reflect. Based on further informal discussions and the literature, we categorized these principles into three main design directions:

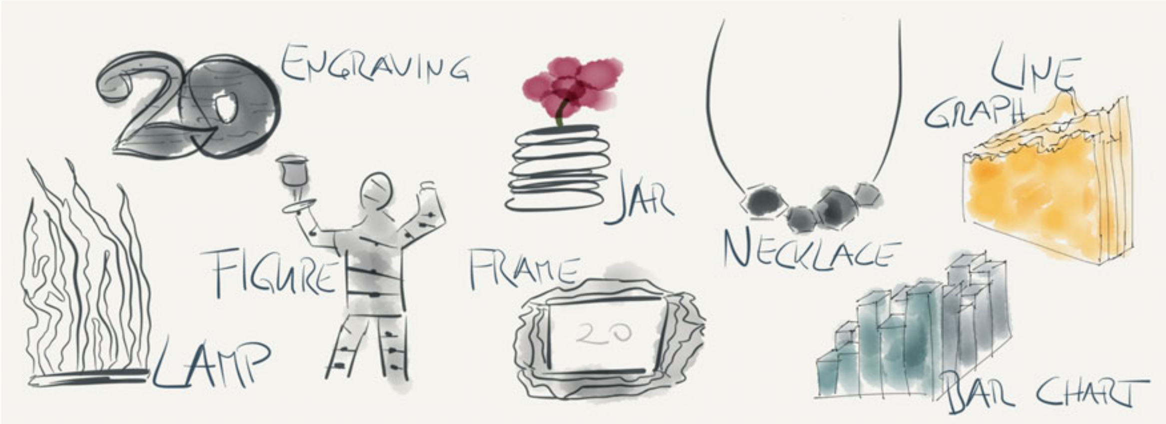

Figure 8.2: Sketches of eight early concepts that where used in the brainstorming session and for the online questionnaire.

- *Reflection:* sculptures should support self-reflection more than a comparison with others; should display intermediate goals and stages; ought to reflect met and unmet goals; should always stay within sight.
- *Motivation:* sculptures should regularly support motivation and feedback; should display good and bad performances.
- *Shape:* should only look aesthetically pleasing if good performances were achieved; should serve some practical purpose; should be modifiable and variable.

From the broad collection of our ideas and the ones generated in the brainstorming session, we identified six concepts which best suited these design directions. These concepts included a necklace, a lamp, a jar, a picture frame, a modular robot and an engraved sculpture (see Figure 8.2). Apart from these abstract and artistic concepts we also included rather pragmatic data representations such as a bar chart and a stacked line graph.

Online survey

To collect a broader feedback for these initial concepts, but also gather information on running behaviors and usage of self-tracking applications as well as visualizations, we conducted an online survey. In total, 47 participants (57% were female and 43% male) between 23 and 50 years old answered our survey.

The answers regarding the general idea of encoding personal data physical were encouraging, as the majority of respondents (35) stated that they would like to have sculptures of physical activity data. The possibility to compare their performances with other runners seemed less essential, as 75% of the respondents rated the visibility of their data as more important. In contrast to related work, which suggests an avoidance of negative feedback, 70% favored seeing all activities, including “bad” performances.

Respondents considered the motivational potential of physical representations positively, with 34% (16) perceiving a very good opportunity and nearly half (23) thinking that it could motivate them a little. The majority (32) considered the motivational aspects of physical visualizations of running activity positively.

Similar answers were given regarding the purpose that such physicalizations of activity data should fulfill. An increase in motivation was considered by 23 participants as important, 14 preferred sculptures supporting self-reflection, nine favored artwork pieces, and 20 participants preferred a mixture of all three purposes.

In general, respondents preferred the artistic and extensible sculptures. The lamp was rated best, followed by the jar, the picture frame, the sculpture with engraving and the modular robot. The more pragmatic data representations, i.e., the stacked line graph and the bar chart were ranked lowest.

We asked questions about the design of the sculptures and about the frequency of receiving them. Most participants (19) preferred to receive sculptures when reaching pre-established goals and 11 chose the option of receiving one sculpture per month. Participants, therefore, prefer longer periods of time between receiving sculptures, as only a few (5) wanted a sculpture for every run.

In summary, the survey revealed an appreciation for the concept of Activity Sculptures as well as interest and belief in the motivational potential of the sculptures. The ranking of the sculptures also highlighted the aesthetic aspects of the sculptures. The slow pace at which participants expected to receive sculptures reveals the importance of excitement and contemplation over instant feedback and quantitative comparison.

8.2.2 Design Decisions

Based on the initial feedback from the brainstorming session and the online survey, we decided to focus on sculptures of an abstract nature, which support self-reflection. The sculptures should also be aesthetically pleasing and not seek constant attention. As participants would use the sculptures for a longer time, and the comparison with other seemed less important, we focused less on comprehensibility and direct readability of the exact data at the first glance.

Participants liked the idea of extensible sculptures, therefore, we decided to make the sculptures modular and rewarding each running session with a piece of the sculpture. The single pieces are comparable and therefore allow *self-reflection*, but also promote regular physical activities and uphold people's interest, as they add up to make a whole sculpture. For practical reasons, we decided on producing one piece after every run, which contradicts the feedback from our survey but allows an evaluation of the concepts after about one month.

We decided to keep four sculptures for the final study, which fitted best our design directions: the necklace, lamp, jar, and figure (see Figure 8.1). As a sculpture that predominantly appealed to women, the necklace served as a fitting contrast to the robot-shaped figure sculpture (which was preferred by men in our survey). While the jar and the lamp also had a practical purpose, both, the necklace and the figure tended to be pieces of scenery.

The most popular variables related to physical activity in our online survey were *average speed*, *duration*, and *distance*. Therefore, these were used an underlying data for every sculpture. To investigate the impact of additional variables, e.g., on motivational aspects, the lamp also included *elevation gain* and the figure *calorie consumption*.

We decided to use two primary data mappings that were common for all sculptures: the performance should influence the size and the shape of the single sculpture pieces. With better performances the size of a single piece should increase and its shape should transform from an angular and sharp appearance to a smoother and in our opinion more aesthetically pleasing one.

All the sculptures consisted of parts which can be assembled, enabling the extension of the sculptures. While the jar and necklace did not indicate a specific number of pieces to add up a whole sculpture, the figure and lamp clearly showed met and unmet goals. We expected the desire to "complete" the sculpture to encourage regular running activity. In contrast, receiving a single piece of the necklace or the jar could provide sufficient satisfaction. As all sculptures represent running data, they can be used for *self-reflection* and may catch one's attention, depending on where the participants would place them.

Jar

The jar sculpture (see Figure 8.3) is composed of an limitless number of round layers, each representing one run. As the center-to-center diameter is fixed, the single layers can be stacked on top of each other in random order. The diameter of one layer encodes the duration of a run and the average speed as well as the distance influence the shape of a layer. The number of width segments of the 3D model is based on the speed and the number of height segments on the covered distance.

Lamp

The lamp sculpture (see Figure 8.4) is composed of ten pillars, each representing one run. Each pillar can be plugged into one of the dedicated holes at the lamp's base. The difference in altitude associated with a run is represented by the two-dimensional progression of a pillar. A run with large differences in altitude, for example, would result in a jagged pillar while a straight pillar means no altitude differences. We had to normalize the elevation gain data, to receive 3D printable models for data with large variances. The number of width segments of the 3D model is based on the covered distance and the number of height segments on the duration of the run. The average speed of a run can be perceived in a pillar's thickness.

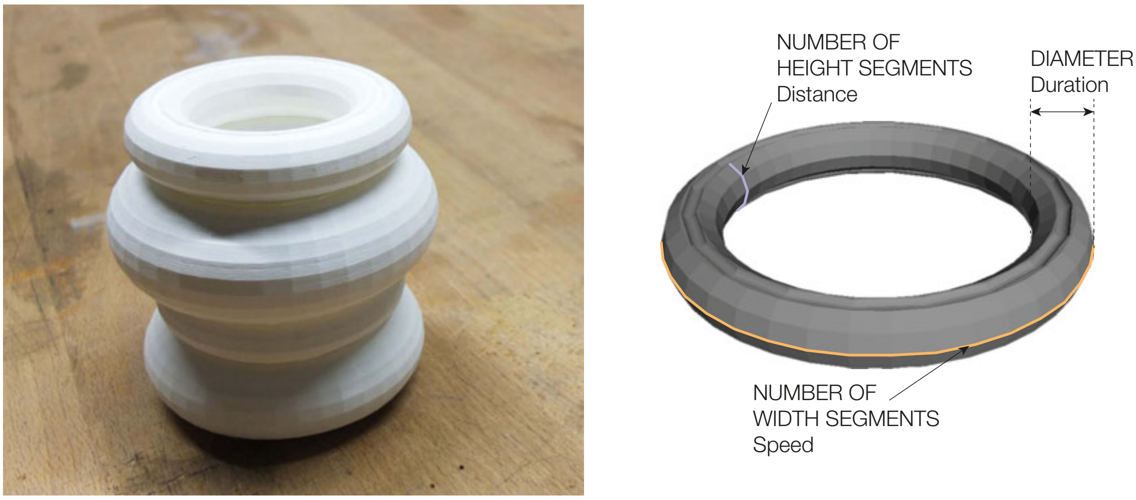

Figure 8.3: Picture of the jar sculpture and the digital 3D model of one layer.

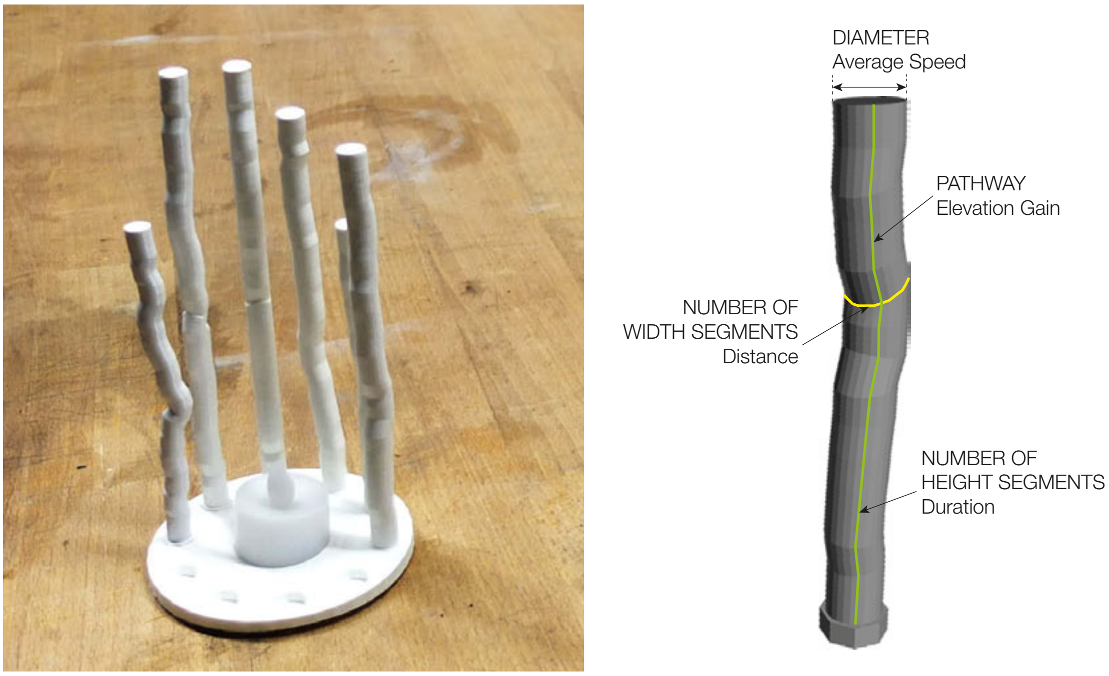

Figure 8.4: Picture of the necklace sculpture and the digital 3D model of one pillar.

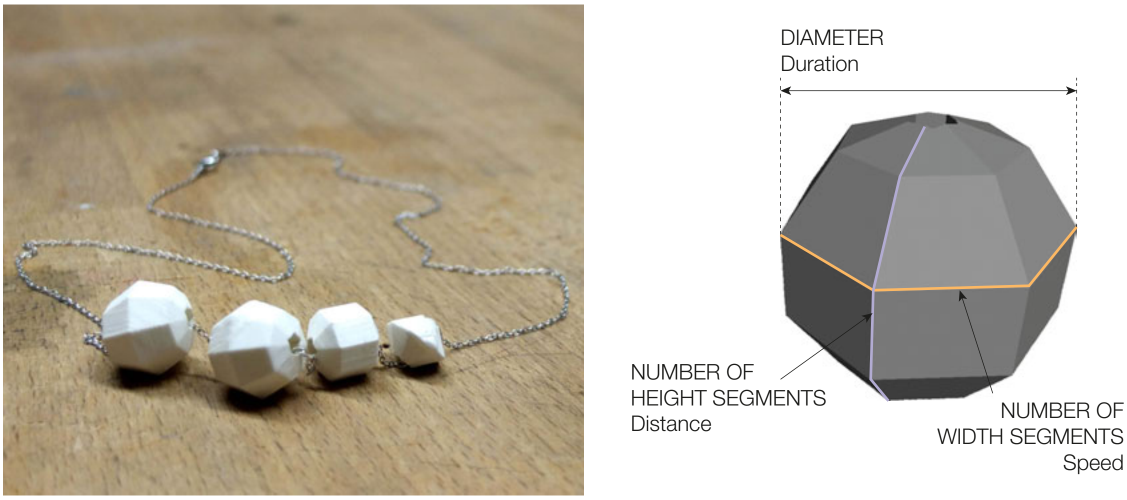

Figure 8.5: Picture of the necklace sculpture and the digital 3D model of one bead.

Necklace

The necklace sculpture (see Figure 8.5) is composed of an undefined number of beads, each representing one run. The single beads can be added to a chain in a random order, resulting in a necklace. The size of the bead encodes the duration of a run. Its shape is influenced by the average running speed, which affects the number of width segments and the covered distance, which is visible in the number of height segments.

Figure

The figure sculpture (see Figure 8.6) is composed of eight body parts, each representing a run. The single body parts can be plugged into the unfinished figure. The height of a body part depends on the duration of a run and its scope on the covered distance. Its shape represents the calories burned through the number of width segments and the average speed through the number of height segments.

8.2.3 Fabrication Process

A general overview of our process to fabricate the sculptures is displayed in Figure 8.7. The activity data was tracked with a mobile tracking application and saved in the cloud (Figure 8.7-1). The data was then gathered either through a website export and e-mail (Figure 8.7-2a) or by API calls (Figure 8.7-2b). Digital 3D models of the sculpture were generated based on the captured data and saved as STereoLithography (STL) files. We then used

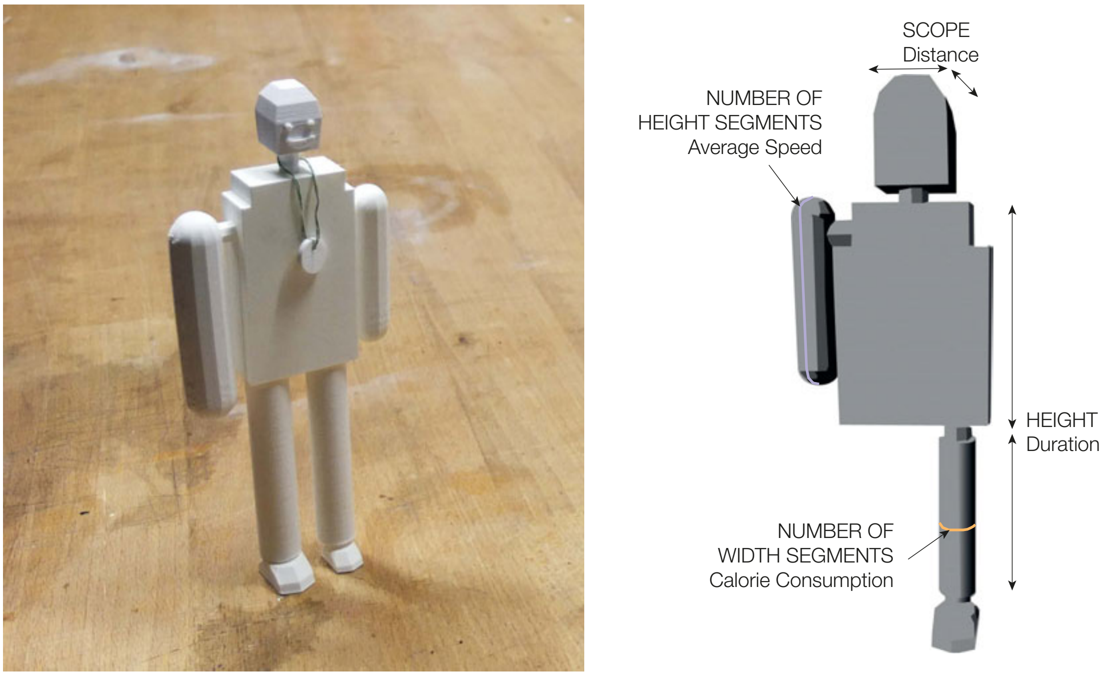

Figure 8.6: Picture of the figure sculpture and the digital 3D model of several parts of it.

an Ultimaker Original[2] to 3D print the sculptures (Figure 8.7-3). The single pieces of were either handed out in person (Figure 8.7-4a) or by letter (Figure 8.7-4b).

Data

We used four popular running applications for mobile phones (Endomondo, Runkeeper, Nike+ Running and Runtastic) to track and extract the activity data. All four applications were available for the mobile operating systems iOS and Android. In total, we focused on five data types to represent in our sculptures: 1. the duration of a run; 2. the distance covered; 3. the average speed; 4. the number of calories burned; 5. the elevation gain of a running session. All applications were able to record these data types and export each run as TCX, GPX or CSV files. Participants could sent us the files directly via e-mail, or we gathered them from their member accounts via website export or API calls.

Digital 3D Models

First we generated digital 3D models based on the collected activity data, which were then converted to obtain printable 3D objects. We used web technologies for the generation of the 3D models, in particular, several JavaScript libraries. We used a combination of Three.js[3],

[2] `https://www.ultimaker.com/` (accessed 2015-12-15)

[3] `http://threejs.org/` (accessed 2015-12-15)

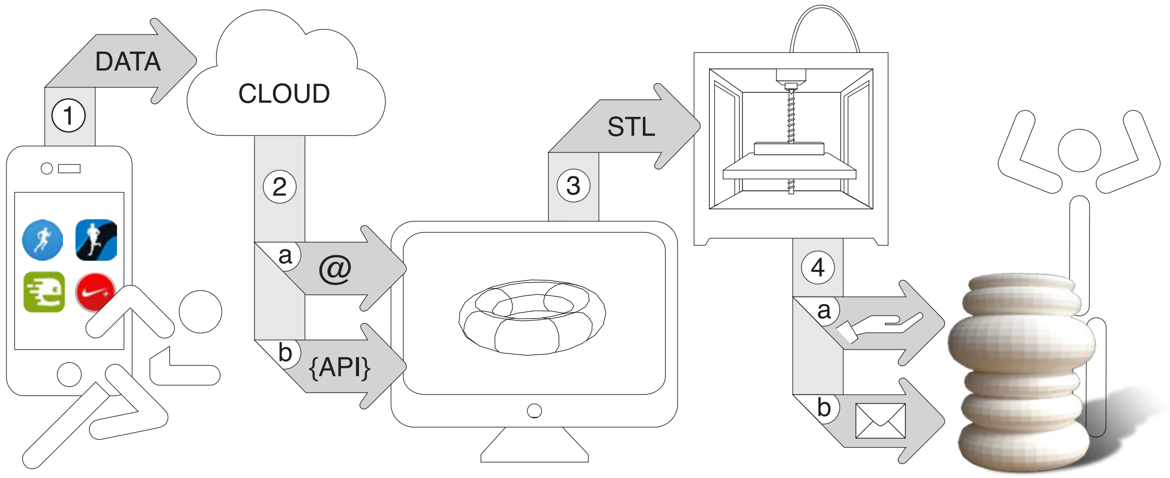

Figure 8.7: The fabrication pipeline of the Activity Sculptures.

a library for WebGL, Csg.js[4], a library for Constructive Solid Geometry (CSG) and ThreeCSG.js[5], as a bridge between them, since the two libraries use different formats for geometry. The CSG library uses boolean operations (i.e., add, subtract, union or intersect) to build complex objects by assembling simple objects. To display the sculptures, we created scenes for each sculpture, including the physical activity data and the 3D geometries. We used HTML templates which could be loaded in a Web browser and exported the 3D models as STL files, a format suitable for 3D printing.

3D printing

As 3D printing software we used Cura[6], which supports a manipulation of the printing options and therefore, allowed us to increase the quality of printing results. The software also transformed the 3D models (STL files) into G-Code, a numerical control programming language and the machine code understood by the Ultimaker Original. We decided to use only white PLA as material for the sculptures to keep the printing process as easy and fast as possible, e.g., by avoiding the manual exchange of different materials.

8.3 Study Design

We conducted a three-week field study to investigate participants' experiences and to gain a better understanding of the impact of physicalizations on running activity. The primary

[4] `http://evanw.github.io/csg.js/` (accessed 2015-12-15)
[5] `https://github.com/chandlerprall/ThreeCSG` (accessed 2015-12-15)
[6] `https://github.com/daid/Cura` (accessed 2015-12-15)

goal of our study was to observe the influence of physicalizations on participants' behavior. In addition to the question whether our Activity Sculptures would evoke self-reflection and discussions, we also were interested in participants' general perception of physicalizations of personal running data.

8.3.1 Participants

In total, we recruited 16 individuals, but one participant did not have time to go for a run, and another had technical issues. Therefore, the data of these two participants was not taken into account, and the following will focus on the remaining 14 participants (8 females, aged between 24 and 62). We announced the study in a Facebook group of our university and used a newsletter with subscribers who are interested in study participation. The participants represented a range of occupations including a controller, designer, business consultant, assessor, students, and research assistants from our university (see Table 8.1 for more details).

Existing running habits

Our participants had various levels of running experience. While five participants had not gone running regularly before the study, the remaining nine participants ran between one and three times a week.

Existing use of tracking applications

Most of the participants (9) already used a mobile tracking application (see also Table 8.2). Four participants stated that they were part of a running team, meaning they worked together in the same building and saw each other several times a day. They already shared their running data in the same mobile tracking app (*Endomondo*), although only three of them run regularly. The five students who took part in our study attended the same university and knew each other by sight. Five participants reported they had never used a mobile tracking application before the study. Reasons were the inconvenience of carrying a mobile device along or the perceived lack of additional value.

8.3.2 Setup

Participants, who wanted to be part of the study, needed a mobile device which allowed the installation of one of the following tracking applications: *Endomondo*, *Runtastic*, *Nike+ Running* or *Runkeeper*. At the moment of study, these were the most used tracking applications, based on the number of downloads specified by the digital distribution platforms such as the Apple App Store or the Google Play Store. The five participants who did not use a mobile tracking application before were asked to choose and install one of the four applications. Participants also had to specify if they would send us the tracked data per e-mail or if they would provide us access to their account for the duration of the study.

Table 8.1: Demographic details of the participants.

ID	Gender	Age	Occupation	Running routine	Running Team
1	male	25	student	once a week, 30-40 min	no
2	male	30	research assistant	3 times a week, 10-20 km	yes
3	male	31	student	1-2 times a week, 5-10 km	no
4	female	29	research assistant	twice a week, 5-10 km	yes
5	female	28	research assistant	non-runner	no
6	male	27	controller	once a week, 5 km	no
7	female	24	student	non-runner	no
8	female	24	student	once in two weeks	no
9	female	24	student	non-runner	no
10	male	29	research assistant	3 times a week, 10 km	yes
11	female	62	assessor	non-runner	no
12	female	30	designer	twice a week, 5 km	no
13	female	30	research assistant	non-runner	yes
14	male	32	business consultant	2-4 runs a week, 7-8 km	no

8.3.3 Procedure

The field study with 14 participants had a duration of three weeks and took place in November 2013 in the local area of Munich in Germany. At the beginning and the end of the study we conducted semi-structured interviews, which were complemented with pen-and-paper questionnaires. We also met several participants throughout the study, if they chose a personal handover of the sculptures. Participants received no compensation, but could keep their Activity Sculptures.

Preliminary session

In the preliminary session participants had to sign a consent form and fill out a questionnaire about demographic data. We also asked about their current physical activity routines and goals, types of running data they are interested in and their experience with physicalizations.

We then introduced the four types of Activity Sculptures by presenting the digital 3D models of each physicalization printed out on paper. First, we showed only the physicalization without any further descriptions, after that we presented variations with explanations about the data mapping. The decision to not show any 3D printed sculptures was made to better observe participants' reactions when receiving their first piece. After the presentation of all four sculpture types, we asked the participants to share their first impressions of each physicalization. Participants rated also aspects such as the potential of motivation or self-reflection on 5-point Likert scales. Finally, each participant had to choose one type of Activity Sculptures, which they would receive throughout the study.

Field Study

Participants had to track their runs during the three-week field study with one of the mobile tracking applications mentioned above. When participants sent us their data or we detected new data through regularly API calls, we generated the digital 3D models according to the runs and 3D printed them. The period between receiving the data and delivering the sculpture pieces to participants was between one and three days. When the handover of the sculpture pieces occurred in person, the study leader observed and took notes of the participants' reactions. We asked them to express their first impressions of the sculpture.

Closing session

The closing session started with a semi-structure interview in which we asked each participant to recall their experiences in the last weeks and gathered feedback on the physicalizations. While we focused on the physicalizations, the social aspects that came along with them and the participants' running behavior, we also left room for personal anecdotes and critique. The session ended with pen-and-paper questionnaires, where participants had to rate the same aspects on 5-point Likert scales as in the preliminary session but also new questions focusing on their impressions on the chosen sculpture.

Data Collected

We gathered data via semi-structured interviews, questionnaires as well as running logs. The interviews were audio recorded and transcribed by two researchers. We followed a qualitative coding approach to identify both overall themes and more specific findings linked to single participants.

8.4 Results

This section describes the key findings from our three-week field study. We begin with an overview of the participants and the results of the questionnaires. The main part will be the qualitative analysis of the semi-structured interviews.

8.4.1 Participants Overview

An overview of the study setup for every participant is displayed in Table 8.2. Five participants used *Endomondo* to collect their data, four participants chose *Runtastic*, three used *Nike+ Running* and two tracked their runs with *Runkeeper*.

Regarding the reasons to go running the most often mentioned reasons were fitness (6), relaxation (4), fun (2), balance (2) and group motivation (2). Similarly to the results of our online questionnaire, the most important types of running data for the participants were speed (6), distance (5), duration (4), progress (4) and route (2). While eight participants did not have any experience with physical visualizations, six reported that they had already seen various examples.

The different sculpture types were almost equally distributed throughout the participants, as the lamp was chosen by four participants, the jar by four as well, the necklace by three, and the figure by three. In total, we had 71 runs across participants over the three weeks of the study, while the number of runs of each participant ranged between one and nine times. Only two participants chose a delivery of the single sculpture pieces by letter, the majority (12) preferred a personal delivery.

Table 8.2: Overview of the study setup for every participant.

ID	Tracking App (*no app use before study)	Physicalization	Delivery	# runs / received pieces
1	RunKeeper*	lamp	personal	6
2	Endomondo	figure	personal	9
3	RunKeeper	jar	personal	6
4	Endomondo	jar	personal	8
5	Endomondo*	necklace	personal	3
6	Nike+ Running	lamp	per letter	4
7	Runtastic*	lamp	personal	5
8	Nike+ Running	figure	personal	5
9	Runtastic	necklace	personal	4
10	Endomondo	jar	personal	6
11	Runtastic*	figure	personal	7
12	Nike+ Running	jar	per letter	4
13	Endomondo	necklace	personal	1
14	Runtastic*	lamp	personal	3

8.4.2 Questionnaires

Participants had to fill out 5-point Likert scale questionnaires (ranging from 1=*very good* to 5=*very poor*) in the preliminary and closing sessions. The results of the questions, which were asked in both the preliminary and closing session are displayed in Figure 8.8. Participants appreciated the general idea of encoding running data through physicalizations. Before the study, four participants were impartial, whereas all other participants rated the idea as good or very good. In the closing interviews all participants rated the idea as either good or very good. The rating of the motivational potential did hardly change. Before the study ten participants suggested potential for motivation and after the study eleven participants rated it as very good or good.

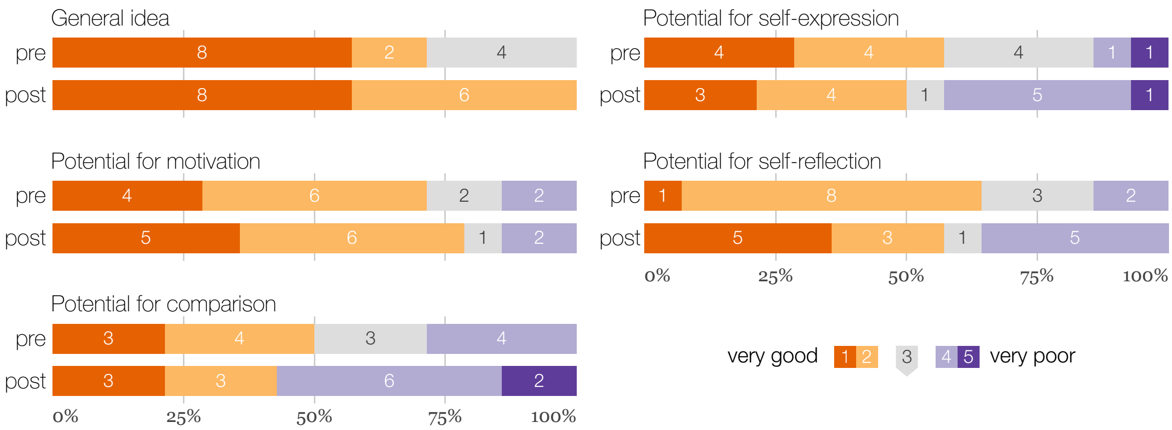

Figure 8.8: Results of the 5-point Likert scale questionnaires participants filled out during the preliminary and closing ("post") sessions.

The results for the potential for comparison with others, self-expression, and self-reflection showed a similar trend. Before and after the study the ratings of half of the participants were good or very good. For self-reflection, the number of participants who rated it very good increased from one to five. The majority of participants who were impartial before the study decreased their ratings afterward and could not be persuaded of these specific potentials. The necklace stood out, as all participants who chose this type increased their scores for comparison with others and self-expression.

The questionnaire used in the closing session included further questions regarding the participants' impressions on their chosen sculptures. The scale ranged again from 1=*very good* to 5=*very poor*. Participants rated the aesthetics, practical benefit, information content and the quality of the sculptures overall as good. It is worth mentioning that the necklace sculpture received the best ratings overall, apart from practical benefit, in which the lamp and the jar scored better.

8.4.3 Interviews

We interrogated the participants throughout the entire study. The semi-structured interview in the preliminary session focused on the first impression of the participants regarding the different sculpture types, e.g., what participants appreciated and disliked about the physicalizations, and their motivation in picking a specific type. Throughout the study, the study leader also collected feedback from the twelve participants who received their sculpture pieces through a personal handover. Finally, in the closing session the interviews included open-ended questions about the physicalizations as well as their influence on participants' experiences and behavior.

We decided to present our findings and observations from all interviews conjointly, instead of separating them into preliminary and closing. We also did not explicitly categorize between the sculpture types but structured the results into four general topics: choice of Activity Sculpture, the perception of Activity Sculpture, the impact on running activity and the reward experience.

Choice of Activity Sculpture

Participants' choice for a sculpture type was based on various considerations. In addition to the general design and aesthetics, practicality and the data mapping were also important aspects. Participants also tried to envision in which ways the sculptures would "scale", look and stand after multiple runs.

Aesthetics Most participants stated that the aesthetic of the sculpture played a major role in the choice. The necklace sculpture was appreciated by *participant 5* just because it was enjoyable jewelry she could wear. Two participants also mentioned that they liked the fact, that the necklace would be an attractive piece of jewelry with only one bead on it as well as many.

Similar to the necklace, most participants expected the jar to scale well and look aesthetic, independent of the number of runs completed, although *participant 11* had difficulties imagining the single pieces of the jar fitting together if large differences between the runs occurred. In general, aesthetics were strongly linked to the concerns participants expressed regarding the ability of certain sculptures to scale and their appearance after several runs. Two participants stated that they did not like the lamp and the figure because the sculptures would look "incomplete" if they would not reach enough runs within the limited period of the study. The robot-like shape of the figure sculpture was criticized by four participants, as they worried that it would look unaesthetic or disproportional when assembled.

Metaphorical Distance Six participants did not like the figure sculpture as it had a strong relation to the running activity. They liked explicitly the physicalizations that encoded data in a rather "abstract" manner. In contrast, two participants rejected the jar sculpture as it would remind them at an office desk at work and would represent the opposite of physical activity.

Interpreting the Data The types of running data that were encoded and the way they were represented, seemed to play a less significant role regarding the choice for a sculpture. None of the participants stated that they chose the lamp or the figure sculpture because they showed additional variables such as the *elevation gain* or *calorie consumption*. Participants rather appreciated the general visibility of progress. *Participant 6* liked the lamp "*because it is clear when pieces are missing.*" Similar to the lamp, two participants valued the same property in the figure sculpture.

Practical Purpose Some participants favored the aspect that two of the sculptures had a practical purpose. They liked the storage ability of the jar sculpture and also noted positively that the lamp actually gives light. In contrast, the perceived lack of usefulness and later use of the figure sculpture led five participants to pick other sculptures.

Playfulness While most participants disliked the figure sculpture because of its aesthetics, all participants who chose the figure, highlighted it as the most interesting option, because the outcome was somehow unpredictable. *Participant 8* stated that "*it is funny and exciting to imagine what will come out in the end, and what it would look like.*"

Perception of Activity Sculpture

In the following we will report in which ways participants perceived the sculptures, e.g., if they could read and understand the underlying data and if the 3D printed artifacts met their expectations. We will also describe the perception of the Activity Sculptures by others than the participants of the study.

Interpreting the Data Most participants had difficulties understanding the way in which their run was mapped to the shape when they received the first sculpture piece. These difficulties diminished as participants received more sculpture parts with different shapes. *Participant 14* noted that his first pillar of the lamp sculpture was not expressive, but once in association with the second piece, the difference between the two runs was noticeable. If runs are very similar this also reflects in very similar sculpture pieces. *Participant 4* had almost identical runs and therefore difficulties in perceiving any differences between the sculpture parts. Most participants only mentioned the most distinct changes in the sculpture pieces based on the underlying data, such as the height of a lamp pillar or the diameter of a jar layer. Particularly for the necklace, participants appreciated the rather simple and clear encoding of an increased running performance into the size of a bead.

Expectations and Aesthetics Statements in semi-structured interviews in the preliminary session showed, that participants' expectations started to form as well as anticipation for the objects they would receive. Participants had concerns about the appearance of their sculpture pieces and their assembly as well as the reliability of the data (particularly about the *elevation gain*). However, scalability concerns were not expressed in the closing session and participants seemed to appreciate how the pieces fitted together.

Participants' reaction when they received their first sculpture part can be split into two broad categories. Most participants were positively surprised about the aesthetics, as until then they only had seen images of the digital 3D models. However, two participants reported a disappointment related to a discrepancy between their expectations and the pieces they received.

All participants who chose the necklace liked their first bead. Although *participant 5* reported that the bead was smaller than she had expected, she found it "pretty" and wore the necklace around her neck immediately. Similarly, *participant 10* liked the first layers of his jar sculpture and enjoyed their usefulness even when the jar consisted of merely two pieces, as he immediately used it to hold a pencil.

Positively surprised by the figure sculpture, *participant 2* reported that the pieces look much nicer then he thought, as he expected them much more clunky. Although he could imagine that the figure may not appear as nice for other people, this seemed to be secondary to him, as he would know what effort he put into receiving the sculpture. The participant explained that watching the sculpture grow created an emotional attachment, which increased the significance of the sculpture to him personally.

Overall, all participants but two were happy with their choice and would have chosen the same sculpture again. *Participant 8* would have chosen the necklace over the figure sculpture since she found that the necklace scaled better. *Participant 10* would have selected the lamp instead of the jar because this sculpture type also encodes differences in altitude.

Participants did not only compare new pieces with the ones they already received but also with the pieces of other participants. *Participant 2* expressed minor disappointment about his first piece as he saw other participants receiving their first jar pieces which were much larger than the small foot of his figure, although he had run for a long time. *Participant 4* was disappointed when she received her third jar layer after a short run but with a relatively high speed by her standards. She criticized that the short duration of her run, compared to her previous runs, was clearly visible in the sculpture piece, but that the increased speed of this run was hardly observable.

Personalization Many participants reported suggestions how they would personalize the sculptures to their liking. Given the minimalist form and the white color of the sculptures, participants were able to appropriate them through various means.

As the single pieces did not encode the date of a run, *Participant 1* had the idea to write the number of the runs at the bottom of each piece of the lamp figure to allow him to track the order. *Participant 5* spelled out a strategy on how to arrange the beads of her necklace by putting the biggest piece in the center and the others around it (see also Figure 8.1). She also had thought about painting the single pieces in different shades of blue according to the date of the run so that she can always track the order despite rearranging them on the chain.

Participant 2 thought of dressing his figure sculpture in a shirt of his favorite soccer club and finally he attached a small medal to his sculpture (see also Figure 8.1).

Two participants also mentioned the request to have further possibilities to customize the sculptures in the beginning. Besides offering more types of sculptures, they also suggested a free choice of the data variables and in which ways they are mapped to the characteristics of the sculpture.

The sculptures were actually embedded in everyday life by several participants (see Figure 8.1 and 8.9 for various examples). The jar sculptures were used as a storage box for a Universal Serial Bus (USB) stick, adhesive tape, and pencils while other participants used it as a tea candle holder or as a "light volcano" by putting an LED lamp inside. The necklace was worn by all participants, and the lamp and figure sculptures were placed at various locations, e.g., an office desk or a nightstand.

Perception by Other People Participants also reported how the Activity Sculptures and the encoded data were perceived by other people. *Participant 5* mentioned that she normally did not like to share her running data, e.g., by posting a run on social media platforms. However, she liked to show and talk about her necklace as she preferred it as a way of self-expression. She also highlighted the fact that she could see peoples' reactions immediately. *Participant 11* enjoyed the necklace because it could be worn openly around the neck and is thus easily noticed by others.

For several participants, it seemed an important aspect that the sculptures were not clearly distinguishable as data representations. This also meant that participants could choose to explain its significance whenever they liked. *Participant 1* stated that one of his visitors liked the idea of having a piece of scenery which cannot be identified as being a data representation or being related to physical activity.

Impact on the Running Activity

The interviews in the closing session revealed some anecdotal evidence of the Activity Sculptures' motivational potential and influence on running routines.

Motivation In contrast to most digital visualizations, our physicalizations had an "always on" aspect, as they were visible at any time the participants were in their vicinity. The most extreme case being the necklace which can be worn and seen at all times. *Participant 13*, who was part of the running team, referred to her only piece as the "pearl of shame" since it indicated that she only ran once.

The feature of comparing single sculpture pieces, e.g., to a previous run or to others' runs, seemed to increase the motivation of some participants. For instance, *participant 9* accidentally saw the necklace sculpture of another participant which had larger beads than her own, which motivated her to achieve larger pieces as well. *Participant 4* was disappointed

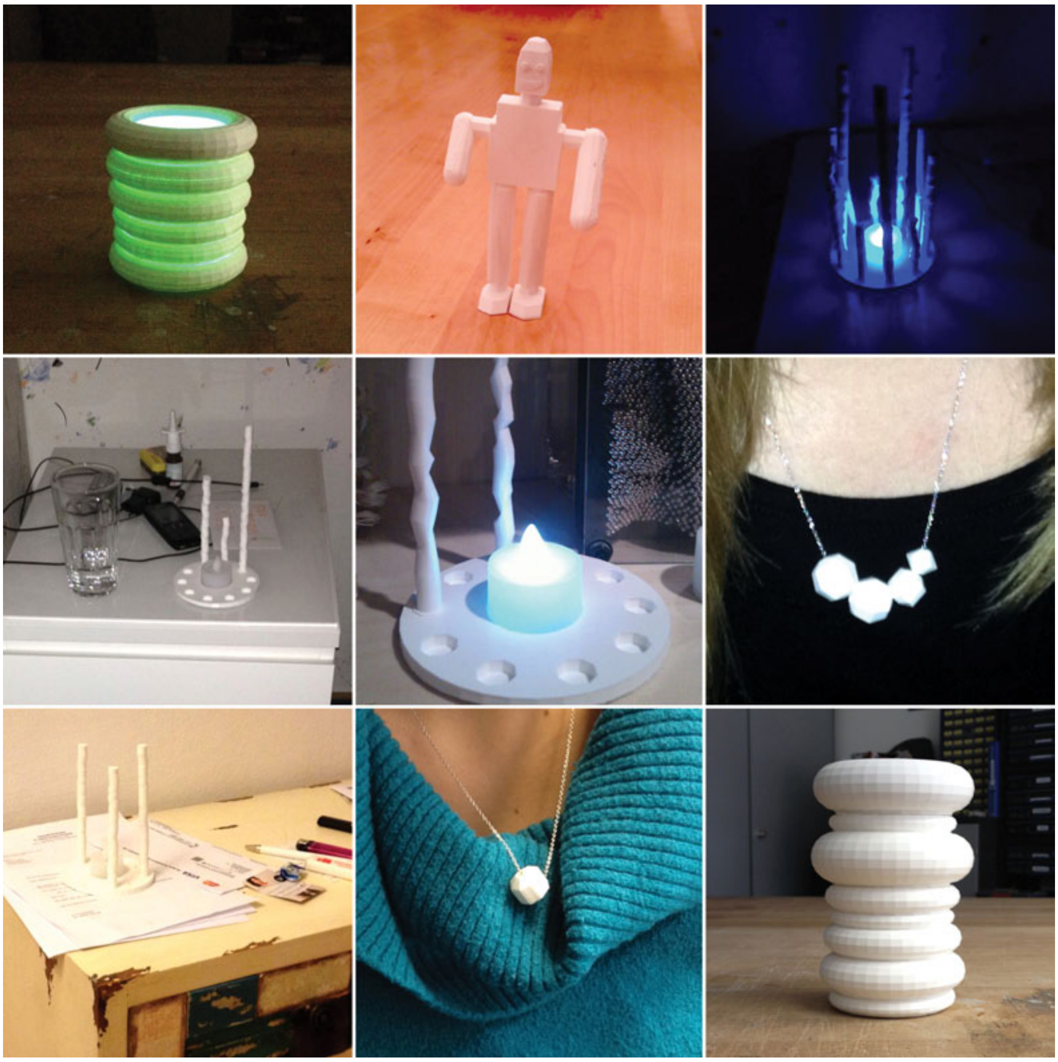

Figure 8.9: Various pictures of the by participants' received Activity Sculptures and in which ways they were embedded in everyday life.

when receiving her third piece, as it was clearly thinner than the first piece. This raised her motivation to a longer subsequent run to get a wider ring for her jar.

Almost all participants who chose the figure or lamp sculpture, which had a defined number of pieces, mentioned that they tried to accomplish enough runs to assemble a complete sculpture eventually. Three participants stated that the lamp influenced their running behavior such that it provided an incentive to fill all the hollows.

Changing Running Habits The interviews also revealed a rather unexpected impact of the Activity Sculptures, as they had a strong influence on some participants' running habits.

Curiosity, playfulness, and aesthetics began influencing the way participants ran as they tried to control the shape of the pieces they would receive.

Participant 9 mentioned having a piece in mind during every run. As the lamp sculpture encoded the *elevation gain*, participants who chose this type felt motivated to experiment with speed and altitude. *Participant 6* intentionally ran uphill, and *participant 7* ran the same route twice in a different manner, to see in which ways this would be reflected in the sculpture pieces.

Participant 5, who had mentioned in the preliminary interviews that she normally did not run when it rains, actually ran in the rain, due to her "*excitement*" about receiving her first sculpture piece. She was also surprised at how small and angular her first bead of the necklace sculpture was. Therefore, she modified her running accordingly to achieve a "*nicer and rounder bead.*" For her third run, she then tried to achieve a performance similar to her first run. Her intention was to have two small beads and one big one, to have a nice appearance with the biggest bead in the center and the smaller ones around it.

In contrast, *participant 11* tried to achieve a disproportional figure sculpture by finishing runs with high variances in the data within and between single runs. Similarly, *participant 10* ran a half marathon to test the limits of the system.

The Reward Experience

The participants also raised questions related to their expectations and the actual reception of the pieces as a reward.

Time of Delivery Participants thought about the best moment for receiving a sculpture part. In general, they seemed to consider that having a delay between the run and the reward was beneficial. *Participant 9* liked the aspect that with a delay of one day between the run and receiving a piece, one has the chance to speculate on the run and what the piece would look like. *Participant 14* also preferred a delay, arguing that directly after a run one already felt the reward of having finished it, whereas receiving the piece a few days later could act as an additional reward for the run. As mentioned in the design discussion, based on the online questionnaire we initially envisioned a slower reward mechanism, e.g., a sculpture piece per month or for specific goals instead for each run. However, none of the participants complained about the high frequency of delivery during the study.

Excitement Several participants mentioned terms such as "surprise" and "excitement" as an important part of the rewarding experience. *Participant 11* wanted to go running immediately after she received her first piece since she wondered what she would receive next. *Participant 8* stated that she skipped her yoga classes several times during the study since she knew that she would not get a physicalization for this kind of activity. She also mentioned it would have been nice to get rewarded with sculpture pieces for any physical activity and not only for running.

Based on participants' statements the figure sculpture seemed to be the most exciting sculpture, as all participants mentioned that they were always looking forward to receiving the next part of their figure. The mystery of which body part would be presented to them next was especially appreciated. For *participant 11* it would have been even more interesting if she had not known in advance the type of her sculpture and how it would look like until she had put the pieces together.

Conversation All participants pointed out the ability of the sculptures to provoke exchanges and discussions. They often served as a conversation starter. Especially the participants who chose the necklace reported, that they were often asked about their beautiful accessory. *Participant 4* mentioned that when she received a new piece she wanted to go to her colleague to show it to him and find out if he also received a new piece. Apparently, her colleague had the same idea and so both met in the corridor holding their new pieces. Both were part of the running team and mentioned similarly to the other two members, that they in general often talked about not only the sculptures but the entire study, e.g., during lunch or coffee breaks.

8.5 Discussion

The design and study of the Activity Sculptures raised various questions of how data can be mapped in a physical form and in which ways this influences the perception and interpretation. It also highlighted the role of experimentation in supporting reflection, sense-making, and engagement with the data. We furthermore observed technical concerns related to scalability and sustainability. We believe that the physical nature of our data representations stresses design questions which are relevant for casual InfoVis, and maybe even InfoVis in general.

8.5.1 Sculptures as Personal Data Representations

It seemed that our Activity Sculptures encouraged participants to interpret and reflect on their personal activity data. Participants improved their reading of the physicalizations over the course of the study. Through experimentation, they developed a finer understanding of how their runs influenced the sculptures. For instance, the mapping of the elevation gain and the impact of different runs on the sculpture parts were explored in a creative and playful way by the participants, in which they also tried to test the limits of our system. The aspect of encoding data in an unusual or unpredictable form to encourage an exploration of the representation possibilities also seems interesting for digital visualizations. One amusing and creative example for this is a current trend of "FigureRunning"[7], in which runners use

[7] `http://app.figurerunning.com/` (accessed 2015-12-15)

the Global Positioning System (GPS) tracking of mobile applications to create drawings with their runs. The intention is not to motivate people to run faster or longer, but to run with more fun. We could observe such dynamics in our study as well and believe that the physical aspect intensified this effect, e.g., as our sculptures are unique and not easily reproducible.

The fact that the physicalizations required personal knowledge to be interpreted seemed to have fostered reflection on the pieces and the corresponding runs. It led participants to engage with the objects, by observing or comparing them. It also meant that participants could display them freely without feeling as if they were over-exposing themselves. It neither felt as bragging about one's performance nor did it felt as displaying something one would have preferred to keep to oneself. As the underlying data is not recognizable by everyone, our sculptures also allow a form of privacy protection. It seems that abstract or casual visualizations might be a promising direction for representing personal data, which can be shared with others, e.g., via social networks or other means.

8.5.2 Challenges of Static Representations

Similar to most prototypes we presented in previous chapters, the Activity Sculptures were static physicalizations. In contrast to digital visualizations, which can be easily updated as new data comes in or manipulated to show different data mappings or views, the variables and the mappings of our physicalizations were set from the beginning and did not change. Our choice of an extensible model which enabled us to augment the sculpture as new data was being produced, seemed a suitable way to reduce this drawback.

As mentioned by some participants, it could be interesting to give more freedom of choice, e.g., by letting participants choose and change the variables and mappings or specify concrete goals. In addition to offering more predefined sculpture types, it is also conceivable to let the people create their own sculptures, for example, with the help of an online configurator. One drawback of supporting more personalization could be the lower comparability of the sculptures between different participants.

8.5.3 Scalability

Scalability seems one of the main concerns in representing personal data in a physical form. Running data often underlies strong variances, e.g., as runners improve or follow a specific training schedule. Furthermore, Activity Sculptures evolve over a long period, as they aim at fostering regular physical activity, which makes scalability challenging. It needs to display both minor and large changes in the data, while supporting comparison and, not the least, resulting in an object that is suitable for 3D printing.

Finding a data mapping that accommodates people's different running patterns can be difficult. A sculpture should accommodate both a runner training for a marathon and someone running short distances at high speeds. While the sculptures should still be readable in both cases and show variations in the data as well as performance advancements, they should also support comparability and increase motivation.

Beside these considerations which are valid for a small number of pieces, the sculptures should also stand on its own and be meaningful after a high number of runs. The necklace and the jar sculpture are theoretically scalable but would become less attractive or less functional at a certain point. The lamp and the figure are not scalable because of their fixed amount of possible parts. A solution could be choosing one type of sculpture for a specified goal and once this is accomplished another can be chosen. This could be combined nicely with well-known gamification principles, e.g., unlocking new sculpture types after attaining specific achievements.

8.5.4 Sustainability

The production of plenty plastic objects for playful or motivational purposes raises issues of sustainability. It should be noted that technical devices to display digital visualization also consume a lot of energy, and their production requires a high consumption of resources. Nonetheless, we acknowledge, that Activity Sculptures increase the number of products in the environment. It could be imaginable to focus on rather small sculptures, which require less material, or to adjust the infill density in the printing process, to print less plastic inside of a sculpture. Another way to decrease the total amount of sculptures would be to decrease the frequency of delivery or only offering "summary sculptures" that represent the data of an entire month. In addition or in complement, old sculptures could be recycled. An increasing number of projects (e.g., Filabot[8], FilaMaker[9], Filastruder[10]) develop technologies to recycle and reuse 3D prints created with PLA. Adidas®, for example, is working on a concept to 3D print shoes consisting of recycled ocean plastic [adidas AG, 2015]. Another possibility is the usage of biodegradable PLA filament. Finally, following the vision by Gershenfeld [2012] we might overcome this problem in the future, as "*Trash is a concept that applies only to materials that don't contain enough information to be reusable.*"

8.5.5 Reflection and Self-Expression

Activity Sculptures are a promising medium for fostering reflection on physical activity, as they make the activity data visible and tangible. Schön [1983] describes that reflective practices are composed of reflection-in-action and reflection-on-action. Reflection-in-action is related to thinking ahead of the action, critically experiencing and adjusting to the activity as

[8] `http://www.filabot.com/` (accessed 2015-12-15)

[9] `http://filamaker.eu/` (accessed 2015-12-15)

[10] `http://www.filastruder.com/` (accessed 2015-12-15)

it unfolds. We observed this precise phenomenon as participants anticipated the sculptures before the runs, thought about them while running, and sometimes adjusted their running to get a specific shape. Reflection-on-action is much more related to the appraisal of the action after it has occurred, which was observed as participants compared their pieces and discussed them with others. Furthermore, we believe that our physicalizations allow a more abstract and enjoyable reflection on ones' physical activities than through detailed activity data composed of precise numbers and histories. We do not propose that this type of representations should replace traditional digital visualization techniques but to complement the range of tools available for representing personal activity data.

Based on participants' statements and our observation it seems of minor importance that the sculptures or single pieces support a comparison in a competitive way. None of the participants who chose the figure were bothered by the circumstance that it was hard to compare these sculptures with each other. For most participants it was more important to see their progress and performance improvements or the general influence of a run on the sculpture's shape.

Out of our four sculpture types, the necklace sculpture received the best ratings and was the only sculpture type which fulfilled participants' expectations regarding self-expression and the comparison with others. The good ratings for self-expression can be explained by the fact, that it was the only sculpture type which can be worn on the body and therefore easily be seen and shown to others. These findings lead to our assumption that the most promising design direction for Activity Sculptures is to be geared to accessory design and wearable physicalizations.

8.5.6 Limitations

Our exploratory field study with 14 participants can only reveal first trends and anecdotal evidence regarding the impact of physicalizations on participants' behavior. To investigate whether the sculptures have a motivational effect in the long term, and to preclude the novelty effect as a predominant explanation of this success, further longitudinal studies with a larger sample are needed. Material costs and the time-consuming printing process play a major role for the practicality of physicalizations of running data. Before realizing this concept for a long-term study or beyond a study, these aspects in particular need to be taken into account.

The results collected through the online questionnaire revealed that participants preferred receiving the sculptures only for the achievement of pre-established goals or once per month. While our field study could not take these preferences into account due to the limited study time, this could be a valuable strategy for a longer term study. It should also be mentioned that the manual handover might have influenced the participants' experience, especially at initial handover. As the participants were in regular contact with the study leader multiple times they might have felt an obligation to comply and be a "good subject" [Brown et al., 2011], e.g., to run several times during the study.

With our four types of Activity Sculptures we only covered a small sample of the design space. We only compared artistic physicalizations and had neither pragmatic physical data representations nor digital visualizations as a baseline. It is also important to mention, that although our physicalizations could be touched, none of the participants reported that they explored or analyzed the data through the haptic sense. The visual sense seemed to provide enough information, and as we mapped the underlying data only to the visible shape of the sculptures, a haptic exploration of the data was unnecessary. Future designs could incorporate physical variables (see also *Chapter 10 - Physical Variables*), such as compliance, weight or coldness, which are only perceivable through the haptic sense. This could also upgrade the privacy aspect, as observers not only need to recognize an object as a data representation and understand the data mapping but also have to touch the physicalization.

8.5.7 Conclusion

Our field study showed a high appreciation of our Activity Sculptures and their ability to improve *motivation* and *self-reflection* convinced our participants in particular. We further uncovered their potential for a more creative and playful view at ones' activity, as participants started to change their running routines to impact the shape and aesthetics of the final sculpture pieces. Participants developed an emotional connectedness to their sculptures and thought about ways to personalize their sculptures.

While bearing in mind the limitations and the exploratory nature of the study, our findings revealed additional benefits of physicalizations for representing personal data and motivate further research in this area. Besides different types of sculptures, future studies could also investigate the utilization of other materials. As running is associated with nature, natural materials such as wood instead of plastic could be an interesting alternative.

It is also imaginable to change the concept of one sculpture for each person to one sculpture on which numerous people collaborate. Each person would then contribute to the common sculpture. In the brainstorming session, for example, one participant had the idea of a Christmas crib, in which each family member would be accountable for one figure. At the end of a year the family could explore together how physically active everybody was during the year. Such group sculptures in various shapes could also be interesting for members of a running team, a group of physically active colleagues or people who share an apartment and want to engage in a more regular physical activity. Another concept would be to focus on large public events such as marathons or triathlons, in which participants would receive a personal trophy tailored to their performance instead of medals.

It could also be exciting to investigate in which ways such sculptures could be integrated into the routine of professional athletes. Our aesthetical mappings of better performances to rounder shapes were purely experimental. Those data mappings could be determined together with experienced trainers, such that the different types of training (e.g., endurance, speed or interval) would each lead to meaning- and beautiful sculptures.

Finally, we only focused on a specific type of personal data: five variables which represent running activity. An extension to other physical activities is conceivable as well. Examples are cycling, hiking or daily routines. Furthermore, the underlying data does not have to be limited to activity data. People are tracking nowadays their sleep quality [Hao et al., 2013] and eating habits [Cordeiro et al., 2015], but also their music listening [Baur et al., 2012] or beverage consumption [Maurer et al., 2013]. Even the progress of completion of to-do lists or Ph.D. thesis writing could be encoded physically and thereby promote an efficient and timely completion in a playful and unobtrusive way.

III

REFLECTING ON THE DESIGN OF PHYSICAL VISUALIZATIONS

Chapter 9

Materialized Self

The design and evaluation of the *Activity Sculptures* project (*Chapter 8 - Potential for Motivation & Self-Reflection*) revealed the various engagement opportunities at disposal with physicalizations for representing personal activity data. Our findings revealed the need for design strategies for such physicalizations of personal activity data and a structured view on which personal feelings as well as social dynamics such data representations can evoke. Independent from our project, Khot et al. [2014] developed and studied a similar system called *SweatAtoms*. During an intensive collocated collaboration for three months with Rohit Ashok Khot, we laid the foundation for a conceptual framework called *Materialized Self*. The framework is based on the insights gained from studying those two systems, supplemented with the knowledge from the literature and our own experiences in designing these systems.

This chapter describes the *Materialized Self* framework and its two lenses: "production lens" and "consumption lens" (see Figure 9.1). These two lenses highlight the shared agency in defining the design and the use of personal physicalizations in an everyday context. Each lens has a set of design properties grouped in three nested layers. The "production lens" describes the areas that the designer prescribes in the creation process of the physicalization and consists of the layers *function*, *form*, and *fabrication*. The "consumption lens" focuses on the range of qualities and effects evoked by the personal physicalizations during its use and consists of the layers *identity*, *meaning*, and *ecology*. Therefore, the framework can be used as a design tool for physicalization by selection and adaptation of the framework's properties but also as an analytic tool for describing final designs regarding the selected properties. We believe that the framework guides interaction designers working in the field of personal informatics to harness the interactive capabilities afforded by digital fabrication and physicalizations for personal data.

Personal contribution statement: The content of this chapter is based on an intensive collocated collaboration for three months with Rohit Ashok Khot. See *Disclaimer* for a detailed overview.

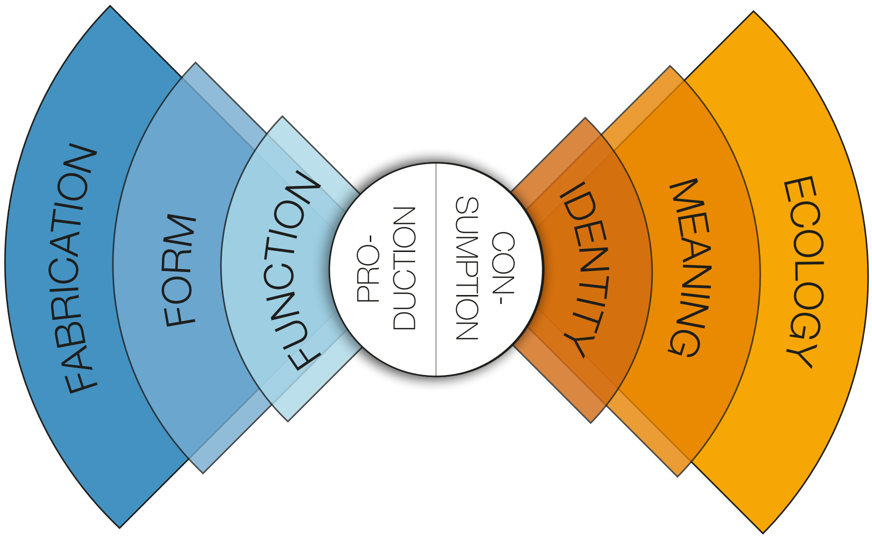

Figure 9.1: Diagrammatic overview of the "Materialized Self" framework consisting of the *production lens* and *consumption lens* and their according layers.

9.1 Motivation & Background

A review of existing literature in HCI to support physical activity suggests that most often a digital medium is used to represent personal activity data. Non-virtual, i.e., material, representations have not been explored much, possibly because creating physicalizations was technically challenging, which recently has changed thanks to digital fabrication technologies (see *Chapter 3 - Digital Fabrication*). The Activity Sculptures system (see *Chapter 8 - Potential for Motivation & Self-Reflection*) and the SweatAtoms system by Khot et al. [2014] were the first approaches in exploring and investigating in which ways activity data can be represented through physical artifacts. Table 9.1 shows a brief comparison of both systems. The results of both studies led to the assumption that physicalizations can have additional qualities compared to their digital counterparts. Therefore, we believe, there is a need to provide researcher and designer with guidelines of ways in which such physicalizations of personal activity data can be designed but also what kind of dynamics and qualities these can evoke for the people receiving them.

By physical activity data, we refer to biofeedback (e.g., heart rate) and data about bodily movements that occur during physical activity. This construction process involves a "physical – digital – physical" mode of interaction in which physical energy is first invested to generate digital data such as heart rate, which is then converted back again into a physical form to make a re-entry into the physical world. As a result, the data, which was previously accessible only through a digital screen, becomes tangible.

Table 9.1: Comparisons of the SweatAtoms and Activity Sculptures systems.

	Sweat Atoms	**Activity Sculptures**
Sensed physical activity data	Heart rate	Running data (distance, duration, average speed, burned calories, elevation gain)
Tracking	Heart rate monitor	Mobile tracking application
Number of representations	Five (Graph, Flower, Dice, Ring, and Frog)	Four (Necklace, Figure, Jar, and Lamp)
Received representations per participant	Five	One
Method of delivery	3D-printing at home	Personal handover or via letter
Choice of color	User defined	White
Study method	Field study in participants' home	Field study
Number of participants	Seven	Fourteen
Number of participants	Two weeks	Three weeks

In addition to our own experiences in designing and evaluating physicalizations, we ground our interest in material representations and their opportunities in the literature on material culture studies [Miller, 1987, 2008, 2010; Woodward, 2007] as well as in HCI and TUI [Kirk and Sellen, 2010; van den Hoven, 2004; Golsteijn et al., 2012; Petrelli et al., 2008], which signify the human fascination towards collecting and making objects. Sennett [2008] refers to humans as "*homo faber: manufacturer and collector of objects*" and as a "*creature who imbues sentiment in external artifacts.*" Miller [2008] argues that people like to express themselves with material representations that embody their lives, personalities, emotions and achievements. For example, the results of one's crafts and awards are often displayed on fridge doors, walls and shelves. Photographs of trips and events are often printed, framed and displayed despite the fact that they could just as well be seen on a screen. Such an arrangement of material representations that spatially represent the identity of an individual is called "autotopography" [González, 1995]. This autotopography can serve as a memory landscape to the owner, triggering reminiscence at a later point of time [van den Hoven, 2004].

Despite the benefits that material representations may provide, we only have a limited understanding of how to design such material representations for physical activity. Laser cutters and 3D printers simplify the fabrication of physicalizations and Gershenfeld [2007] envisions that 3D printers will soon be found in every home. As a result, design and HCI researchers are now considering the role of digital fabrication in HCI (see *Section 3.2 - Digital Fabrication in HCI*)). But there is still a limited understanding of the benefits and uses of personal digitally fabricated artifacts. Additionally, we identified a growing interest within the HCI community of exploring the potential of material representations of personal data (e.g., Nissen et al. [2014]; Nissen and Bowers [2015]; Lee et al. [2015]). We, therefore, consider it a timely endeavor to investigate the significance of digital fabrication for supporting physical activity.

The structure of the framework was made during an intensive exchange of our experiences and findings discovered through the design and evaluation of the two systems. We also engaged in informal discussions with colleagues for feedback and iterations of the framework. Inspired by techniques such as open coding [Seidel and Recker, 2009] and affinity diagrams we further extracted the key terms and results and recorded them on index cards. By sorting the cards into groups, we narrowed down the framework regarding the key concepts. The form-driven materiality framework by Jung and Stolterman [2012] was also influential in grounding our understanding of materiality and framing of the main components.

9.2 The "Materialized Self" Framework

We propose the "Materialized Self" framework as a descriptive design framework that takes a cross-sectional view on the design of physicalizations for personal activity data. The designer of the physicalizations and the people, who are receiving and using them, have a shared agency in defining the design and the use of the material artifacts in an everyday context. We frame this regarding two lenses: "production lens" and "consumption lens". The "production lens" helps in shaping the physical appearance of the physicalization by describing aspects of the physical form and the fabrication process. The "consumption lens" is crucial in understanding the intrinsic cognitive relation and value of the representation as driven by the people's data and properties. Table 9.2 gives an overview of the entire framework in tabular form consisting of the two lenses and their according layers and properties.

Each lens allows examining a set of design properties that are grouped in three nested layers, in decreasing order of priority from the center. These design properties help in understanding, analyzing and contrasting the qualities expressed in the design and the use of the physicalization. Furthermore, the grouping of these properties into layers was done based on commonalities and level of importance we observed among the properties. As a result, the layer closest to the center has more importance than the other layers (see Figure 9.1).

9.3 Production Lens

The "production lens" has in total nine properties that are grouped in three layers: *function*, *form*, and *fabrication*. We put the *function* layer in the center as it describes the essential properties while designing physicalizations for personal activity data. The other two layers *form* and *fabrication* are outer layers which conceptually follow the *function* layer. It is

Table 9.2: Tabular overview of the “Materialized Self” framework.

Production Lens		
Layer	**Property**	**Description**
Function	Purpose	Designer’s intended purpose for the physicalization, e.g., to enable richer reflection on physical activity.
	Qualities	Qualities of the physicalization that go beyond the intended purpose, e.g., sustainability.
	Use	Values of the physicalization concerning its use, e.g., decorative or practical object.
Form	Data	Aspects regarding the used data, e.g., data type.
	Physical Variables	Physical properties that can be used for representing data, e.g., size or texture.
	Data Mapping	Process of mapping abstract data to a material form, e.g., mapping size to amount of physical activity.
Fabrication	Process	General process of fabrication, e.g., manual or automatic.
	Timing	Duration and point in time the physicalization is fabricated, e.g., during a physical activity.
	Frequency	How often the physicalization is fabricated, e.g., every month or on special occasions.
Consumption Lens		
Layer	**Property**	**Description**
Identity	Self	Extent to which the physicalization is in line with the user’s identity, thoughts and likes.
	Authenticity	Identification and mapping of distinctive characteristics of individuals in material form.
	Autonomy	Abilities to affect the design of the physicalization by experimenting with physical activity routines.
Meaning	Information	Perceived understanding of the physicalization and the mapped data.
	Motivation	Incentives provided by the physicalization for doing physical activity.
	Utility	Other imagined uses of the material artifact by people.
Ecology	Context	How situations and environment affect people‘s interactions with the physicalization.
	Pairing	Association of the physicalization with other material artifacts and people.
	Attachment	Level of engagement with the physicalization in terms of time.

noteworthy that the *fabrication* can limit the *form* (by technological restrictions), which in turn can also affect the desired *function*.

9.3.1 Function

The *function* layer is at the core of the "production lens" and points to the central goals of the physicalization. In general, the *function* layer has the closest relationship to the "consumption lens" as the choice of its properties can have a substantial impact on how people can and should use the physicalization. First, there is the intended *purpose*, which was in our projects to encourage physical activity through positive reinforcement. Apart from motivating to start or maintain a physically active lifestyle, other *purposes* could be changing a specific behavior or keeping track of the progress. As those *purposes* can be fulfilled in various ways, they should be adapted to the diversity of individuals [Prochaska and Velicer, 1997].

Besides supporting the primary objective, e.g., being physical active, physicalizations can fulfill additional *qualities*. A classical example which is also valid for digital representations is aesthetic aspects. In our projects, we also observed desired *qualities* that go beyond digital representations, e.g., sustainability. Similar to these *qualities*, which focus more on feelings and emotions, physicalizations can also fulfill a practical *use* in everyday life. Such additional *qualities* and practical *uses* prescribed in the design could help in further supporting the main *purpose* and overall engagement with the physicalization. In our projects, the physicalizations were used, for example, as a decorative object or fashionable jewelry.

9.3.2 Form

The *form* layer involves considerations regarding the aesthetic and appealing possibilities of the physicalization. The *data* property describes aspects of the data such as its type and the used tracking method. Physical activity can be measured, for example, as physiological output (e.g., heart rate data) or movement based data (e.g., distance). It should also be considered how and when the data is tracked, how reliable it might be and if additional preparation is needed to gain a form that is suitable for a data representation, e.g., normalizing the data.

Another aspect is how the data will be encoded physically, i.e., which *physical variables* can be used (see also *Chapter 10 - Physical Variables*). Volume and shape were the primary physical variables used in both projects because those are controllable through the technique of 3D printing. Finally, the *data mapping* process has to be defined, i.e., in which ways the digital data will be encoded into the object and material properties. We used a rather simple data mapping for most of the physicalizations. In the majority, an increase of physical activity resulted in a bigger artifact. We believe, it would be worth investigating in which ways people perceive and understand other physical variables such as texture or compliance.

9.3.3 Fabrication

Fabrication, as the outer layer of the "production lens" is concerned with all aspects regarding the actual physical creation of the artifact. Swaminathan et al. [2014a] have argued that assembly and manufacturing features are also important for physicalizations along with the design goals (*function*) and the aesthetic features (*form*). The *process* property describes the fabrication procedure of the physicalizations. One aspect is whether the consumer is involved in the process, e.g., by printing the artifacts at home, or not. The technique choice (e.g., 3D printing or laser cutting) and their limitations and capabilities do also define what kind of physicalizations can be produced. Both projects used rather simple shaped and small objects for 3D printing to keep time and costs on a reasonable level.

The *timing* and *frequency* properties play key roles in determining the duration of the fabrication process and answering questions such as how often and when the material representation is fabricated and received. The 3D printing or laser cutting could take place during the physical activity in which people could directly influence the material representation by changing the course of the activity. If the fabrication happens after the physical activity designers should consider the duration between these two actions, to enable short-term or long-term reflection [Li et al., 2010]. The *frequency* of how often the physicalization will be fabricated can vary from a specific period to a specific occasion. The *frequency* of fabrication is also related to the frequency of *data* collection [Li et al., 2010]. Additionally, the designer can also consider the amount of data and its mapping to the artifact. For example, some users may appreciate the data for a particular event or one-week long training session, encapsulated into one design rather than dividing and fabricating data physicalizations every day.

9.4 Consumption Lens

After explaining the "production lens," we turn our attention to the "consumption lens" and its three layers *identity*, *meaning*, and *ecology*. The "consumption lens" focuses on the experiences and emotions of the people that are using the personal physicalizations. This lens is constructive, as it draws our attention to how people reframe their understanding of physicalizations through their use. Social science research designates these qualities as materiality and defines them in terms of the relationship between representations, people and the environment [Miller, 1987].

9.4.1 Identity

The *identity* layer looks at reflective qualities of physicalizations, synonymous with the individual's personality, values, and ethics. The *self* property refers to a representation about oneself, in parallel to the representations people have of other individuals [Swann and Bosson, 2010]. James [1890] differs between the “material self”, which describes in which ways an individual appears to the external world through his body, likes and personalities and the “spiritual self”, which reflects individual’s ideas, goals, and state of mind. Physicalizations can blend both these aspects nicely by making its visual appearance in line with the individual’s preferences (material self) and by being reflective of the individual’s state of mind through the capture of personal data (spiritual self).

The property of *authenticity* refers to the degree to which the created physicalization is true to the individual and the captured physical activity data. Personal physicalizations can be a unique and authentic type of self-representation which cannot be purchased. It is also important that the data mapping is understandable, and the underlying data is reliable. The property of *autonomy* refers to the levels of individuality and creativity at which people can innovate the design of their physicalization through the use of their body and movements. In our studies participants followed a playful exploration of the systems and their possibilities as well as their limitations. We believe that physicalizations can leverage the opportunities to be self-expressive and autonomous. Instead of just mimicking predefined exercises, personal physicalizations could inspire to be more physically active and also to be creative within the exercise, which could lead to an engaging experience.

9.4.2 Meaning

The *meaning* layer describes the emotional responses such as intrigue, disappointment, and satisfaction that people may experience when they encounter a physicalization of their data. The *information* property defines the internal mapping between the data and the physicalization, as understood by the user. A lot of this understanding strongly depends on the *form* and the *function* of the representation as discussed earlier in the “production lens.” However, individuals have different expectations and interpretation abilities when it comes to understanding a design, in our case a physicalization. Furthermore, these abilities are influenced by the context and might change over time and with use.

The *motivation* property describes the range of incentives that physicalizations provide and whether they can fulfill the goal to encourage people being physical active. The reward structure of physicalizations should be tailored to suit an individual’s needs and aspirations. Moreover, for sustaining people’s interest and motivation, providing a variety of rewards and changing rewards over time might be a valuable option. The *utility* property puts forward new and imagined uses of the physicalizations that go beyond predefined uses as sketched by the designer. Our studies showed, that participants were creative in discovering new values for their physicalizations, such as using them as a candleholder, or tried to personalize them, e.g., by coloring them.

9.4.3 Ecology

The *ecology* layer is concerned with the nature in which the artifacts are embedded in everyday life and in which ways the surrounding reacts to them. The *context* property identifies the ways in which individual's interactions with the physicalizations are influenced by the situations and the environment they are used. This is based on the concept of "the social self" by James [1890] and the theory of self-representation by Goffman [1959]. Unlike digital visualizations that sit mainly on a digital screen, physicalizations have to fit the context in which they will be placed and have to satisfy and cater to existing aesthetic details and surroundings. Another aspect is the level of abstraction, as an individual might desire more abstraction and privacy in a public setting while she might appreciate a more detailed and clear representation in a private setting.

The *pairing* property describes the extent to which a physicalization pairs with other artifacts as well as the people who would interact with it. Although the physicalizations from both studies worked as standalone artifacts, participants reported the request to receive artifacts that can easily pair with things that they already have. The artifacts also played the role of a social catalyst, inviting conversations around their aesthetics and use. The *attachment* property points to the continuance of an individual's relationship with the physicalization. While material artifacts might have a longer life and value in people's life than its digital counterparts, they are also much harder to create and destroy. As a result, designers should focus on how these representations could be able to sustain a user's interest over a longer period or instead use temporal or disposable materials.

9.5 Discussion

By differing between the "production lens" and "consumption lens," we want to highlight the importance of the user's role and agency in designing material representations of personal data. In our experience, the users seem to develop a greater sense of value and emotional connectedness to personal physicalizations than to their digital counterparts. In particular, as they are influencing the shape of real-world physical objects through their personal data. Therefore, the "production lens" targets the aspects that are controllable through design and fabrication while the "consumption lens" highlights the evolution of understanding and emotional bond to the physicalizations during its use.

The framework should be useful for designers as a design tool to ideate and design physicalizations of physical activity data. Additionally, designers can also utilize the framework to analyze existing designs and identify whether the intended purposes of the system are met. Through the set of design properties, the framework provides an overarching collection of possible design opportunities. We hope to broaden the often limited view when designing technology that supports physical activity. The emphasis on encouraging better performances and achieving efficiency goals often covers other ways of engaging humans with physical activity. We hope that the framework will be helpful in striking the balance between what is possible ("production lens") and what is desirable ("consumption lens") regarding physicalizations encoding activity data. Furthermore, we believe, it can serve as inspiration for the design and the potential of physicalizations in general, especially for representing personal data.

Chapter 10

Physical Variables

Visual variables are a set of characteristic properties that can be applied to data to represent information visually. By understanding the variables' internal properties (what they can represent) and their external properties (how they are perceived) designers can choose them accordingly. To our knowledge no counterpart for physicalizations does exist. Inspired by the tradition of InfoVis, we investigate potential variables associated to physicalizations. These variables describe the ways in which physicalizations can encode data, e.g., by modifying the size, shape, roughness or weight of physical artifacts. In contrast to the visual variables targeting tradition data representations, we focus on variables that are not only visual but also aimed at additional senses such as tactile or kinesthetic. The goal is to lay a foundation for a discussion of how physical variables can be defined and in which ways they can be used to represent data.

In this chapter, we propose a preliminary definition of variables for modular data physicalization. Modular data physicalizations are physical representations of data made out of multiple pieces (modules), with each module corresponding to a data point. Such modular data physicalizations were used, for example, in *Section 6.2 - Modular Physical Bar Charts* and for the Activity Sculptures project in *Chapter 8 - Potential for Motivation & Self-Reflection*. In total we outline 14 dimensions grouped into four categories, but focus on the nine dimensions that are novel and related to data physicalizations: geometric variables (position, orientation, *global shape*, *exact shape*), color variables (hue, saturation, luminance, *optics*), tactile variables (*roughness*, *lay*, *temperature*, *compliance*), and kinesthetic variables (*slipperiness*, *weight*). We describe each dimension, give examples in which ways they can be used to encode data and address their performance for interpretation tasks. We conclude with a short discussion on how the variables relate to personal or social perception, such as emotional and associative aspects.

Personal contribution statement: The content of this chapter is the result of an collaboration with Aurélien Tabard. See *Disclaimer* for a detailed overview.

10.1 Motivation & Background

To create effective physicalizations that are explorable and readable by people, it is essential, that an observer can decode an object and its underlying data. Similar to the visual encoding process for visualizations, a structured way of representing data in a physical form, with its physical properties is necessary. This can guide researchers, designers, and artists in creating physicalizations, e.g., by specifying what type of data can be conveyed with specific physical properties and which role they play in the perception and interpretation of data. In the following, we will briefly discuss related topics from the InfoVis area, in particular, visual perception as well as visual marks and variables, but also delimit the scope of our proposition.

10.1.1 Visual Perception

Human perception and especially the visual sense play a major role in the area of visualization. However, the exact process from receiving sensory inputs and their way to perception and cognition is still unclear. In psychology, two theories of perception are controversy discussed. The bottom-up theory by Gibson [1962] on the one hand suggests that sensory information is analyzed in one direction. The top-down theory by Gregory [1970] on the other hand refers to the use of contextual information and argues that prior knowledge and past experiences are crucial in perception.

Healey and Enns [2012] give a thorough overview regarding research on attention and visual perception in their paper "Attention and Visual Memory in Visualization and Computer Graphics". They highlight that each fixation of our eyes influences our mental experience but that our current mental states are also guiding saccades in a top-down mode to new locations for more information.

One of the most important discoveries in the early studies regarding visual perception was "the identification of a limited set of visual features that are detected very rapidly by low-level, fast-acting visual processes" [Healey and Enns, 2012]. Although attention is also important at this early stage of vision, these properties are called pre-attentive. Typical examples of visual features that are pre-attentive are size, color (hue) and curvature. Typical tasks to identify such features are the detection of a target element or a texture boundary between two groups of elements. If these tasks can be performed in less than 200-250 milliseconds, they are considered as pre-attentive. It is worth mentioning that a target only "pops out" if its visual property is unique, when a target is encoded by two or more visual properties, it often cannot be found pre-attentively.

Some theories have been proposed to explain in which ways pre-attentive processing occurs within the visual system, such as the feature integration theory (e.g., Treisman and Gelade [1980]; Treisman [1985]) or the texton theory (e.g., Julesz [1971]). In addition pre-attentive vision there exist also related phenomena such as post-attentive vision or change blindness, which are relevant for the design of effective visualizations (see Healey and Enns [2012] for more details).

10.1.2 Visual Marks & Variables

To appreciate the aim to investigate and identify physical variables it is necessary to understand the value of its counterpart in visualization: visual marks and visual variables. A lot of studies explored in which ways data can be encoded visually and how efficiently the various visual variables are.

Bertin [1983] developed the semiology of graphics as a practical approach for his data graphics. He defined marks as the basic unit to present something visually and identified three types of marks:

- *Points* are dimensionless locations in space that need properties such as size or color to be visually perceived.
- *Lines* represent information with a certain length, but with no width and need properties such as size or color to be visually perceived.
- *Areas* have a length and width and operate in a 2D space.

Those three types were later expanded with two additional marks (e.g., Card and Mackinlay [1997]; Carpendale [2003]):

- *Surfaces* are similar to areas but in a 3D space with no thickness.
- *Volumes* have length, width, and depth, while their size is their meaning.

Bertin further identified variables that can be used to vary these marks to encode data on a two-dimensional space: *x and y position on a two-dimensional plane, size, value (gray scale saturation/color value), texture, color (color hue), orientation, and shape*. This list of variables was later expanded and renamed by MacEachren [1995] resulting in a catalog of 12 variables in total: *location, size, crispness, resolution, transparency, color value, color hue, color saturation, texture, orientation, arrangement, and shape*. Please note that MacEachren indicates Morrison [1974] as the first author who suggested *arrangement* and *color saturation* as additional visual variables.

Based on this work a great amount of studies has been conducted to extend and validate the variables (e.g., Cleveland and McGill [1984, 1985, 1986, 1987]; Mackinlay [1986]) and is still an important topic in current research (e.g., Chung et al. [2015, 2016]; Skau and Kosara [2016]). Among other things those studies led to a ranking of perceptual tasks which is useful for designers of visualizations by supporting the data mapping process.

10.1.3 Disclaimer

Bertin [1983] and Carpendale [2003] prefaced their work with a disclaimer to delimit the scope of their concepts. Bertin considered the creation of data graphics on a white paper in which the data is visible at a glance. He also assumed standard book reading conditions, such as constant light and a reading distance of an arm's length. Carpendale mentioned the low resolution of digital displays compared to prints on paper, at the time, but also the technical process in software and hardware, which will change what can be displayed visually. To narrow down our initial classification of physical variables we also implied various external preconditions. Therefore, this should not be considered as a definitive description but as a practical first pass and a working classification.

We only focus on modular physicalizations, which presents several benefits. Modules can be parametrized and produced quickly with digital fabrication technologies, e.g., laser cutting or 3D printing. They can also be assembled in a systematic manner and enable physicalizations to be "updated" as new data points come in. We follow the argumentation by Bertin [1983] and only consider the design and perception of modular physicalizations in "normal conditions" by "normal sighted" people. We only included "substantial surfaces", i.e., ignoring liquids and gases. We also follow the argumentation by Jansen et al. [2015], that physicalizations are perceived "actively," through exploratory actions involving hand, arm, and body movements, based on an "intermodal" approach, which allows cohesive and realistic multi-sensory experiences. This active exploration also means, that the condition by Bertin that the data representation is perceivable at a glance is not valid for physicalizations, as the active exploration takes time and occurs sequentially.

To limit the list of potential variables we focused on material properties and characteristics that are most studied in the field of haptic perception (see *Section 2.2 - Haptic Perception*), are part of active research in HCI (e.g., changing weight [Niiyama et al., 2013] or stiffness [Follmer et al., 2012; Ou et al., 2013]) and can be fabricated with state-of-the-art digital fabrication technologies. Finally, we did not take into account and did not intend to characterize the role actuation could play in the design and perception of physicalizations. We, therefore, skipped properties that seemed less appropriate for encoding data at the moment, based on technological complexity and their limitations. We believe that technical advancements, especially regarding digital fabrication technologies and shape displays, will simplify the creation of physicalizations as well as change and extend what can be represented physically and perceived haptically, in the near future.

10.2 Description of Variables

This section describes each dimension by specifying in which ways the material and object properties can be used to encode data. In total, we have identified 14 dimensions but will focus on the nine dimensions that are novel and most relevant for data physicalizations. We classified them into the following four categories: geometric variables (position, orientation, *global shape*, *exact shape*), color variables (hue, saturation, luminance, *optics*), tactile variables (*roughness*, *lay*, *temperature*, *compliance*), and kinesthetic variables (*slipperiness*, *weight*).

Throughout the presentation of the variables, we use the beads from the *Activity Sculpture* project (see *Chapter 8 - Potential for Motivation & Self-Reflection* as well as Figure 8.5) as an example to illustrate the ways in which the dimensions could be applied. If we could find real examples of physicalizations using those variables, they are also listed. We furthermore give a brief description of how each variable could be realized using current digital fabrication technologies.

10.2.1 Geometric Variables

Geometric variables consist of four dimensions, but we will focus on *global shape* and *exact shape* as position and orientation are intensively discussed in previous articles about visual variables. The *global shape* can be described as the bounding box of a module and the *exact shape* as the contour of it. Please note that *roughness* and *lay* could be classified as a micro-level of the *exact shape*, but we categorized them as *tactile variables* since they are directly related to touch.

Position and Orientation

The characteristics of the position and orientation of single physical modules are similar to their descriptions for visualizations. As physicalizations are part of the physical world their positions can be defined in three dimensions, as positional variables x, y, and z. However, physicalizations are also subject to gravity which hinders the free positioning of modules in 3D space. While it is out of scope for this article, the kinesthetic location, i.e., the location of the hand in relation to the body and the reachability of a module, i.e., in an arm's length distance, are aspects worth considering for physicalizations.

For the beads of the Activity Sculptures project, the position (on one axis) of multiple beads (or modules) on a chain can be used to encode the order of the runs. If the shape of a bead is not homogeneous or the weight distribution is controlled, the orientation could also be used for data encoding. We believe that for modular physicalizations both, position and orientation, are rather managed through manual control than through fabrication techniques.

Global Shape

With *global shape*, we mean the global dimension of a module. This variable is similar to the visual variable size, which is based on the length, area or volume of a mark. It can also be described as a coarse bounding box for a module, to highlight the focus on the global appearance and to exclude finer details of a shape.

The *global shape* of the bead would be the size or volume of a surrounding sphere and therefore, ignoring the exact shape, defined by the width and height segments. The *global shape* can be perceived with the visual and haptic sense. We believe the visual sense is more crucial as with the haptic sense objects are not perceived by its *global shape* but rather by its local features, such as the *exact shape* or the *roughness*. Furthermore, the module has to be of a size, which can be perceived with the haptic sense.

Similar to digital visualizations the *global shape* or size is one the most used variables for physicalizations. A classical example could be the size of the bars forming a physical bar chart. The *global shape* depends on the scale of the digital model and the physical artifacts and can be limited by external conditions, e.g., the build volume of a 3D printer.

Exact Shape

The *exact shape* of a module is its actual contour or its outline. We also see the surface finish term *waviness* as part of the *exact shape*. It is related to the visual variable shape. In general, shape is already a complex phenomenon in InfoVis [Munzner, 2014] and there is no precise definition, e.g., if shape is based on simple geometry or also includes icons, symbols or compound glyphs. Furthermore, there is an extensive list of visual attributes associated with shape, such as closure, hole, curvature, or line ending (see Brath [2010, 2014] for a more detailed description). We focus our initial categorization of *exact shape* as a physical variable on well-known 3D modeling techniques, such as constructive solid geometry and polygon mesh to describe and define the exact shape of a module.

The *exact shape* of the bead is defined by the number of width and height segments. It is worth mentioning that the *global* and *exact shape* are influenced by each other and might constrain each other. When the number of width and height segments changes, for example, also the volume of the bead changes. They also can be equal, e.g., if the module is a primitive, such as a sphere or a cuboid. The *exact shape* can be perceived with both, the visual and haptic sense. While the visual sense is primarily used to perceive the *exact shape*, the haptic sense can support the perception of small shape changes.

We believe that the *exact shape* might play a more important role for physicalizations to encode data than the visual variable of shape does for digital visualizations. Similar to the *global shape*, the *exact shape* can be limited by external conditions. To represent delicate changes in the physical shape, the fabrication machine needs a respectively level of precision.

10.2.2 Color Variables

The category of color variables includes four dimensions, three of them (hue, saturation, luminance) are already discussed in previous works. We add to these three well-known color dimensions the new dimension *optics*, which in particular focuses on physical properties of materials and objects, that influence the behavior of visible light.

Hue, Saturation and Luminance

The color variables hue, saturation, and luminance have the same characteristics for physicalizations than they do for digital visualizations. Therefore, we refer for more details on these variables to other sources, e.g., Bertin [1983], Carpendale [2003] or Munzner [2014]. Please note, that multi-color 3D printing within one object is challenging, however, physical artifacts can be colored manually afterward.

Optics

Under the umbrella term *optics*, we refer to the branch of physics which involves the behavior and properties of visible light. For digital visualizations, the environment and the incoming light influences the entire screen and therefore the entire visualizations in a similar way. For modular physicalizations, in contrast, single modules can be influenced based on the material properties independent from the other modules in various ways.

Most relevant for physicalizations are the transparency and reflection properties, which are also related to absorption, scattering, and refraction. They are only perceivable through the visual sense. We combine these properties for clarity reasons and as they rank similarly in the performance characteristics. Please note, that transparency was also supposed as a visual variable for maps by MacEachren [1995].

It could be imaginable, that each bead has a different level of transparency or reflection. It is worth mentioning that these properties are highly dependent on the environment and the position of the observer. Without any light source, reflections are not perceivable. It can also be necessary for the observer to move his head or the entire body to perceive and notice possible differences in these properties.

One project that experimented with the transparency of physical materials is x.pose by Chen and Oliveira [2014] (see Figure 10.1-right). The wearable data sculpture makes the collection of the wearer's location data visible in real-time through reactive displays that change in opacity to reveal the wearer's skin. Static physicalizations can be built, for example, with variations of acrylic glass, which have different levels of transparency.

10.2.3 Tactile Variables

We classified *roughness*, *lay*, *coldness* and *compliance* as the most relevant dimensions in the category of tactile variables. For all four dimensions, the cutaneous cues seem to be the most important ones. *Waviness* is also used to describe a surface texture, but we already included as part of the *exact shape* dimension.

Roughness

Roughness is a component of surface texture and received most attention within haptics research. When a surface has irregularities or ridges, it can be described as rough. The *rough-*

Figure 10.1: Examples for the use of transparency and temperature as physical variables: Left: Perpetual (Tropical) SUNSHINE installation by fabric.ch [2005] (Image © Milo Keller). Right: x.pose by Chen and Oliveira [2014] (Image © Roy Rochlin).

ness variable is related to the visual variable texture or grain (see Bertin [1983]; Carpendale [2003]). We will focus here on the physical surface, i.e., textures that are also perceivable with the haptic sense and not only visual.

It could be possible to provide each segment of the bead or each bead itself with a different level of roughness according to the underlying data. While the roughness of a surface in some cases can be perceived visually, e.g., different grits of sandpaper, the haptic sense is necessary and allows a more delicate perception. A 3D printer with a corresponding resolution can print surfaces with different forms and levels of roughness, and a laser cutter can engrave suitable patterns.

Lay

In manufacturing *lay* indicates the direction of the predominant surface pattern. Therefore, it has relations to the visual variables of orientation and texture, but also our proposed dimensions of *roughness* and *exact shape*. While there can be surfaces with no predominant pattern direction, we base our considerations on patterns, that are applied in manufacturing [De Garmo et al., 2011].

The *lay* can have one linear direction, which, for example, can be parallel or perpendicular to the observer. It can also have two crossed directions or more, which is called multi-directional and be can be pictured as scattered. To our knowledge, there are no studies specifying how many different directions are perceivable by humans and under which circumstances. A *lay* can also be approximately circular or radial, relative to a center point on the surface. Similar to the application of *roughness* different *lay* patterns can be used for various segments of a bead or for each bead. Also, lay patterns could be perceived visually, but the haptic sense allows a more detailed perception. Similar to *roughness*, *lay* can be realized easily through digital fabrication machines with a suitable precision.

Coldness

As actuated physicalizations are out of scope for this proposition, it is important to mention, that we focus on the *coldness* of an object at room temperature. This is distinct from the object's temperature, which is independent of the material. Different materials have different cooling curves, which define the perceived coldness, which is related to the heat extraction from the fingers when touching a material.

As an example, each bead could have a different cooling curve. It is noteworthy that in addition the thermal properties of the material and its geometry, which both can be controlled, the perceived coldness is also influenced by the manner of touching and the contact resistance between finger and object. While coldness can only be perceived with the haptic sense, the visual sense could influence the expectancy based on previous experiences, e.g., metal is perceived colder than plastic.

The only example to our knowledge that uses temperature for data encoding is the Perpetual (Tropical) SUNSHINE installation by fabric.ch [2005] (see Figure 10.1-left). This physicalization represents weather data through the heat and light emitted from infrared bulbs. However, it uses the actuated object's temperature without direct touch and not *coldness*. As the cooling curve depends on the material and its geometry, it can be realized through 3D printed artifacts with different materials and designs.

Compliance

Compliance can be expressed physically in various ways and has different characteristics, e.g., malleability, elasticity or plasticity. We focus on the perceived *compliance* which can be described as softness or hardness of a material. While compliance perception does not depend on kinesthetic force information, it can be influenced by it.

In the example of the beads, each bead or even specific parts of it could have altered levels of compliance. While the visual sense could influence the expectancy, e.g., metal is harder than plastic, varying versions of plastic can have different levels of *compliance*, which can be perceived only with the haptic sense. Stiffness also depends on the object's dimension as a thick, narrow object can be compressed more than a thin, wide object made of the same material, using the same force.

Compliance can be realized, for example, through the use of different 3D printing material for each module. The infill density and pattern (e.g., linear, concentric, honeycomb) of the physical artifact can also define the level of *compliance*. Specific laser cut pattern, e.g., the "living hinge", allow some form of bending of rigid pieces as well.

10.2.4 Kinesthetic Variables

Into the category of *kinesthetic variables*, we classified the dimensions *slipperiness* and *weight*. Both depend on the combination of cutaneous and kinesthetic cues for an accurate perception.

Slipperiness

As *slipperiness*, we describe the friction that occurs when one surface, e.g., a finger, slides over another. Therefore, the movement is essential for an accurate perception of *slipperiness*. While *slipperiness* and *roughness* are quite distinct from a physical point of view, there may be some overlap perceptually and linguistically [Tiest, 2010].

As an example, each bead could have a different level of *slipperiness*. While people can feel clear differences in resistance for various materials when they move their finger over the surface, there is little research about the relationship between the perceived intensity and the physical intensity. *Slipperiness* can only be perceived by the haptic sense and depends on humidity, but also force and speed of movement. For controlling several levels of *slipperiness*, it seems most suitable to use a raw material with accordant characteristics for fabrication.

Weight

The perceived *weight* depends on a wide variety of mechanisms, such as prior experience, volume or thermal properties. The weight of an object can only be perceived through the haptic sense, by lifting or at least moving it. The object, therefore, should be of a size that can be grasped by humans.

In the example of the beads, each bead could have a different *weight*. It is important to mention that the *weight* of a module can only be perceived when it is detached. In contrast to dimensions such as *roughness* or *slipperiness* the perception of *weight* will change when multiple modules are combined, i.e., the object will get heavier. The *weight* of a module can be manipulated by the choice of material and its infill density.

10.3 Performance of Variables

To discuss the previously introduced dimensions in a structured way regarding their performance, we use four characteristics of visual variables supposed by Bertin [1983]:

- *Selective:* A variable is selective if a change in this variable alone makes it easier to select that changed module from all other modules.
- *Associative:* A variable is associative if modules can be grouped according to this variable alone as they differ in other variables (following Carpendale [2003], while Bertin [1983] uses the term differently).

- *Quantitative:* A variable is quantitative if the relationship between two modules can be obtainable as a numerical difference of this variable.
- *Order:* A variable is ordered if changes in this variable support an ordered reading of the modules.

We believe these characteristics are not only applicable for visual variables but also for physical variables. They help to understand in which ways a change in a specific variable can affect the perception and therefore, the performance of a particular task (see also Carpendale [2003]). We will rank the performance as "good" (✓), "possible" ($\sim$), and "impossible" (X).

In contrast to visual variables, physical variables can hardly be judged based on pre-attentive processing, as haptic sensation processes linear. Therefore, the ranking relies on the possibility that these tasks can be accomplished in a reasonable time frame of a few seconds and on study results, whether changes in this variable are perceivable and predictable. The differentiation between "possible" and "good" is based on the afore mentioned studies and the experiences collected during the design and evaluation of physicalizations. They, therefore, serve as an initial suggestion and basis for discussion whether and in which ways these dimensions can be used for data encoding.

In the following sections, we summarize the discussion for each category while focusing on our proposed dimensions and only highlighting specific aspects if the characteristics of the dimensions vary. A detailed overview can be found in Table 10.1.

10.3.1 Geometric Variables

Global shape and *exact shape* are both *selective* and *associative*, as a module that has changed this characteristic alone will become distinct and selectable from the other modules, but can also be used to create groups. However, for the *exact shape*, it depends on the number of modules displayed, the actual shapes and how strongly the various shapes differ.

Changes of the *global shape*, e.g., the volume, are difficult for comparative numerical interpretations. However, if the change is based on a repetition of the same module, a numerical reading could be possible and therefore can be *quantitative*. Variations in the *exact shape* can hardly provide any numerical interpretation, therefore, it is not *quantitative*. While it could be argued, that the number of height and width segments of the bead from the Activity Sculpture project could be used for a numerical difference, we do not believe that this is suitable.

While changes in the *global shape* are *orderable*, this is not the case for *exact shape*. A shape does in general not support an ordered reading, or the criteria would be of personal preference. However, the bead from the Activity Sculpture project changes its shape from angular (few segments) to smooth and round (more segments). Such modifications in the exact shape could be assumed as *orderable*, but it has to be learned.

Table 10.1: All variables and their performance ("good" (✓); "possible" (∼); "impossible" (X)) based on the characteristics of visual variables by Bertin [1983]. Mainly discussed variables in this chapter have a colored background.

Variables	Dimensions	Selective	Associative	Quantitative	Order
Geometric Variables	Position	✓	✓	✓	✓
	Orientation	✓	✓	✗	∼
	Global Shape	✓	✓	∼	✓
	Exact Shape	✓	✓	✗	∼
Color Variables	Hue	✓	✓	✗	✗
	Saturation	✓	✓	✗	✓
	Luminance	✓	✓	✗	✓
	Optics	✓	✓	✗	✓
Tactile Variables	Roughness	✓	✓	✗	✓
	Lay	✓	✓	✗	∼
	Coldness	✓	✓	✗	✓
	Compliance	✓	✓	✗	✓
Kinesthetic Variables	Slipperiness	✓	✓	✗	✓
	Weight	✓	✓	✗	✓

10.3.2 Color Variables

The newly introduced dimension *optics* is similar to the well-known visual variables saturation or luminance. A module that has changed its level of transparency or reflection alone will become distinct, and modules with the same level can be interpreted as belonging together. The relationship between different levels of transparency or reflection cannot be seen as numerical. For example, one module will not be perceived by humans as four times as transparent as another one. Both, transparency and reflection support ordered readings, as one module can be perceived as more transparent or reflective than another one.

10.3.3 Tactile Variables

All four tactile variables (*roughness*, *lay*, *coldness*, and *compliance*) are *selective* and *associative*. A module that has a change regarding one of these dimensions will become selectable from the other modules, but changes can also serve to create groups of modules. Also, *roughness* and *coldness* can support under specific conditions a haptic pop-out effect [Plaisier et al., 2008a; Plaisier and Kappers, 2010].

None of the dimensions can be seen as *quantitative*. While there are definitions, e.g., for the *roughness* of a surface or possibilities for measurements, e.g., the *coldness*, humans are not able to perceive those characteristics accurate enough, that one object can be perceived as two times as warm or rough as another one.

All dimensions beside *lay* are *orderable*. One module can be rougher, colder or harder than another one. *Lay* is similar to the visual variable *orientation*. There can be a notion of order if the changes are progressive, e.g., only the direction of the pattern changes clockwise. However, it has to be learned, and an order between a circular and a linear pattern is not possible.

10.3.4 Kinesthetic Variables

Both dimensions, *slipperiness*, and *weight*, are *selective* and *associative*, as a module with a different weight or level of friction will become distinct and selectable. Modules with the same weight or level of friction can be interpreted as belonging together.

Although the *slipperiness* and *weight* can be expressed physically, both dimensions are not *quantitative*, as a module can hardly be perceived by humans as twice as heavy as another one. Both can be *ordered*, as a module can be heavier or can have a higher level of friction than another one.

10.4 Discussion

Our list of physical variables and the initial rating regarding their performance for specific characteristics show a general trend: most dimensions are as *selective*, *associative*, and *orderable* but not as *quantitative*. The only exceptions are *exact shape* and *lay*, which both are *orderable* only under specific conditions as well as *global shape*, which might be *quantitative* under particular circumstances.

Please note that we excluded the characteristic of *length*, which describes how many distinct values a dimension supports, and therefore how much information it can convey. We argue that the number of changes for all dimensions is theoretically infinite but practically limited. Too delicate changes, for example, might neither be perceivable through human senses nor be producible with digital fabrication technologies. A couple of studies showed strong relationships between the human perception and the physical expression for various dimensions. Further studies need to investigate additional aspects, such as the just-noticeable differences that a dimension can convey [Jansen et al., 2015] or the total number of changes that are suitable for encoding and perceiving data within one physicalization.

Apart from such studies that focus on the general perception, it is also important to observe in which ways the perception is influenced by the context of a data representation. It is not clear how the ability to haptically perceive aspects of a physical artifact transforms into interpreting and understanding abstract data. Little is known about the process of how people haptically explore the characteristics of a physicalization, about the time it takes and in which ways people cope with memory challenges associated with sequential exploration. Furthermore, subjective aspects incorporating the observer of a physicalization need to be considered. We believe that hedonistic sensations (e.g., comfortable/uncomfortable, elegant/ugly), when a surface is touched and existing personal experiences with specific materials, might have a substantial influence on the perception and therefore, the interpretation of data. Similarly, it needs to be investigated in which ways the combination of multiple physical variables affects the perception, e.g., whether specific dimensions overrule others under particular circumstances.

Finally, as previously mentioned, we see our classification as a first pass, which has to be extended, elaborated, and questioned by other researchers and their studies. We excluded physical variables that need actuation such as air resistance, pressure, vibration or temperature. We also focused on variables for haptic perception and left out other senses such as sound, taste and smell. We believe that technological advancements will further simplify and broaden the creation of physicalizations and the incorporation of additional variables. It is worth mentioning that we hardly found any examples of physicalizations using physical variables that require haptic exploration. Although dimensions such as *roughness* or *compliance* can already be controlled with a 3D printer, most installations and artifacts used only the visible shape for data encoding. We hope our preliminary suggestion of promising physical variables encourages and motivates researchers and designers to experiment with new ways of encoding data and to build data representations, which have to be explored with all our senses. We believe it highlights the necessity for additional studies, e.g., regarding the performance or interplay and serves as an elaborate starting point for further discussions on physical variables.

Chapter 11

Summary and Future Work

This thesis explored the potential of encoding data in a physical form. After reviewing related literature in the fields of haptic perception and digital fabrication, we presented six initial prototypes of physicalizations, ranging from static to digitally augmented to dynamic ones.

In more detail, we explored three promising directions, in which physical data representations can provide benefits for exploring data: perception & memorability, communication & collaboration, and motivation & self-reflection. Among other things, our findings revealed that the higher distinctiveness of 3D physical bar charts affects information recall in a positive way compared to their digital counterparts and 2D variations. Similarly, physicalizations of personal activity data can provide additional benefits such as strengthening emotional connections and allowing a more playful look at ones' physical activity. However, we also observed skepticism and discovered the importance of a sophisticated and effective design, to be on par with traditional digital visualizations, especially in more work-related settings.

Based on our practical experience in building and evaluating a number of physicalizations we proposed a conceptual framework for the design of personal physicalizations and an initial categorization of physical variables. Both schemes can guide and inspire artists, researchers, and designers in creating and studying data physicalizations for various purposes.

In this last chapter, the contributions of this thesis will be discussed in a more concrete way and in light of the designed and evaluated prototypes. Furthermore, the limitations of our approach will be reported, and the ways in which the presented work can be continued and its results can stimulate further research in the field of data physicalization.

11.1 Contribution Summary

This thesis started with two broad research questions investigating the ways physicalizations can and should be designed and in which ways they affect the perception and experience of data exploration. During the course of designing and evaluating various data physicalizations three promising directions and related research questions emerged. With this thesis, we gain first insights to tackling these issues and thereby offer two overall contributions to the field of data physicalization.

11.1.1 Design of Physicalizations

In the course of this thesis, eleven different prototypes of physicalizations were built and evaluated in several studies in the lab as well as “in the wild” for multiple weeks. This offers a broad first glimpse into the design space of physicalizations. As data physicalization is a new area of research, we believe this to be a suitable approach to gaining first practical insights to the design and evaluation as well as potential benefits of data physicalization.

Based on our experiences with these prototypes and literature reviews, we furthermore proposed a conceptual framework for personal physicalizations and a working classification for physical variables. The conceptual framework “Materialized Self” targets researchers and designers interested in exploring physical data representations for personal data. By taking a look at such physicalizations from a “production lens”, and a “consumption lens” we illustrate on the one hand various design criteria which researchers should consider and can choose from. On the other hand, we highlight the role of the individuals receiving and using the personal physicalizations. Compared to their digital counterparts, physical visualizations seem to generate a stronger emotional connectedness and arouse new aspects such as practical purposes or their embedding in everyday life.

The initial classification of physical variables complements our undertaking of providing researchers and designers with guidance and inspiration for uncovering alternative strategies for physically representing data as well as positioning their ideas and prototypes. Based on our experience in creating physicalizations and a literature review in the area of haptic perception, we identified 14 dimensions of material properties grouped into four categories of physical variables. In particular, we discussed those nine dimensions that differed from visual variables or were unique for physicalizations. Our performance rating of the variables showed, that most of them are *selective*, *associative* and *oderable*. As none of them allow a comparative numerical interpretation, they cannot be classified as *quantitative*.

While all these findings are not conclusive, we believe that they cover broad insights into a possible design space for data physicalization and can guide future projects, prototypes and studies in this field.

11.1.2 Potential for Physicalizations

By designing, building and evaluating various types of physicalizations, we identified three promising areas, which were investigated in more detail: perception & memorability, communication & collaboration, and motivation & self-reflection.

Two lab studies related to the perception of physicalizations and the information recall of the perceived data revealed that physicalizations can have advantages to digital or “flat” data representations. The results of the first study led to the conclusion that participants who perceived abstract data with a physical bar chart forgot less information about maximum and minimum values within two weeks, while no difference in the recall performance between the digital and physical modality could be seen for numeric values and general facts. In contrast to the first study, in which we compared the digital and physical modality, the second study focused on the dimensionality of physicalizations. While the findings of the first study regarding extreme values could be confirmed, the second study pointed to the aspect, that not physicality alone but the higher distinctiveness of the 3D modality affects the perception and recall of abstract data in a positive way.

Two explorative studies, one “in the wild” study at a scientific conference, the other in the lab, explored in which ways physicalizations might affect the communication about and the collaboration with data. Both studies stressed the high expectations people might have when interacting with physicalizations and emphasized a sophisticated design, especially when compared to interactive digital visualizations. The lab study further illustrated the challenges in conducting a comparative study, in which only the presentation modality is manipulated. The studies also revealed a polarization, as people either strongly enjoyed working with physical data representations and appreciated their tangible features or rejected them as toys and inconvenient compared to their digital counterparts. However, physicalizations might support participants with an aversion against new technologies in engaging in collaboration by diminishing the technical barrier.

A three-week field study explored the potential of physicalizations for representing personal activity data and supporting aspects such as motivation and self-reflection. Participants acknowledged the general idea of encoding their running data into 3D printed sculptures and rated their potential for motivation and self-reflection as high. Questionnaires and semi-structured interviews also showed, that participants developed an emotional connection to their sculptures, as they had a sculpture piece in mind during a run, thought about personalizing them and also embedded the final sculptures in their everyday life. Furthermore, we observed that participants, driven by curiosity and playfulness, changed their running habits and tried to control the shape of the pieces they would receive as well as test the limits of our system. This initial study demonstrated that physicalizations can have additional benefits compared to digital visualization, particularly for representing personal data.

11.2 Limitations and Future Work

As previously stated, data physicalization is a new area of research and an unexplored domain which left us with many options regarding the design and evaluation of physical data representation. Our choices were carefully made by taking into account related work from the fields of InfoVis and TUI but also based on a "research through design" approach, in which the iterative process of building and evaluating a number of prototypes helped in rejecting unfavorable ideas early and pursuing more promising directions. Nonetheless, this does not save our work from certain limitations that we would like to use to light the way for future research in the domain of physicalizations.

11.2.1 Perceiving Physicalizations

Our studies regarding information recall showed that it can be beneficial if data is perceived with a physicalization. Similarly, the Activity Sculptures project revealed additional benefits when personal activity data is encoded physically. As most of our prototypes represented the data through size and shape, participants primarily perceived our physicalizations with their visual sense. As motivated by our classification of physical variables many additional ways to encode data in a physical form, which require haptic exploration, are possible. An open question is in which ways the data mapping of such physical variables should be explained to an observer. Additionally, it is unanswered in which ways individuals could be instructed to discover data variables haptically, which are not recognizable visually. More studies have to be conducted to investigate in which ways individuals perceive and experience the exploration of abstract data through physical variables such as roughness or compliance. Furthermore little is known about the process of perceiving abstract data haptically, understanding the data and finally generating knowledge. Similarly, more fundamental research regarding the perception of physical variables has to be done to understand in which ways physical variables can be encoded effectively, following, for example, the approach by Jansen and Hornbæk [2016]. The findings of such experiments will answer whether and how physicalizations are applicable for scenarios beyond artistic installations, particularly for the field of pragmatic physicalizations.

11.2.2 Interacting with Physicalizations

Interacting with physicalizations is strongly related to the ways they are perceived. Apart from the modular bar chart study, in which participants assembled a physicalization, the prototypes were simply manually held by participants and not haptically explored. While this can be explained by our chosen physical variables, it opens up the questions in which ways interactions with a physicalization can and should be designed to be effective and understood. While Taher et al. [2015] started to explore interaction techniques for dynamic physical bar charts, the ways in which physical interactions, such as grasping and lifting, might affect the data exploration process are unclear. Furthermore, it should be investigated in which ways "affordances" [Gibson, 1986; Norman, 2002] that physicalizations might implicate can be designed and incorporated to imply that an action is possible, similarly to digital visualizations [Boy et al., 2016]. Apart from studies with artificial exploration tasks, integrating the interaction and analysis of a physicalization into practical problem-solving tasks seems eligible. Thereby the comprehension of the underlying data is required and meaningful for the participants, and the physicalizations take a back seat as a tool, that might support a task or not. Additionally, the question arises in which ways physical and digital visualizations can be combined and complement each other. An example would be choosing to perceive data through a specific modality and switching in between tasks, depending on the comfort, speed or facility the data can be explored in the individual modality (e.g., Wun et al. [2016]).

11.2.3 Collaborating with Physicalizations

While our study regarding collaboration with physicalizations revealed interesting insights, it also highlighted the challenges in conducting a comparative study and allowing a fair comparison between the physical and the digital modality. One problem seems to be that due to technological challenges and a much shorter research history physicalizations are not comparable to state-of-the-art digital visualizations. Especially regarding interactivity, degrading digital visualizations to attain similar conditions for both modalities is often necessary. For participants with experience in using current digital visualizations, this might be irritating. Further studies could consider focusing less on competition between the physical and digital modality and more on how physicalizations can complement the digital ones. One compelling example is to support a collaboration process between able sighted and visually impaired or blind. The highly evolved haptic perception of the visually impaired and blind, may lead to an advantage at feeling even delicate changes in various physical variables and therefore, reading and decoding a higher range of the underlying data. Investigating in which ways these different audiences can collaborate using digital and physical visualizations seems worth further research.

11.2.4 Communicating with Physicalizations

In our hands-on-evaluation at a scientific conference, we explored if paper-based physicalizations can engage individuals in exploring the data, which might also lead to spending more time with it or sharing and discussing the content with others. While our study could not confirm this assumption, we still believe that physicalizations have a great potential in presenting and communicating data. Excellent examples are the talks by Hans Rosling (see *Section 1.1 - Motivation*), in which physical objects are not only used to explain the data but also serve as tools to emphasize the message and tell a gripping story. In the field of InfoVis, a growing number of researchers propose to attach a higher importance to the aspect of presenting data and recommend integrating elements from storytelling to portray information in a more engaging manner and with greater efficiency (e.g., Gershon and Page [2001]; Kosara and Mackinlay [2013]). Researchers, who explore and study data representations for communication, especially in scenarios such as public space or museums, should consider and investigate the potential of physicalizations for expressing data in an engaging way.

11.2.5 Personal Physicalizations

Our Activity Sculptures project identified additional benefits of encoding personal data through a physical from compared to a digital visualization. We investigated the specific case of representing physical activity data in a three-week field study. While we could find promising trends, longer studies with more participants should be conducted to allow stronger conclusions on whether and how physicalizations can increase motivation or support behavioral change. Possible explanations such as the "novelty effect" or being a "good subject" should be resolved, e.g., by conducting comparative studies in which novel ways of digital visualizations are examined against physical ones. While the emotional commitment participants evolved seems to be a key factor regarding physicalizations further studies have to confirm these findings and also examine if this is true for other types of data. We hope that physicalizations will become a part of the ongoing research in the InfoVis field on personal visualization and personal visual analytics (e.g., Huang et al. [2015]; Thudt et al. [2016]) and future work will demonstrate the ways in which the strengths of both worlds will complement each other in exploiting the enormous potential of personal data "*to understand ourselves better and make positive changes in our lives*" [Huang et al., 2015].

11.2.6 Dynamic Physicalizations

Although we created two projects experimenting in which ways physicalizations can be augmented digitally and two early prototypes of dynamic physicalizations, our main projects focused on static physicalizations, made out of wood or plastic, created with a 3D printer or a laser cutter. Similarly, most prototypes were inspired by traditional types of visualizations such as bar or line charts. While we argue that our approach was effective in studying fundamental aspects of the perception of physicalizations, we also observed the importance and ubiquity of interactive data representations. Our modular physicalizations supported a rearranging of data points and "updates" as new data was introduced. To be comparable to the functionality of current digital visualizations, which allow operations such as automatic filtering or ordering as well as switching the type of the representation or the data mapping, much more research is needed. Jansen et al. [2015] specified the importance and challenges in designing and implementing effective dynamic physicalizations but also stressed that they are essential in supporting "*not only reusability across datasets, but also a wider range of analytical and communication tasks.*"

11.2.7 Multi-Sensory Data Representations

This thesis and its projects focused primarily on static physicalizations that could be perceived through the visual and haptic sense. However, auditory, gustatory, and olfactory senses can also provide information about objects and therefore encode data. Various projects explored ways in which food can act as a medium for data expression and in which ways edible and palatable materials can convey data stories (e.g., Zorina et al. [2012]; Stefaner [2014]; Khot et al. [2015b]; Wang et al. [2016]). Similarly, in the field of "sonification", a number of researchers investigated in which ways acoustic variables such as pitch, volume or timbre can be used to represent data (e.g., Krygier [1994]; Hermann and Ritter [1999]; Franklin and Roberts [2003]; Zhao et al. [2008]). One question which emerges is whether data representations which provide a multi-sensory data exploration, including the visual sense, should be called physicalizations or if other terms should be found. Future research should also consider in which ways the usage and combination of various variables and multiple senses affect the experience of data exploration and whether such data representations are only beneficial for aesthetic and artistic purposes, or can also aid pragmatic data analysis [Hogan and Hornecker, 2016].

11.3 Closing Remarks

This thesis offered a first glimpse into the design of physicalizations, explored their potential and revealed some first benefits of representing data in a physical form. As the research field of data physicalization is at its beginning and the design space is still largely unexplored, I believe the projects and findings presented in this thesis will inspire designers and researchers to continue the investigation of the ways in which physicalizations can enrich our experiences of exploring and analyzing data.

I think that the digital and the physical world will continue to merge and that data, which is captured and saved digitally, will shift beyond the digital flat screen and will be represented by interactive objects and surfaces, which are non-flat, non-solid and shape-changing. We live in a data-driven world and all this data can eventually help to understand the world and ourselves better. But to make the right choices and positive changes, people first have to become engaged in exploring and thinking about the data in a meaningful way. This will hopefully result in understanding the data and gaining new knowledge. I believe that physicalizations and multi-sensory data representations have the power to transform plain numbers and statistics into fascinating stories and allow us to relive the data with all our senses.

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Eidesstattliche Versicherung

(Siehe Promotionsordnung vom 12.07.11, § 8, Abs. 2 Pkt. 5)

Hiermit erkläre ich an Eidesstatt, dass die Dissertation von mir selbstständig und ohne unerlaubte Beihilfe angefertigt wurde.

München, den 02. August 2016

Simon Stusak