Studying black and white textures for visualization on e-ink displays

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Summary

E-ink displays are now widely used on many devices such as smartwatches, electronic shelf labels, and e-readers. There are needs for information visualization on such devices. Typically an e-ink display is in black and white, but many charts require color hue or saturation to encode data. With the absence of color, in this thesis, I explored 2D textures as an effective way to visualize ordered and categorical data on black and white displays, for example, e-ink displays.

By reviewing and analyzing the previous design of black and white textures in the information visualization field, I summarized different texture attributes (e.g., shape, size, density, etc) and their features, which may help designers to understand what attributes they can use to encode data and which one is more suitable for different cases. I came up with a new direction, which I call it the iconic texture.

I developed a prototype of a design tool that can customize different black and white textures by manipulating texture attributes I summarized. Compared to similar tools available for the community, this tool provides people with a graphic user interface to easily customize the textures without writing code. It gives more flexibility in adjusting the attributes of textures, such as more rotation options. With an upload function, it can also change textures' minimal components to most SVG and png pictures. The prototype is available at https://textures.isenberg.cc/tool/pieicon.html.

I present findings from an exploratory online study ($N = 9$) where professional designers created black and white textures for pie and bar charts by using our design tool and choose their preferences between the iconic texture and the normal shape texture in different chart size in terms of easy to read and aesthetically pleasing. Main findings include that most participants chose different shapes and remained the same density and size for different bars/ pie slices. Three types of rotation options were used by most participants. X and Y offsets were frequently adjusted in bar charts. Participants prefer the iconic texture when the chart size is large, but they prefer the normal shape texture when the chart size becomes smaller.

Contents

Chapter 1

Introduction

1.1 Background

Black and white displays are common on many of today's devices. For example, e-ink displays (commonly found on e-readers, electronic shelf labels, and some smartwatches because of their low cost and power consumption) are often monochromatic. The monochromatic displays used in these application areas require much information to be shown on such displays. For example, black-and-white electronic shelf labels could display nutritional information, while e-ink smartwatches may need to display health data charts or graphs.

The wide application of black and white displays, especially e-ink displays, has led to much research focusing on improving the design on such displays. Shanghai currently has e-ink displays deployed in more than 2,500 bus stops to display bus timetables. Information visualization design can be found on these devices. Claes et al. [4] presented how they design the interaction and information visualization on a public information system with an e-ink display. Kerber et al. [14] studied how to improve the presentation of notifications on smartwatches and tested their idea on a black and white LED screen. By studying three commercial e-reader products, Pearson et al[20] raised problems in the current e-reader design and pointed out that, from the perspective of interaction and information visualization, e-readers paid too much attention to hardware and ignored software and interface design. From these examples, I find that e-ink displays become more and more important in our daily life nowadays, and there is a need to provide better design on such devices.

The drawback of monochromatic displays such as e-ink displays is its refresh rate and lack of color, leading to challenges for visualization design on such devices. Because many charts require color hue or saturation to encode quantitative or categorical data. To effectively visualize data in the absence of color, a leading method of displaying quantitative information on black-and-white displays such as e-ink displays is to use *texture*.

Throughout my discussion, I use the term *texture*, following definitions in computer graphics where a *texture* is a 2D image applied to (the surface of) a graphical object that is potentially repeated multiple times through some form of tiling. Specifically, here we refer to *texture* as a tiling pattern that is characterized by the type of shapes

we use as part of the pattern (lines, dots), the density of the shapes, their size, orientation, and position.

1.2 Motivation

By reviewing and analyzing historical practice, I find that textures are frequently used in black and white visualizations. For example, Brinton [3, p.32] shows an over 100-year-old example of a heatmap (Figure 1.1) that uses black and white textures. The power of textures and the limitation of using textures on visualization nowadays motivate me to explore the way to use textures to encode data on black and white displays.

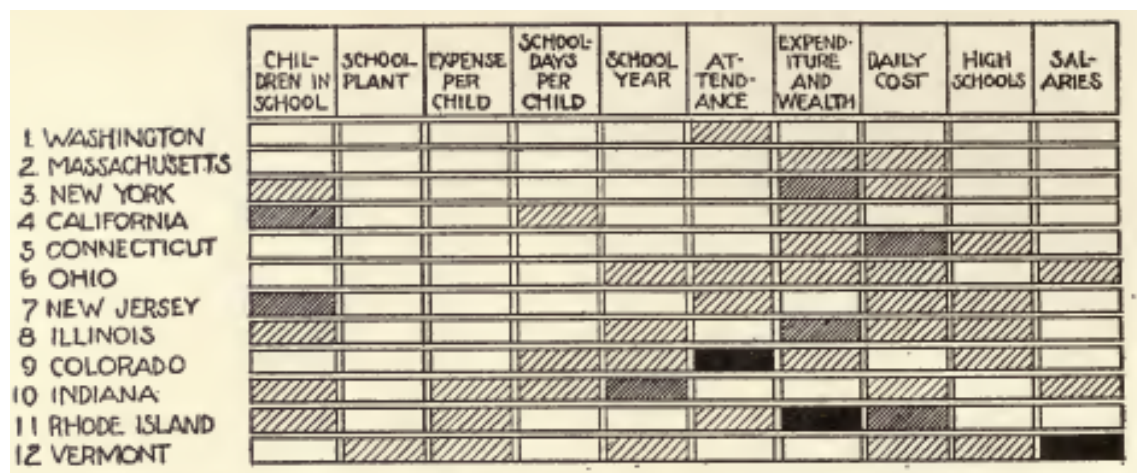|	CHILDREN IN SCHOOL	SCHOOL PLANT	EXPENSE PER CHILD	SCHOOL-DAYS PER CHILD	SCHOOL YEAR	ATTENDANCE	EXPENDITURE AND WEALTH	DAILY COST	HIGH SCHOOLS	SALARIES
1. WASHINGTON										
2. MASSACHUSETTS										
3. NEW YORK										
4. CALIFORNIA										
5. CONNECTICUT										
6. OHIO										
7. NEW JERSEY										
8. ILLINOIS										
9. COLORADO										
10. INDIANA										
11. RHODE ISLAND										
12. VERMONT										

Figure 1.1: Rank of US states in ten education features, 1910. Taken from [3, p.32].

1.2.1 The power of textures

The rich attributes of textures make it suitable for encoding data. For example, textures with the same shape but different density can be used to encode quantitative data, textures with the same density but different shapes can be used to encode categorical data. These rich combinations give designers much space to design visualization.

1.2.2 Limitation of using textures on visualization

Why do we rarely see visualization examples that encoding data with textures nowadays? I think that is because today's electronic devices are basically equipped with a color screen, and the research on color is relatively mature. There are many color models like HSV, RGB. With these models, people can identify any specific color precisely. There are also many design guidelines for color in the graphic design field. People have a clear idea of how to choose a suitable color based on these guidelines. In contrast, there seem to be no clear texture models to specify a texture. Lack of

guidelines also leads to the textures not commonly used.

Another reason that textures are not used is the lack of design tools available. When I think about color, there are thousands of color pickers and color palettes; however, the availability of texture tools is limited. Among the tools available, it lacks key functions to help designers, such as enough orientation options, using most SVG or png pictures as minimal textures components and customizing textures without writing code. A design tool with these additional functions could help graphic designers use textures more easily.

A third reason that textures are not used frequently use is there are just a few design guidelines about how to use black and white texture attributes, to be more specific, how to use the size, shape, and orientation of black and white textures to encode data in data visualization tasks. Part of the reason for this is that there are few studies done on the textures that evaluate how designers create appealing textures. Studying how professional designers make textures appealing can help design a better support tool for them.

Based on these three reasons, we believe exploring textures in black-and-white visuals can help design for products such as e-ink displays, grocery shelf labels, and other graphics.

1.3   Research question and methodology

The primary research methodology for this study is the literature review, web application development, and exploratory study. First of all, I summarized a design space of visualization on the e-ink display based on the literature review on historical texture encoding examples. I figured out what are the attributes a texture has and what are the features of each attribute. I also introduced a new style of textures, which we call it the iconic texture.

I then developed a prototype of a design tool that allows designers to customize their textures without writing code, which helps them quickly verify their design ideas. Comparing to existing similar tools available for the community, I built the prototype with some functions helpful for further research, such as more orientation options, a graphic user interface, and adjusting most of the SVG and png pictures as the minimal components of textures.

Third, to explore possible uses and designs of black and white textures and people's preferences on the iconic texture and the normal shape texture in different chart size, I ran an exploratory study, and I invited 9 professional designers to apply the different textures on a bar and a pie chart by using this tool and asked them to compare their design with different types of textures in different sizes.

Through exploring the design space, I want to know:

- What are the attributes of black and white textures?

- What features do these attributes have?

To build a prototype of a texture design tool I want to solve:

- How can designers easily implement textures and verify their design ideas on the chart quickly?

Through my exploratory study and online experiment, I want to figure out:

- What are professional designer's design preferences and styles for categorical black and white textures

- Will people prefer the iconic texture than the normal shape texture in terms of aesthetically appealing and easy to read? Will chart size affect their preferences?

1.4   Contribution

The key contributions of this work include (i) a design space of black and white textures that supports designers to use suitable black and white texture attributes to encode data in different cases. (ii) a new direction about black and white textures, which we call it the iconic texture. (iii) the first version of a prototype of a design tool that helps designers customize their textures without writing code. (iiii) an exploratory online experiment shows how professional designers use black and white textures in a pie chart and a bar chart to make the chart aesthetically appealing and easy to read, and their preferences on the iconic texture and the normal shape texture.

1.5   Thesis structure

The thesis is structured as follows.
Chapter 2 covers the related work on texture encoding examples, texture dimensions, existing guidelines on black and white texture design, and existing tool/library for customizing texture.
Chapter 3 explains my design space of black and white textures for visualization, how I constructed it, and gave examples of how can designers use it to support their design.
Chapter 4 introduces my prototype of a design tool which can help designers to customize their textures and implementation detail.
Chapter 5 describes the procedure, results, and analysis of an exploratory online study on professional designers' preference for black and white textures.
The last chapter summarizes the contributions and suggests future work in this area.

Chapter 2

Literature Review

2.1 Basic concept and terminology about visualization

The terminology and basic concepts about visualization in this thesis come from Tamara's Visualization analysis and design [19] and Jacque Bertin's Semiology of graphics [2]. These basic concepts give us a clear path to evaluate the efficiency and usability of textures and are the theoretical basis of our design space. These concepts include types of data attributes, marks and channels, types and effectiveness of channel, and channel dimensions.

2.1.1 Types of data attributes

The definition of types of data attributes varies. In my discussion, I use the terminology of types of data attributes from Munzner's Visualization Analysis and Design [19]. The major types used in by Munzner [19] are categorical versus ordered (Figure 2.1). Ordered data can be further divided into ordinal data and quantitative data.
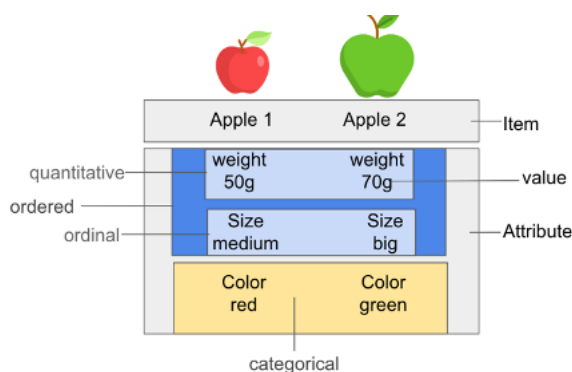

Figure 2.1: terminology about data used in this thesis

Categorical data. Categorical data is used to identify different types of items. For example, in Figure 2.1, the color of the apple defined 2 different items, red and green. It does not imply any order.

Ordinal data. The ordinal scale is more accurate than a fixed scale. It categorizes items while giving various orders, and its data is still expressed as categories, but the order between the various types can be more or less. For example, in Figure 2.1, the size of the apple can be divided into medium and big. But we can not tell precisely how bigger the red apple is with this ordered data.

Quantitative data. Quantitative data can reflect the obvious order and can be measured precisely. As in Figure 2.1, the weight of the apple, 50g, and 70g. with these two numbers, people can tell which one is heavier, and how much is green apple heavier than the red apple.

2.1.2 Marks and channels

According to the definition in Munzner's book [19], All visualizations are composed of *marks* and *channels*. *Marks* are a geometric element used to represent different data. *Marks* can be dot, line, or area. A *channels* is an attribute of the appearance of the *marks* (like color, rotation, and so on).

Figure 2.2 from Munzner's book [19, p.97] shows examples of marks and channels. The bar chart uses the bar (Figure2.2 a), which is an area mark to represent data, and the length of the area is the number if the data. So it uses a length channel to encode different quantitative data on an area mark. In the scatter chart (Figure2.2 b), it uses dots as marks and using the position channel to encode the quantitative data on it. If we want to categories the data into the different groups (Figure2.22 c), we can use the color channel to encode different groups. We can also use size channel to imply the number of each dot (Figure2.2 d).
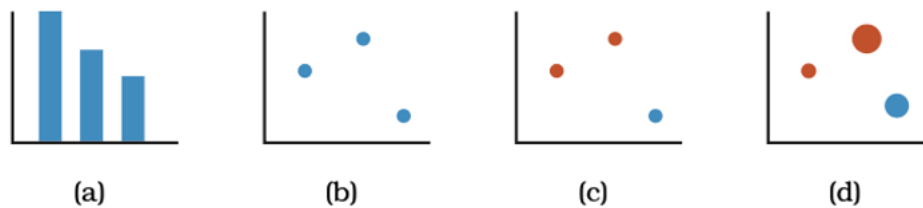

Figure 2.2: example of marks and channels, taken from [19, p.97]

2.1.3 Channels' expressiveness and effectiveness

As we mentioned data types, marks, and channels, but when we design real visualization cases with different data types, how can we choose suitable channels? By analyzing previous work and results from experiments, Munzner [19] listed all of the channels that can be used and categorize them with expressiveness types and effectiveness ranks [19, p.93]. These two concepts give us a standard to evaluate each attribute of textures in further work.

Channels: Expressiveness Types and Effectiveness Ranks

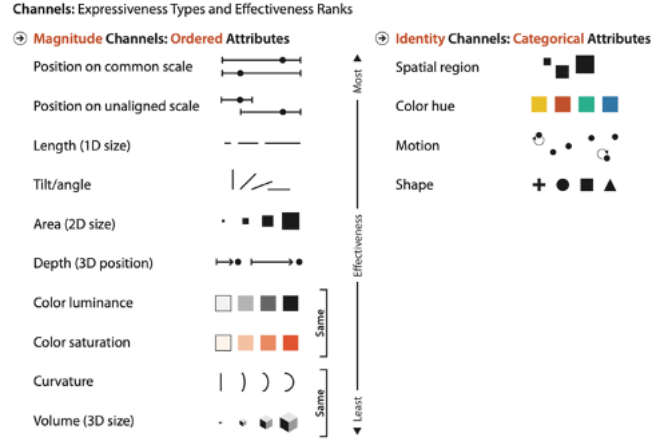| Magnitude Channels: Ordered Attributes	Identity Channels: Categorical Attributes
Position on common scale	Spatial region
Position on unaligned scale	Color hue
Length (1D size)	Motion
Tilt/angle	Shape
Area (2D size)	
Depth (3D position)	
Color luminance	
Color saturation	
Curvature	
Volume (3D size)	

Figure 2.3: expressiveness types and effectiveness rank of channels, taken from [19, p.93]

The *expressiveness* principle proposed by Munzner in her book [19] means when we are using the channels to encode data, channels should match the data types. For example, in Figure 2.3, she divided channels into magnitude channels and identify channels. Which magnitude channels are used to encode ordered data because all these channels imply orders. In contrast, the identity channel does not imply any order, and it is suitable for encoding ordered data.

The *effectiveness* principle means different channels have difference performance when encoding data, the effectiveness of these channels was concluded and verified by experiments by Munzner [19].

2.2 Visualization on e-ink displays

Devices using e-ink display such as public screens, e-books, and smartwatches are currently widely used, the need for information visualization gradually appears on these devices. In the hospital loaner project, an e-ink screen displays a dashboard about patient information (Figure 2.4). Although it did not use charts for information visualization, this project showed rich application scenarios of e-ink and the space for improvement in information visualization design.
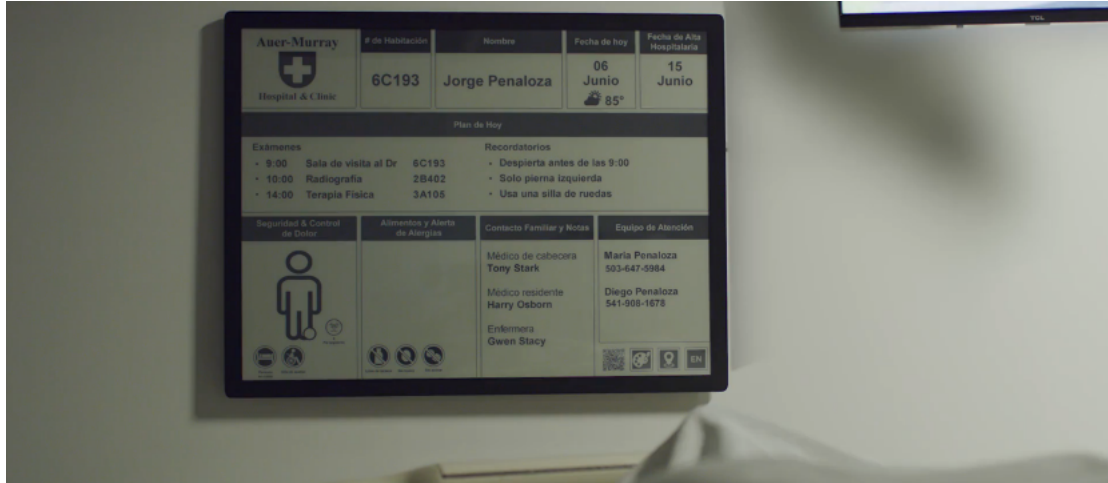
Figure 2.4: e-ink display in the hospital loaner project, taken from [13]

The Sony e-reader product shows that a texture line chart works well on this e-reader. It gives us a good example of how to use different line dash types to encode categorical data on e-readers.
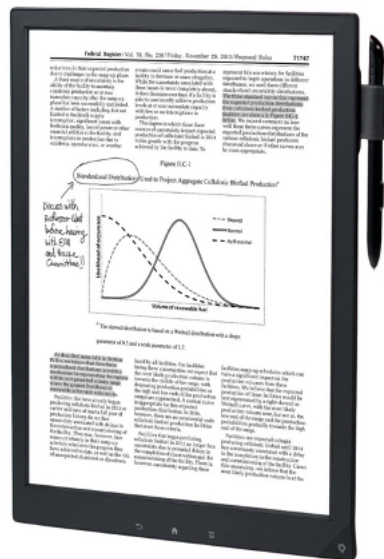

Figure 2.5: visualization on Sony 13.3 e-reader, taken from Amazon

A progress circle and a bar chart work well on the e-ink display of the Lenovo VB10 smart band (Figure 2.6). It uses black, white, and grey to identify different items, which is a frequently used design on e-ink displays.

These examples show the application of information visualization on e-ink displays, but they mainly use greyscales and line dash types to encode data. Lack of more effective data visualization techniques on such devices has led to a limitation of displaying more complex visualizations. It makes me believe that applying textures can help design better and more efficient data visualization on these devices.

Figure 2.6: visualization on Lenovo VB10 smart band, taken from Amazon

The sizes of these devices vary, which reminds me that when making the design for e-ink displays, I should consider the usability of our design on different size of the devices.

2.3 Historical black and white visualization examples

I find examples of black and white visualization from many places. These examples include ancient visualizations, examples in Bertin's book - semiology of graphics [2], and newpapers. I introduce some of the most enlightening charts which useful for my research.

Pictogram. A pictogram is a graph uses symbols or pictures to represent data. Figure 2.7 from Mulhall's Dictionary of Statistics [18] shows an example of pictogram. This chart uses symbolic images to encode different trains and using the size of the image to encode the numbers. It is very straightforward. There is no need to draw an external legend to read this chart. This type of chart gives us the original idea of a new type of textures – the iconic texture which use icons or pictures as the smallest units of textures.

Textured line chart. Bertin [2, p.16] shows a good example of using textures on lines (Figure 2.8). It uses different line dash types to encode different cities and using the line-width to encode different stocks.

Textured map. Bertin [2, p.77] shows a good example of using textures on area
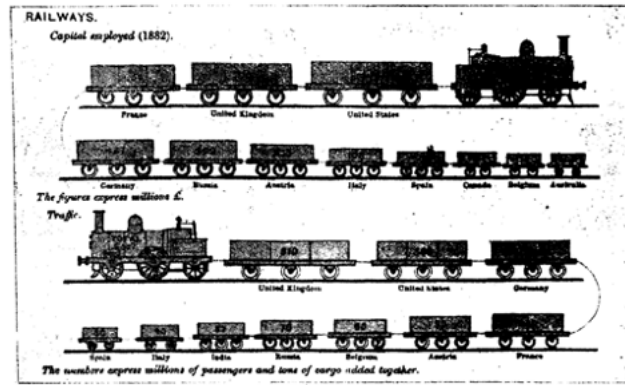
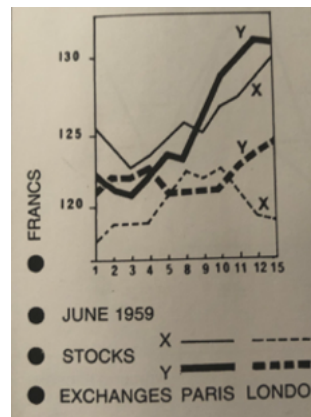Figure 2.7: Example of a pictogram, taken from [18, p.52]

Figure 2.8: Example of textured line chart, taken from [2, p.16]

marks (Figure 2.9). It encodes different numbers with the density of the textures inside the area. Each area represents an area in Paris city, and the different textures encode the annual deaths number. It also uses different orientation of the line to make the chart clearer.
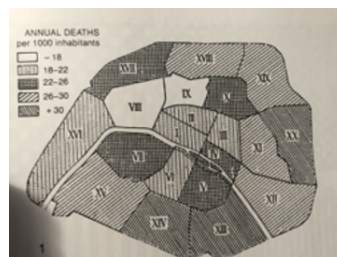

Figure 2.9: Example of textured map, taken from [2, p.77]

Comprehensive textured chart. Figure 2.10 shows a good example of using textures on multiple marks to present a complex data visualization. It uses different textures of the line to represent USSR and USA. The icon of the national flag also can consider as a special texture. Different decisions are encoded by size of the line. And the position of each node implies the danger in different time. It is a good example of how to organise a complex visualization by just using textures.
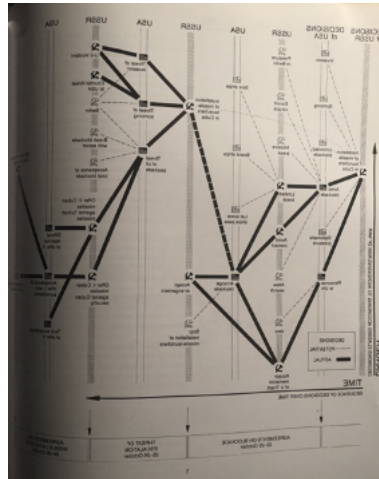
Figure 2.10: Example of comprehensive textured chart, taken from [2, p.18]

Stunning data visualization can be also found in newspapers. And typically, the visualization in black and white, following are two representative examples of visualization in newspaper. Figure 2.11 uses different types textures on the stroke of the line to identify different items.
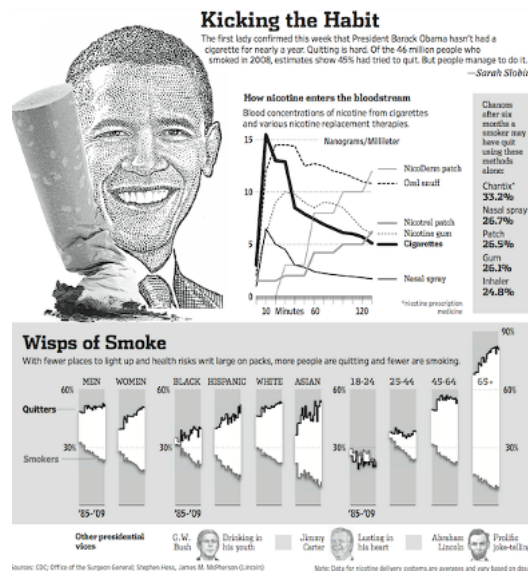

Figure 2.11: data visualization on the Wall Street Journal, taken from [24]

Figure 2.12 uses different textures inside the area marks to identify different items. The attributes of textures used in this chart include different rotation (Christian democrats compare to free democrats), shapes (altentative list compare to free democrats) and density (altentative list compare to social democrats).
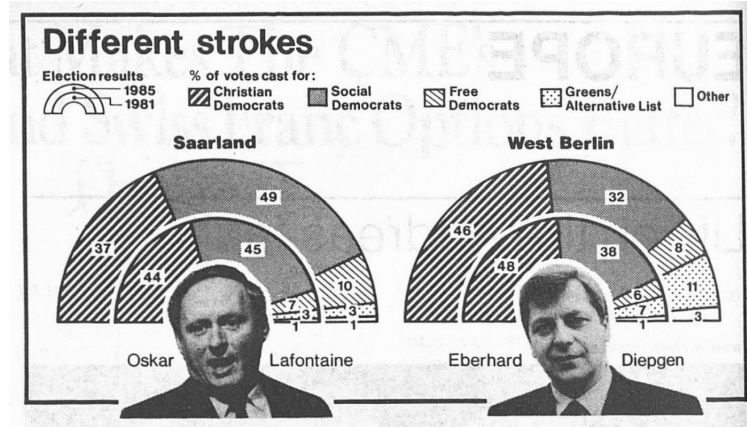
Figure 2.12: data visualization on the Economist newspaper, 1987, taken from [7]

2.4 Texture attributes

Ware and Knight [28] proposed that *orientation*, *size* and *contrast* of the textures is suitable to encode ordered data. Compare to the HSV model for color, they defined these three dimensions as the OSC model for textures.

As summarized by Shenas and Interrante [23, p.443]: Other dimensions includes *contrast*, *coarseness*, and *directionality* proposed by Tamura et al [26], *repetitive* vs. *non-repetitive*, *low-complexity* vs. *high-complexity*, and *high contrast* and *non-directional* vs. *low contrast* and *directional* proposed by Rao and Lohse [21], *periodicity*, *directionality*, and *randomness* proposed by Liu and Picard [16].

Most of these analyses of texture dimensions are based on natural textures, which requires space to deal with lots of distinguishable greyscale options. Some of these dimensions might not suitable for e-ink displays, and there might be more dimensions that can be used in e-ink displays.

He[10] discussed about the texture mapping for line marks. He summarized different types of line textures used as map symbol, like *dashed lines* and *dash-dotted lines*, He proposed an algorithm that can draw two types of line texture - *dots pattern texture* and *solid pattern texture* (Figure 2.13), he showed how to use concrete pictures on line marks.
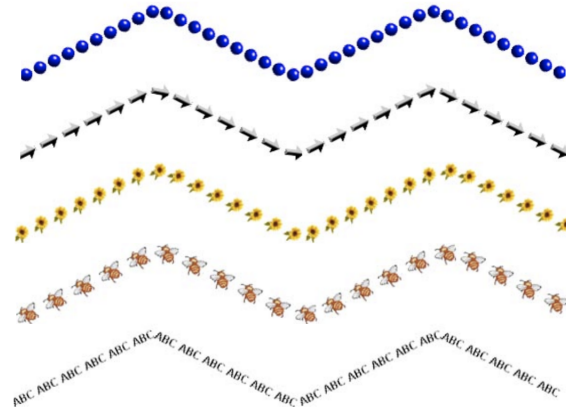
Figure 2.13: two types of textured line proposed by He, taken from [10]

2.5 Existing Design advice for black and white textures

Both Tufte [27] and Bertin [2] warn that textures may produce Moir vibrations (Figure 2.14) which leads to distortion effect and hard to read, and Tufte [27] even goes so far to say that they should be avoided altogether.
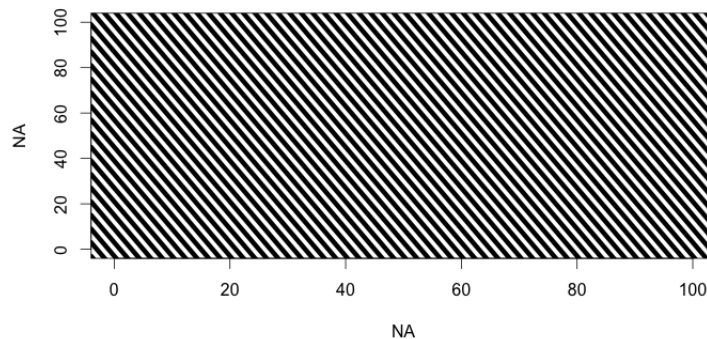

Figure 2.14: Moir vibrations, taken from [27, p.108]

Bertin also has given many advices on using density and size of the texture to encode quantity data. For example, when using the texture's density or size to encode quantitative data, the density or size should imply the order. And in a right proportion(Figure 2.15).
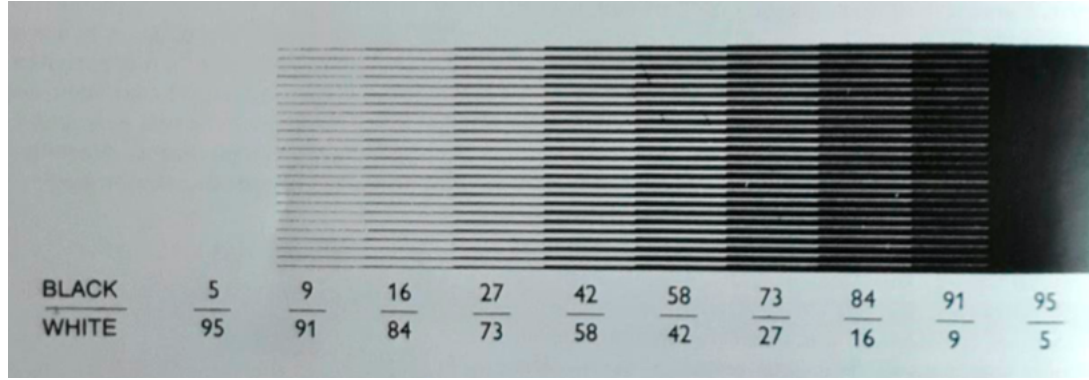
Figure 2.15: density change with a fix level, taken from [2, p.67]

2.6 Existing tool/library for customizing textures

Without a suitable design tool, research on textures will be very inefficient. Even if a reasonable design guideline came up, designers would still find it not convenient to apply it to real cases in their work if it requires programming to implement textures. So I did some research on existing tools or libraries that is available for the visualization community to customizing textures.

Both Ware and knight [29] and He [10] proposed algorithms for implementing their design idea. However, these algorithms are focused on how to develop the specific design they proposed. It can not be considered as a tool that can be used by the designer directly.

JavaScript is now the most popular programming language to implement visualizations. There are many JavaScript libraries for data visualization charts drawing like D3, P5, and so on. So I first tried to find some existing JavaScript library for customizing textures and can be embedded in the charts implement by the charts drawing library.

Textures.js. Texture.js is a JavaScript library for creating SVG patterns [22]. It has many default settings that allow customizing the texture by changing the shape, density, size, and rotation via programming with JavaScript (Figure 2.16). I find it has rich options for customizing. For example, it has more than 10 types of shape options and even allows the user to change the shape's path. I tried to use this library to design textures and apply it to my design tool, but there are two reasons why I did not choose this library in the end. First, it is a JavaScript library which still needs to generate textures by programming. I foresee issues when professional designers have to write code to customize their textures, which are not very efficient. We conclude that our system's requirement is to build a user interface where the designers can generate textures they want by simply clicking and dragging like how they use color picker and wheel. Second, it still has lots of limitations on customizing textures. For example, it only provides 5 degrees of rotation options which might limited exploratory space for research on textures. So another requirement for our system is to give more freedom of changing the texture to the designers.
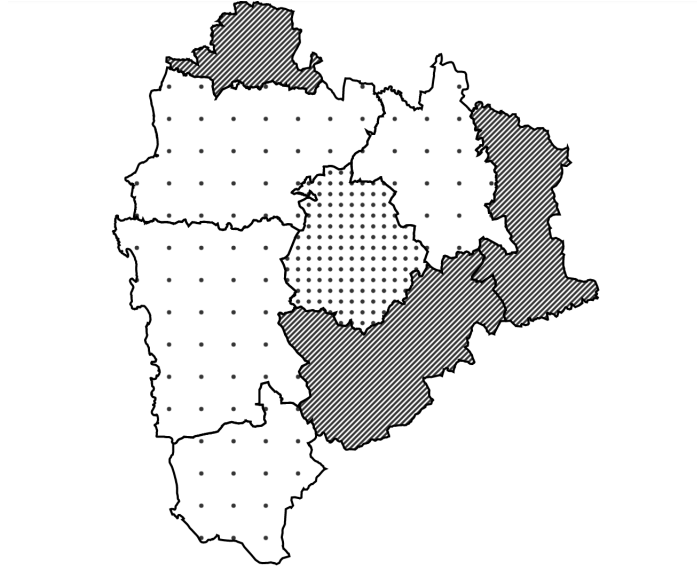
Figure 2.16: textured map made with textures.js by programming

Hero Pattern. Many websites provide different types of texture images in an SVG format. Let's take the most popular one - hero pattern[1] as an example. On the hero pattern's website, users can download the image with textures or copy the code to implement the texture in JavaScript. It provides rich types of textures and allows users to slightly change some appearance like color and opacity of the texture (Figure 2.17). It is a good website to download beautiful images with textures, but it didn't meet our goal because these textures are not especially for information visualization and can not conveniently apply to charts.
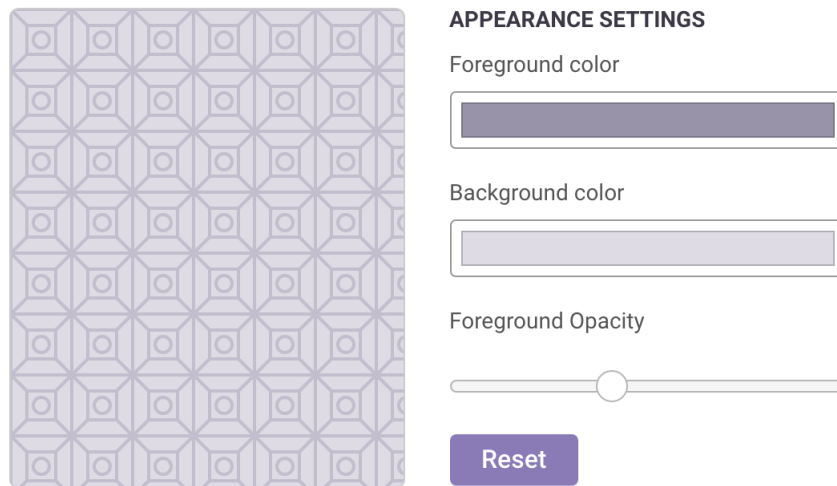

Figure 2.17: modifiable parameters of Hero pattern website, taken from [1]

By reviewing these existing tools available for the community, for the purpose of my research, I conclude three limitations of these tools. First, these tools provide insufficient orientation options. Second, these tools cannot use customized pictures as the minimal components of textures, even by writing code. In the end, these

tools still need to write code to customize most attributes of textures, which might be inconvenient for people who do not have too much programming experience. So, in this thesis, I decided to make a design tool for customizing textures combined with the chart and try to address these limitations.

2.7   Important elements for good visualization

The standards for a good visualization vary. We find many important elements for a good visualization proposed by professional designers and researchers.

Debois [6], after years of practice in this field, concludes a good visualization should show the tight connection between the chart and the data, and allows users to more easily and quickly understand the story behind the data. McCandless [17] proposed four elements for a good visualization - *information*, *function*, *visual form*, *story*. Data labs in data presentation news [5] proposed *story-telling*, *analysis*, *design* as three important elements. Tableau community[25] summarized a good visualization as a visualization that tells the story behind the data, highlights the most important information, and leaves out any unnecessary information.

By reviewing these articles, I conclude 3 elements important for a good visualization, which are aesthetic, easy to read, and efficient. Aesthetic means let the reader feel that this visualization is beautiful and get visual pleasure. Easy to read refers to the chart is well organized without any elements which may distract the readers. Efficient means readers can understand the meaning behind the chart faster and more accurately.

There are many methods to measure the efficiency of visualization like Lin et al's work [15]. From my experience, *aesthetic* and *easy to read* might largely affect the *efficient*. Thus, before I run a scientific experiment to measure the efficiency of textures encoding, it is important to first design visually pleasing and well-organized charts with the texture encoding.

2.8   Previous experiment

Before we can address specific research questions for black and white textures encoding. We need to first make the chart beautiful and easy to read. One of our future research questions is whether the iconic texture outperforms than the normal shape texture in chart reading tasks. The independent variable will just be the shape of the texture. However, we still need to design our textures' size, density, and rotation in our experiment material to make the chart easy to read. So we want to design ideas of how to design these materials.

Conducting an exploratory study is a frequently used research method in information visualization fields to get design ideas from professional designers. Goffin's work [8] showed a complete exploratory study for data visualization ideas from professional

designers. Goffin et al [8] invited 9 professional designers to help him design different word-scale visualization, by summarizing different types of visualization done by the participant and analyzing the similarity of their design preference. We will follow the approach to explore design preference and styles of designers on black and white textures.

Lin et al. [15] propose an experiment method to compare the efficiency of different types of color for visualization. They conducted a controlled study that let participants do a chart reading task where the chart is color by semantically-resonant color, expects designed color, and random color by measuring the accuracy and reading speed of different charts to find the different efficiency of different colors. It provides a scientific way to compare the efficiency of different encoding techniques for visualization. And the semantically-resonant colors is the idea of the iconic texture. We will propose a similar follow-up study to investigate whether icon textures increase efficiency on chart reading tasks. However, this is out of the scope of this master thesis, in which we will make a first preparatory step to explore the design preferences and styles of professional designers regarding aesthetic and easy to read.

Chapter 3

Design Space

By reviewing and summarizing existing graphics and designs, I summarize a unified design space for black and white textures. This chapter first compared the black and white pattern textures and natural textures' advantages and disadvantages on the e-ink display. Then I introduce all the attributes of black and white pattern textures, which can be used to encode data and features for each attribute. In the end, I introduce the concept of the iconic texture, which I think is an effective texture, especially when using it on e-ink displays.

3.1   Black and white Pattern textures

As mentioned in the related work, natural textures such as the material of wall, brick, grass, etc. are used extensively in scientific visualization. The natural texture shows in Figure 3.1(left) was used by Tang et al. [30] to encode weather information. The natural texture has more attributes than the pattern texture, like the perspective information, and it can convey extra information itself because of the detailed images. However, for design on e-ink displays, there are not too many greyscales to display the perspective information. Pattern textures (Figure 3.1 right) has relatively fewer components and attributes, which might be easier to implement, and it can be defined with just black and white. So in my thesis, I will focus on exploring black and white pattern textures.
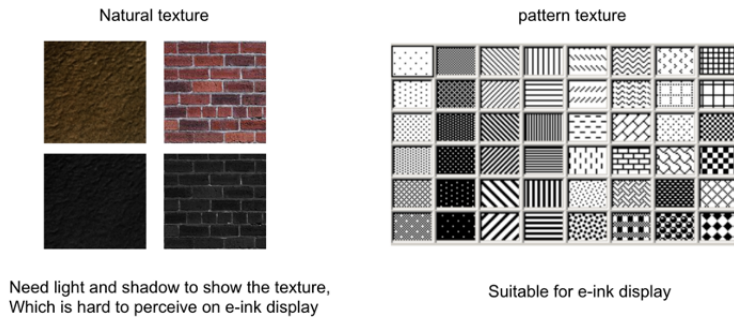

Figure 3.1: natural textures (left), taken from [30], and pattern textures (right), taken from [11].

3.2 Texture attributes and features

In data visualization, textures can be applied to both the stroke and the fill of a data-representing mark. We discuss textures as repeated (tiled) shapes, such as lines or dots. Shapes can be applied both to the fill of a mark or along its outline.

By literature review and redesign, I summarized texture attributes that can be used to encode data from historical black and white visualization, newspapers, and books. I used some criteria proposed by Tamara [19] and Bertin[2] to categorize and feature these attributes. These criteria include length, expressiveness, and usability on different marks. I detail the texture attributes I found useful to configure black-and-white textures and their features in Figure 3.2. I gave some explanations and recommendations on the usage of these attributes in the following part.
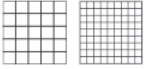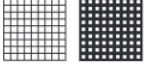
Texture property	Example Fill	Example Stroke	Length	Categorical Data	Ordered Data
Density			2–5	∿	✓
Shape Size			4–5	✗	✓
Orientation			2–4	✓	✗
Shape type			large	✓	✗
Grouping			small	✓	✗

Figure 3.2: texture attributes and features

Fill-density. Fill density means the density of the minimal components of the texture inside the marks. It is more suitable for ordered data because it implies an obvious order. Theoretically, it can encode infinite degrees, but due to the relatively small resolution on the e-ink display, we recommended it to have 5 degrees max. It works well on area marks, which have enough space inside the area to see the detail. But for dot and line mark, the length of this attribute will be limited by the size of the mark. Fill density is frequently used in historical visualizations, and based on our experiences, it seems to have the same effect as the color luminance. When we need to encode quantitative data, It is an ideal solution to replace color on area marks.

Fill-shape size. Fill shape size means the sizes of the minimal components of the texture inside the mark. It is very similar to fill density and color luminance, which encode differently ordered data by controlling the ratio of black pixels. It is also frequently used in historical visualizations.

Fill-orientation. Fill orientation means the orientation of the components of the texture inside the mark. It can only encode a few degrees because too much dif-

ferent orientation is hard to identify. It does not imply order, so it is suitable for categorical data. It works well on area marks which have enough space. But for dot and line mark, the length of this attribute will also be limited by the size of the mark. Fill orientation is not recommended to use alone. It has the risk of causing the Moiré vibrations. It is more suitable to combine with other attributes to create new grouping attributes.

Fill-shape type. Fill shape type means the shape of the minimal components of the texture inside the mark. It is an ideal attribute for categorical data. It can have large degrees and is frequently used to identify different items. It also can be used on all of the marks. We can replace the dot mark and line segment with shapes to solve the limitation of size. Even in many common colored charts, we can also find examples of combining shapes and colors to identify different items. The flexibility of a fill shape texture also inspired us towards the idea of the iconic texture.

Stroke-density. Stroke density is defined by the gap distance between each stroke segment. Stroke density is frequently used on line marks to encode quantitative data. It is not suitable for dot marks due to the size of dot marks and also not suitable for area marks because the stroke of the area often implies extra information.

Stroke-shape size. The width of the stroke defines stroke shape size. Stroke shape size is frequently used on line marks to encode quantitative data. It is not suitable for dot marks due to the size of dot marks and also not suitable for area marks because the stroke of the area often implies extra information.

Stroke-shape orientation. Stroke shape orientation means different angles of the stroke segment. Stroke shape orientation is suitable for line marks to encode categorical data.

Stroke-shape type. Stroke shape type is suitable for line marks to encode categorical data. Shape types can be different shapes of the line segment and also the arrangement of the different shapes on the same line.

Grouping. Grouping means the arrangement of the component of the texture inside the mark. The most common example is regular versus random. Theoretically, any attributes can be used to a grouping, leading to grouping has many possibilities that make its development more difficult. So in this master thesis, we will first exclude this special attribute.

Other. Other attributes include with or without stroke, with a dash or without a dash that can only encode data in 2 degrees. So we don't recommend using it alone. We can use it in some special cases like we just need to identify 2 categories or combine it to another attribute to create a new attribute.

3.3 A new direction - the iconic texture

As mentioned in 3.2, I find that shape attributes are a good solution for encoding categorical data, so there might be more space to explore how to use this attribute effectively. Lin et al. [15] proposed semantically-resonant color, and she finds that using semantically-resonant color to encode categorical data can improve the efficiency in chart reading tasks. The main reason is that people can link the color with items based on their daily life experience. For example, in a bar chart that presents the quantity of different fruits, if people saw a yellow bar, they may link it with banana without too much thinking. Lin also mentioned that by proper design and applying the semantically-resonant color, it might be unnecessary to conduct a legend. Inspired by this concept, I explored more on using icons as shape attributes to encode categorical data (Figure 3.3) cause the following 2 factors make me believe that icons might have the same effect as semantically-resonant color in chart reading tasks.
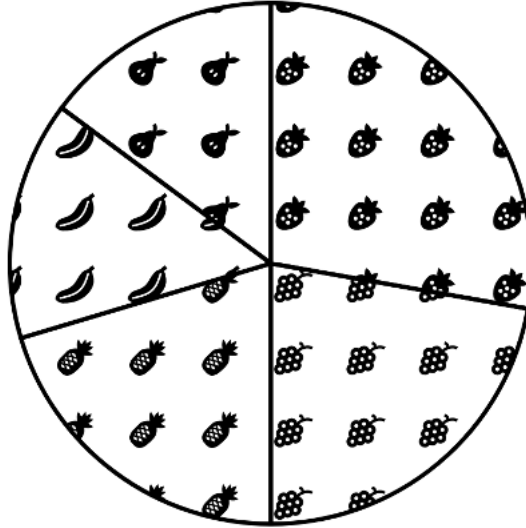

Figure 3.3: the iconic texture

Advantage of pictogram. As mentioned in the literature review, the pictogram is another point that inspired me towards the iconic texture. Pictogram uses symbolic icons to encode different items, and in most cases, there is no need to conduct a legend, because icons can convey the metaphor itself. Pictograms are also frequently used nowadays to make the chart interesting. From the results of Haroz et al.'s [9] experiment, he found that using pictogram to present data can make the data more memorable, and people will be more engaged in chart reading tasks.

Advantage of using icons. There are many design guidelines for icons such as the Icon book by K.Horton [12], where K.horton explained the process of design icons explicitly, how to combine the information into the icons, and so on. Based on these guidelines, and also stimulated by the development of applications on smartphones and web pages, we can easily find the resource of well-designed icons. Using icons on data visualization is not required to spend too much time designing and

implementing specific icons. Simultaneously, from our daily life experience, people are gradually forming the link between different icons and items.

Chapter 4

A prototype of a design tool

This chapter will first introduce why it is necessary to build a prototype of a design tool for customizing textures. I will then introduce our prototype's capability and present the technical details about how I implement this prototype.

4.1   Motivation for making our prototype

By reviewing existing tools for customizing textures in 2.6, we pointed out these tools' main limitations nowadays.

1. Tools with relatively more flexibility, such as texture.js, still need to customize textures through programming, which will reduce the efficiency of textures realization for designers who may not have too much experience in programming. Imagine that in a data visualization software, every time we want to add a specific color to the chart, instead of using the color palette, we have to open a programming interface, import the library, and then write 10 lines of code, the entire design process will become very inefficient.

2. The flexibility provided by most tools such as hero pattern is still very limited, and it is hard for designers to get the exact textures they want. Even textures implemented with texture.js by programming still have a limitation on the rotation and cannot customize the minimal units inside textures.

The lack of suitable design tools will hinder our further research. To address some of these limitations, we developed the first version of a design tool that can customize textures by simply clicking buttons and dragging sliders. Two other reasons motivate us to develop this prototype:

1. The tool will be used in our online study to explore designers' design preferences.

2. We want to develop a design tool that can customize textures by manipulating all the attributes of textures mentioned in our design space. In this way, our design space will be more practical.

4.2 Capability of our prototype

Comapared with similar tools available for the community, this tool provides people with a graphic user interface to easily customize the textures without writing code. This tool gives more flexibility on adjusting the attributes of textures such as more rotation options. With an upload function, it is also able to change the minimal components of textures to most of the SVG and png pictures.

The first version of our tool is more research-oriented. I currently offer one simple dataset based on counts for fruits and two types of texture shapes: iconic representations of fruits and more abstract shapes. I will introduce the following features of our prototype: a user interface, more customization options, and predefined icons for our experiment.

4.2.1 Graphic User Interface

I made a graphical user interface (Figure 4.1). Instead of programming, users only need to manipulate the controller to customize textures and get real-time feedback on the chart. Our graphical interface consists of legend, chart, and controller. Our prototype allows designers to customize textures of each bar/pie slice. By clicking on one of the bar/pie slices, the triangle indicator will highlight the chosen bar/pie slice, and also in the legend, the corresponding text color will be changed to blue. the controllers on the side will affect the selected bar/pie slice only.
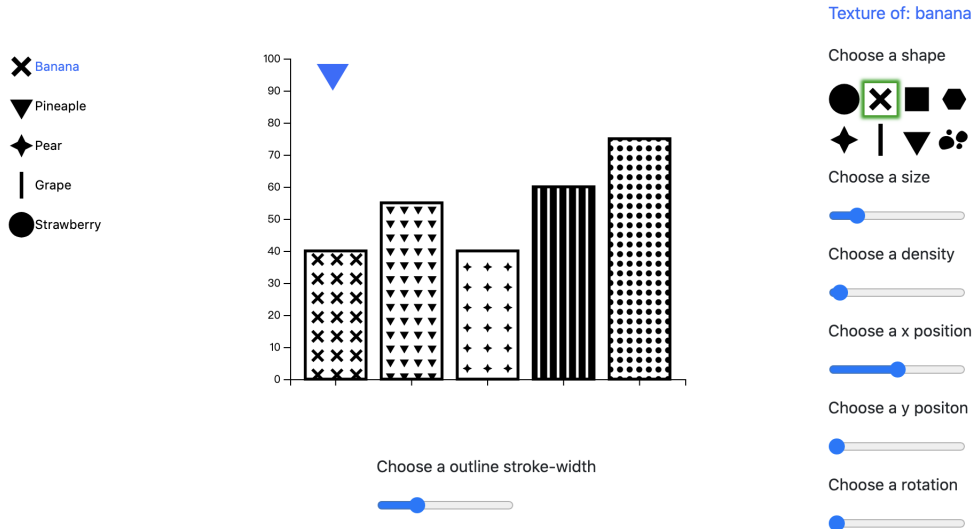

Figure 4.1: graphic user interface of our prototype

4.2.2 More customization options

All of the texture attributes that can be modified in our prototype is from our design space except for x and y offset. During development, on the bar chart, we find that bars have limited space. Textures inside the bars have always been cut off, so we

add these new attributes - x and y offset to avoid this problem. Our prototype also provide more flexibility for changing these attributes than existing tools, like more options on shape and orientation.

Shape. With an upload function, Our prototype can apply most of pictures (in an SVG or png format) as the minimal units of textures (Figure 4.2). According to the designers' needs, it can be normal shapes or icons like company brands, landmarks, etc.
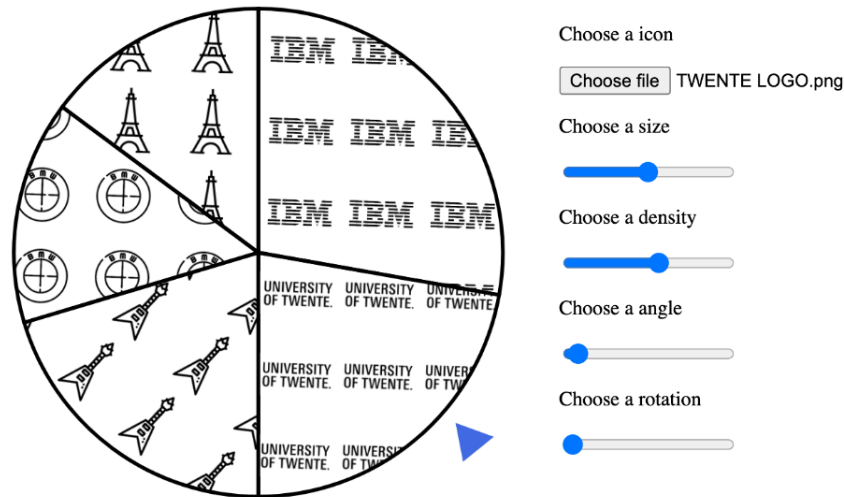

Figure 4.2: textured chart with custom shapes made with our prototype

Orientation. I provide two types of orientation. One is rotated all the icons insides one pie piece/ bar together. Another rotates the shape itself. Both theses two orientation I provide a 0-360 degree range with a 1-degree minimal step (Figure 4.3).
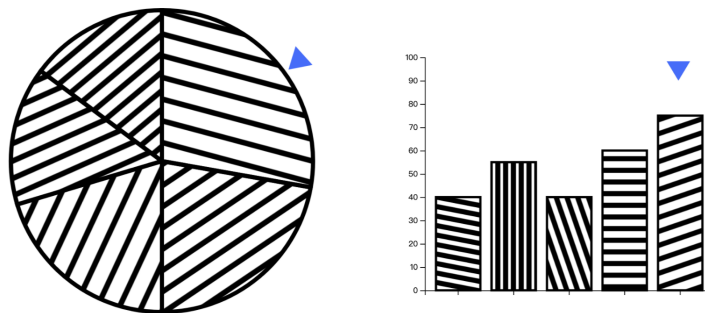

Figure 4.3: textured chart with a different rotation made with our prototype

Size. It can change the size of the shape inside textures (Figure 4.4). In this version I set the range from 0-100px with a minimal 1px step (diameter of the pie chart/ max length of the bars are both 400px).
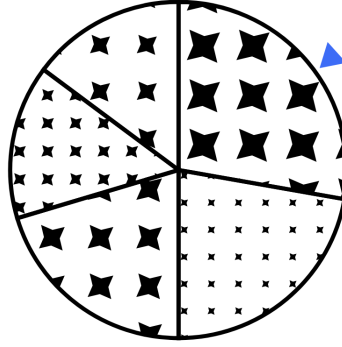
Figure 4.4: textured chart with different sizes textures made with our prototype

Density. It can change the density of the shape inside textures (Figure 4.5). I provide different density options for users. To avoid the shape cut off with each other, the minimal space between each shape is 0. Negative numbers are not allowed.

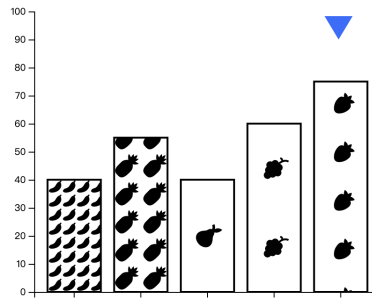Figure 4.5: textured chart with different density textures made with our prototype

X and Y offset. For the bar chart, I provided options on x and y offset which allows the user to adjust the textures' position to avoid cut off in a relatively small space.
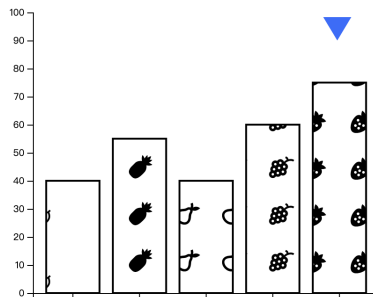

Figure 4.6: textured chart with different offsets made with our prototype

4.2.3   Predefined texture sets

To prepare for our online study, we predefined two types of texture sets inside our tool. One is normal shape texture sets. Another is iconic texture sets.

The normal shape texture. This type of textures used normal shapes like circles, lines, and triangles. As the minimal component of textures (Figure 4.7). This type of textures is mainly used in the previous black and white visualization. By predefining this texture set, we can implement most of the filled textures used in the examples mentioned in chapter 2.2.
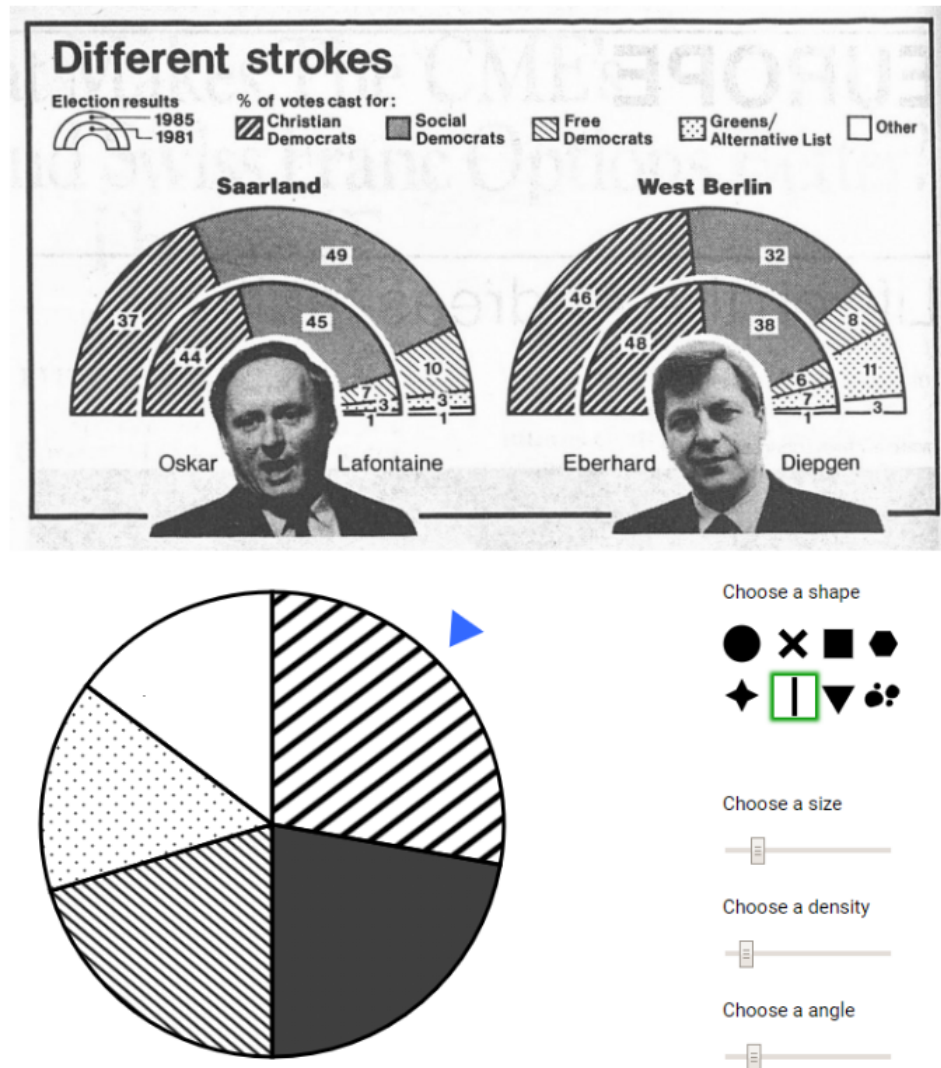
Figure 4.7: our tool is able to create the shade textures(bottom) used in historical black and white visualization (top)

The iconic texture. The other type of textures is the iconic texture that we newly proposed in chapter 3.3. For the purpose of our online study, we designed icons for 5 different fruits. We designed 3 types of icons for each fruit - filled detailed, filled plain, and outlined plain (I used different terminology to describe the types of icons to avoid confusion about the terminology about fill and stroke of the marks used

in our design space). To avoid implying order, I designed these icons with Adobe illustrator, and I used Opencv library with python accurately calculated the ratio of black pixels of each icon, to make the same type of icon sets for different fruits I designed have almost the same value. (Figure 4.8)

Figure 4.8: 3 types of icon for 5 fruits(left), percent black per image(right)

4.3   Implementation detail

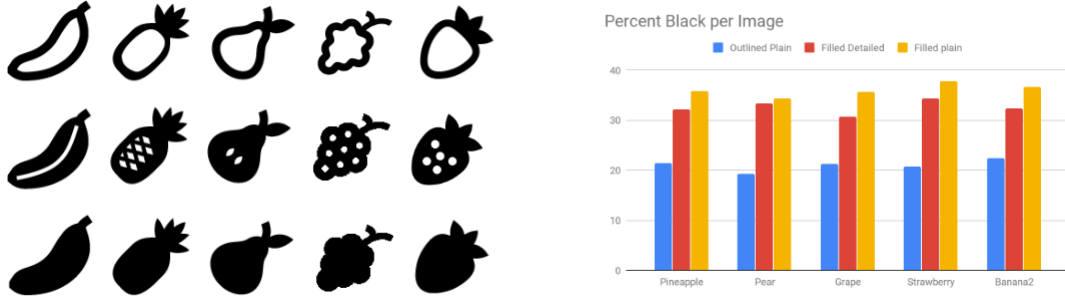At this stage, our implementation goals are more suited for our online study. We currently offer one simple dataset based on counts for fruits and two types of texture shapes: iconic representations of fruits and more abstract shapes. Our tool is composed of 3 main parts. The controllers, the chart, and the legend.

The controllers. For each pie slice/bar, we have 5-6 sliders to control the textures inside the pie slice/bar, which means with the standard predefined 5 fruits categories, we would end up with 25-30 sliders in total. If we put them separately, the whole page will be cluttered, resulting in users find it hard to make the right connection between the chart and the controller. So we just kept 5 sliders to control all the parameters. We first let users select one part, we will highlight this part, and then the controller will only control this slice's parameter. By the local storage function of javascript, it will remember the setting made by the user for each slice, so when the user comes back to an edited slice, the slider will all change to the position of the last setting.

Textures of the chart. Our tool uses SVG pattern fills and their parameters to realize textures and is compatible with D3 and other SVG visualizations. Realizing the above-outlined texture parameters in the tool was not trivial. First, allowing people to choose density while ensuring that each mark's black/white ratio remains the same was not possible with SVG patterns. This would have meant to analyze the applied textures on a mark by sampling its contribution of black and white to an area, while also taking possible perceptual effects of the size of shapes into account. Instead, we realized density by controlling the SVG pattern width/height. Shape size is manipulated by setting the width/height of the SVG shape embedded in the pattern. This meant that both density and size affect each other; high densities are only possible with small shapes. Otherwise, the images embedded in each pattern are cut off. To allow us to use different grouping patterns, we introduced an angle of

rotation for the complete pattern. We also provided a single image rotation. We also needed to add controllers to shift textures in x- and y-direction to avoid unaesthetic white space introduced with large densities or small shape sizes for bar charts with relatively small space. See the pseudo-code for this part in Figure 4.9.

The legend. Our legend corresponds closely to our chart. To make the designer's design easier to read, I made the picture and text of the legend also controlled by the controller. When the user clicked on one pie slice/ bar. I highlighted the corresponding text in the legend to remind the user which one is currently selected, and all controllers will only affect this selected pie slice/ bar. The button on the right will also control the picture of the legend's shape.

```
<image>
Url ='local/image/banana.svg';
width=height=20;
</image>

//Deifine a pattern element
<pattern>
width=height=100
<pattern>

//make the pattern element as a canvas, put image inside, the image will
repeated in this canvas
<pattern>
width=height=100

<image>
Url ='local/image/banana.svg';
width=height=20;
</image>

<pattern>

//create a pie chart with d3.js, make the pattern as the fill
Create pie chart, data= {banana:15, pinapple:20,  ....}
Banana slice fill = pattern

//manipulate the parameter of pattern and size
Pattern width=height=50, the whole canvas becomes smaller; the
repeated image will arrange tighter.
Pattern rotate=50 deg, rotate the whole pattern.
Image width=height=10, a single image will become smaller.
Pattern position x=-10, x offset.
Image rotate= 10 deg, rotate single image

....
```

Figure 4.9: Pseudocode for realizing the textures

Chapter 5

An exploratory online Study

Chapter 2.7 concluded three important factors for a good visualization design: easy to read, aesthetic, and efficiency. From our experience, efficiency may be affected by the other two elements. Before I can address specific research questions related to the effectiveness of black and white texture encoding, it is important to make the chart beautiful and easy to read. For example, one of our future research questions is, will the iconic texture outperform than the normal shape texture in chart reading tasks? The independent variable will be the shape of the texture. However, I still need to design the size, density, and rotation of our textures in our experiment material to avoid the loss of efficiency due to the layout's clutter, unsuitable design, and other factors related to easy to read and aesthetic.

To explore the possible use of the iconic texture and the normal shape texture on a pie chart and a bar chart. I conducted an online study. I asked 6 professional UI/UX designers and 3 researchers in the information visualization field to design a bar chart and a pie chart with these two different texture sets. These designers need to help us design charts of a dataset with 5 fruit quantities using our web design tool and compare charts they designed with different texture types. I want to know how they will use the attributes of these two types of textures to make the chart aesthetic and easy to read. From their perspective, I also want to know which type of textures is better in terms of aesthetic and easy to read. Chapter 2.7 also mentioned that the size of the e-ink screens used in our life varies, so I also want to know, Will the change of chart size affects the designers' preference for these two types of textures?

5.1 Participants

Same as Goffin's experiment[8], I also recruited nine designers to give us sufficient design inspiration, more detailed demographic information, see in Figure 5.1. Six of them are professional UI/UX designers from the industry, and three of them are researchers in the information visualization field. I found them via word-of-mouth. These participants all had formal experience in graphic design and information visualization and actively working in this field.

Gender	**Female:** 4 **Male:** 5
Age	**Age 18-24:** 3 **Age 25-34:** 4 **Age 35-44:** 1 **Age 45-54:** 1
Related working experience	**1-3 years:** 4 **3-5 years:** 2 **More than five years:** 3

Figure 5.1: detailed demographic information

5.2 Task

In this online study, the participants need to design textures for different charts without writing code. Participants need to design a bar chart and a pie chart. I prepared two types of texture sets mentioned in chapter 4.3 - the normal shape texture and the iconic texture for each chart. Participants will set the texture attributes like shape, size, density, and orientation inside each pie slice or bar by manipulating sliders and buttons. After participants fished design on one type of chart with different texture sets, they will compare the same chart with different textures in three different sizes in terms of easy to read and aesthetic.

5.3 Setup and materials

I built an online study website with HTML, CSS, and javascript for front-end and PHP for backend. This online study website is similar to our online design tool, but with more pages like introduction, tutorial, welcome, and a logging function. I also limited the chart and textures choosing function. I show these four charts, one by one and added three comparison pages after design on one type of chart is finished. I send the link of our study to our participants. They need to open the study by using a computer with a screen resolution of more than 1366*768. They will use their keyboard and mouse to design the charts.

5.4 Study procedure

The study started with an introduction that briefly explained the study procedure. Next, participants needed to complete a calibration task to help us collect their screen resolution. After this calibration, participants started a tutorial session to familiarize themselves with the design tool. After they felt confident about the design task, they started this online study with different charts and different texture sets.

Order1	Pie_icon → Pie_shape → Compare pie charts with different texture sets in 3 sizes → Bar_icon → Bar_shape → Compare bar chart with different texture sets in 3 sizes
Order2	Pie_shape → Pie_icon → Compare pie charts with different texture sets in 3 sizes → Bar_shape → Bar_icon → compare bar charts with different texture sets in 3 sizes
Order3	Bar_icon → Bar_shape → Compare bar charts with different texture sets in 3 sizes → Pie_icon → Pie_shape → Compare pie chart with different texture sets in 3 sizes
Order4	Bar_shape → Bar_icon → Compare bar charts with different texture sets in 3 sizes → Pie_shape → Pie_icon → Compare pie charts with different texture sets in 3 sizes

Figure 5.2: 4 conditions randomly assign to participants

The order of the appearance of the charts is random. The participant will be assigned one of these four sequences (Figure 5.2). Let's take the first order as an example. Participants started the study with a pie chart with icon texture sets. Participants manipulated the attributes of the texture inside each texture (Figure 5.3). When participants think they finished their design, by clicking the next button, they then move to the next page where they see a pie chart with shape texture sets. They designed the chart with the same method. After finishing the pie chart design, they saw the two pie charts with different texture sets designed by themselves. They choose their preference in terms of more aesthetic and easier to read. They did the same comparison task for the half-size chart and quarter size chart (kept their design and just rescaling) on the next two pages.
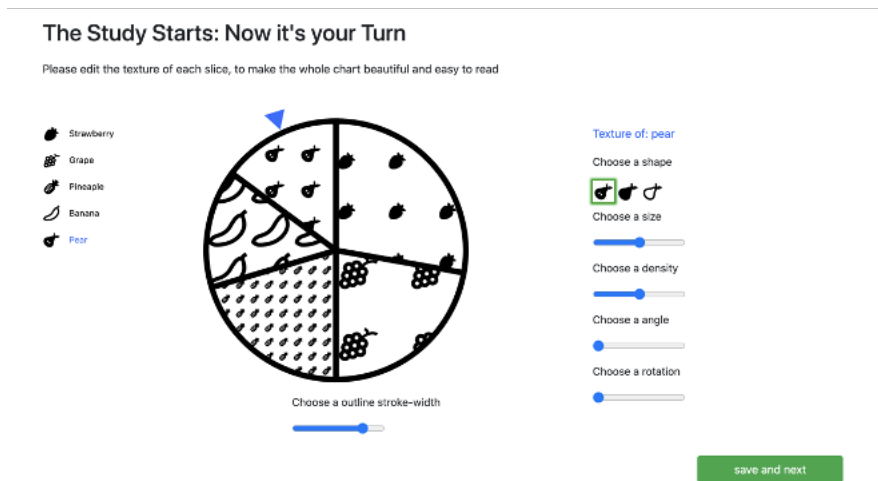

Figure 5.3: online study, design part - pie chart with the iconic texture

In the next part of the study, participants needed to design a bar chart with icon

textures and a bar chart with shape textures. All the interaction remains the same. After finishing the design, participants compared the two bar charts with different textures in 3 different sizes (kept their design and just rescaling). Our goal is to get design inspiration from our participants, so I do not count the time spent on design as a measurement. At the end of the study, participants need to answer a questionnaire that collects their demographic information and asks them to describe their design path or ideas briefly.

5.5   Analysis procedure

To better analyse our participants' design, I added a logging function with our online study website. After participants finished their design, the data of their settings will be recorded to 3 CSV files. I assigned a unique participant ID to identify different users.
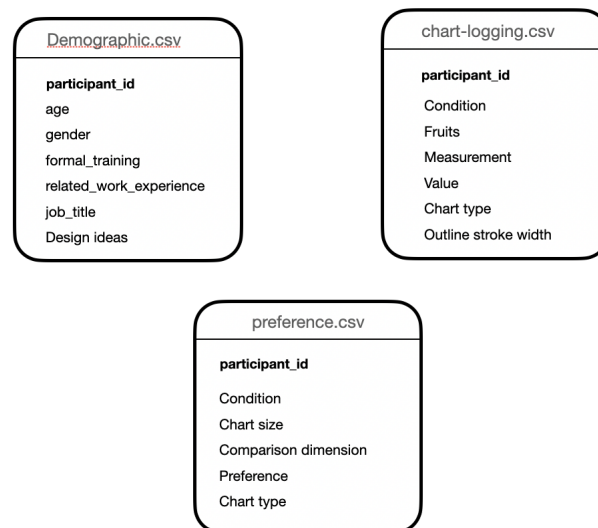

Figure 5.4: logging data structure

In the chart logging file, I collect the settings for each pie slice/bar made by the participants. In the demographic logging file, I collect the participants' necessary demographic information. I log the participants' preference for charts with different textures in different sizes in the preference logging file.

I wrote a simple script that can redraw the design made by the participants. Once I input the participant's data, our script reads the chart logging and preference CSV file, then draws the chart based on the data. By doing so, I can easily compare different design and show the representative design in chapter 5.6, where I analyze the result.

In this analysis script, by choosing participant ID, I can check the design made by different participants chart by chart. I design a blue dot under the chart to indicate if the participant chose a chart with this type of texture sets as preference in terms of aesthetic and also a green dot in terms of easy to read (Figure 5.5).
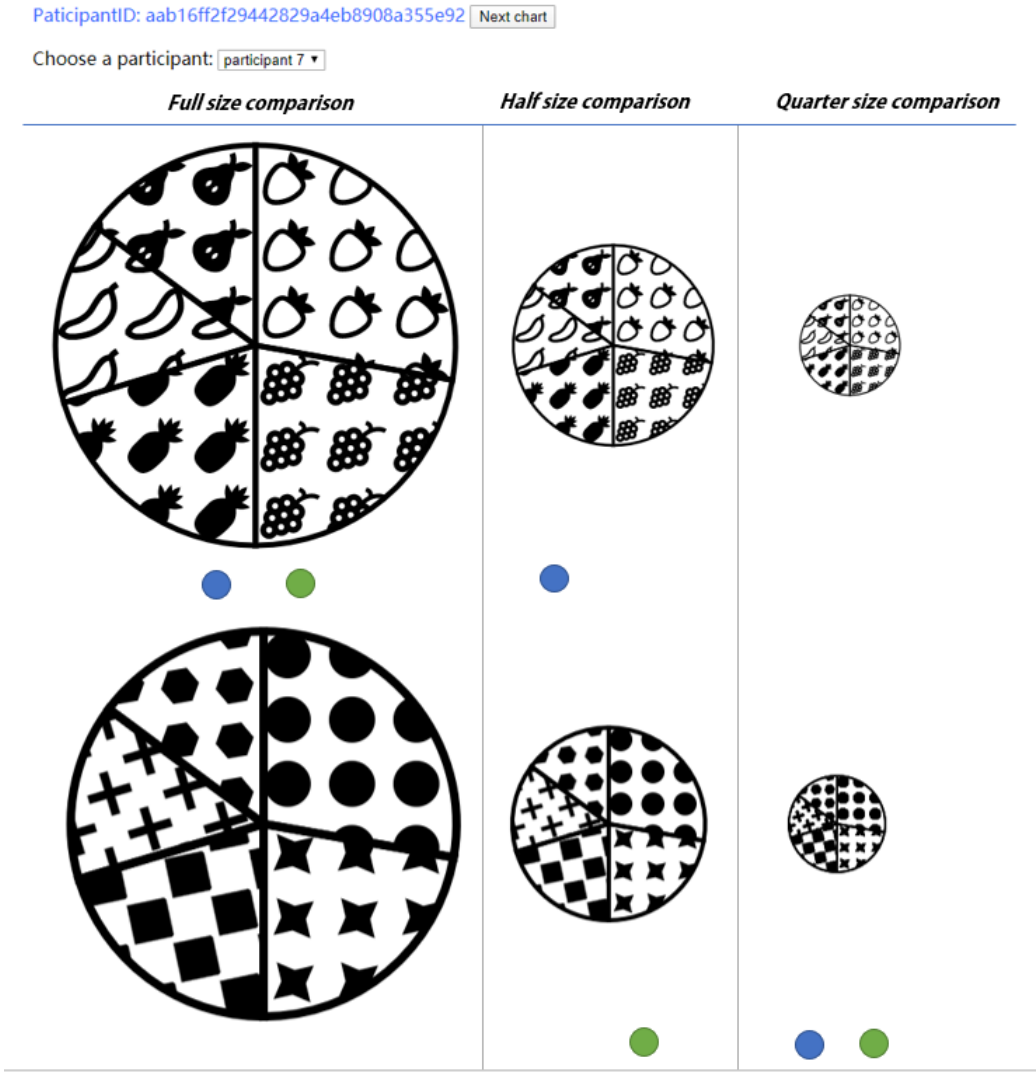

Figure 5.5: recreated pie charts designed by a participant, the green dot indicates preferred as easier to read, blue dot indicated preferred as more beautiful

5.6   Result

108 textured charts were collected in the end, 36 for each size. I redrew them by our script. I then tried to find the similarity of these designs and professional designers' preferences on different texture types in different sizes. I will introduce our insight chart by chart.

5.6.1   Pie chart

Outline stroke width. For iconic textured, most participants (6/9) made the outline stroke width as rough as the icon's stroke width visually (Figure 5.6 left). For normal shape textured pie charts, most of them (7/9) made the chart's outline stroke width as rough as the stroke width of the shape when that shape has a stroke (like crosses) visually (Figure 5.6 right). The other 2 participants designed relatively small icons, and they chose a 2.8 and 3.1 outline stroke width. No participant chooses a very thick (<2.8) or very rough (>6) outline stroke width. One participant mentioned in the questionnaire that the outline stroke width will distract the user from reading the chart if the outline stroke width is very rough or very thick.
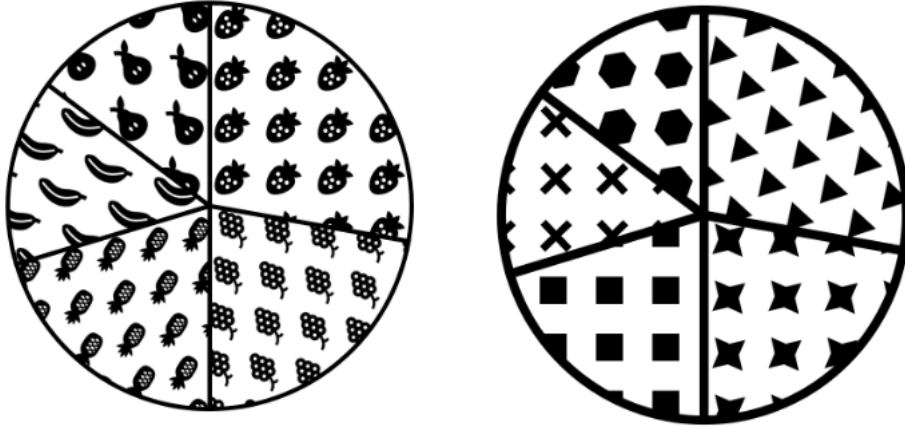

Figure 5.6: participants matched the stroke of the outline with the icon stroke(left) and the shape stroke(rights)

Shape. Participants' choice of shapes varies. For the iconic pie chart, most of them (7/9) chose the same types of icons for each slice to maintain consistency. The type of filled detailed icon is most popular (5/9). 3 participants chose the type of filled plain icon as the basic shape. Only one participant used an outlined plain type (Figure 5.7). I think that might be because the pie chart already has many strokes. If we apply the stroke only icon again, the chart might be cluttered (Figure 5.7 right).
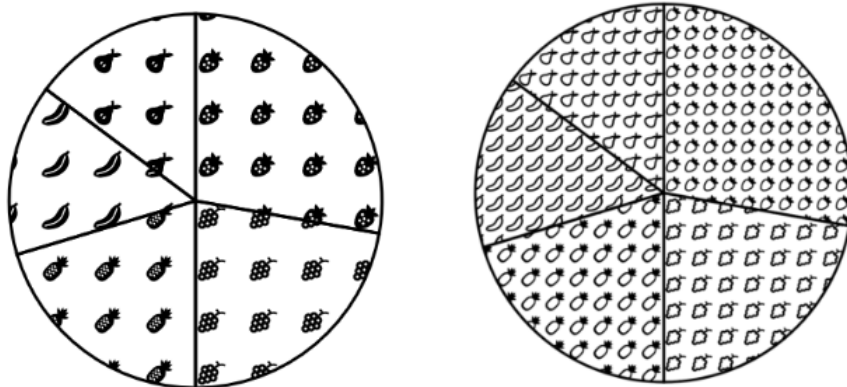
Figure 5.7: pie chart with filled detailed icons and pie chart with outlined plain icons

For the shape textured pie chart, 8 out of 9 participants choose different shapes for different pie slices (Figure 5.8 left). Only one participant chose lines with 2 different rotations for 2 pie slices (Figure 5.8 right) and mentioned in the questionnaire that it should be better to have more linear shapes, it will make people easier to distinguish different items.
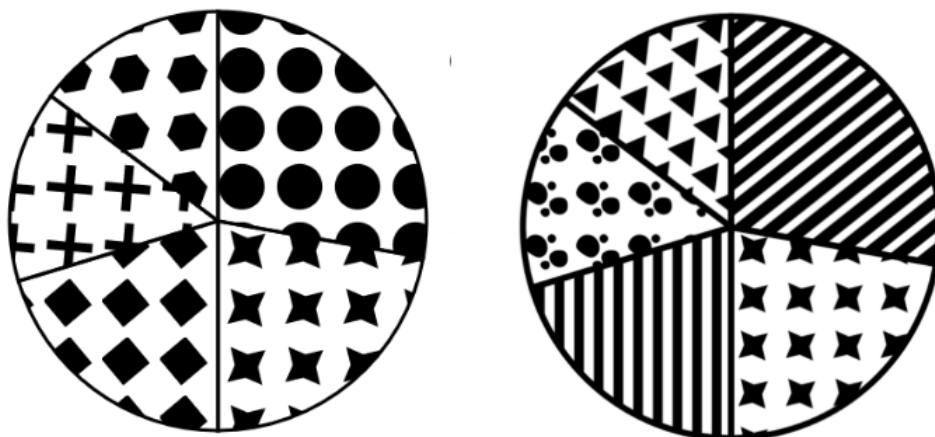

Figure 5.8: chart using different shapes for different slices and the chart using lines twice

Size and density. Size and density also vary. Only 2 participants choose a relatively small size. One of them reported that he would prefer to choose a bigger size if they know they will compare the chart in a small size. Most participants (6/9) kept the size and density of each slice almost the same (Figure 5.9), which meets our expectation because the size of each pie slice already implied the order of the

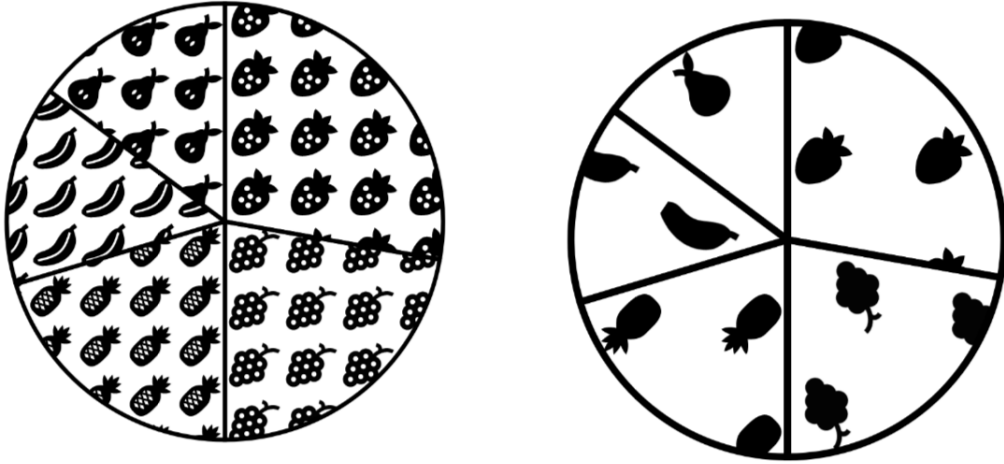data, the size, and density of the textures should not imply it again.

Figure 5.9: same size and density for each slice

Rotation. There are 2 main rotation settings (Figure 5.10). One is pointed to the center of the circle(4/9), another one remains the same rotation(3/9). All of these 3 participants choose both the angle and rotation of 0 to remain the image's default angle. The other 2 participants rotate every slice randomly. There is no clear rule founded.
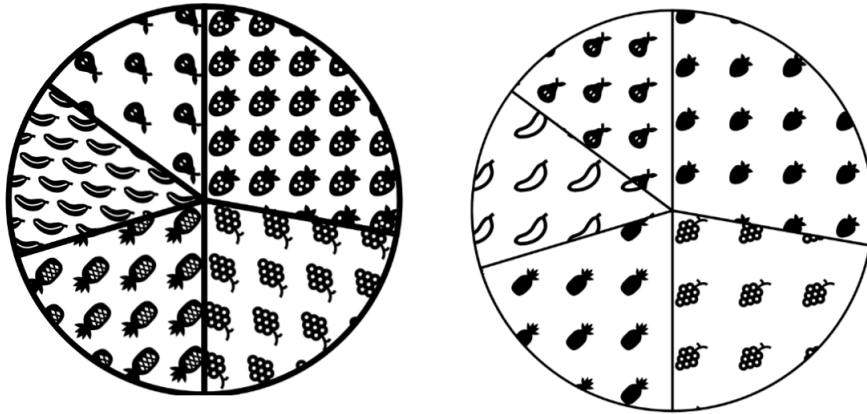

Figure 5.10: two types of rotation, rotate toward the center of the pie chart(left), kept same rotation(right)

For the shape textured pie chart, I did not find an obvious similarity of the rotation setting. It varies a lot. I think that might be because not all of our shape
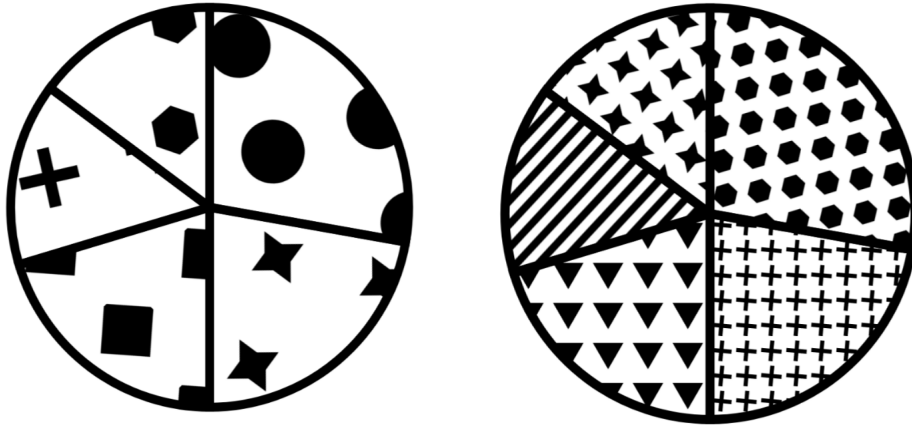
has an obvious point direction(like a circle)

Figure 5.11: no similarity found in the rotation of the shape

Preference. For the full-size chart, most participants chose the iconic textured pie chart as a more aesthetically pleasing chart(7/9) and easier to read chart (8/9). But when I rescale the chart to half size, 7 out 9 participants think iconic textured pie is more aesthetically pleasing, only 4 participants think the iconic texture pie is easier to read. When the chart size comes to quarter size, most participants think shape textured pie is more aesthetically pleasing(6/9) and easier to read (7/9). I think that might be because when the space of each pie slice scales down, the detail of the icon can not be perceived, participants find it hard to distinguish different items (Figure 5.12). The same situation happened in the bar chart.
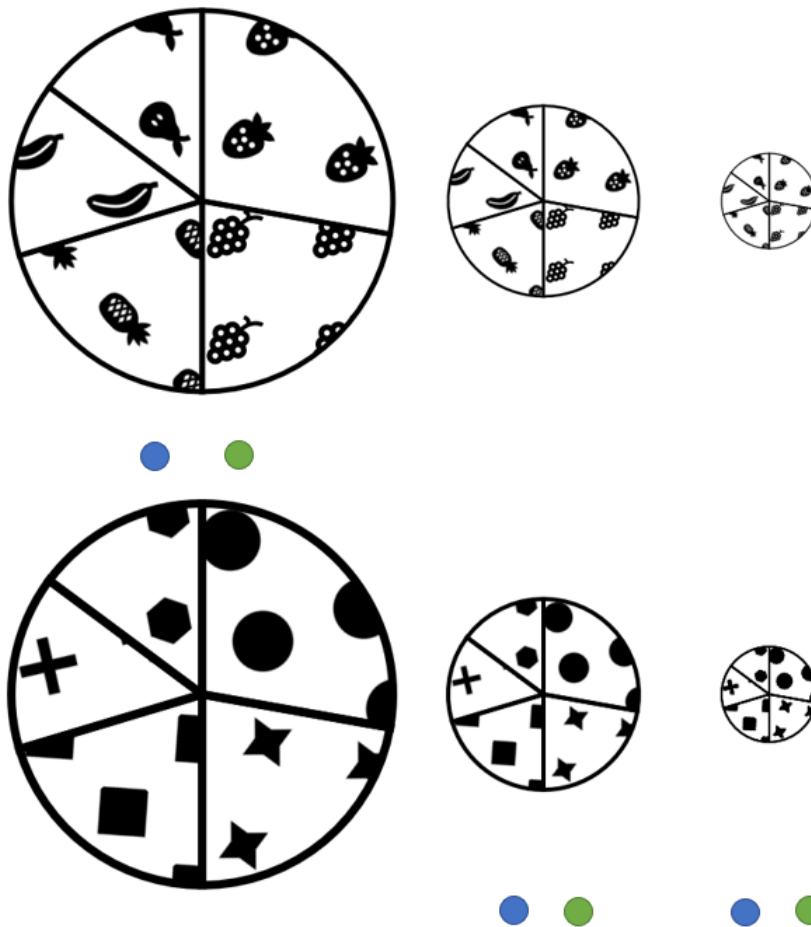
Figure 5.12: chart size affects participants' preference on the iconic texture

5.6.2 Bar chart

Outline stroke width. For both iconic textured and shape textured bar charts, I did not find too many participants(2/7) adjusted the outline stroke width with the stroke of the icon/shape inside the bar, I think that might be because of the bar charts has x and y-axis, they want to adjust the stroke of the bar to match the stroke of the axis (Figure 5.13).

Figure 5.13: match the stroke of the outline with the axis

Shape. participants remain the same design strategy for bar chart. Same as pie chart, participants' choice on icon types varies. Most of them choose the same types of icons set (6/9) to maintain consistency. But in the iconic textured bar chart, the outlined plain icon (Figure 5.14) became popular (4/9).
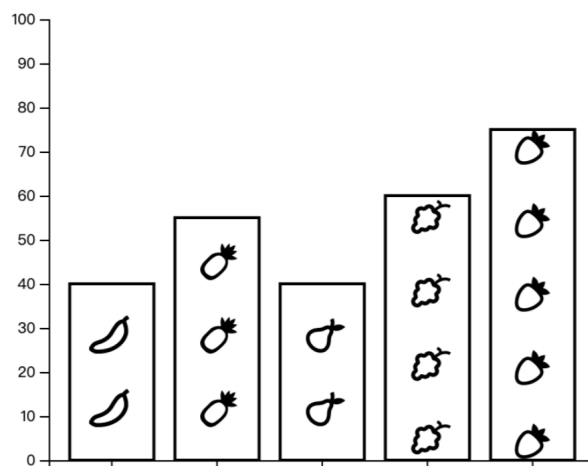
Figure 5.14: participants used stroke only icon for all bars

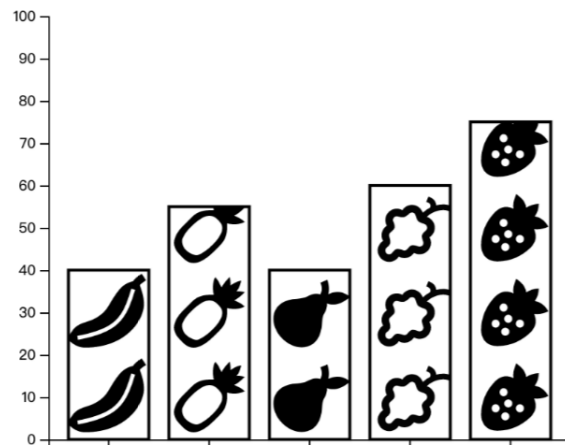For the shape textured pie chart, 7 out of 9 participants choose different shapes for different pie slices. one participant chose lines with different rotations for all the bars (Figure 5.15).
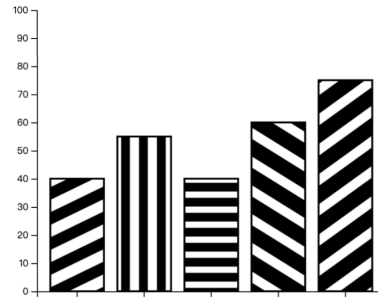
Figure 5.15: using the lines with different rotations for all bars

Size and density. Participants remained their design strategy as the pie chart. Although the size and density vary. but most participants (7/9) still kept the size and density of each part almost the same (Figure 5.16).
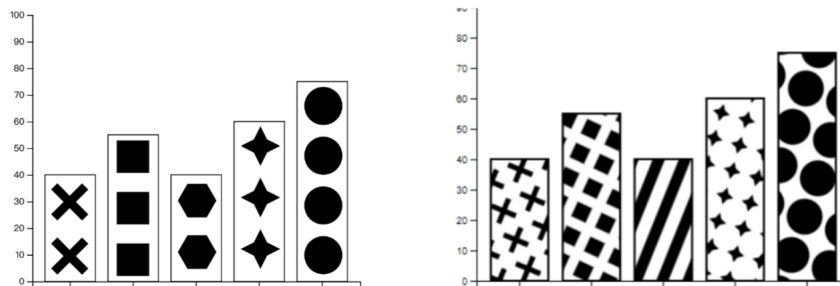
Figure 5.16: keep the size and density almost the same at different bars

Rotation. I find that when participant made the shape inside the bar with a big size, they prefer to rotate the texture align to the y-axis, but when they made the shape relatively small, they will rotate it with the same angle (Figure 5.17).
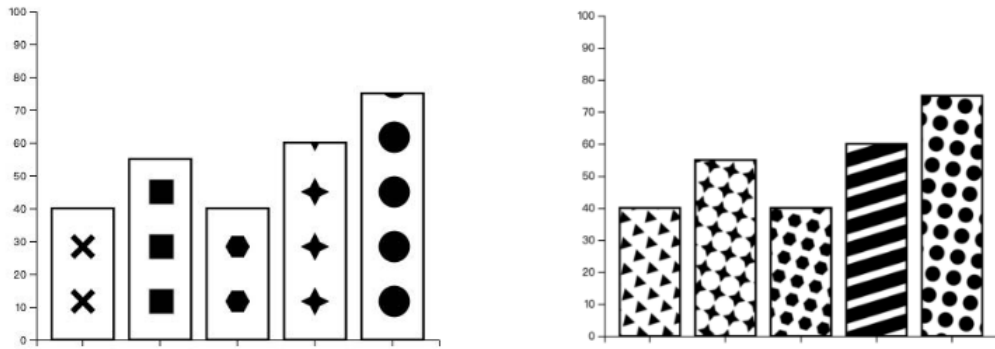
Figure 5.17: participants rotate the texture to align with the y-axis when choose a relatively big size(left) and rotate the texture when choose a relative small size(right)

X and y position most of the participants adjust the x and y position to avoid a cut off of the texture to make the chart aesthetically pleasing (Figure 5.18).
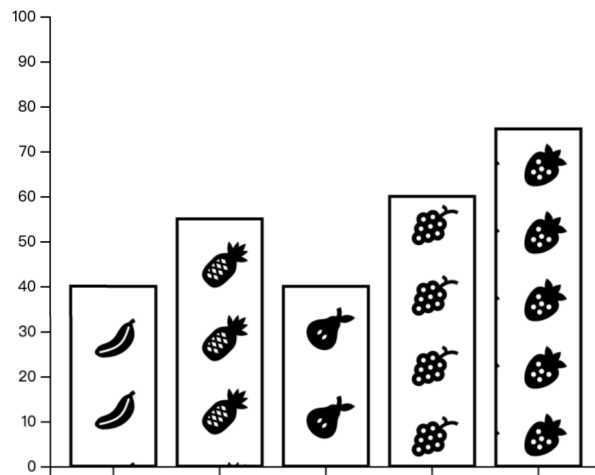
Figure 5.18: adjust the x and y position to avoid cutoff

Chapter 6

Discussion and future work

6.1   Summary of results

In this thesis, I introduced a design space for black and white textures. I summarized different texture attributes that can be used to encode categorical and ordered data from historical black and white visualization, newspapers, and books. I also gave recommendations on how to use these attributes. By exploring the advantage of pictogram and usage of the icons, I also proposed a new direction, which I call it the iconic texture. This type of texture might encode categorical data more efficiently than the normal shape texture used in historical black and white visualization.

To facilitate our research on black and white textures. I made a prototype of a design tool that supports people to explore different black and white textures for visualization on e-ink displays. Compared to current tools available for the community to customize textures, our prototype has a graphical user interface where people can easily customize black and white textures without writing code. Our prototype also provides more customization options. With an upload function, our prototype can adjust most of the SVG and png pictures as the minimal components of the texture. Most of the attributes used to customize the texture in our tool are from our design space. During prototype implementation, we find provide x and y offsets are necessary as textures in the bar chart often cut off with bars, so we set x and y offsets as an adjustable attribute in our prototype and used it in our user study, The usage of x and y offsets will be discussed next in the context of the user study discussed below.

I ran an exploratory online study in which experts designed four different categorical encodings using different types of black and white textures. I wanted to find how professional designers adjust the iconic texture and normal textures to make a pie chart and a bar chart beautiful and easy to read. I also wanted to know their preference for these two types of textures and whether their preferences will be affected by the chart size. I found from the results of our study that most participants used different shapes for different pie slices/bars, and they kept almost the same size and density for each pie slice/bar. Three types of rotation were seen for the iconic texture: texture icons point toward the circle center, all texture icons have the same rotation, or all texture icons have a random, different rotation. Most participants adjusted the x and y offsets to avoid the cut-off. This attribute is necessary. Out-

lined plain icons were rarely used by participants on pie charts but frequently used on bar charts. I think that might be because the outlined plain icons make the pie charts look cluttered. Participants prefer the iconic texture when the chart size is large. But when the chart size becomes smaller, they prefer the normal shape texture. I think that might be because, in a small size chart, detailed information of the icon becomes hard to perceive, but the relatively simple normal shapes still can be recognized.

In the end, this work resulted in a poster submission for the IEEE VIS conference, and it is accepted. So, we got a chance to introduce our design space, the idea of the iconic texture, and the prototype to the community.

6.2 Limitation

This thesis is more exploration oriented on this topic, a Ph.D. topic will follow our work in the INRIA Aviz team. We contributed a preliminary design space, the prototype of the tool, and an exploratory study website framework, which indicated some interesting first indications and offered a good start for future research. However, there are also a few limitations and ample opportunities for future research. Some of these topics will be briefly discussed below.

6.2.1 Preliminary design space

I built the preliminary design space by reviewing historical examples and using the criteria from Bertin [2] and Munznser's [19] study to categorize and feature these attributes. However, there may be more attributes that can be used for visualization, which I overlooked (for example, we found an x and y offset is necessary when implementing our tool), and all of these features need to be validated in the future by more scientific experiments. This preliminary design space gives the initial idea of how and from what perspective to analyze features of these attributes, but there is still room for expanding it.

Based on our analysis, we came to the idea of and briefly described the iconic texture. I think it might be a more efficient texture. However, to measure the efficiency of this texture, a formal scientific experiment is needed. I briefly conducted a very simple pilot study, which indicated better performance benefits for the iconic texture. One of the first things in the follow up Ph.D. project should look into is how to measure the efficiency of these types of textures in a scientific way.

6.2.2 First version of the Prototype

The first version of this prototype is more research-oriented and designed to support the online study, so I just provided limited function. For example, the prototype has 2 types of chart options, and with a simple dataset. For now, This prototype can help design black and white textures and supports us to verify our design idea

quickly, but when going towards a commercial solution like texture.js, the additional feature is needed in the future, like import data, more chart type and so on.

However, our work still matters a lot, because we solve many technical problems, such as how to adjust most of the png and SVG pictures as the minimal component of the texture, how to embed the texture into the chart with D3, how to generate textures fill by manipulating the SVG pattern, and so on. In the future, we need to adjust the same method to different charts, which will be relatively easy. Furthermore, we also used these methods to build the framework of the whole online study website. It is also easy to adjust these methods to explore designers' possible design on other charts, making it a possibly valuable tool for the stakeholder

6.2.3   Online study

I built the online study website and ran the study, but the sample we collected is not very large. Although we followed Goffin's method, this is still oriented at designers. One reason is that I ran this study during the summer vacation. Therefore the earliest reachable participants are mostly from the industry. So we want to get more ideas from the researchers in information visualization fields in the future. we also want to reach more end-users of e-ink devices for further research on efficiency.

This study is still conducted on the computer with a color screen. We just designed the chart and texture in black and white, a further study on real e-ink display might be necessary. All the findings might just suitable for pie and bar charts, in the future, we need to collect more preferences on other charts. There might be a bias in our online study. In the study design, I randomize all the attributes to make the chart look messy so that participants will adjust all the attributes by their ideas. However, I put our own design in the tutorial part, our original idea is to give the participant a good impression of the textured chart at the start, but one participant reminded us that this might give the participants a clue of the design direction we want to the participants, it may affect their design in the design part.

6.3   Future work

Research on black and white textures for visualization is a broad topic. In this study as the first step we provided the preliminary design space and the prototype for further research, in addition to improving the limitations mentioned in 6.1, we also have other research question need to address in the future. Our ultimate goal is to study the features of black-and-white textures to come up with guidelines that help designers build beautiful and effective data visualizations specifically for e-ink displays. To reach this goal, we have to figure out the following research question in the future:

Marks: Are certain textures better suited to specific marks (rectangles, circles, arbitrary shapes of different dimensions)?

Shapes: Are textures with data-relevant shapes more effective than arbitrary shapes?

Shape similarity: Is it more effective to use textures of similar shapes that vary in orientation or grouping, or should textures of different shapes be used?

Perception: How many differences in one texture property can be meaningful distinguished?

Interplay of density and size: To which extent do changes in density or shape size affect the effectiveness of a texture?

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Appendix

A. IEEE VIS Poster submission

Black-and-White Textures for Visualization on E-ink Displays

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ABSTRACT

We introduce a design space for black and white textures and the prototype of a design tool that supports designers to explore different black and white textures for visualization on e-ink displays. We are currently working on an exploratory online study in which experts will design four different categorical encodings using different types of black and white textures.

Index Terms: Human-centered computing—Visualization—Visualization systems and tools

1 INTRODUCTION AND BACKGROUND

E-ink displays are now widely used on devices such as smartwatches, electronic shelf labels, and e-readers. E-ink displays are popular for their low power consumption, relatively low cost, and reduced eye strain when reading. As a tradeoff, they have only a few colors and low refresh rates. While research and development for e-ink displays has increased the number of displayable colors, most e-ink displays are still black and white or have only a few additional colors that could be used for visualization. Yet, many types of charts require color hue or saturation to encode quantitative or categorical data. With our research we want to understand how we can effectively visualize data in the absence of color. We explored several strategies and, inspired by historical practice, focused on texture encodings.

We first explored alternatives to the use of color hue or saturation in data graphics, then derived a design space of black-and-white texture dimensions, and finally designed a tool to explore different types of textures to encode categories on bar and pie charts. Our ultimate goal is to study the features of black-and-white textures to come up with guidelines that help designers build beautiful and effective data visualizations specifically for e-ink displays.

Throughout our discussion we use the term *texture*, following definitions in computer graphics where a texture is a 2D image applied to (the surface of) a graphical object that is potentially repeated multiple times through some form of tiling. Specifically, here we refer to a texture as a tiling pattern that is characterized by the type of shapes we use as part of the pattern (lines, dots, ...), the density of the shapes, their size, orientation, etc.

The challenge of a limited number of displayable colors has been present in the use of virtually all printing technology as well as the early days of computer screens. Many historical examples exist that showcase beautiful and stunning data graphics, drawn without color. Brinton [2, p.32], e. g., shows an over 100 year old example of a heatmap (Fig. 1) that uses black and white textures. Bertin's Semiology of Graphics [1] discusses textures extensively, for points, lines, and areas and with various graphical properties. Bertin uses the term *texture*, however, to refer to differences in density applied to a shape[1] (e. g., ▦ vs. ▦) and the term *pattern* to instead refer to differences in shapes applied to a mark (e. g., ▨ vs. ▧). Here, we use a slightly different terminology as outlined above but Bertin's advice on the use of his visual variables *texture (density), orientation, and shape* was valuable for our work. Both Tufte [6] and Bertin [1]

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[1]To be precise: to Bertin changes in texture only affect the number of separable marks in an area and not the overall value.
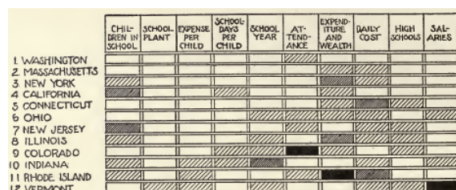

Figure 1: Rank of US states in ten education features, 1910. Taken from [2, p.32], trimmed to 12 states. Picture in the public domain (Ⓢ).

warn that textures may produce Moiré vibrations and Tufte [6] even goes so far as to say that they should be avoided altogether.

Some examples of using Tufte's and Bertin's advice for black-and-white visual representations exist, such as Perin et al.'s Bertifier [5]. In computer graphics, black-and-white textures are also used, usually in the sub-field of non-photorealistic rendering such as for stippling [3] or hatching [4]. Here the goal is, however, the replication of traditional drawing techniques that represent shading and material properties, as opposed to data representation like in our case.

2 TEXTURE FEATURES

In data visualization, textures can be applied to both the stroke ◌ and the fill ◯ of a data-representing mark. We discuss textures as repeated (tiled) shapes, such as lines ▦ or dots ▦. Shapes can be applied both to the fill of a mark or along its outline. We detail the texture properties we found useful to configure black-and-white textures with examples in Table 1. In particular, we considered:

Density: how closely packed shapes inside the texture are while maintaining the same black to white ratio (value). That is, if more black shapes are to cover a certain mark, they will be reduced in size to maintain the same black/white ratio.

Shape Size: the size of the shape inside the texture. Increasing the size while leaving density the same will result in a change in value (black/white ratio). Changing size and density together allows keeping the black/white ratio (value) the same.

Orientation: orientation/angle of shapes inside the texture

Shape type: shape type used inside the texture (line, dot, square, ...)

Grouping: This texture property is not a visual variable listed by Bertin. It describes how shapes are placed on a mark. For example, in a regular grid, with an offset, randomly etc. Changes in grouping result in a visually different texture but do not change overall value, and—depending on the grouping—also not the perception of density.

From the descriptions of texture parameters it becomes clear that choosing correct parameters for visualization is not a trivial task. Which we further explored for categorical data.

3 VISUALIZING CATEGORICAL DATA FOR BLACK AND WHITE TEXTURES

Past work in visualization [1] and in particular computer graphics [3, 4] includes advice on how to generate textures with a given value encoding that could be used for the visualization of ordered

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Table 1: Texture properties with examples and characteristics with lengths for density, orientation, and shape as recommended by Bertin [1]. Recommendations on density, shape, orientation use for categorical or ordered (incl. quantitative) data also follows Bertin.

Texture property	Example Fill	Example Stroke	Length	Categorical Data	Ordered Data
Density			2–5	∿	✓
Shape Size			4–5	✗	✓
Orientation			2–4	✓	✗
Shape type			large	✓	✗
Grouping			small	✓	✗

data. Little advice, however, exists on the use of different shapes, orientations, and grouping for the encoding of categorical data, which led us to explore the replacement of color hue with black-and-white textures. We first attempted our own designs to replace color hues in common visualizations such as area charts, cloropleth maps, heatmaps, or bar- and pie charts to observe the effects of changing categorical texture parameters. Fig. 2 highlights two non-optimal designs that highlight the non-trivial choices to make when replacing color hue with textures. The left image, for example, shows that changes in value happen quickly when changing the shape, for example from dots to lines or crosses. The right image illustrates that certain orientations can interfere with the perception of horizontal (or vertical) lines. In addition, not every shape is suited to thin and long areas; the cross on the top series on the left is almost invisible. Lines on the left and right begin to produce the vibratory effects both Bertin [1] and Tufte [6] warn about.

Following our investigations, we formulated several concrete research questions for black-and-white textures for categorical data representation. We use the word "effective" below to refer to multiple possible benefits such as data reading correctness, memorability, aesthetics etc.—none of which have yet been explored in depth.

Marks: Are certain textures better suited to specific marks (rectangles, circles, arbitrary shapes of different dimensions)?
Shapes: Are textures with data-relevant shapes more effective than arbitrary shapes?
Shape similarity: Is it more effective to use textures of similar shapes that vary in orientation or grouping, or should textures of different shapes be used?
Perception: How many differences in one texture property can be meaningful distinguished?
Interplay of density and size: To which extent do changes in density or shape size affect the effectiveness of a texture?

4 STUDYING TEXTURE DESIGN

We built an online tool (Fig. 3) that allows us to more formally experiment with texture parameters for bar and pie charts to explore some of these questions. Our tool uses SVG pattern fills and their parameters to realize textures and is compatible with D3 and other SVG visualizations. Realizing the above outlined texture parameters in the tool was not trivial. First, allowing people to choose density, while ensuring that the black/white ratio on each mark remains the same, was not possible with SVG patterns. Essentially this would have meant to analyze the applied texture on a mark by sampling its contribution of black vs. white to an area, while also taking possible perceptual effects of the size of shapes into account. Instead, we realized density by controlling the SVG pattern width/height. Shape size is manipulated by setting the width/height of the SVG shape embedded in the pattern. This meant that both density and size affect each other; high densities are only possible with small shapes,
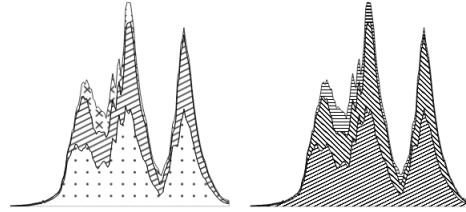

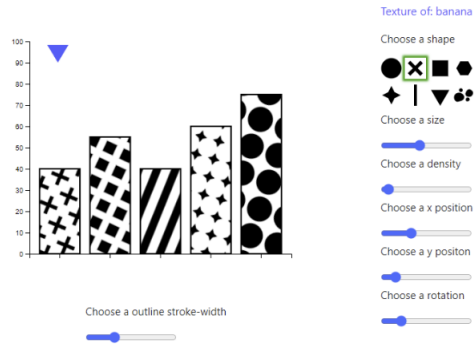Figure 2: Experiment for replacing categorical color in an area chart.

Figure 3: Screenshot of our tool for testing texture parameters.

otherwise the images embedded in each pattern are cut off. To allow us to use different grouping patterns we introduced an angle of rotation for the complete pattern (rather than for individual shapes). For bar charts we also needed to add controllers to shift the texture in *x*- and *y*-direction to avoid unaesthetic white space introduced with large densities or small shape sizes. We currently offer one simple dataset based on counts for fruits and two types of texture shapes: iconic representations of fruits and more abstract shapes (Fig. 3).

Our next goal is to study how visualization designers apply textures to these two simple representations. In particular, we are interested in studying the different use of iconic vs. general patterns. We plan to ask visualization designers to participate in a small texture generation study and then analyze the results, before we start addressing some of the other research questions about textures that we outlined above.

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Tutorial

Before the experiement, let's first get familiar with the interface and interaction

You can change the shape on each pie piece by clicking on the one of these buttons.

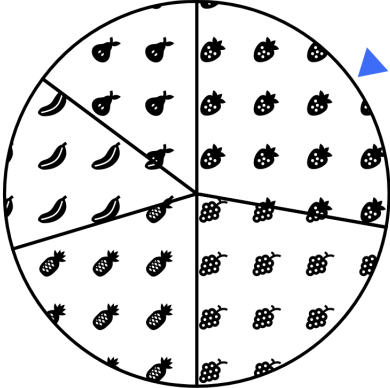Texture of: strawberry

🍓 Strawberry

🍌 Banana

🍍 Pineaple

🍐 Pear

🍇 Grape

Choose a shape

Try now

Choose a outline stroke-width

The Study Starts: Now it's your Turn

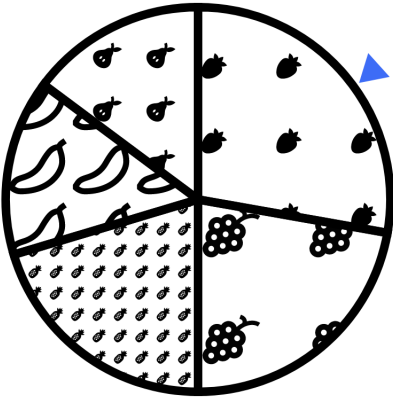Please edit the texture of each slice, to make the whole chart beautiful and easy to read

🍓 Strawberry

🍇 Grape

🍍 Pineaple

🍌 Banana

🍐 Pear

Texture of: strawberry

Choose a shape

Choose a size

Choose a density

Choose a angle

Choose a rotation

Choose a outline stroke-width

save and next

Here are your two designs again

Please let us know which one you prefer according to general aesthetics (beauty) and how easy it might be to read.

- 🍓 Strawberry
- 🍇 Grape
- 🍍 Pineaple
- 🍌 Banana
- 🍐 Pear

- ● Strawberry
- ✕ Banana
- ■ Pineaple
- ⬡ Pear
- ✦ Grape

○	More aesthetic	○
○	Easier to read	○

save and next

Here are your two designs again

We made them a little smaller. For this size please again let us know which one you prefer according to aesthetics and how easy it might be to read

- 🍓 Strawberry
- 🍇 Grape
- 🍍 Pineaple
- 🍌 Banana
- 🍐 Pear

- ● Strawberry
- ✕ Banana
- ■ Pineaple
- ⬡ Pear
- ✦ Grape

○	More aesthetic	○
○	Easier to read	○

save and next