Beyond Physical Bar Charts – An Exploration of Designing Physical Visualizations

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Abstract

Physical visualizations only recently started to attract attention from the InfoVis and HCI communities. They are well known to encourage playful exploration and to stimulate curiosity, but are also considered to support analytical information visualization tasks. However, creating effective and usable physical visualizations has not been explored in much detail. In this work, we present our early approaches and experiences in designing and building novel physical visualizations. We started with sketches on paper, created first low fidelity prototypes out of cardboard and built the final visualizations with thread, acrylic glass and a laser cutter. An initial user study was conducted to investigate if basic information retrieval tasks can be accomplished with our physical visualizations and how users interact with them.

Author Keywords

Design Process; Physical Visualization; Information Visualization; Tangible User Interfaces

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Design

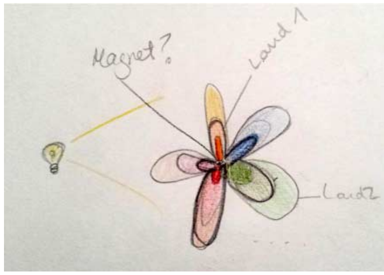

Figure 1. Layered flowers represent countries, its petals different topics.

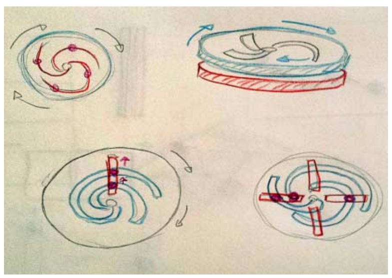

Figure 2. Sketch of a rotary disk. By rotating parts of the physical visualization the displayed countries or dimensions can be changed.

Figure 3. Low fidelity prototype of the layered flowers.

Introduction

Physical Visualizations (PVs) are visualizations in which data is mapped to a physical form [2]. Artists and designers have produced a large variety of physical representations of data and companies already used them in the early 20th century [1]. They are used to convey messages beyond the data itself and can engage people to reflect on its meaning [5]. While these benefits are widely recognized, their analytical value and the creation of effective PVs remain to be explored.

In this paper we describe our design process which is inspired by rapid prototyping techniques such as paper prototyping. We believe that using basic materials (e.g. paper and cardboard) in the initial design steps has advantages over digital fabrication tools. The use of laser cutters and 3D printers is still more time consuming, expensive and produce a lot of waste. Furthermore access to these tools is needed as well as a lot of experience to receive good results. In contrast paper and cardboard can be easily processed further with common tools such as pencils, scissors or glue, which are well-known and accessible to everybody.

In addition we present an initial user study in which we evaluated two physical visualizations against two digital visualizations to investigate if basic information visualization retrieval tasks can be accomplished. We collected qualitative data through questionnaires, semi-structured interviews and observations during the study.

Related Work

The most common type of PVs are data sculptures. The physicality of information visualization was extensively explored by Vande Moere [5,6,7], who introduced different degrees of 'data physicality' which vary in the level of abstraction of how data is mapped and perceived by human senses. He argues that PVs can represent information in pleasant ways and turn data analysis in an engaging and educational experience.

The first study that evaluated the efficiency of physical visualizations was conducted by Jansen et al. [2]. This study compared physical 3D bar charts to their on-screen 2D and 3D counterparts. The physical touch and the perfect visual realism of physical objects seem to be an essential cognitive aid for information retrieval tasks. They point out that further research is needed and that recommendations for designing effective visualizations are necessary.

Jansen et al. [3] presented an interaction model for beyond-desktop visualizations. They describe a modified information visualization pipeline in which raw data is processed into a visualization and then rendered into the physical world.

Designing Physical Visualizations

In the following we will discuss our design process. We describe our early steps, in which we sketched ideas and built low fidelity prototypes out of paper and cardboard. Furthermore we present our final designs and the results of a conducted focus group.

Dataset

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

[1] http://www.oecdbetterlifeindex.org/

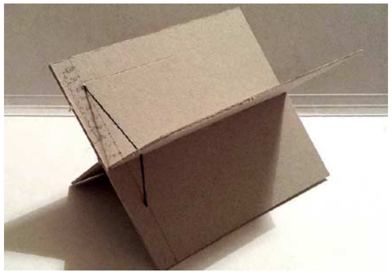

Figure 4. Low fidelity prototype of the thread star plot.

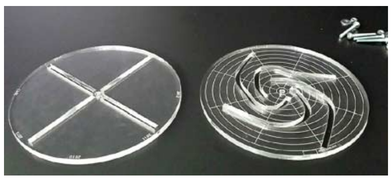

Figure 5. "Middle" fidelity prototype of the rotary disk.

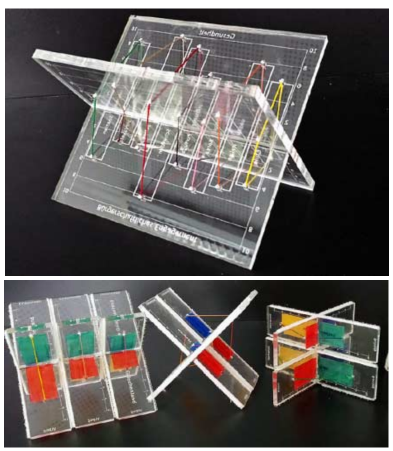

Figure 6. Two variations of the thread star plot prototype.

of well-being across countries, based on eleven dimensions such as health, income or education. The higher the values in each dimensions the better the country ranks on the scale. We chose this dataset as it is easy to understand and seemed an interesting topic for users to analyze.

Sketches

To avoid concentrating too much on external influences such as material or size, we started by sketching different ideas on paper.

Figure 1 shows an example that is inspired by the Better Life Index website and its interactive visualization, where 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. The flowers could be fixated in the middle by a screw to enable rotation. Using magnets instead of a screw would allow an easy disassembling and reassembling.

The idea of a rotary disk is shown in Figure 2, which is inspired by traditional interactive visualizations and their controls to e.g. change the view. By rotating or sliding parts of the PV it would be possible to change the displayed countries or dimensions. The primary goal in this approach was to evoke users' fascination and curiosity through playful exploration of the dataset.

Low Fidelity Prototyping

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.

Figure 3 shows the above mentioned idea of the layered flowers. To order the petals according to the different dimensions we used color instead of labeling them. In this early stage of prototyping the problem of occlusion from small petals by larger petals was already obvious.

Figure 4 shows the first approaches of a thread star plot. The idea was to use bar charts and star plots, both well-known 2D visualizations, and combine them into one compact physical object. Each of four orthogonal arranged layers represents the values of a dimension of various countries by a bar chart. A thread connects the four dimensions of the same country and forms a star plot for each.

"Middle" Fidelity Prototyping

To create more sophisticated prototypes we used transparent acrylic glass and a laser cutter, which enables rapid fabrication with high precision.

Our approach of a rotary disk is shown in figure 5. Two disks with the same size and different cut gaps are combined with screws, which in addition serve as markers for the data points. We did not pursue with this prototype as even small datasets are difficult to display due to overlapping gaps on one disk. In addition the screws often twisted and prevented easy rotating.

Further developments of the thread star plot are presented in figure 6. The top picture shows the initial idea built with transparent acrylic glass, where the bar charts and its labeling are carved. We experimented with the thickness and the size of the acrylic glass to find a good compromise between stability and handling.

The prototype had no interactive parts so far. To enable filtering and reordering we tried various techniques to add and remove countries from the prototype. Important characteristics for the assembling are the stability once

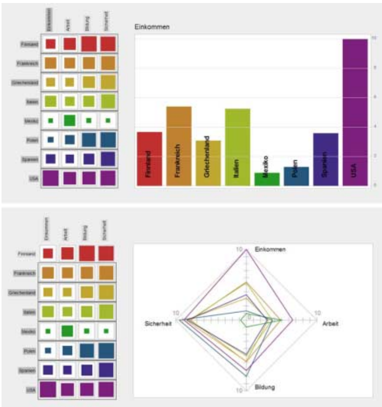

Figure 7. Screenshots of the digital visualizations used for the evaluation.

Figure 8. The hardware setup that was used for the evaluation.

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 6 bottom).

Focus Group

To get some early feedback regarding our first prototypes we conducted a focus group with six computer science students. After a general discussion about PVs we presented our visualizations. Both the flower and the rotary disk prototype were rated negatively. Common statements were that they were "too confusing", "difficult to understand" and "hard to get any insights from". Both variations of the thread star plot prototype were perceived positively. It is "easy to understand" and "the handling/size is suitable". Furthermore the participants liked the idea of disassembling and reassembling the countries with the interactive prototype.

First Evaluation

The goal of our first evaluation was to investigate how people interact with our PV. Furthermore we were interested in how well basic information retrieval tasks could be accomplished in comparison to 2D on-screen visualizations. The study was inspired by Jansen et al. [2].

Visualizations

We compared four different visualizations. The two variations of the thread star plot (physical static (PS), physical interactive (PI)), described in the previous section and two 2D on-screen 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 7). In addition to the static digital visualization (DS) the interactive digital visualizations (DI) enabled filtering and reordering of the countries.

Tasks

The participants 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?

Procedure

Each participant completed an initial training phase in which each task was practiced, followed by an exploration phase to get familiar with the four visualizations. Participants were asked to complete all five tasks for each visualization. The input and output of the instructions, the tasks and their responses were done on a separate touch tablet. Participants were instructed to be as accurate and as fast as possible.

Hardware Setup

The experimental setup with a laptop, a computer mouse and a separate tablet is shown in figure 8. The PVs were only present during the relevant condition.

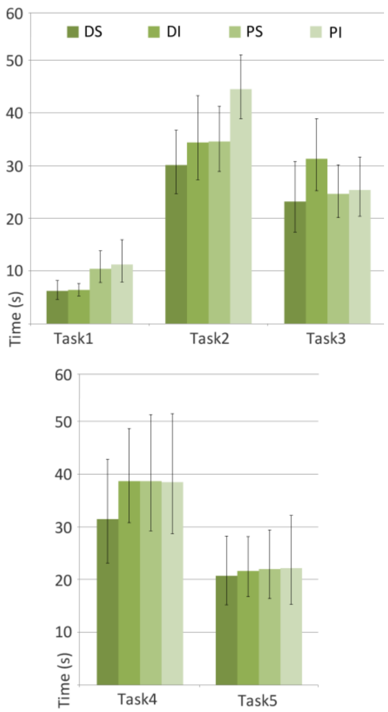

Figure 9. Average *task completion time* in seconds per visualization (digital static (DS), digital interactive (DI), physical static (PS), physical interactive (PI)) and task (error bars: 95% confidence interval).

Measures

The *task completion time* (interval between the press on “start” and the press on “done”) as well as the *error rate* were recorded. All errors were normalized between 0 and 1.

Participants

16 participants (6 female) took part in our study. Age ranged between 13 and 41 years (mean age 25). Eight were computer science students, 2 pupils and 6 employees. All were right handed, 2 had experience in information visualization.

Design

A Latin square design was used for the presentation order of the visualizations. The order of the four (TODO) datasets and questions were kept constant. The main factor was *visualization* (digital static, digital interactive, physical static, physical interactive) and the secondary factor was *task*.

Hypotheses

Based on the results of the experiment done by Jansen et al. [2] we expect that the digital visualizations outperform the physical ones. As tasks 4 and 5 require the use of the entire displayed data, we assume a minor difference since the PVs provide a particularly good overview.

Results

Aside from the measurements of time and error we describe in this section our observations during the study and the feedback given by users through a questionnaire and a semi-structured interview.

Time and Error

A repeated measure ANOVA did not reveal a significant effect of neither *visualization* ($F_{(3,45)} = 2.781$, $p = .052$) nor of *task* ($F_{(4,60)} = 1.996$, $p =.107$) on the *error rate*. Contrary to our assumptions a repeated measure ANOVA did not reveal an effect of *visualization* ($F_{(3,45)} = 1.429$, $p = .247$) on *task completion time*. Only the *task* had a significant effect on *task completion time* ($F_{(4,60)} = 31.271$, $p < .001$). All *task completion time* measures were log-transformed to correct for skewness [4]. Reported means are antilogged and indicate geometric means [4]. Figure 9 summarizes the average *task completion time* per visualization and task. Only task 1 shows a noticeable separation between the digital and the PVs. The static digital visualizations perform best in all tasks.

User Feedback

When asked to rank techniques according to preference the digital interactive visualization was ranked 13 times at position one. We furthermore collected subjective data through questionnaires using 5-point Likert scales ranging from 1 (“strongly agree”) to 5 (“strongly disagree”). Participants had the impression that the tasks were most easily fulfilled with the digital interactive visualization (*digital interactive: median*=1, *all others: median*=2). It was easier to interact with the digital variations than with the physical ones (*both digital: median*=1, *both physical: median*=2). This corresponds with participants’ statements that the PVs are more complicated to understand than the digital ones. In addition the holding and turning of the PVs was mentioned as laborious. The physical static visualization aided the completion of the tasks less than the other visualizations (*physical static: median*=2, *all others: median*=1). Both interactive visualizations were more interesting to interact with (*physical interactive: median*=1, *digital interactive: median*=1.5, *both static: median*=2).

Observations

We observed differences between subjects in the ways in which they used and interacted with the PVs. Seven participants constantly used only one hand to interact with the physical static visualizations, but all participants used both hands to interact with the interactive one. Four participants did not disassemble the interactive visualization, 2 because it seemed impractical, 2 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 physical interactive prototype while trying to demount it.

Discussion and Future Work

Our design process shows that the use of simple material such as paper or cardboard and common tools such as pencils and scissors to build PVs can have advantages. In an early stage it is possible to identify problems regarding the design and get a good impression about size and interaction possibilities. Limitations are stability and the general haptic characteristics, dependent on the material the final PV will be made of. The user study revealed that a mature design is crucial if the PVs are aimed at supporting analytical tasks. Especially stability and affordances are essential properties.

Our next step is to develop a prototyping toolkit, which includes different materials and tools to build PVs. We would like to present and evaluate this toolkit during various workshops. We are also planning to build more sophisticated PVs, possibly involving mechanical constructions, elastic parts or even liquids. Although the PVs we discuss here are only specific instances of a much larger design space, we hope to provide a solid starting point for a discussion on how to design effective physical visualizations.

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