

DATA SCIENCE, DASHBOARDS, AND THE WAY IT WORKS WITH  
STATISTICS

by

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DATA SCIENCE, DASHBOARDS, AND THE WAY IT WORKS WITH  
STATISTICS

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Here is my abstract. (*350 word limit*)

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## DEDICATION

Dedicated to...

## ACKNOWLEDGMENTS

Thank you to all my people!

## Table of Contents

<b>List of Figures</b>	vii
<b>List of Tables</b>	viii
<b>1 Introduction</b>	1
1.1 Perceptual and Cognitive Process of Graph Perception . . . . .	3
1.2 Data Considerations . . . . .	24
1.3 Audience-Data Interactions . . . . .	39
1.4 Dashboard Design . . . . .	54
1.5 Dissertation Map . . . . .	58
1.6 Conclusion . . . . .	58
<b>2 Chapter Paper on Rural Shrink Smart Manuscript submitted to Journal of Data Science Special Issue</b>	60
2.1 Abstract . . . . .	60
2.2 Introduction . . . . .	60
2.3 Data Description . . . . .	62
2.4 Dashboard Design Considerations . . . . .	64
2.5 Guiding Design Principles . . . . .	68
2.6 Dashboard Design Process . . . . .	69
2.7 Discussion . . . . .	77

2.8 Future Work . . . . .	78
2.9 Conclusions . . . . .	79
<b>3 Dashboard Poetry</b>	<b>81</b>
3.1 Introduction . . . . .	81
3.2 Dashbaord Construction . . . . .	91
3.3 Cognitive Principles . . . . .	94
3.4 Ensemble Perception . . . . .	104
<b>4 Does Color Help?: Multidimensional Ensembles in Bland-Altman Plots: An Exploration</b>	<b>111</b>
4.1 Introduction: . . . . .	111
4.2 Methods: . . . . .	118
4.3 Discussion: . . . . .	120
<b>Conclusion</b>	<b>121</b>
<b>A The First Appendix</b>	<b>122</b>
<b>B The Second Appendix, for Fun</b>	<b>124</b>
<b>Colophon</b>	<b>125</b>
<b>References</b>	<b>130</b>

## List of Figures

1.1	An example of how the retina signals the visual cortex . . . . .	6
1.2	Example of eyetracking using noting the F-pattern reading flow on dashbaords used in a white paper written by Amy Albert with Tableau . . . . .	8
1.3	Example of eyetracking using noting the Z-pattern reading flow on dashbaords used in a white paper written by Amy Albert with Tableau . . . . .	9
1.4	Gestalt Principles with Examples . . . . .	11
1.5	Perceptual Grouping illustrated by Stephen E. Palmer in 2002 . .	13
1.6	Visual Attentionn can repersented by the following . . . . .	16
1.7	Working Memory Model created by Baddeley (left) and Informa- tion Processing Model created by Atkinson and Shiffrin (right) . .	19
1.8	Working Memory Model created by Baddeley (left) and Informa- tion Processing Model created by Atkinson and Shiffrin (right) . .	20
1.9	Grammar of Graphics Diagram of Wickham and Wilkinson's work	30
1.10	Grammar of Graphics Diagram of Wickham and Wilkinson's work	30
1.11	van Wijj Simple Visualization Model . . . . .	36
1.12	GOMS Model created by Card Moran and Newell . . . . .	40
1.13	Multi-dimensional visualization efficiency (a) modified from Tuovi- nen et al. [2004]; (b) modified from Kalyuga et al. [1999] . . . . .	46

1.14 Four different visual composition operators (from the left): juxtaposition, superimposition, overloading, and nesting. . . . .	50
2.1 Diagram of considerations for our dashboard design process. . . . .	65
2.2 Initial dashboard design sketch (top) and implementation (bottom). . . . .	72
2.3 A second iteration of the sketched design (top) and the implementation (bottom). . . . .	74
3.1 Grammar of Graphics Diagram of Wickham and Wilkinson's work	89
3.2 Grammar of Graphics Diagram of Wickham and Wilkinson's work	89
3.3 An example of how the retina signals the visual cortex . . . . .	95
3.4 Working Memory Model created by Baddeley (left) and Information Processing Model created by Atkinson and Shiffrin (right) . .	103
3.5 Working Memory Model created by Baddeley (left) and Information Processing Model created by Atkinson and Shiffrin (right) . .	103

## List of Tables

## Chapter 1

### Introduction

Statisticians use graphs in almost every stage of their work. They create charts to summarize and explore new data and identify potential problems and opportunities. Models are fit based on relationships between variables which are often identified visually. We identify problems with those models based on residual plots and other visual diagnostics. When our modeling work has been completed, we present our results to interested parties using visual displays, because non-statisticians often find it easier to understand data and models through an intuitive visual medium rather than through the mathematical formulae which underlie the statistical work.

Given the wide range of uses for graphs and visual data displays in statistical modeling, it is unsurprising that some graphs are more useful for specific applications, such as exploratory analysis, and are unsuitable for other applications, such as presenting to an outside group. In addition, not all visual displays have equal perceptual value Aspíllaga (1996). The best graphics are designed to account for both the dataset and the intended audience's features. Some design constraints stem from limitations of the human perceptual system and are common to most potential consumers of the visualization. For

example, the sine illusion affects anyone with binocular depth perception, and color recommendations are built around the specific characteristics of the human retina (VanderPlas & Hofmann, 2015b). Other design constraints are due to the audience’s experience level and if they are used to working with data and understand specialized techniques (e.g., enough familiarity with principal component analysis such that a plot of factor loadings might be useful). Do they understand specialized techniques such as principal component analysis to the point where a plot of factor loadings might be a useful visual display? When we create visualizations for public consumption, we have to consider both perceptual factors and the target audience’s domain knowledge. This introduction presents previous research on constructing interactive and static visual displays for different audiences and the implications of this research when designing interactive data displays such as dashboards.

Most research in statistical graphics has been done on static graphics; usually, research also strips away all but the most essential contextual information, sacrificing external validity for statistical control. As a result, it can be hard to generalize this research to practical applications, where the contextual information surrounding the data is critical and the chart does not just exist in a vacuum.

In the real world, however, conventions and familiarity often win out over best practice validated by perceptual experiments. For example, in sports, many coaches desire printable diagrams containing all necessary and valuable information on a single page. As data in sports becomes more prominent, extensive, and collected, this information must be refined.

Dashboards have seen a significant increase in day-to-day usage as a potent

data visualization and decision-making tool. The proliferation of dashboards can be attributed to several factors, including the growing availability of data from various sources and the increasing need for organizations to extract actionable insights. Steven Few found that the widespread use of dashboards is attributable to their capacity to present key performance indicators and relevant metrics in a visually appealing and easily digestible format, (Few, 2006a). Moreover, technological advancements and the development of user-friendly dashboard platforms have facilitated the creation and effective utilization of dashboards by individuals from diverse fields. Dashboards have revolutionized data analysis and presentation, allowing users to gain valuable insights and make data-driven decisions more effectively.

Thus, in addition to the experimental evidence, we must consider the human element: how to introduce new graphical concepts to stakeholders, and the considerations involved in encouraging stakeholders to adopt these improved graphics. Let us first consider the audience characteristics that affect the selection of graphics. Then, we will engage with considerations based on the data to be displayed. Finally, we will consider the interactions between the audience and the data: how graphics are tested, amended, and hopefully eventually adopted into common use.

## **1.1 Perceptual and Cognitive Process of Graph Perception**

Several factors influence an individual's ability to read and engage with data visualizations, including perception, attention, and expertise.

Perception and attention are crucial cognitive processes that allow users

to interpret and make sense of data visualizations. Perception refers to the manner in which we interpret and organize sensory information from our environment, whereas attention refers to the capacity to selectively focus on particular aspects of this information (McCallum, n.d.). Expectations of perception and attention are important in data visualization interactions, however expertise is the in-depth knowledge and skills that come from having a lot of experience and learning over a long period of time.

In addition to perception and focus, domain-specific knowledge is essential for understanding and interacting with data visualizations. Expertise in a particular field can enable individuals to better interpret and comprehend the significance of the presented data, as well as identify potential biases or errors in the visualization. Thus, the ability to perceive and interact with data visualizations requires a combination of perceptual and attentional processes, as well as domain-specific knowledge, to interpret and comprehend the presented information. This suggests that data visualization involves the misuse of human visual perception in the visual presentation of data. Assigning meaning to visualization is not a statistical or computational step but a cognitive one. Each step in the data analysis process is part of a more extensive mental process of constructing meaning with important cognitive-based concepts.

Studying cognitive science, human-computer interaction, and statistical graphics reveals fascinating connections and interdependencies that must be thoroughly investigated. The cognitive theory of working memory clarifies the mechanisms underlying our capacity to store and manipulate information temporarily. Expertise in long-term memory, on the other hand, sheds light on how our knowledge and experiences shape our cognitive processes. Atten-

tion concepts such as feature integration theory investigate how attention is directed and how the brain integrates various features into a coherent perceptual experience. The Gestalt principles illustrate the fundamental means by which we organize and perceive visual information. Statistical graphics and dashboard design bring together data visualization techniques, empowering effective communication and decision-making through meaningful visual representations. Ultimately, this knowledge paves the way for creating more effective and impactful interactions between humans and technology in our increasingly information-rich world.

### 1.1.1 Visual System

Perception can be understood at the biology level through sensory systems and their corresponding neural mechanisms. The retina is a multi-layered sensory tissue that lines the back of the eye and acts as the interface of input light and visual perception. The retina is the primary function that captures the photons and convert those photons into electrical impulses that travel along the optic nerve to the brain where they turned into images. The transduction of sensory stimuli into neural signals is a crucial aspect of perception. Each sensory modality, including sight, hearing, and touch, has specialized receptors that convert physical stimuli into electrical signals that the brain can interpret. For example, in vision, light enters the eye. It activates photoreceptor cells in the retina, initiating a cascade of neural signals transmitted to the brain's visual cortex via the optical nerve, ?? (Hubel & Wiesel, 2004).

Human perception is an essential component of data visualization that can significantly enhance both the content and quantity of displayed informa-

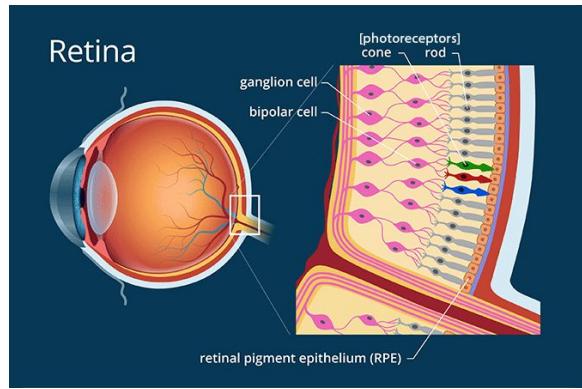


Figure 1.1: An example of how the retina signals the visual cortex

tion, (Ware, 2012). Perception refers to the organization, interpretation, and conscious experience of sensory data. Perception is also defined as “the process of recognizing (being aware of), organizing (gathering and storing), and interpreting (binding to knowledge) sensory information,” (Ward, Grinstein, & Keim, 2010). Ward et al. explain the notion of perception as the following, “The brain makes assumptions about the world to overcome the inherent ambiguity in all sensory data, and in response to the task at hand.”

Human visual perception is a highly complex and subjective process, and the efficacy of a visualization in communicating objective understanding depends on a vast array of subtle factors, (Reuter, Tukey, Maloney, Pani, & Smith, 1990). Furthermore, certain situations present unique challenges and lead to systematic errors; can these provide insight into how the brain solves the problem of which objects are represented by which images in general (Gregory, 1968).

The principles of eye-tracking involve the investigation of eye movements and fixations during visual perception. Eye-tracking technology permits researchers to monitor and record where individuals look and how their gaze traverses a visual scene. This data can be utilized to analyze patterns of

attention, gaze behavior, and the sequence of fixations. The principles of eye-tracking provide valuable information regarding how individuals allocate their attention, which elements attract their gaze, and how they visually explore and process information.

Gestalt principles, on the other hand, examine how humans perceive and organize visual elements into meaningful patterns and wholes. These principles originated in the field of Gestalt psychology, which emphasized that perception is influenced by the arrangement and grouping of its constituent parts. The Gestalt principles of proximity, similarity, closure, and continuity describe how our brains organize visual stimuli to form coherent and meaningful perceptions.

Eye-tracking provides objective data on how individuals visually interact with a stimulus, revealing attention patterns and fixation sequences. This data can be used to determine how individuals explore and process visual data over time.

Eye-tracking and Gestalt principles together contribute to our understanding of visual perception. Eye-tracking provides empirical data on eye movements and attention, whereas Gestalt principles provide frameworks for comprehending the organization and interpretation of visual stimuli. By combining these methodologies, researchers can better understand how humans perceive and interpret the visual world.

The F-pattern theory is founded on the observation that website visitors frequently scan content in a “F” shape. When interacting with text-heavy pages, such as articles or search engine results, this pattern is prevalent. The F-pattern suggests that users should initially scan horizontally across the top of the page (forming the top bar of the F), then move down slightly and scan

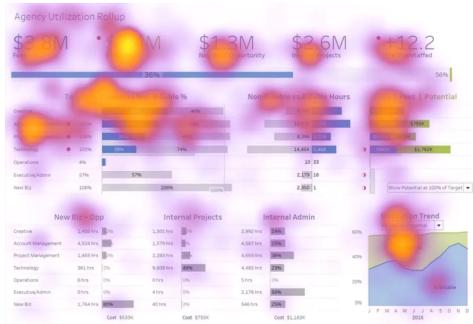


Figure 1.2: Example of eyetracking using noting the F-pattern reading flow on dashbaords used in a white paper written by Amy Albert with Tableau

horizontally across a shorter line (forming the middle bar of the F), and finally scan vertically along the left side of the page (forming the vertical bar of the F), (Nielsen, 2006).

As demonstrated by figure ??, (Alberts, 2019) provides F-pattern reading flow support. The highlighted areas indicate where the user's attention was drawn. The users began with the top-left corner, scanned the first line with KPIs (big font attracted the attention), moved to the second line, scanned each chart (colors attracted the attention), and only glanced briefly at the last line to focus more on the last chart (colors also attracted the attention).

The Z-pattern theory is another commonly observed eye-tracking pattern when users interact with webpage content. This pattern is better suited for pages with more visual elements, such as landing pages and ad layouts. In the Z-pattern, users scan horizontally across the top of the page (from left to right), then move diagonally to the left (forming the first diagonal of the Z), and finally scan horizontally across the bottom of the page (from left to right), (Nielsen, 1997).

Figure ??,(Alberts, 2019), has less content density and supports a Z-pattern reading flow in which users begin in the upper-left corner and zigzag

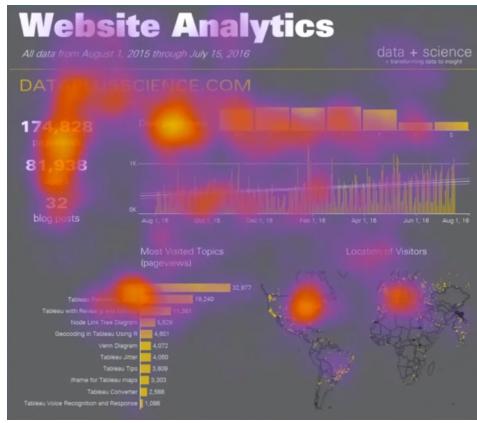


Figure 1.3: Example of eyetracking using noting the Z-pattern reading flow on dashboards used in a white paper written by Amy Albert with Tableau

to the bottom. Users only viewed the title briefly, most likely because it is brief and large, making it easy to read quickly.

Examining the Gestalt principles, which describe how our brain organizes and interprets sensory information to form coherent patterns and objects, is one way to gain a deeper understanding of how this particular perception functions.

### 1.1.2 Gestalt Principles

Visual interpretation describes how humans perceive the world and its objects as organized, regular, and simple shapes, schemas, figures, or forms. The theory of Gestalt has philosophical and psychological roots that date back to the late 1800s.

Gestalt principles describe how humans perceive and organize visual information into meaningful patterns and structures to help the brain to effectively process and organize incoming visual information, making it easier to attend to and remember. Gestalt principles are grounded in cognitive psychology and address how the human brain processes visual information. Gestalt ther-

Gestalt psychology is founded on the notion that overall perception is contingent upon the interaction of numerous factors. These principles include proximity, similarity, closure, continuity, symmetry, and figure-ground relationships formally outlined in “Principles of Gestalt Psychology”, (Koffka, 2013).

Gestalt principles include:

- Proximity: Objects close to each other are perceived as related or grouped.
- Similarity: Objects that are similar in some way (e.g., shape, color, size) are perceived as related or grouped.
- Continuation: The human eye follows lines and patterns, so designers can use this principle to guide the viewer’s gaze through a display.
- Closure: The human brain tends to complete incomplete figures or patterns, so designers can use this principle to create the illusion of missing information.
- Figure-Ground: The human brain separates the foreground (figure) from the background (ground), so designers can use this principle to create visual hierarchy and emphasis.
- Contrast: The human eye is drawn to high-contrast areas, so designers can use this principle to create emphasis and hierarchy.
- Symmetry and Balance: The human eye finds symmetry and balance visually pleasing, so designers can use this principle to create a sense of harmony and order.

By applying these principles to dashboard design, designers can create visual arrangements that make it easier for viewers to understand the relationships between data elements.

## Gestalt's Principles of Visual Perception

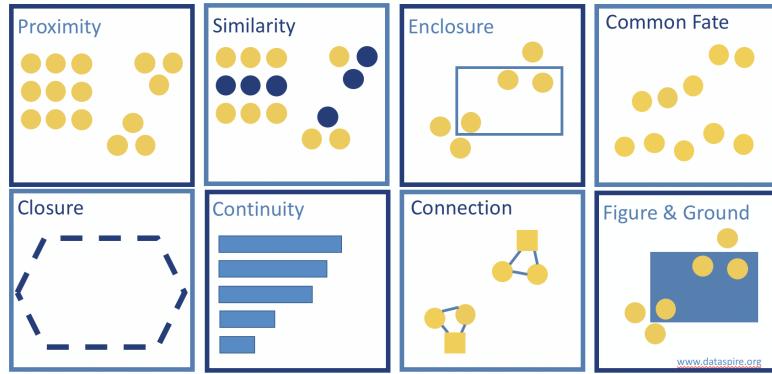


Figure 1.4: Gestalt Principles with Examples

ships between data elements. For example, proximity can be used to group related elements together, while symmetry can be used to create balance and harmony in the overall layout of the dashboard. At its most basic, the entire form is perceived (or emerges to our visual pathways) as opposed to its component parts, seen in the following figure xxx provided by (EVALUATION LLC, n.d.).

This suggests that our brains frequently perceive things differently than what is present. For example, optical illusions or the “gorilla in the crowd” experiment show that we do not always process everything in our visual field because there is too much information for our brains to process. We organize the world according to Gestalt principles and pre-attentive attributes so that it is familiar, makes sense, and is easy to process. These principles guide how people perceive and make sense of the world around them, and they play a critical role in designing effective visual displays, such as dashboards. Understanding Gestalt principles can also illuminate how information is processed and stored in short-term memory and attention’s critical role in this process.

Perceptual grouping is a fundamental process in visual perception that involves organizing individual graphical elements into coherent perceptual units based on their inherent properties and spatial relationships. It helps us make sense of the complex visual world by grouping elements that belong to the same object or structure and separating elements that belong to different entities. Gestalt psychologists have extensively studied the concept of perceptual grouping, proposing principles such as proximity, similarity, closure, and continuity as grouping's underlying mechanisms. These principles govern our perception of objects, edges, contours, and patterns, enabling us to perceive organized and meaningful visual information ((Wertheimer, 1938), (Wagemans et al., 2012), (Palmer, 2002)).

Figure xxx shows that the perceptual grouping introduced by (Palmer, 2002), focuses on proximity, similar size, similar orientation, and common region concepts that will directly impact dashboard design through the lenses of the user. Perceptual grouping introduced by (Palmer, 2002), focuses on the proximity, similar size, similar orientation, and common region concepts that will directly impact dashboard design through the lenses of the user.

The proximity principle states that elements occupying close spatial proximity are perceived as belonging. Gestalt psychologists emphasized this principle when they argued that nearby elements are more likely to be grouped (WERTHEIMER, 1923). Due to the proximity of a series of dots arranged in a line, we perceive them as a single line rather than individual dots.

The principle of similar size states that perceptually similar-sized elements are grouped. This principle is based on the observation that similar-sized objects or elements are typically perceived as belonging to the same group.

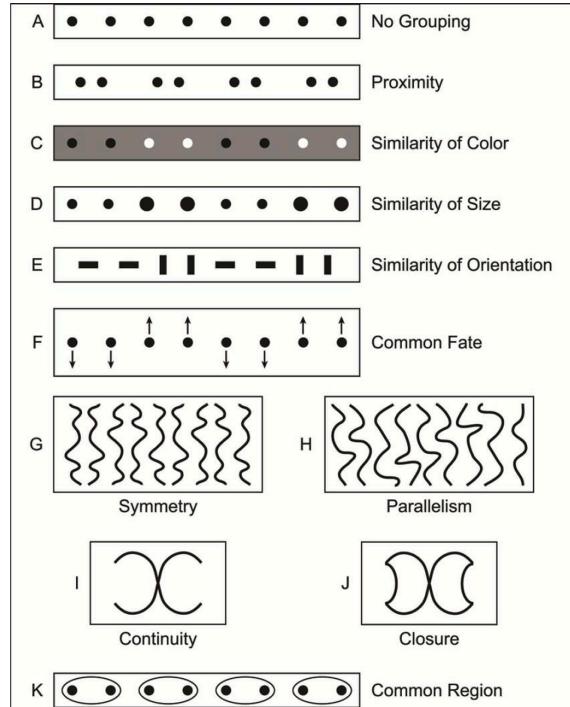


Figure 1.5: Perceptual Grouping illustrated by Stephen E. Palmer in 2002

For example, when we see a collection of circles of varying sizes, we tend to perceive those with similar dimensions as belonging to the same group and those with distinct sizes as distinct entities.

According to the principle of similar orientation, elements with relative orientations or directions are grouped. This principle proposes that elements with similar orientations are perceived as constituting a coherent pattern or object. For instance, when we see lines arranged at various angles, we tend to group lines with similar orientations, such as horizontal or vertical lines.

The principle of common region states that elements that share a boundary or area should be grouped. This principle states that elements within the same enclosed space are perceived as a unit. For instance, we perceive a collection of dots arranged in a circle as a single entity due to the shared region they

occupy.

### 1.1.3 Role of Attention and F.I.T. (Feature Integration Theory)

Starting with Wertheimer's experiments on the perception of motion, he examined the phenomenon of apparent motion, which refers to the perception of motion when successive stationary stimuli are presented. Wertheimer investigated the principles underlying the perception of motion and provided insights into the Gestalt principles of visual perception by conducting a series of perceptual experiments.

(Wertheimer, 1912) investigated the phi motion, a type of motion in which the rapid presentation of two stationary stimuli creates the perception of movement. By manipulating the temporal and spatial arrangement of stimuli systematically, Wertheimer was able to identify critical factors that influenced the perception of motion. His experiments revealed that motion perception results from the interaction between sensory input and perceptual organization processes.

The work of Wertheimer emphasized the significance of perceptual grouping principles, such as proximity and similarity, in the perception of motion. He hypothesized that the visual system tends to group stimuli that are close in space or have similar properties, resulting in the perception of a continuous and smooth motion between them. The results of Wertheimer's experiments on the perception of motion were instrumental in developing Gestalt psychology, which emphasized the significance of holistic and organized perceptual experiences. Wertheimer's work influenced our understanding of how the brain processes visual information to create motion perception by laying

the groundwork for subsequent studies on motion perception.

According to (Goldstein & Cacciamani, 2021), preattentive processing automatically extracts and analyzes basic features such as color, shape, orientation, and motion. These features are processed in parallel across the visual field, allowing for the rapid detection and identification of salient environmental stimuli. Preattentive processing occurs effortlessly and outside conscious awareness, laying the foundation for subsequent attentional selection and more elaborate perceptual processing.

The theories of Goldstein emphasize the significance of preattentive processes in various perceptual domains. For instance, he discusses the preattentive analysis of visual features such as color and orientation, which contribute to the visual perception of objects, scenes, and graphic patterns. In the auditory domain, preattentive processes automatically extract basic acoustic features like pitch and loudness. This makes it easier to find the source of sounds and tell them apart.

By examining preattentive processing, Goldstein's theories provide a framework for comprehending the initial stages of sensory processing and the automatic extraction of fundamental perceptual features. These theories have significant implications for understanding how automatic and controlled processes shape perception.

Visual attention is defined as “the process of allocating cognitive resources to specific regions or features of the visual input based on their relevance and salience,” (A. M. Treisman & Gelade, 1980) and (Itti & Koch, 2001).

The famous experiment in optical illusion, “Gorilla in the Midst” or “Invisible Gorilla” video, which was utilized in a well-known 1999 study conducted

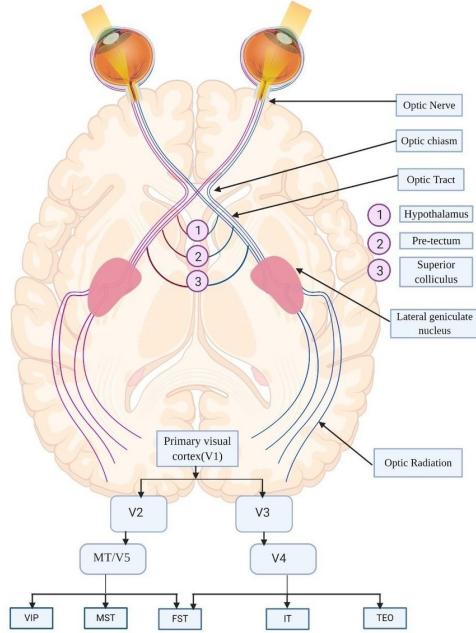


Figure 1.6: Visual Attention can be represented by the following

by Daniel Simons and Christopher Chabris (Scot Covey & Simons, n.d.). The video aims to demonstrate a phenomenon known as “inattentional blindness” and highlight some visual attention principles.

Short-term memory (STM), also known as working memory, is the stage of temporary storage and processing where most memory retention effort is expended. According to Alan Baddeley’s Working memory: Theories, models, and controversies, STM is a limited-capacity system prone to interference and decay, (A. Baddeley, 2012). Selective attention is essential for the maintenance of STM because it allows us to filter out irrelevant information and concentrate on what is essential, (Cowan, 2001).

Visual aids such as charts and diagrams can improve short-term memory by allowing us to encode and retain information more effectively, (Alvarez & Cavanagh, 2004). Utilizing visual aids such as charts can enhance our short-term memory by . Furthermore, annotations can also help aid short-term

memory. By adding annotations, such as notes or highlights, to information we are trying to remember, we can improve our recall of the information later on, (Alvarez & Cavanagh, 2004).

According to the Feature Integration Theory (FIT), STM is composed of two stages: pre-attentive processing and focused attention (A. Treisman, 1998). Parallel and independently, the brain processes the physical characteristics of an object, such as its color, shape, and orientation, during pre-attentive processing. However, focused attention is required to bind these features into a coherent object representation in STM. STM can be improved through various strategies, such as rehearsal, chunking, and elaboration (Oberauer, 2009). For example, by repeating a phone number several times or breaking it down into chunks of two or three digits, we can increase the likelihood of it being stored in STM. Similarly, by elaborating on the information we want to remember, such as creating mental associations or visual images, we can enhance its retention in STM (Bui & Myerson, 2014).

STM is a dynamic and malleable cognitive system that is crucial to our daily lives. Understanding the mechanisms underlying STM and how to improve it can have significant implications for learning, memory, and the treatment of memory disorders. By analyzing the relationship between attention and working memory, we can gain insight into how we construct meaning from the information in our environment.

#### **1.1.4 Top-Down vs. Bottom-Up (Constructing Meaning)**

Gestalt psychology indicates that humans actively construct meaning by organizing information into patterns and wholes (Wertheimer, 1938). Both

top-down and bottom-up processing are involved in the process of meaning construction. Bottom-up processing entails analyzing sensory data from the environment and constructing perceptions based on this data. Top-down processing reflects the influence of prior knowledge, expectations, and context on the perception and interpretation of incoming sensory data.

Together, top-down and bottom-up processing facilitate the encoding and retrieval of information from STM. Selective attention, which is the ability to focus on relevant information while ignoring irrelevant information, is an example of top-down processing that aids in the encoding and retrieval of information in STM (Cowan, 2010).

According to FIT, perceiving objects involves both the bottom-up analysis of individual features and the top-down processing of higher-level features in order to form a complete perception (A. M. Treisman & Gelade, 1980).

The Gestalt principles of perception address how humans construct meaning from sensory data through both bottom-up and top-down processing. Both types of processing are involved in encoding and retrieving information, which has significant implications for understanding the mechanisms of STM.

These principles guide how people perceive and make sense of the world around them, and they play a critical role in designing effective visual displays, such as dashboards. Understanding the Gestalt principles can also cast light on how information is processed and stored in short-term memory and attention's critical role in this process.

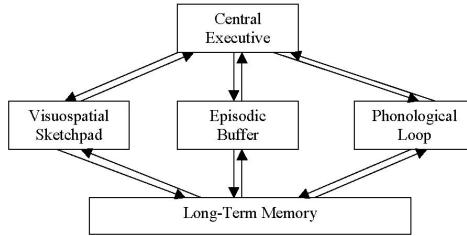


Figure 1.7: Working Memory Model created by Baddeley (left) and Information Processing Model created by Atkinson and Shiffrin (right)

### 1.1.5 Working Memory (Why can't I remember someone's phone number?)

Baddeley expanded our understanding of working memory by emphasizing its active processing nature, expanding upon the model of Atkinson and Shiffrin's Information Model developed in the 1968, which emphasizes the process of encoding, storage, and retrieval. Unless actively practiced, short-term memory has a limited capacity and a short duration of retention. If information is deemed significant or sufficiently rehearsed, it can be encoded and transferred to long-term memory, which has an almost unlimited capacity and long-term storage. The influential model developed by Baddeley, known as the working memory model, proposed a more complex structure with multiple components, (Baddeley Alan D., 1976).

The Baddeley Memory Model is an updated and influential model of working memory. It includes the phonological loop (maintenance of verbal information), the visuospatial sketchpad (maintenance of visual and spatial information), the central executive (attentional control), and the episodic buffer (integrated storage). Together, these components facilitate the active processing and temporary storage of data in working memory.

Visual and spatial information is processed and temporarily stored in the

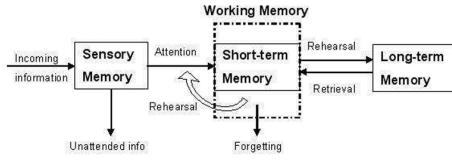


Figure 1.8: Working Memory Model created by Baddeley (left) and Information Processing Model created by Atkinson and Shiffrin (right)

visuospatial sketchpad when individuals view statistical graphics. The central executive component facilitates the interpretation and analysis of the presented data by directing attention to pertinent aspects of the graphic. Utilizing working memory resources effectively can aid in comprehending and remembering the statistical information conveyed by the graphics.

Together, Baddeley's model of working memory provided a comprehensive framework for studying memory and cognition. They contributed to the understanding of how information is processed, encoded, stored, and retrieved in human memory systems, laying the groundwork for subsequent research and theories in cognitive psychology.

### 1.1.6 Role of Expertise

However, creating effective graphics is not a simple task, and proficiency in this area is required to create high-quality visualizations. In the upcoming sections, contributions made to the field of graphics by research on psychological processes, automaticity, readily available information, and practice effects are described.

The first concept - **cognitive processes** in the long-term memory (LTM) process are defined as the way we think about and approach a task. As we become more proficient in a particular skill, we develop more complex and effi-

cient mental models or schemata, a heuristic technique to encode and retrieve memories, the majority of typical situations do not require much strenuous processing. These mental models help us to organize information in a meaningful way, and to quickly identify and solve problems related to the task. This process is known as cognitive restructuring and is facilitated by developing domain-specific knowledge (Ericsson & Lehmann, 1996). For example, a basketball coach is able to quickly recognize patterns and positions on a court that are common in basketball to do so we can mentally visualizing the arrangement and relationships between teams in a scatter plot, individuals are able to encode the spatial patterns and interpret the data points and relationships later.

The second concept - **Automaticity** in the LTM process can be defined based on the ability to perform a task without conscious effort or attention. It occurs when a particular task or piece of information has been repeatedly practiced and encoded to the point where it is readily accessible and automatic (Anderson, 1992). While the concept of automaticity may not be directly related to statistical graphics, it can have an impact on how individuals interpret and process statistical information presented in graphics. As our proficiency in a task increases, our performance becomes more automatic, thereby freeing up cognitive resources for other tasks. The development of procedural knowledge, which is the ability to perform a series of steps or actions in a particular order, facilitates this process (Fitts & Posner, 1967). For example, a well-trained quarterback can throw a ball without looking at the wide receiver because their throwing movements have become automatic. In this case, the hypothesis testing will be the probability that the wide receiver will always be there

80% of the time when not being defended by a safety or cornerback.

The degree to which statistical concepts and procedures are automated can affect how individuals interact with statistical graphics. Those who have a deep understanding of, say, hypothesis testing or statistical significance may apply these concepts automatically when analyzing data presented in a graph. This automated application of statistical principles can influence their perception of the data and guide their decision-making processes.

The third concept - **Information Readily Available** is defined by how we process information related to a task in the LTM process. As our proficiency increases, we can recognize and retrieve pertinent information more rapidly and precisely than a novice. This is made possible by the creation of domain-specific knowledge structures that allow us to retrieve pertinent information from memory quickly (Chase & Simon, 1973). Statistical graphics are often presented in specific contexts, such as scientific research, business reports, or news articles. LTM contains a wealth of contextual knowledge that can be drawn upon to better understand and interpret the statistical graphics within their specific domains. Contextual knowledge can help individuals connect the presented information to real-world scenarios, evaluate the credibility of the data, and make informed decisions based on the graphics. For example, a medical expert can quickly identify signs and diagnose a patient using their knowledge of disease symptoms and risk factors.

The fourth concept - **Practice effects** effects are the improvements in performance that result from repeated practice. The most gains generally occur at the outset of a new practice, but the gains gradually diminish as the individual approaches their performance ceiling (Anderson, 1982). Procedural

knowledge and automaticity, which allow for more efficient and accurate task performance, facilitate practice effects. When statistical graphics are used alongside explanations and discussions of statistical concepts, repeated exposure to these graphics strengthens the retention of the underlying statistical principles. Repetitive interaction with statistical graphics aids in the retention of concepts like distributions, central tendencies, variability, and correlations. This practice effect in LTM facilitates statistical knowledge integration and its application to data analysis and decision-making.

The contributions of research on psychological processes, automaticity, readily available information, and practice effects to the field of graphics have significant implications. Expertise is required to create high-quality graphics, which requires a thorough understanding of design principles and the capacity to work quickly and efficiently. The use of automatic processing and domain-specific knowledge can aid designers in processing and deciding on design elements efficiently and quickly. The creation of standardized design templates, workflows, and other tools can aid in enhancing the efficiency and effectiveness of the design process. Design skills can be improved through deliberate guidelines, and educators must focus on developing skills that can be applied in a variety of contexts.

As the significance of graphics in numerous fields continues to rise, the demand for specialists in this area will only intensify. By comprehending the contributions of research on psychological processes, automaticity, readily accessible information, and practice effects, designers, educators, and trainers can develop more effective approaches to graphics design and education. This can help ensure that the graphics used to convey complex information are

clear, concise, and effective, making it easier for individuals to comprehend and interpret the required information.

### **1.1.7 Engagement with the data**

The goal of data analysis is to extract meaningful insights, patterns, and knowledge from data. The process of data analysis involves collecting, cleaning, transforming, and modeling data, followed by the use of statistical and machine learning methods to uncover patterns and relationships within the data. The end goal of data analysis is to support decision making and provide a basis for informed action. Data analysis can help organizations to better understand their customers, market trends, and operational performance. Additionally, data analysis can support scientific research by helping researchers to test hypotheses, develop theories, and gain a deeper understanding of complex phenomena. Ultimately, data analysis aims to turn data into actionable insights and information that can inform and improve decision-making.

## **1.2 Data Considerations**

John Tukey was the first to organize the collection and methods associated with philosophy into Exploratory Data Analysis (EDA). Previous research by Tukey focused on graphics as a tool for exploratory analysis. In “Exploratory Data Analysis,” Tukey wrote that graphics and charts often display data with more enhanced understanding than a table, (Tukey & Wilk, 1966). Tukey outlines detailed the types of different graphics and in which situations to utilize these graphics. He was a strong advocate for the importance of EDA as a crucial first step in the data analysis process and emphasized the need for visu-

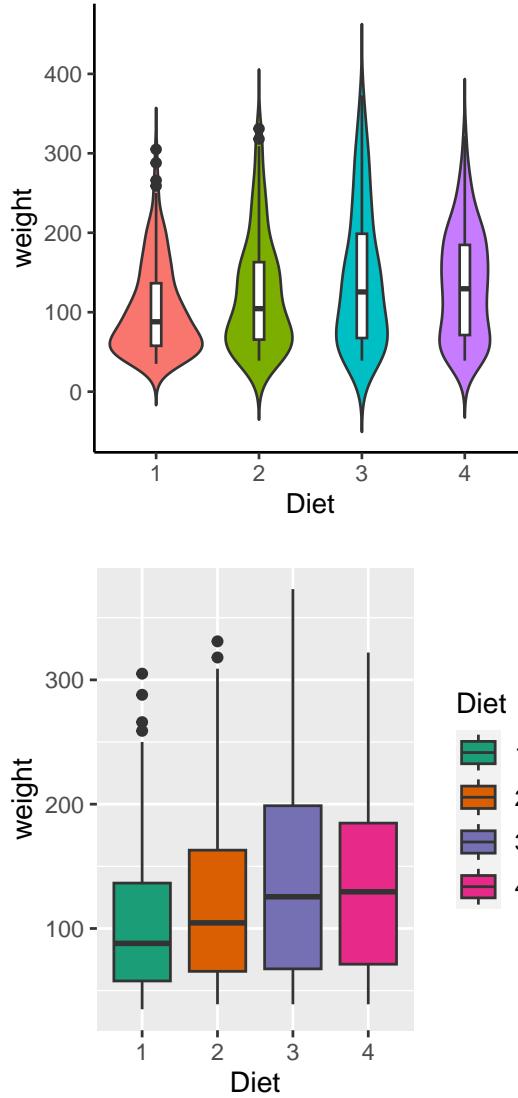
alization and interactive techniques to understand patterns and relationships in data.

Tukey's Principles of EDA have become a cornerstone in the field of statistics and have been adopted by data professionals in various industries. Tukey's principles have enabled data professionals to understand complex data sets better and make more informed decisions by emphasizing the importance of visual exploration, data characterization, and model critique. In this way, Tukey's Principles have revolutionized our data analysis approach and become the foundational framework for EDA.

Tukey's Principles in EDA:

1. Graphical exploration, looking for patterns or displaying fit, the method demonstrates things about data that a single numeric metric does not understand. This has been useful in graphing the data before you develop summary statistics.
2. Describing the general patterns of the data. This step should be insensitive to outliers. In general, think about the types of resistant measures (i.e., median or mean). This step is making sure to determine data patterns.
3. The natural scale/state that the data are at their best. This will be the step at which the scale of data can be helpful for analysis. The reexpressing data to a new scale by taking the square root or logarithmic scale.
4. The mostly known parts of EDA but is done in the way of assessing fit of the data. This is taught in every statistics 101 class. The growth of

machine learning and prediction methods have now used residuals more in the toolbox to assessing the best prediction models.



Data visualizations are an integral part of the EDA process, enabling analysts to discern patterns and relationships in the data that would otherwise be difficult to discern from tabular data alone. Through data visualization, analysts can quickly identify trends, outliers, and other patterns that may be missed through numerical analysis alone. Moreover, visualizations facilitate

the communication of findings to non-technical stakeholders, allowing them to comprehend complex data sets more efficiently. Through visualizations, analysts can also identify potential issues or biases in the data, resulting in better decisions and models. Thus, visualizations play a crucial role in the EDA process by enabling analysts to more effectively explore, comprehend, and communicate data-derived insights. During the initial EDA stage, an analyst may find that a variable or a covariate is directly related to the dependent variable when looking at a correlation heatmap or a scatterplot. The basic understanding can be formalized to visualize the discovery process.

The field of graphical communication, which is directly related to EDA, semiology, and their use in touch, has been a valuable tool and extension of the EDA thoughts that Tukey expressed. One of the fundamental principles of semiology is the relationship between signifier and signified, in which a visual element (the signifier) represents a particular meaning or concept (the signified), (**barthes1972?**). Another essential concept in semiology is using syntax and semantics to convey meaning in graphic communication effectively. This includes both the syntax and semantics of a graphic's visual elements, (Monmonier, 1985).

Using color to represent data on maps is an example of successful graphical communication utilizing semiology. By using different colors to represent different data points, viewers can comprehend patterns and relationships in the data quickly and easily. Jacques Bertin writes in “Semiology of Graphics” that color can be used to “emphasize a point, distinguish one category from another, or establish a relationship between two points”, (Monmonier, 1985). In addition, Bertin explains that the use of color can help overcome language

barriers, making it easier for the audience to comprehend the presented information.

The application of semiology in graphical communication is not devoid of obstacles. One difficulty is the possibility of misinterpretation, in which viewers may assign a different meaning to a visual element than was intended, (Monmonier, 1985). Another concern is the possibility of cultural differences in interpretation, in which a visual element may have a different meaning in one culture versus another, (Norman, 2013).

Despite these obstacles, semiology in graphical communication remains an indispensable tool for effectively conveying information. By understanding semiology principles and syntax and semantics' role in graphical communication, designers can create compelling visual representations that convey information clearly and concisely.

By utilizing visual elements such as bars and lines to represent data, graphs can make complex information more understandable to viewers. For instance, a line graph can be used to illustrate the change in the value of a stock over time, making it easier for investors to identify trends and patterns. Leland Wilkinson writes in his book “The Grammar of Graphics” that “graphical methods are not only superior to other forms of communication, but also superior to numerical or verbal methods for certain types of data and reasoning,” (Wilkinson, 2012).

It proposes that any statistical graphic can be broken down into a set of essential components, or “grammar,” that can be combined in different ways to create a wide range of visualizations, following a layered approach to describe and construct visualizations or graphics in a structured manner.

The components of the grammar of graphics include:

- Data: The raw data being visualized represents a set of observations or values.
- Aesthetic Mappings: The mapping of data variables to visual properties such as position, color, shape, and size.
- Scales: The mapping of data values to visual values, such as mapping a numerical value to a bar height.
- Geometries: The basic shapes representing the data, such as points, lines, bars, and histograms.
- Facets: The plot division into multiple subplots, each representing a different subset of the data.

For example, a bar chart can be created by mapping a categorical variable to the x-axis, mapping a numerical variable to bar heights, and using rectangular bars as the geometry. Moreover, mapping two numerical variables can create a scatter plot to the x and y positions and use points as the geometry. Finally, the “Grammar of Graphics” provides a systematic way of thinking about visualizations, making it easier to choose the appropriate visual representation for a given dataset.

Michael Friendly, a leading expert in data visualization, has utilized the principles of the grammar of graphics to develop innovative teaching methods that make complex data visualization concepts more accessible to a broader audience. Friendly has investigated the origins and development of graphic techniques, tracing their evolution from antiquity to the present. He used

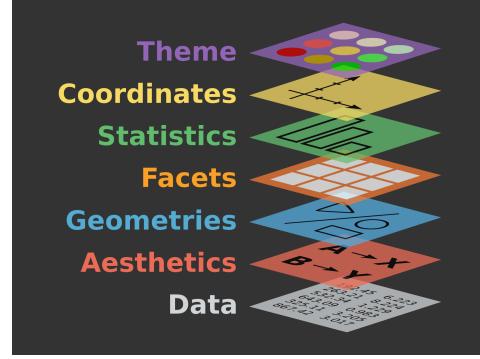


Figure 1.9: Grammar of Graphics Diagram of Wickham and Wilkinson’s work

VERB      NOUN      ADJECTIVE

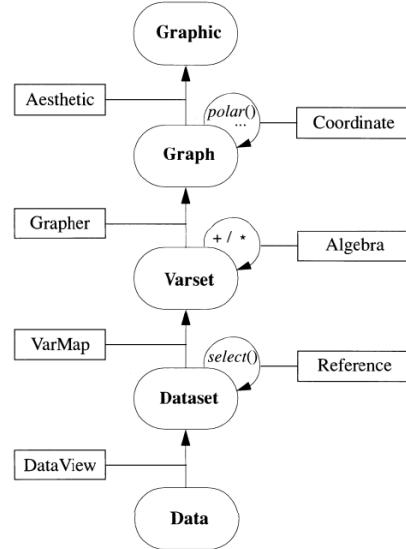


Figure 1.10: Grammar of Graphics Diagram of Wickham and Wilkinson’s work

SAS with hands-on experiments to present categorical data analysis visually, Friendly (2014). By emphasizing the role of graphical methods in scientific discovery, Friendly has helped promote his use in various disciplines, from the natural sciences to the social sciences and beyond. In his book “Milestones in the History of Thematic Cartography, Statistical Graphics, and Data Visualization,” Friendly provides a comprehensive overview of the key milestones in the evolution of statistical graphics, including the contributions of pioneers

like William Playfair, Charles Minard, and John Tukey, (Friendly & Denis, 2001).

As discussed regarding semiology, Tukey's Exploratory Data Analysis (EDA), and the introduction of the Grammar of Graphics, we should be mindful that a well-constructed graphic can be misleading out of context. Compelling graphics can be a powerful tool for communicating complex information, making numerical accuracy, engagement, correct decision-making, and accurate predictions crucial.

In the context of data visualization, numerical accuracy refers to the precision and correctness of the numerical data displayed in graphics. Accurate graphics can assist users in comprehending complex numerical data and making more informed decisions, Cardoso, Leite, & Aquino (2016).

Engagement in the context of data visualization is the extent to which viewers are drawn to and interested in the displayed data. Engaging graphics can encourage users to interact with and explore data further, resulting in a more thorough comprehension of the data.

Correct decision making refers to the capacity of data visualization to enable users to make informed and precise decisions based on the presented information. Clear, accurate, and well-designed graphics can help users recognize patterns and insights, resulting in more effective decision making.

Correct predictions refers to the capability of graphics to accurately forecast or predict future events or outcomes. For accurate predictions, data visualization must include trustworthy data, sound statistical models, and efficient visualization techniques.

“Graphical Tests for Power Comparison of Competing Designs” by Hofmann et al. presents a graphical method for comparing the power of two or more competing designs in an experimental study (Hofmann, Follett, Majumder, & Cook, 2012). The article demonstrates that the graphical method is a useful tool for comparing the effectiveness of various experimental designs. It enables researchers to visualize and compare the effectiveness of different designs in an intuitive and straightforward manner.

Two methods for measuring the particle size distribution in a chemical process were compared in one study. The study evaluated both designs under various operating conditions and compared their power using a graphical method. The results demonstrated that one design was more effective at detecting differences in operating conditions than another.

Static Visualization is commonly used in the communication phase of data science workflows, and data scientists sometimes use them as part of the analysis. John Tukey’s EDA methods are currently known and well-vetted in the field. However, Satyanarayan et al. addressed this by introducing a high-level grammar of graphics called “Vega-Lite,” which presents a set of standardized linguistic rules for producing interactive information visualizations using a concise JSON format for data to be represented by the grammar (Satyanarayan, Moritz, Wongsuphasawat, & Heer, 2016). Vega-Lite has been directly implemented in R via the `ggvis` package using the same - albeit slightly lower-level.

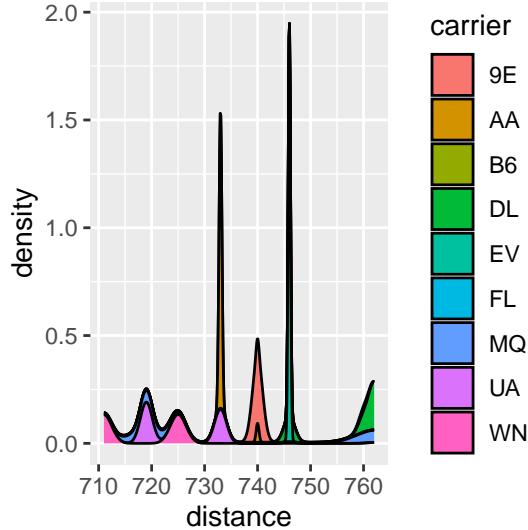
Understanding cognitive load is crucial for designing compelling data visualizations, as it influences how users perceive, process, and remember the data presented in the visualization. When designing visuals, it is essential to consider the cognitive load they may place on the viewer. Cognitive load is the

amount of mental effort required to process information, and minimizing it can enhance a graphic's effectiveness. In addition, displaying as much raw data as possible while minimizing cognitive load can improve the graphic's clarity and precision. Here are some general guidelines for making better graphics with works from Few (**few2012?**), Tufte (**tufte1983?**), and Cairo (Cairo, 2016):

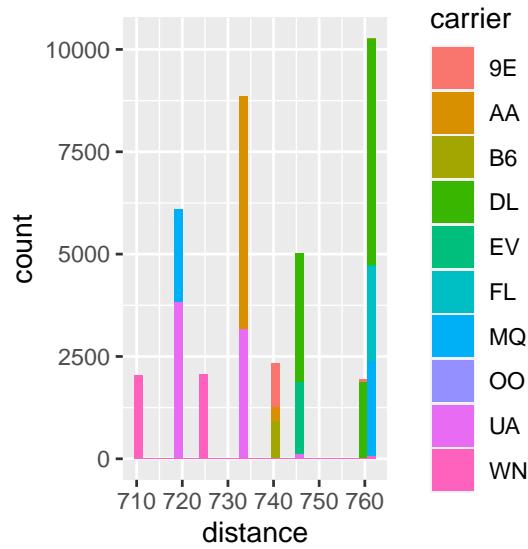
1. Keep it simple - Avoid overwhelming the viewer with too much information at once by employing a clear and concise design with minimal distractions.
2. Use visual hierarchy - Utilize size, color, contrast, and placement to highlight important information and direct the viewer's focus.
3. Choose appropriate charts - Choose the chart type that best illustrates the data and facilitates comprehension.
4. Label clearly - Use labels that are clear and concise for axes, legends, and other essential information to avoid confusion.
5. Use data-to-ink ratio - Focus on the data by minimizing the amount of non-data ink, such as decorative elements or excessive grid lines.
6. Avoid distortion - Use appropriate scaling and avoid distortions to ensure that the graphics accurately represent the data.
7. Provide context - Add context to assist the viewer in comprehending the significance of the data and its relevance to the topic.

```
## Warning: Groups with fewer than two data points have been
## dropped.
```

```
## Warning: Removed 1 rows containing missing values
## (`position_stack()`).
```



```
## `stat_bin()` using `bins = 30`. Pick better value with
## `binwidth`.
```



On the other hand, Interactive graphics provide a more dynamic and engaging way to explore and analyze complex data sets than traditional static visualizations. By allowing users to manipulate and explore data in real-time,

interactive graphics can reveal hidden patterns and relationships that may be difficult to discern in static visualizations, making them a valuable tool for data analysis.

#### 1.2.0.1 Interactive Graphics

As previously mentioned, theories behind visual representation include - graphical comprehension (Cleveland & McGill, 1984), preattentive processing (Ware, 2012), gestalt theory (Few, 2009), and graphical excellence (Edward R. Tufte, 2001). Interactive graphics offer a number of advantages when analyzing complex data sets, and technological progress has played a crucial role in making these tools more accessible and widely adopted, especially in interactive graphics. Compared to static visualizations, interactive graphics offer a more engaging and dynamic way to explore and analyze complex data sets. To gain a deeper understanding of the data, users are able to modify parameters, zoom in on specific regions, and rapidly explore various variables. In addition, interactive graphics offer a more intuitive method of communicating findings to non-technical users, making them a valuable asset for data-driven decision making. Interactive graphics are excellent for EDA; they are designed for exploring rather than presenting information (and more) and can be obtained by directly querying the graphic, Unwin et al. (2003). Overall, interactive graphics are a potent data analysis tool, allowing analysts to gain a deeper understanding of complex data sets and to make more informed decisions.

The area of interactive graphics is still very much a work in progress despite existing as a field of research since the late 1960s. Developments are driven partly by new technology, such as d3 (Bostock, Ogievetsky, & Heer, 2011).

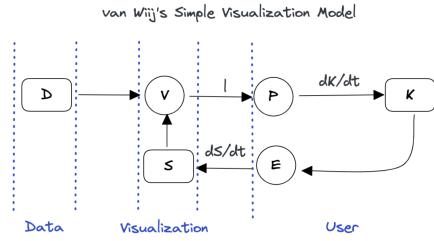


Figure 1.11: van Wijj Simple Visualization Model

Visualizations are more than just a picture. They are now a tool that facilitates analytic activity through different modes of interaction (Yi, Kang, Stasko, & Jacko, 2007). Visualization is context-free, as it can mean different things to different people depending on the situation (Parsons & Sedig, 2014).

In recent years, interactive graphics that enable users to manipulate and explore visualizations in real-time have grown in popularity and align with the van Wijk Simple Visualization Model framework. The van Wijk Simple Visualization Model is a diagrammatic representation that provides a simple and effective way to understand and visualize the flow of information and data through a system. van Wijj's simple visualization model shows how insights are generated as the human participates in a feedback loop between reading and interacting with visualization, (Van Wijk, 2005). It is a commonly used tool in EDA, the initial step in the data analysis. The van Wijk model can represent data flow from data sources, through intermediate processing stages, to the final visualization of results. This model is also context-free, allowing for the focus to be on the feedback loops between visualization and the user. The model helps to identify the various steps involved in the visualization process, from the collection and processing of data to the presentation of results. By doing so, it supports the design of more effective and user-friendly visualizations, which can enhance the overall user experience.

While the van Wijk Simple Visualization Model provides a valuable framework for designing compelling visualizations, it should not be used in isolation. Instead, effective data visualization requires a thorough understanding of human perception, cognition, and Human-Computer Interaction (HCI) principles. Later in this review, we will explore the fundamental principles of Human-Computer Interaction and how they can be applied to the design of compelling interactive graphics.

Based on the above best practices on the concept of cognitive load in graphics, the theory of manipulation of visualizations provides a set of guidelines and best practices for designing interactive graphics that minimize cognitive load and facilitate practical data analysis.

As interactive visualizations play a more significant role in information systems, designers must know what tasks, visual representations, and interaction techniques are available and how they work to facilitate analytical reasoning. They must decide on the most effective visual representation without being able to estimate every user's ability to read and interpret the visualization.

An influential framework developed by Vessey et al refers to the degree to which a person's cognitive abilities match the cognitive demands of a task, (Vessey & Galletta, 1991), in the field of cognitive load research has been improved by Heer and Bostock, providing examined how the complexity of interactive visualizations influences users' cognitive load, (Heer & Bostock, 2010). The authors discovered that more intricate visualizations tend to increase cognitive load, especially for users with lower visual literacy. They recommended that designers consider the cognitive load of interactive visualizations and strive to reduce complexity whenever possible.

While the direct relationship to traditional mobile devices, such as phone screens, will not be discussed, it is noteworthy to account for the impact of larger screen mobile devices, such as iPads and other portable devices, concerning a user's cognitive abilities. Eissele et al investigated the cognitive load of mobile interactive visualizations, (Eissele, Weiskopf, & Ertl, 2009). The authors discovered that the limited input options and small screen size of mobile devices can increase cognitive load in interactive visualizations. To reduce cognitive load on mobile devices, they suggested that designers employ suitable visual encoding techniques and simplify interactions.

Lastly, Toyama et al. investigated the impact of interactive elements on cognitive load in visualizations, (Toyama, Sonntag, Orlosky, & Kiyokawa, 2015). Based on the nature of the task and the user's familiarity with the interactive features, the authors discovered that interactive features can both increase and decrease cognitive load. They suggested that designers should evaluate the cognitive load caused by the interactive elements they include in visualizations

These studies suggest that designers should carefully consider the cognitive load implications of interactive graphics and strive, whenever possible, to reduce complexity. Simplifying interactions and implementing suitable visual encoding techniques can reduce cognitive load, especially on mobile devices. In addition, designers should evaluate the cognitive load caused by the interactive features they include in visualizations.

## 1.3 Audience-Data Interactions

Effective design of interactive graphics necessitates a comprehensive knowledge of Human-Computer Interaction (HCI) and User Experience (UX) design principles to ensure that the visualizations are engaging, informative, intuitive, and user-friendly.

Designing an effective interactive dashboard involves much more than simply selecting a set of visualizations and arranging them on a page. It requires a comprehensive knowledge of Human-Computer Interaction (HCI) and User Experience (UX) design principles and the ability to apply these principles to data analysis and visualization. Before designing an interactive dashboard, it is crucial to have a thorough understanding of the underlying HCI and UX frameworks and the specific needs and preferences of the intended audience. By understanding the principles of HCI and UX design, it is possible to create interactive dashboards that facilitate effective data analysis and offer a seamless and engaging user experience. This can result in greater engagement with the data, more profound insights, and better-informed decisions.

### 1.3.1 Human-Computer Interaction (HCI)

Human-Computer Interaction (HCI) refers to the study of the interaction between humans and computers. It encompasses the design, evaluation, and implementation of computer systems that are intuitive, efficient, and effective to use.

In the 1970s and 1980s, HCI researchers began to concentrate on developing user interface design theories and methodologies. The “GOMS” model, created by Card, Moran, and Newell in 1983, was an influential framework

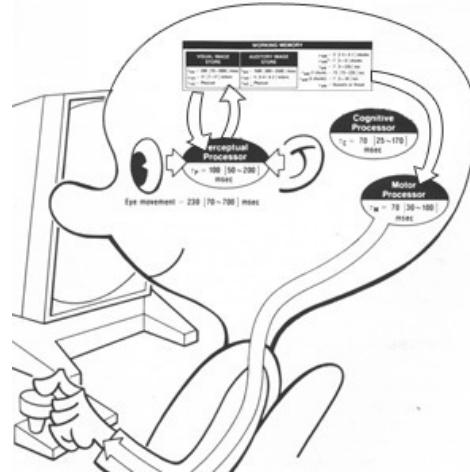


Figure 1.12: GOMS Model created by Card Moran and Newell

that provided a way to model user behavior when interacting with computer systems, (S. Card, Moran, & Newell, 1983). During this time, the field of usability engineering emerged, which involved designing and testing interfaces to ensure that they were user-friendly and efficient.

The 1990s witnessed a significant rise in the popularity and accessibility of personal computers, as well as the emergence of the World Wide Web as the dominant information-sharing platform. This resulted in an emphasis on designing interfaces for web-based applications and research into the usability of websites. In 1995, Don Norman published his influential book “The Design of Everyday Things,” emphasizing the importance of designing intuitive and user-friendly products and interfaces (revisited and revised in 2013, (Norman, 2013)). His influential book examines the principles of user-centered design and the critical role that psychology plays in shaping user experiences. It emphasizes the significance of user-friendly and intuitive designs in everyday objects.

In the 2000s, HCI research expanded to include new technologies such as

mobile devices, touchscreens, and virtual and augmented reality, O'Brien & Toms (2008). There was also an increased focus on designing interfaces for diverse user populations, including people with disabilities and older adults.

HCI research evolves and adapts to new technologies and user requirements. The use of artificial intelligence and machine learning in interface design, designing interfaces for wearable devices, and designing interfaces for social and collaborative systems are some current research areas.

### **1.3.2 User Experience (UX)**

The history of UX can be traced back to the early days of human-computer interaction (HCI) research, but it has evolved to become a distinct discipline in its own right. User Experience (UX) refers to the overall interaction between a user and a product or service. It includes the interface, functionality, content, and aesthetics.

The origins of user experience research can be traced back to the 1970s and 1980s. At this time, researchers were primarily focused on developing efficient and effective user interface design theories and methodologies. As computer use became more prevalent in the 1990s, the emphasis shifted to designing interfaces that were not only functional but also enjoyable to use. In his influential 1995 book, “The Design of Everyday Things,” Donald Norman argued that good design should center on the needs and behaviors of the user. Jesse James Garrett coined the term “user experience design” in 2000 to describe the process of designing intuitive, efficient, and enjoyable user interfaces, Garrett (2003). The rise of mobile devices in the late 2000s and early 2010s presented UX designers with new challenges and opportunities.

As users began interacting with devices featuring smaller screens and touch-based interfaces, designers were forced to reevaluate traditional interface design principles and adopt new interaction paradigms, (Hassenzahl, 2010).

Alan Cooper's "The Inmates Are Running the Asylum" - Cooper discusses the significance of user-centered design and the challenges and opportunities in the software design field in this book. He advocates placing the needs and objectives of users at the forefront of the design process, (Cooper, 1999). "About Face: The Essentials of Interaction Design" - This comprehensive guide covers interaction design principles, methods, and best practices. It provides designers with useful insights and real-world examples to assist them in developing effective and engaging user experiences, (Cooper, Reimann, Cronin, & Noessel, 2014).

Dan Saffer's "Designing for Interaction: Creating Smart Applications and Clever Devices" delves into the history and evolution of interaction design and offers practical advice for creating meaningful user experiences. The book examines a variety of design strategies and techniques for designing interactive applications and devices, (Saffer, 2007).

"A Project Guide to UX Design: For User Experience Designers in the Field or in the Making" by Russ Unger and Carolyn Chandler provides step-by-step approaches, techniques, and examples for the entire UX design process. It is intended for both seasoned designers and newcomers to the field, (Chandler & Unger, 2012).

"Information Architecture: For the Web and Beyond" by Louis Rosenfeld and Peter Morville focuses on the optimal organization of information for online and offline user experiences. It investigates the principles and methods

of information architecture as well as its influence on user-centered design, (Morville, Rosenfeld, & Arango, 2015).

Overall, understanding the design principles of UX and HCI and the importance of testing static graphics can significantly inform the design of interactive dashboards, as we will explore in more detail later in this review.

### 1.3.3 UX and Cognitive Load

Since 1980s, cognitive load theory (CLT) of Human-Computer Interaction (HCI) was developed by cognitive psychologist John Sweller. The primary focus of Sweller's research was on learning and the cognitive processes underlying the acquisition of new knowledge and skills.

The evolution of CLT was influenced by a number of fundamental concepts and theories. Information processing theory, which posits that individuals process information sequentially using sensory memory, working memory, and long-term memory, was one of the major influences. Sweller's research extended this theory by highlighting the limitations of working memory and its role in cognitive load, (Sweller & Chandler, 1994). In addition, CLT distinguished between intrinsic, extraneous, and relevant cognitive load. The intrinsic load of a task is its inherent complexity, which cannot be altered by the interface design. On the other hand, the extraneous load is the cognitive load imposed by the design of the learning environment or interface, which can be reduced through practical methods. Finally, germane load refers to the cognitive effort required for learning and acquiring knowledge, (Hollender, Hofmann, Deneke, & Schmitz, 2010).

The original purpose of CLT was to improve instructional design and learn-

ing outcomes by minimizing irrelevant cognitive load and optimizing relevant cognitive load. However, its principles and concepts have been applied to the field of HCI, recognizing the significance of cognitive load in the design of interactive systems and user interfaces.

The cognitive load theory of HCI illuminates human-computer interaction cognitive processes. By comprehending the cognitive load imposed by interfaces and learning environments, designers can create more efficient and user-friendly systems that maximize users' mental resources. CLT has continued to evolve and inform interface design over time, improving HCI's usability, user experience, and cognitive support.

Both CLT and HCI were based on the same theories of cognition. Both emphasized the reduction of unnecessary cognitive load. With the concept of germane cognitive load, CLT incorporated principles to promote germane learning processes, which may result in a rise in cognitive load.

In relation to Cognitive Load Theory (CLT), the split-attention principle addresses the negative effects of dividing a learner's attention between multiple sources of information during learning tasks. The split-attention principle focuses specifically on reducing extraneous cognitive load, which refers to cognitive processing that does not contribute directly to learning, (Nielsen, 1994).

Because the goal of instructional design should be to present information in an integrated and coherent manner to reduce the effect of divided attention. This can be accomplished by spatially aligning relevant text and visuals, such as by placing labels near the corresponding elements in a diagram or by employing captions to provide explanations directly alongside visual representations. The split-attention principle optimizes cognitive resources for

learning tasks by reducing the necessity for learners to mentally integrate distinct sources of information.

#### **1.3.4 Infomation Search Enviroment**

In the article, “Web Designers and web users: Influence of the ergonomic quality of the web site on the information search,” written by Aline Chevalier and Maud Kicka outline investigate the difficulties of web designers or compare their respective activities, Chevalier & Kicka (2006). The two experimental studies presented in this article compare the strategies developed by professional web designers and (novice versus experienced) web users while searching for information on websites with varying ergonomic qualities. The results of the two experiments, that web designers are incapable of predicting the strategies of novice users and do not behave like novices. Therefore, techniques for assisting web designers in developing a user-centered activity are required, and a few of these techniques are suggested at the conclusion of this article.

In the article, “Predicting graph reading performance: a cognitive approach, by Huang, Hong, and Eades outlines that performance and preference metrics are frequently employed in evaluating visualization techniques, (Huang, Hong, & Eades, 2006). To introduce a cognitive method for assessing the effectiveness and efficiency of visualization. Huang et al. propose a model of user performance, mental effort, and cognitive load (memory demand) and incorporate additional mental effort and visualization efficiency measures into our analysis.

Huang et al. build on the understanding that Richard Atkinson and

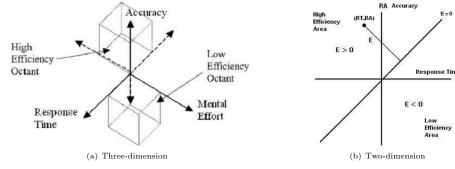


Figure 1.13: Multi-dimensional visualization efficiency (a) modified from Tuovinen et al. [2004]; (b) modified from Kalyuga et al. [1999]

Richard Shiffrin, wrote the information processing model of memory.

Measuring Visualization Efficiency can be calculated using the method proposed in 2004 to measure the relative effectiveness of various instructional conditions, Tuovinen & Paas (2004). This method relates mental effort to performance measures within the context of visualization efficiency, which is defined as the ratio of cognitive cost (in this study, mental effort and response time) to response accuracy

The efficiency ( $E$ ) is calculated by converting mental effort (ME), response time (RT) and accuracy (RA) into z-scores, and combining them using the following formula:

$$E = \frac{RA - ME - RT}{\sqrt{3}}$$

where  $E$  of zero means that cognitive cost and performance accuracy are balanced.

### 1.3.5 Chart Coordination/Viusal Linking

Visual Linking, also known as visual connections or coordinated views, refers to establishing relationships or connections between various visual representations or charts within a data visualization system. Visual linking enables

users to explore and analyze data by making it easier to identify patterns, trends, and correlations across multiple charts or views. The goal of visual linking is to enable users to explore and analyze data by facilitating the identification of patterns, trends, and correlations across multiple charts or views.

“Snap-together visualization: A user interface for coordinating visualizations via relational schemata” is a research paper by Chris North and Ben Shneiderman, (North & Shneiderman, 2000). The paper introduces the concept of a user interface called Snap-Together Visualization (STV) that facilitates the coordination of multiple visualizations using relational schemata. The STV system enables users to create, modify, and manipulate relational schemata, thereby enabling coordinated interactions between visualizations. Users can link multiple views by specifying data attributes or values that serve as connection points between the visualizations. They illustrate how users can create meaningful connections between visualizations in order to gain insights, compare data across different views, and discover relationships that may not be apparent in individual visualizations.

“A framework for unifying presentation space” is a research paper by Melanie Tory and Colin Swindells, (Carpendale & Montagnese, 2001). The paper presents a framework that seeks to unify the presentation space in visualizations, thereby facilitating the coordination of multiple visual representations. The framework highlights the significance of integrating various visualization components into a cohesive and coordinated presentation. It addresses the difficulties associated with managing the spatial arrangement and interaction of different visual elements within a visualization system. They illustrate how the framework can be utilized to create coordinated views, manage inter-

actions, and provide users with a unified visual experience.

The research paper titled “Software Design Patterns for Information Visualization” was written by Jeffrey Heer and Maneesh Agrawala, (Heer & Agrawala, 2006). Specifically tailored software design patterns for information visualization systems are introduced in this paper. The authors propose a set of design patterns to improve the development of interactive visualizations and address common challenges. Information visualization emphasizes the importance of adopting well-established software design principles. It discusses the advantages of employing design patterns, which are reusable solutions to common design problems, to improve visualization systems’ adaptability, scalability, and maintainability.

Among the design patterns discussed in the paper are the following:

**Marks** pattern focuses on the visual representation of data items, including points, lines, and bars. It discusses techniques for rendering and interacting with marks efficiently.

**Layout** pattern addresses the organization of visual elements in the visualization space. It investigates various strategies for organizing and positioning visual elements to maximize screen real estate.

**Axes** pattern addresses the presentation of axes and scales in order to provide context and reference for interpreting visualizations. It discusses various labeling, formatting, and scaling strategies for axes.

**Interaction** pattern addresses techniques for enabling user interactions and exploration in visualizations. It examines techniques such as brushing and linking, direct manipulation, and coordinated views to facilitate data analysis

and exploration.

**View Coordination** pattern focuses on connecting multiple views or visualizations to facilitate coordinated analysis. It discusses techniques for visual linking and synchronization that permit users to establish connections between distinct views.

“Exploring the design space of composite visualization” is a research paper by Waqas Javed and Niklas Elmqvist, (Javed & Elmqvist, 2012). This paper examines the concept of composite visualization, which combines multiple interconnected visualizations to support complex data exploration tasks. The authors discuss the design space of composite visualization, which encompasses multiple facets of effectively creating and employing multiple linked visualizations. They investigate various methods for designing and arranging visualizations, such as juxtaposition, superposition, and overlay.

The article highlights the concept composite visualization initially introduced by Card et al., (S. K. Card, Mackinlay, & Shneiderman, 1999)’s pipeline concepts:

- visual structure: the mapping from data to visual form (i.e., the result of a visualization technique);
- view: the physical display space (typically 2D) in which a visual structure is rendered.

CVV (Composite Visualization View) design patterns refer to reusable solutions or approaches for designing composite visualizations, which involve combining multiple linked visualizations into a cohesive and interactive whole.

$$\mathbf{A} \otimes_{\text{jux}} \mathbf{B} = \boxed{\mathbf{AB}} \quad \mathbf{A} \otimes_{\text{sup}} \mathbf{B} = \boxed{\mathbf{AB}} \quad \mathbf{A} \otimes_{\text{ov}} \mathbf{B} = \boxed{\mathbf{AB}} \quad \mathbf{A} \otimes_{\text{nd}} \mathbf{B} = \boxed{\mathbf{A} \square \mathbf{B}}$$

Figure 1.14: Four different visual composition operators (from the left): juxtaposition, superimposition, overloading, andnesting.

The method for visual composition is an emerging theme in the literature on composite visualizations. In other words, the various compositions of two visualizations A and B in the same visual space appear to be a useful organizing principle in this domain. Based on the literature, we derive the four visual compositions that give rise to four broad categories for composing visualizations, which we refer to as CVV design patterns:

- Juxtaposition: Placing visualizations side-by-side in one view, (Roberts, 2007);
- Superimposition: Over laying two visualizations in a single view;
- Overloading: Utilizing the space of one visualization for another;
- Nesting: Nesting the contents of one visualization in side another visualization; and
- Integration: Placing visualizations in the same view with visual links.

### 1.3.6 Testing static graphics

While understanding HCI and UX design principles helps create compelling interactive graphics, it is equally important to rigorously test and evaluate the usability and efficacy of both interactive and static graphics to ensure they achieve their intended purpose. Kosara highlighted the significance of user testing in identifying potential problems in static visualizations,

(Kosara, 2007). User testing aids in comprehending the users' behavior and perceptions of the visualization, thereby facilitating the identification of issues that designers may have overlooked. User testing also identifies the graphic's confusing or ineffective visual aspects, allowing designers to refine the design and increase its effectiveness.

The evolution of testing static graphics has progressed through several chronological moments, each building on the knowledge and techniques of the past, starting with the thoughts of Cleveland and McGill to Hofmann, who explored the statistical testing of categorical data.

Firstly, Cleveland and McGill investigated the effect of various bar chart designs on the accuracy with which viewers perform simple perceptual tasks Cleveland & McGill (1986). People perform significantly worse on stacked bar charts than on simple bar charts, and bar charts with filled bars are generally superior to those with empty ones.

“The cognitive style of PowerPoint: Pitching out corrupts within” examined the effect of static graphics, such as bar charts, line charts, and pie charts, on the comprehension and decision-making of viewers, (Edward R. Tufte, 2008). The results indicated that the bar chart was most effective at accurately communicating information, while the pie chart was least effective. In addition, the researchers discovered that the type of graphic employed influenced the viewers’ perceptions and decision-making, highlighting the significance of selecting the most appropriate graphics when conveying information.

“Using color to code different types of uncertainty in visualization,” investigated the effect of color on the communication effectiveness of static graphics Ware (2010). Researchers discovered that the use of color in static graphics

enhanced viewers' comprehension and memory retention of the presented information. Specifically, it was determined that the use of color to highlight particular data points or trends in a graph or chart was particularly effective.

"Communicating Uncertainty: A Look at Graphical Representations of Error Bars, Box Plots, and Confidence Intervals" examined the efficacy of static graphics in communicating data uncertainty and variability (**wainer2020?**). Researchers discovered that static graphics, such as boxplots and error bars, effectively communicated the range and variability of data. Furthermore, the use of static graphics enhanced viewers' comprehension and decision-making in uncertain situations.

Overall, these above studies indicate that static graphics effectively convey information to viewers. Nonetheless, their effectiveness is influenced by the type of graphic exercised, the use of color, and their capacity to express uncertainty and variability in data. It is essential to note that the effectiveness of static graphics can also be affected by audience knowledge and experience, the complexity of the presented information, and the context in which the graphics are used.

### **1.3.7 Testing interactive graphics**

The significance of testing and evaluating static graphics to ensure their effectiveness and user-friendliness naturally segues into the similar, yet distinct challenge of evaluating interactive graphics

The design space of interactive visualizations, including the use of multiple views and coordinated various perspectives, is discussed in a paper by Heer and Bostock Heer & Shneiderman (2012). The authors argue that interactive visu-

alizations can enhance comprehension and decision-making by enabling users to investigate complex data and the relationships between multiple variables. It was discovered that interactive graphics are beneficial for investigating data that is difficult to comprehend with static graphics, such as time series data or data with multiple aggregation levels.

Compared to static graphics, interactive graphics can improve users' ability to identify patterns and outliers in data, according to a second study, ([wu2017?](#)). This is because interactive graphics enable users to zero in on particular aspects of the data and adjust the visualization in real-time to reveal hidden patterns.

It has also been discovered that interactive graphics increase user engagement with data and improve their decision-making abilities. Moreover, interactive graphics can help users identify potential biases or errors in their data analysis by allowing them to rapidly explore various visualizations and test their hypotheses.

In addition to their benefits for data exploration and analysis, interactive graphics have been found to be more engaging and enjoyable for users (Eppler & Bresciani, 2013). This can increase the motivation of users to explore and analyze data, resulting in better decision-making.

In summary, the studies highlighted indicate that interactive graphics can be an effective data visualization and analysis tool, especially for complex and multidimensional data. They can improve users' comprehension, engagement, and decision-making skills, and are ideal for examining data that is difficult to comprehend with static graphics.

## 1.4 Dashboard Design

Given that the intended audience has limitations, there are design constraints around the data, and the ability of the audience to successfully use the graphical displays of the data, what can we take from this body of research that applies to more complicated sets of graphics? How do we maintain user attention, desire to explore, and accurately communicate the data through the medium of an interactive data dashboard? Solutions to these questions can start with a dashboard.

A dashboard is a visual display of the essential information needed to achieve one or more objectives, consolidated and arranged on a single screen so the data can be monitored at a glance (Few, 2006a). Dashboards have particular characteristics:

- Achieve specific objectives
- Fits on a single computer screen
- Information can be displayed in multiple mediums (web browser or mobile device)
- Can be used to monitor information at a high level

Dashboards can present various statistical data, such as financial performance, website traffic, or customer engagement metrics. They allow users to quickly and easily understand complex data sets using visual elements such as charts, graphs, and tables to display the information. Additionally, statistics can be used to analyze data presented on a dashboard, providing insights into trends and patterns that can inform decision-making.

While a dashboard can be handy, it may be worth describing that a poorly designed dashboard will not be used. A dashboard should be concise, clear, and intuitive when displaying components in combination with a customized list of requirements of users.

Much of the work done within statistical research and dashboard design involves collaboration with other researchers and users. While this may be the best for the growth of the discipline, one will find that working with collaborators with non-STEM backgrounds. Dashboards can help understand and support many data types in essential business objectives. There are many different ways to label and utilize dashboards in different kinds.

Dashboards are cognitive tools that should be used to improve understanding of data, which should help people visually find relationships, trends, patterns, and outliers. Most importantly, dashboards should leverage people's visual cognitive capabilities.

These principles are based on cognitive psychology and understanding how the human brain processes visual information. By applying these principles to dashboard design, designers can create visual arrangements that make it easier for viewers to understand the relationships between data elements. For example, proximity can be used to group related elements together, while symmetry can be used to create balance and harmony in the overall layout of the dashboard. At its most basic, the entire form is perceived (or emerges to our visual pathways) as opposed to its component parts.

Cowan suggested that the average person can only hold two to six pieces of information in their attention, (Cowan, 2001). People can develop detailed understandings of reality, which is infinitely complex.

It is important to consider how users construct mental models of the presented data and information. Researchers have introduced cognitive structures consisting of mental models and their relationships (Rumelhart & Ortony, 1976), (Carley & Palmquist, 1992); (**jonassen1996?**). In cognitive psychology, a schema is a mental model representing a person's general knowledge or expectations regarding a particular concept or situation. Schemas are organized into semantic networks based on their relationships to other schemas [Wertheimer (1938),(Rumelhart & Ortony, 1976)]. This arrangement helps the brain process its experiences instead of storing every sensory observation; the brain only needs to maintain its schemas, which are good summaries of all previous observations. Some "memories" may even be complete recreations built with a schema (Bartlett & Remembering, 1932), (Klein, Phillips, Rall, & Peluso, 2007)

Wixon introduced the concept of "contextual design" as a systems development method in which the researcher partners with the user at the user's place of work to "develop a shared understanding" of the user's activities, and they define contextual inquiry as the first part of the broader process, (Cowan, 2001). Contextual inquiry is the data collection step of the field research element of the contextual design method, and it emphasizes four essential principles:

1. The context of the activity being performed by the user
2. The partnership between the researcher and the participant
3. The spoken verification that the investigator's interpretation of the activity matches the user's

4. The focus of the study is central to the approach taken by the interviewer

Combining two compelling graphics does not necessarily result in a successful visualization. In certain instances, suboptimal combinations can result in confusion, misinterpretation, and the failure to convey the intended message. Combining two charts with distinct scales or units is an example of suboptimal graphic design, which can result in misinterpretation and flawed comparisons. For example, if a bar chart displaying the number of sales is combined with a line chart showing revenue, meaningful comparisons between the two metrics can be challenging. According to a study conducted by Cleveland and McGill, people frequently make inaccurate judgments when comparing graphs with different scales, (Cleveland & McGill, 1984).

In addition, combining two difficult-to-compare graphics with redundant visual cues or unnecessary embellishments such as colors, 3D effects, or patterns can increase cognitive load and reduce the dashboard's effectiveness. Although adding extra elements to a chart or graph may be tempting, doing so can detract from the primary message and make it more difficult for the audience to focus on the essential information. Tufte discovered that adding unnecessary visual cues to a graph decreases its effectiveness because viewers are more likely to focus on the embellishments rather than the data, (Edward R. Tufte, 1985).

For instance, if a scatter plot and a bar chart are combined, the resulting visualization may be difficult to interpret due to the two graphics types' incompatibility. This issue was highlighted by Hullman et al., who discovered that viewers had difficulty interpreting a visualization that incorporated a scatter plot and a line chart, (Hullman, Adar, & Shah, 2011).

## 1.5 Dissertation Map

This dissertation will be constructed as follows.

Chapter 1 thoroughly reviews the literature regarding graphical and human-computer interaction/UI-UX methods. Chapter 2 will explore the process of designing dashboards for public use through parallel coordinate plots as a central component of data exploration to make decisions. Chapter 3 focuses on graphical methods for multidimensional categorical variables and visualization methods have for growth. We conclude with a Shiny application that facilitates a better understanding of the possible forms a parallel coordinate plots in exploratory data analysis can take by accommodating a thorough examination through variables and structural changes to the parallel coordinate plot with a click of a mouse. Chapter 4 further explores multidimensional categorical data visualizations and develops an approach to using parallel coordinate plots to assess predictive model. We identify visual indicators for parameters in different models and extend the connection between parallel coordinate plots of binary tables and odds ratios to include logistic regression models with categorical variables.

## 1.6 Conclusion

The lack of integration between statistical interactive graphics and Gestalt principles is a research gap in this field. Gestalt principles provide a framework for understanding how visual elements are perceived and organized in the human brain, whereas statistical interactive graphics enable the manipulation and exploration of complex data sets. This integration can result in more effective and efficient visualization tools that take human perception and

cognition into account.

In addition, there is a lack of research on the application of dashboards in visual communication. Dashboards are becoming increasingly popular to present data and information in a concise and easily accessible format. Still, there is a shortage of research on designing and employing dashboards to communicate complex data effectively.

This research seeks to bridge the gap between statistical interactive graphics, Gestalt principles, and dashboards so that users can more effectively explore complex data. This can be accomplished by designing interactive visualizations that adhere to Gestalt principles, enabling users to recognize patterns and trends in the data quickly and easily. Incorporating statistical interactive graphics into dashboards can also provide users with a more comprehensive view of the data, enabling them to make more effective data-driven decisions.

## Chapter 2

### Chapter Paper on Rural Shrink Smart Manuscript submitted to Journal of Data Science Special Issue

#### 2.1 Abstract

Many small and rural places are shrinking. Interactive dashboards are the most common use cases for data visualization and context for exploratory data tools. In our paper, we will explore the specific scope of how dashboards are used in small and rural area to empower novice analysts to make data-driven decisions. Our framework will suggest a number of research directions to better support small and rural places from shrinking using an interactive dashboard design, implementation and use for the every day analyst.

#### 2.2 Introduction

As the amount of data has increased in nearly every facet of life, the need to make sense of that data in an approachable, accessible form has become ever more important. As a result, many companies and organizations use interactive dashboards to present these data in a more useful and visually appealing form (Sarikaya, Correll, Bartram, Tory, & Fisher, 2019).

In many cases, dashboards support viewers' information processing, helping to make sense of complex data, navigate through a dataset, and supporting decision making based on the data.

Dashboards are often used, as with the car display of the same name, to provide summary information about many separate attributes of a common entity. One glance at a car's dashboard will tell you the speed, RPM, engine temperature, amount of gas in the tank; more importantly, however, the goal is not for the user to remember all of these characteristics, but to assess whether any of these quantities is outside of the expected range. Similarly, interactive dashboards for data are often used to display many different attributes and performance metrics which are of importance for stakeholders.

In this paper, we discuss the process of designing a dashboard to present publicly available government data to stakeholders in small Iowa towns to facilitate decision making and objective comparison with other similarly-situated towns.

Some communities continue to thrive as they lose population because they adapt, maintaining quality of life and community services for residents while investing in the future. This process, *smart shrinkage*, is important for rural areas who have experienced shrinking populations for decades. As small rural towns do not have access to data scientists or even the ability to easily leverage data collected locally to support decisions, our research team will provide communities with data about services in small town Iowa in order to assist with developing strategies to improve quality of life for their residents amid shrinking populations (Rural Shrink Smart Team, 2022). We hope to allow towns to explore their own data and compare to other similar towns, centering

decision-making on data in the context of small-town Iowa life.

## 2.3 Data Description

The Smart and Connected Community (SCC) dashboard data are primarily assembled from [data.iowa.gov](#) (State of Iowa, 2020), with some additional datasets assembled from federal and private sources. Most of these data sets are collected at a town/city or county spatial resolution, requiring us to carefully join data to ensure that these differences are respected while collating relevant information at the city level. In addition to the more commonly available statistics derived from e.g. the census and American Community Survey, [data.iowa.gov](#) contains several unique data sets, including local liquor sales, school building locations, town budgets and expenditures, hospital beds, Medicaid reimbursements, and other details that may provide information about local quality of life.

Data available on Iowa's data portal were augmented in some cases with higher-quality data sets in cases where the Iowa data were out of date or insufficiently accurate. Data collected from ELSI (National Center for Education Statistics, 2020) from <https://nces.ed.gov> were used to show the distance to any private or public school. The National Center for Education Statistics (NCES) is the primary federal entity for collecting and analyzing data related to education (Zarecor, Peters, & Hamideh, 2021).

Data collected from the Index of Relative Rurality (IRR) (USDA - ERS, 2020a) were used in the SCC dashboard to help classify the towns. The Index of Relative Rurality (IRR) is a continuous, threshold-free, and unit-free measure of rurality. It is an alternative to the traditional discrete threshold-based

classifications. The IRR ranges between 0 (low level of rurality, i.e., urban) and 1 (most rural). Four steps are involved in its design:

1. Identifying the dimensions of rurality: population size, density, remoteness, and built-up area.
2. Selecting measurable variables to adequately represent each dimension:
  - Size: logarithm of population size
  - Density: logarithm of population density.
  - Remoteness: network distance.
  - Built-up area: urban area (as defined by the US Census Bureau) as a percentage of total land area.
3. Re-scaling the variables onto bounded scales that range from 0 to 1.
4. Selecting a link function: unweighted average of the four re-scaled variable.

Data collected from Rural Urban Commuting Area Codes (USDA - ERS, 2020b) were used to help identify towns with commuting behaviors in our rural areas. The rural-urban commuting area (RUCA) codes classify U.S. census tracts using measures of population density, urbanization, and daily commuting. This data is on a zip code-level that will help identify those communities that commute to more urban areas. The most recent RUCA codes are based on data from the 2010 decennial census and the 2006-10 American Community Survey. The classification contains two levels. Whole numbers (1-10) delineate metropolitan, micropolitan, small town, and rural commuting areas based on the size and direction of the primary (largest) commuting flows.

One of the interesting features of this assembled data set is that missing data can be missing for multiple reasons: not all state data is complete, but data about certain services may also be missing because towns do not offer that service. Thus, in addition to the usual challenges of working with real-world data that is “messy” in a variety of ways, we also have to contend with missing data that is missing due to the size of the community or the lack of services. This makes both visualization and statistical analysis more complicated (and more interesting).

## 2.4 Dashboard Design Considerations

One problem we identified early in the process of assessing smart-shrinkage strategies in small towns is that these towns do not have the resources to make data-driven decisions. Typically, small towns in Iowa are managed by at most a few part-time employees or volunteers. In some cases, essential management functions of the town are paid, but the municipalities we are interested in do not have sufficient funding to hire professionals to gather and analyze data.

As part of a wider project investigating the strategies towns use to maintain quality of life amid shrinking population, our research team provides communities with data about their own town, but also comparable towns across the state which may have a different approach to city services. In combination with other engagement strategies that are more qualitative, we hope to use this interactive dashboard approach to assist small Iowa cities with generalizing and developing strategies to improve or maintain quality of life amid shrinking populations.

One factor at the forefront of our visualization design is the importance of

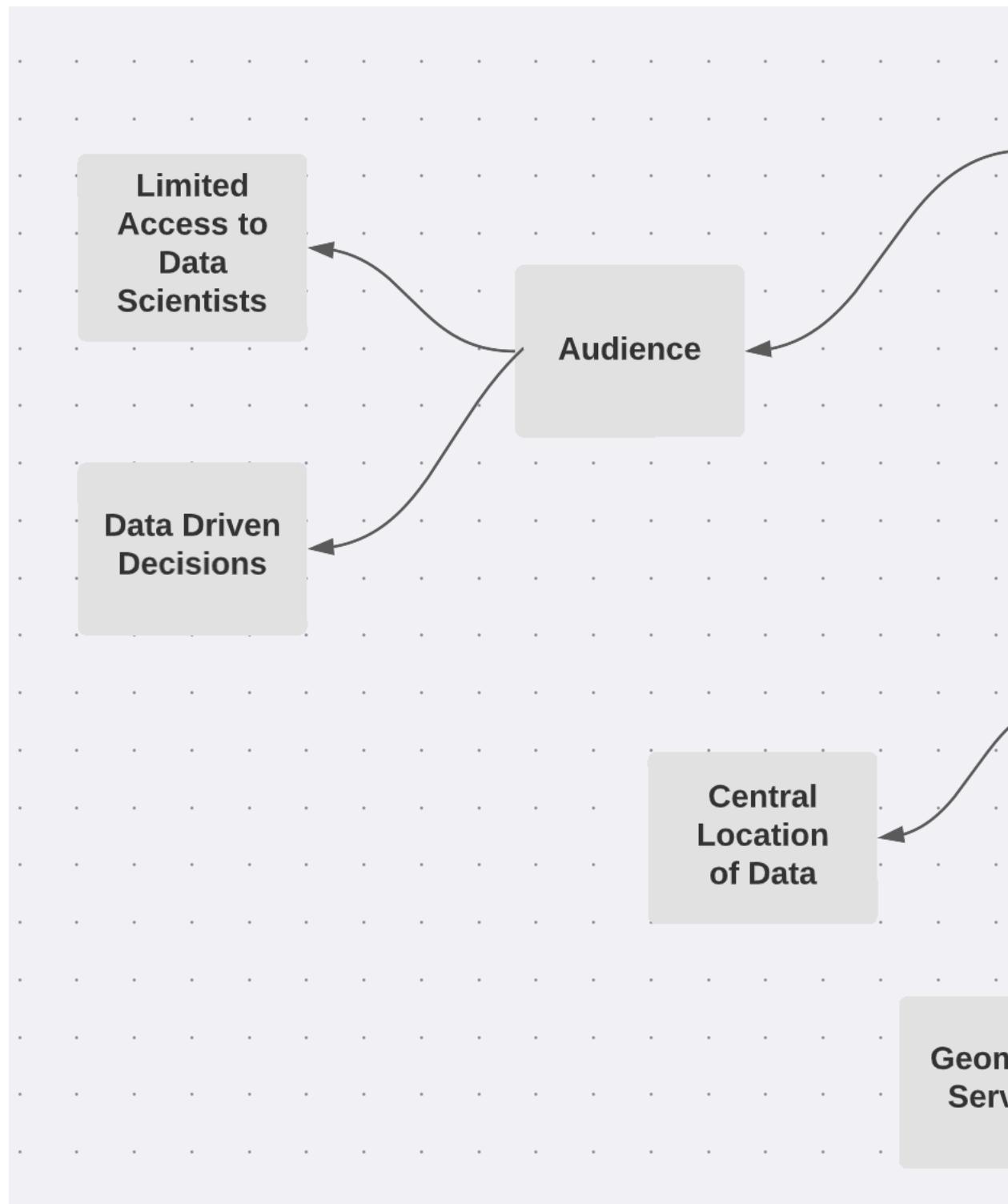


Figure 2.1: Diagram of considerations for our dashboard design process.

reducing the cognitive demands on viewers: we have assembled an incredible amount of data, and it is easy for even statisticians who deal with much larger datasets to get lost in the details of this data. At the same time, we want to invite viewers to engage with the data - to imagine, to draw comparisons, to generalize across towns, and to integrate outside information into the conclusions drawn based on the data we present. This invitation to engage with the data is similar to the approach advocated in Guided Discovery Learning, a framework leverages hints, feedback, and other helpful information to guide users in interactive exploration (DeDonno, 2016).

We expect that users will be interested in “sets” of variables from the wider dataset, which we assembled based on quality of life factors in the Iowa Small Town Poll (Peters, 2019). For instance, users might be interested in medical and social services available to residents, such as a local primary care clinic, nursing homes which are within driving distance, and the distance to the nearest emergency room; these factors might be explored separately from variables describing the services provided directly by city government, such as parks and recreation expenditures, snow removal services, and the distance to the closest fire station.

As a consequence of this massively multivariate structure, we very quickly focused on the use of parallel coordinate plots; other alternatives, such as tours (Wickham, Cook, Hofmann, & Buja, 2011), require much more sustained attention to interactive plots as well as a deeper understanding of projections in multidimensional space which we cannot assume our users will have. Introduced in the 1880s (d’Ocagne, 1885), parallel coordinate or parallel set plots feature a series of vertical axes representing different variables arranged

horizontally, with lines connecting each observation. When representing categorical data, parallel set plots may show “blocks” of data instead of individual lines, and are useful for representing conditional relationships between adjacent variables (Bendix, Kosara, & Hauser, 2005); modifications of this design, such as common-angle plots (Hofmann & Vendettuoli, 2013), address the issues which arise due to line-width illusions VanderPlas & Hofmann (2015a). Parallel coordinate plots have been generalized to allow for continuous data and additional summaries beyond individual data points, such as densities (Heinrich & Weiskopf, 2009). In this paper, we use the `ggpcp` package, which leverages the grammar-of-graphics framework introduced in Wickham (2016), allowing us to use not only parallel coordinate plots, but also to overlay other statistical summaries, such as boxplots or violin plots, to provide additional context about the marginal distributions of each variable in addition to allowing for exploration of the multivariate space.

We also anticipate that users will be interested in comparing their town to other, similar towns. We will discuss the different ways that this comparison strategy was implemented in each dashboard in the next section, which describes the evolution of the dashboard over time and accounting for feedback from users and other researchers on the wider project.

One final component of this project is that our dashboard is part of a wider effort to work with towns to understand the different strategies used to maintain resident quality of life amid shrinking populations. Thus, while the town leaders are our primary audience, we also are creating this applet for use in parallel with a team of other researchers: sociologists, economists, city planning specialists, and artists. These researchers opinions and feedback

about the dashboard are also useful and important, as they regularly work with town leaders in different capacities and have an understanding of what factors are most important to them and what types of questions these leaders may have when faced with data and unfamiliar statistical visualizations.

Throughout the design process, we will assess our visualizations to determine which strategies for user interface and interactive graphics design are most useful to empower town leaders to make discoveries in publicly available data assembled with a focus on items that impact rural quality of life.

## 2.5 Guiding Design Principles

Research on dashboard creation and interactive visualization tends to be very task-specific and hard to apply to more generalized settings. That is, it is relatively easy to create a dashboard that works for a particular task, but it is hard to generalize from that process what will work for the next dashboard. With this in mind, we set out to clearly document our intentions at each stage of the design and evaluation process, with the goal of gathering some useful information about general dashboard design from the process of creating this specific dashboard.

Thus, our initial set of dashboard design principles is as follows:

- The town leaders are the focus audience; thus, the town itself should be the central focus of the app.
- We should facilitate comparisons with other towns in order to allow the user to explore other potential solutions to offering services that enhance resident quality of life.

- We will present the user with peer comparisons in order to widen the scope of exploration beyond the initial set of obvious peers in the local region.
- We will implement feedback mechanisms that allow us to provide more detailed data and respond to feature requests to improve the dashboard design over time.

As with many dashboards, this project is under continuous development; while it makes for an unsatisfactory conclusion, we do not have a “final” dashboard design because the application will continue to evolve. However, we have some useful insights into the process of creating an application designed to invite users to explore a large and complex dataset that we believe to be a useful contribution to work in this area.

## 2.6 Dashboard Design Process

### 2.6.1 Dashboard Components

In this section, we discuss the philosophy behind the basic “building blocks” of the dashboard. This philosophy is present in all of the iterations of the dashboard that we present in this discussion, and we will evaluate the overall philosophy’s effectiveness in the conclusion.

The large set of publicly available data (primarily from [data.iowa.gov](http://data.iowa.gov)) we have assembled is useful, but we must be careful with how we present this data because it would be easy to overwhelm the user with small details that mask the bigger picture. We select a small subset of towns (out of the 999 towns in Iowa) and a small subset of variables of interest to start with, and

then allow the user to increase the complexity of the display in accordance with their interest. This avoids some of the pitfalls of dashboard design that can easily lead to user overload (Few, 2006b).

Our primary objective is to provide users with a town-centric approach: their town is at the center of our application, and comparisons to other, similar towns are secondary. As a result, the next component of the dashboard is intended to provide a brief overview of the information we have about a specific town of interest. This design is based on research into visualization sensemaking (Lee et al., 2016), in that we allow users to explore outward from the familiar to the unknown. The map visuals were built using Open Source Routing Machine (OSRM) route functions (Luxen & Vetter, 2011) in R (R Core Team, 2022) to amplify the accuracy of the distances from necessary services in town-centric point. OSRM allows for finding the “As the Crow Flies” distance and time on the road for our vital services map, since OSRM technology is similar to Google maps.

When faced with the next component, a parallel coordinate plot (PCP), a novice user will be able to determine two basic components: Visual Object (textual objects and non-textual objects) and Frame (frame of content and frame of visual encoding).

Taken together, the app is a single page; the initial “solid ground” which the user explores from consists of maps showing the route from the center of town to necessary services, including the fire department, schools, post offices, and hospitals. In version 2, as shown in [Figure 2.3](#), the map portion is condensed, and more space is given to value boxes that show vital statistics about the town’s QoL and financial metrics. This relatively straightforward

display is followed by a parallel coordinate plot that allows the user to see similar towns along dimensions such as economic indicators or population size.

### 2.6.2 Initial Draft

The initial design sketch and implementation are shown in [Figure 2.2](#).

Users' towns are at the center of our application, and comparisons to other, similar towns are secondary. As it can be extremely difficult to predict which towns are optimal for comparison purposes (similar may involve population, region, economic indicators, sports rivalries, and any number of other variables), we allow users to modify a set of suggested comparison towns to indicate other towns of interest.

We implemented some suggested town comparisons using unsupervised clustering methods to help our towns make decisions that are informed in comparison to similar towns, for budget size, population size and location. We initially focused on determining the next five to ten similar towns, based on distances to services. This feature became an important diagnostic for our data quality, as it became clear that towns which were grouped with big cities but which did not have a large population were so grouped because of missing data. Unfortunately, this clustering feature was not as useful to the application users, as they came to the dashboard with a pre-existing set of towns to compare to; our suggested comparisons were in the way.

The initial dashboard design featured several responsive maps showing the distance to the nearest hospital, fire department, post office, and school. These maps were ineffective for several reasons:

- Town residents already know this information (though it was useful for

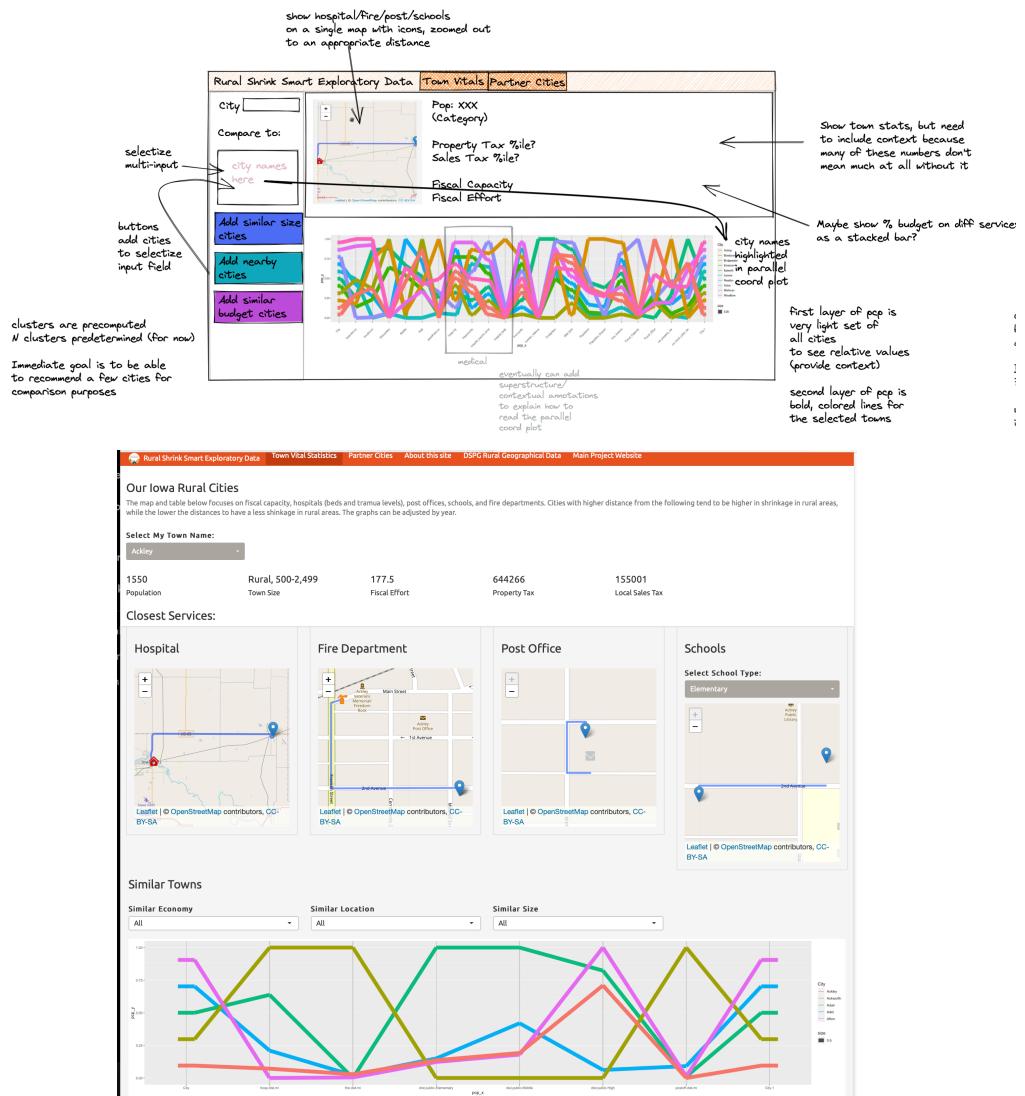


Figure 2.2: Initial dashboard design sketch (top) and implementation (bottom).

us as the dashboard designers, because we aren't nearly as familiar with the 900+ small towns in Iowa)

- We computed distance from services relative to the center of town - coordinates provided in the data from [data.iowa.gov](#). Generally speaking, the post office is at the center of town and the fire department is usually very close to the center of town; these two maps were useless. The school and hospital maps were less useless, but still did not provide particularly useful information to people already familiar with the town.
- It became clear that it might be more useful to show the comparison towns on a map (relative to the town of interest) so that users could compare geographical ratings for unfamiliar data to familiar data.

In addition, we received feedback on the parallel coordinate plot at the bottom of the app which was surprising: the viewers (in this case, other researchers on the team) were not as intimidated by the parallel coordinate plot as we had expected. They did need some explanation of how to read the plot, and these hints need to be included in the dashboard, but they grasped the fundamental idea of the plot very quickly.

Our conclusion, based on this initial dashboard draft, was that we needed to restructure the application. Our attempt to show familiar information first to "build up" to the more unfamiliar structure of a parallel coordinate plot was not effective; there was too much clutter and not enough new information to draw users in.

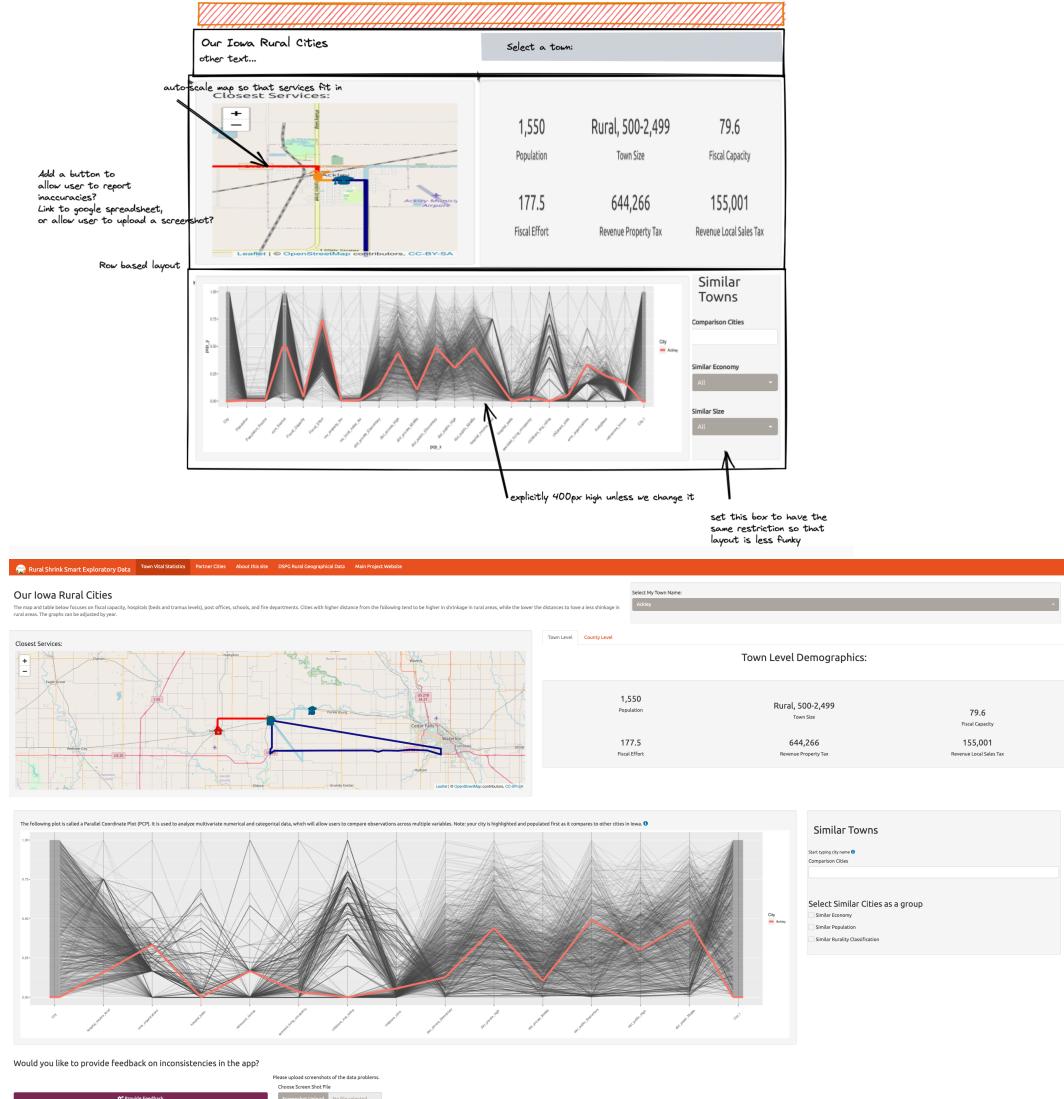


Figure 2.3: A second iteration of the sketched design (top) and the implementation (bottom).

### 2.6.3 Redesign

In the initial design, we included a map for each vital service, this initially created a lag for the users' experience. As a result, we cached map directions from OSRM for each service in our database, which drastically reduced the response time for the user. Our initial design did not naturally focus the user's eye on the most important parts of the dashboard; the redesign allowed for a cleaner flow from the top to the bottom.

In addition to the timing due to the map loading slowly, we added the vital statistics at the county level to allow for a more robust understanding of the town and it's surroundings. The rurality index provided a better classification and the USDA sources allowed for the town to understand the impact of the closest major city due to commuting for work and shopping at larger stores not available within the town.

We also modified the parallel coordinate plots in several ways:

- Our x-axis had a large number of variables that we as researchers believed to be the most strongly associated with quality of life. However, there were still too many variables for users to successfully parse. We reduced the number of variables, focusing on variables that had the highest data quality, and we grouped these variables by quality of life factor (Peters, 2019).
- Originally, parallel coordinate bands were scaled based on the selected comparison towns. This had the effect of truncating the range of variables and over-emphasizing differences between selected towns relative to the overall range of each variable over all towns in our data set. We

chose to show all towns in the data set in a very light  $\alpha$  grey color to provide some information about the overall range of each variable. Unfortunately, even with the low- $\alpha$  value, this increased the visual complexity of the plot and confused users. Future iterations will likely make use of another aesthetic, such as boxplots or violin plots, to show the range of values for all towns, and then use lines only for towns that are selected by the user. This should strike a balance between visual complexity and representing the data accurately.

- We noticed that users did not make use of our suggested comparison towns, and so we removed that option in favor of allowing users to enter their own comparison towns directly. Users already had pre-determined towns they wanted to compare to, and our suggestions were just in the way.

While not all of these modifications were well received in our second round of user testing, the changes did incrementally move the dashboard display towards our goal of allowing users to explore the data and engage with it. We continued to be surprised with how well users reacted to the parallel coordinate plots, which we initially thought might be too abstract for users unfamiliar with multivariate data displays, but the ability to compare towns across multiple dimensions and examine the similarities and differences between their approaches to different services seemed to be intuitive for users once they understood that each vertical axis was a different variable.

## 2.7 Discussion

Our dashboard design philosophy worked primarily to promote a town-centric approach application with comparisons to other similar towns being secondary. This approach created a way for the user to see their town information at the top of the page and to explore the PCP after reviewing their own town's essential statistics. The PCP in the lower part of the dashboard allowed for the user to see the plot and adjust to the fact that they could add more towns to the plot, providing an opportunity to explore the wider dataset from a base of familiar knowledge.

While we initially framed the design around guided discovery learning, the approach did not seem to suffice for our user base; instead, we found that users were more drawn to the unfamiliar from the start. We will likely leverage this in future iterations by using visual forms such as flower plots to draw the users in; even though these plots are not ideal for numerical display of data, the visual novelty and aesthetic appeal will provide some motivation to continue exploring and thinking about the data.

One factor that we have briefly considered and have seen hints of in our user feedback is that towns may not want to be compared negatively with other towns. While users have very definite ideas about which towns they would like to compare to, we can always mask the town names and move back to comparisons based on town size and other factors (for instance, whether or not a town is the county seat is a factor that is important outside of population). Using this approach, we would label each town as "Town 1", "Town 2", and so on, which would eliminate some of the fears about negative comparisons, but would also remove some of the novelty of the data dashboard for our users.

and would prevent users from drawing on their own outside knowledge about each of the comparison towns.

We also recognize that we need to leverage the expertise of others in our research team: we are working with artists, researchers in architecture, economists, and sociologists; these researchers provide outside knowledge that we do not have and may be able to help us create insightful use-cases to showcase the app and teach towns how to use it. We can also leverage the app to connect users with our research team, providing additional value to those who use the applet and facilitating development of strategies for maintaining quality of life amid shrinking populations.

## 2.8 Future Work

One avenue we will explore in future iterations of the dashboard is to incorporate other dashboards generated by different groups within this project. This will create a wider field of information to explore: for instance, some of the additional work will focus on the 99 towns featured in the Iowa Small Town Poll; this will allow us to showcase survey-based measures of quality of life alongside the more objective measurements assembled in the dataset discussed in this paper. While at least one tab of this omni-dashboard will still focus on wider EDA and discovery, we hope to incorporate other information as well to provide a more well-rounded data display encompassing most of the facets of this complex project.

We are also mindful of a distinction between “eye candy” and purpose-driven data visualization. While we have typically focused on the latter, there is certainly a place in our dashboard for the former as well. “Eye candy”

visualization is intended to draw the viewer in and motivate them to explore; while these visualizations may not be particularly effective at communicating quantitative information, if they motivate the user to engage with the rest of the dashboard, they still serve a purpose. It is with this mindset that we intend to explore the use of flower plots - the artistic opportunities combined with the display of quantitative information (even in a form that isn't optimal for quantitative comparisons) may be useful to engage viewers before transitioning to more useful data visualizations intended to provide accurate quantitative comparisons.

EDA can be a difficult for a variety of groups of people, novice users and experienced researchers. One of the more difficult components of this project has been clearly articulating the purposes of EDA to a diverse group of researchers unfamiliar with the concept. One of the most useful parts of this dashboard iteration process has been as an aid to data discovery: that is, the dashboard motivated us to find additional data sources and incorporate them into the project. Having conversations with other researchers about the EDA process helped to facilitate these conversations, as each discussion seemed to uncover additional data sources that someone remembered after looking at the dashboard. While this facet of the dashboard process may be difficult to study formally, it would be an interesting avenue for investigation.

## 2.9 Conclusions

In this paper, we have documented the process of designing a dashboard for exploration and visualization of a large and complex data set assembled from many different sources. Our primary audience was leaders of small towns

in Iowa, with a secondary audience of researchers in fields other than statistics collaborating on this project with us. Through the process of revising our dashboard, we found that the idea of guided discovery learning as implemented in our first version did not work as well as we had anticipated. It was more important to focus on allowing users to explore their questions about the dataset by facilitating user-driven comparisons and exploration, rather than attempting to anticipate user desires by providing comparison towns. In addition, we found that it would be more effective to draw users in with novel visual displays, as these seemed to attract more interest than providing known facts and an opportunity to explore outwards from an initial area of familiarity.

While it is hard to apply the findings from one fairly specific visualization project more widely, there is a lack of resources in this area that provide both design philosophies and actual analysis of user feedback in a qualitative sense. We have attempted to address this dearth of information by providing the design strategies, user feedback, and our planned and executed modifications, in the hopes that others facing the daunting challenge of designing a dashboard for EDA may learn something from our experiences.

## Chapter 3

### Dashboard Poetry

#### 3.1 Introduction

Statisticians use graphs in almost every stage of their work. They create charts to summarize and explore new data and identify potential problems and opportunities. Models are fit based on relationships between variables which are often identified visually. We identify problems with those models based on residual plots and other visual diagnostics. When our modeling work has been completed, we present our results to interested parties using visual displays, because non-statisticians often find it easier to understand data and models through an intuitive visual medium rather than through the mathematical formulae which underlie the statistical work.

Given the wide range of uses for graphs and visual data displays in statistical modeling, it is unsurprising that some graphs are more useful for specific applications, such as exploratory analysis, and are unsuitable for other applications, such as presenting to an outside group. In addition, not all visual displays have equal perceptual value (Unwin et al., 2003) and (Aspíllaga, 1996). The best graphics are designed to account for both the dataset and the

intended audience's features. Some design constraints stem from limitations of the human perceptual system and are common to most potential consumers of the visualization. For example, the sine illusion affects anyone with binocular depth perception, and color recommendations are built around the specific characteristics of the human retina (VanderPlas & Hofmann, 2015b). Other design constraints are due to the audience's experience level and if they are used to working with data and understand specialized techniques (e.g., enough familiarity with principal component analysis such that a plot of factor loadings might be useful). Do they understand specialized techniques such as principal component analysis to the point where a plot of factor loadings might be a useful visual display? When we create visualizations for public consumption, we have to consider both perceptual factors and the target audience's domain knowledge.

Most research in statistical graphics has been done on static graphics; usually, research also strips away all but the most essential contextual information, sacrificing external validity for statistical control. As a result, it can be hard to generalize this research to practical applications, where the contextual information surrounding the data is critical and the chart does not just exist in a vacuum.

In the real world, however, conventions and familiarity often win out over best practice validated by perceptual experiments. For example, in sports, many coaches desire printable diagrams containing all necessary and valuable information on a single page. As data in sports becomes more prominent, extensive, and collected, this information must be refined.

Dashboards have seen a significant increase in day-to-day usage as a potent

data visualization and decision-making tool. The proliferation of dashboards can be attributed to several factors, including the growing availability of data from various sources and the increasing need for organizations to extract actionable insights. Steven Few found that the widespread use of dashboards is attributable to their capacity to present key performance indicators and relevant metrics in a visually appealing and easily digestible format, (Few, 2006a). Moreover, technological advancements and the development of user-friendly dashboard platforms have facilitated the creation and effective utilization of dashboards by individuals from diverse fields. Dashboards have revolutionized data analysis and presentation, allowing users to gain valuable insights and make data-driven decisions more effectively.

Thus, in addition to the experimental evidence, we must consider the human element: how to introduce new graphical concepts to stakeholders, and the considerations involved in encouraging stakeholders to adopt these improved graphics. Let us first consider the audience characteristics that affect the selection of graphics. Then, we will engage with considerations based on the data to be displayed. Finally, we will consider the interactions between the audience and the data: how graphics are tested, amended, and hopefully eventually adopted into common use.

Interactive data dashboards are frequently employed to present many pertinent qualities and performance measures that carry significance for stakeholders. Each chart on the dashboard contributes to the overall comprehension of the situation, similar to how each sentence in a paragraph contributes to the larger concept. A chart is similar to a sentence in that it presents a straightforward piece of information and visually represents data to facil-

itate comprehension. For example, a chart could be a bar graph depicting sales over a year, a pie chart illustrating the percentage distribution of a budget, or a scatter plot illustrating the correlation between two variables. A dashboard may combine multiple graphs, tables, and metrics to provide an all-encompassing view of a company's performance, a project's development, or market trends.

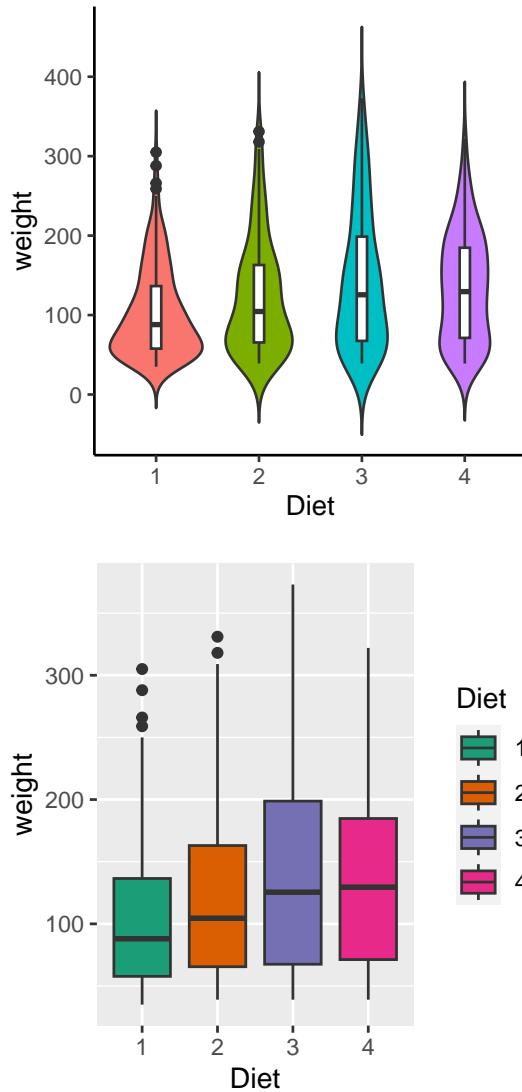
However, a counterexample to this analogy could be a poorly designed dashboard presenting overwhelming information without clear organization or hierarchy. In such a case, the charts may compete for attention and confuse the reader, similar to how a paragraph with too many disjointed sentences can lead to confusion and a lack of coherence. This counterexample highlights the importance of thoughtful design and effective communication in creating an informative and comprehensible dashboard. The research objective of this study is to investigate how changes in real-time data displayed on a dashboard affect ensemble perception and the user's ability to make accurate and rapid decisions based on summary statistics in a dynamic environment.

John Tukey was the first to organize the collection and methods associated with philosophy into exploratory data analysis (EDA). Previous research by Tukey focused on graphics as a tool for exploratory analysis. In “Exploratory Data Analysis,” Tukey wrote that graphics and charts often display data with more enhanced understanding than a table (Tukey & Wilk, 1966). Tukey outlines in detail the types of different graphics and in which situations to utilize them. He was a strong advocate for the importance of EDA as a crucial first step in the data analysis process and emphasized the need for visualization and interactive techniques to understand patterns and relationships in data.

Tukey's Principles of EDA have become a cornerstone in the field of statistics and have been adopted by data professionals in various industries. Tukey's principles have enabled data professionals to understand complex data sets better and make more informed decisions by emphasizing the importance of visual exploration, data characterization, and model critique. In this way, Tukey's Principles have revolutionized our data analysis approach and become the foundational framework for EDA.

Tukey's Principles in EDA:

1. Through graphic exploration (looking for patterns or displaying fit), the method demonstrates things about data that a single numeric metric does not understand. This has been useful in graphing the data before you develop summary statistics.
2. Describing the general patterns of the data. This step should be insensitive to outliers. In general, think about the types of resistant measures (i.e., median or mean). This step makes sure to determine data patterns.
3. The natural scale or state in which the data are at their best. This will be the step at which the scale of the data can be helpful for analysis. Reexpressing data on a new scale by taking the square root or logarithmic scale.
4. The most known part of EDA is done by assessing the fit of the data. This is taught in every statistics 101 class. With the growth of machine learning and prediction methods, residuals are now more widely used in the toolbox for assessing the best prediction models.



Data visualizations are an integral part of the EDA process, enabling analysts to discern patterns and relationships in the data that would otherwise be difficult to discern from tabular data alone. Through data visualization, analysts can quickly identify trends, outliers, and other patterns that may be missed through numerical analysis alone. Moreover, visualizations facilitate the communication of findings to non-technical stakeholders, allowing them to comprehend complex data sets more efficiently. Also, analysts can use visualizations to identify potential issues or biases in the data, resulting in better

decisions and models. Thus, visualizations play a crucial role in the EDA process by enabling analysts to more effectively explore, comprehend, and communicate data-derived insights. During the initial EDA stage, an analyst may find that a variable or a covariate is directly related to the dependent variable when looking at a correlation heatmap or a scatterplot.

Using color to represent data on maps is an example of successful graphical communication utilizing semiology. By using different colors to represent different data points, viewers can comprehend patterns and relationships in the data quickly and easily. Jacques Bertin writes in “Semiology of Graphics” that color can be used to “emphasize a point, distinguish one category from another, or establish a relationship between two points”, (Monmonier, 1985). In addition, Bertin explains that the use of color can help overcome language barriers, making it easier for the audience to comprehend the presented information.

By utilizing visual elements such as bars and lines to represent data, graphs can make complex information more understandable to viewers. For instance, a line graph can be used to illustrate the change in the value of a stock over time, making it easier for investors to identify trends and patterns. Leland Wilkinson writes in his book “The Grammar of Graphics” that “graphical methods are not only superior to other forms of communication but also superior to numerical or verbal methods for certain types of data and reasoning” (Wilkinson, 2012).

It proposes that any statistical graphic can be broken down into a set of essential components, or “grammar,” that can be combined in different ways to create a wide range of visualizations, following a layered approach to describe

and construct visualizations or graphics in a structured manner.

The components of the grammar of graphics include:

- Data: The raw data being visualized represents a set of observations or values.
- Aesthetic Mappings: The mapping of data variables to visual properties such as position, color, shape, and size.
- Scales: The mapping of data values to visual values, such as mapping a numerical value to a bar height.
- Geometries: The basic shapes representing the data, such as points, lines, bars, and histograms.
- Facets: The plot division into multiple subplots, each representing a different subset of the data.

For example, a bar chart can be created by mapping a categorical variable to the x-axis, mapping a numerical variable to bar heights, and using rectangular bars as the geometry. Moreover, mapping two numerical variables can create a scatter plot to the x and y positions and use points as the geometry. Finally, the “Grammar of Graphics” provides a systematic way of thinking about visualizations, making it easier to choose the appropriate visual representation for a given dataset.

A dashboard is a visual display of the essential information needed to achieve one or more objectives, consolidated and arranged on a single screen so the data can be monitored at a glance (Few, 2006a). Dashboard design

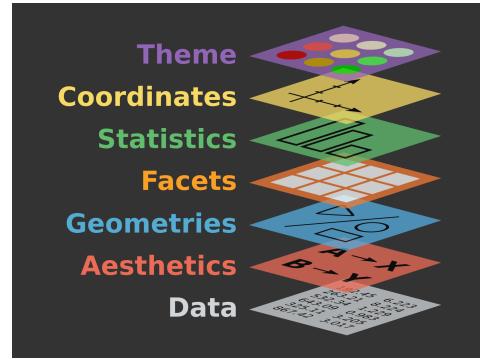


Figure 3.1: Grammar of Graphics Diagram of Wickham and Wilkinson's work

VERB            NOUN            ADJECTIVE

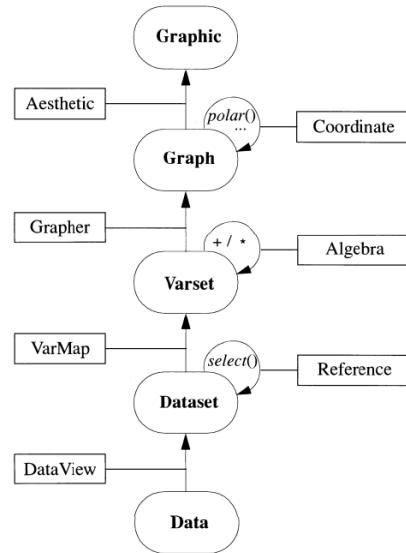


Figure 3.2: Grammar of Graphics Diagram of Wickham and Wilkinson's work

creates visually informative and interactive interfaces that present data and key performance indicators (KPIs) in a consolidated and simple-to-understand format.

The objective is to provide users with insights and enable them to make intelligent decisions based on the presented data.

As organizations increasingly rely on data-driven decision-making, well-designed dashboards become pivotal.

The literature on dashboard design provides a comprehensive roadmap for understanding and implementing effective dashboards, focusing on critical frameworks such as evaluation criteria in healthcare, learning dashboards in educational settings, design patterns and trade-offs, academic literature reviews, and practical tips for implementation.

Each of these frameworks offers unique perspectives and actionable insights. These frameworks serve as pillars for the subsequent discussion on creating functional and impactful dashboards.

However, it is essential to note that even with a comprehensive roadmap, the success of dashboards heavily relies on the quality and accuracy of the presented data. If the data used in the design and implementation of dashboards is flawed or incomplete, it can lead to misleading insights and ineffective decision-making. Additionally, different user groups' specific needs and preferences may not always align with the frameworks provided, requiring customization and adaptation that may not be adequately addressed in the comprehensive roadmap.

A systematic literature review by (Schwendimann et al., 2016) discusses the state-of-the-art in learning dashboards. The paper identifies critical design features, dividing them into functional and visual features.

This study is particularly useful for educational institutions implementing learning analytics dashboards. Conducted as a systematic literature review, the study categorizes critical design features into functional and visual aspects, providing a comprehensive understanding of what makes a learning dashboard effective.

The research is especially relevant for educational institutions implementing

or optimizing learning analytics dashboards.

By identifying key design elements and their impact on student performance, the paper is a foundational resource for educators and administrators looking to leverage dashboards to enhance educational outcomes.

### 3.2 Dashboard Construction

Given that the intended audience has limitations, there are design constraints around the data, and the audience has the ability to successfully use the graphical displays of the data, what can we take from this body of research that applies to more complicated sets of graphics? How do we maintain user attention, create a desire to explore, and accurately communicate the data through the medium of an interactive data dashboard? Solutions to these questions can start with a dashboard.

A dashboard is a visual display of the essential information needed to achieve one or more objectives, consolidated and arranged on a single screen so the data can be monitored at a glance (Few, 2006a). Dashboards have particular characteristics:

- Achieve specific objectives
- Fits on a single computer screen
- Information can be displayed in multiple mediums (web browser or mobile device)
- Can be used to monitor information at a high level

Dashboards can present various statistical data, such as financial performance, website traffic, or customer engagement metrics. They allow users to quickly and easily understand complex data sets by using visual elements such as charts, graphs, and tables to display the information. Additionally, statistics can be used to analyze data presented on a dashboard, providing insights into trends and patterns that can inform decision-making.

While a dashboard can be handy, it may be worth mentioning that a poorly designed dashboard will not be used. A dashboard should be concise, clear, and intuitive when displaying components in combination with a customized list of user requirements.

Much of the work done in statistical research and dashboard design involves collaboration with other researchers and users. While this may be the best for the growth of the discipline, one will find that working with collaborators with non-STEM backgrounds Dashboards can help understand and support many data types for essential business objectives. There are many different ways to label and utilize dashboards of different kinds.

Combining two compelling graphics does not necessarily result in a successful visualization. In certain instances, suboptimal combinations can result in confusion, misinterpretation, and the failure to convey the intended message. Combining two charts with distinct scales or units is an example of suboptimal graphic design, which can result in misinterpretation and flawed comparisons.

For example, if a bar chart displaying the number of sales is combined with a line chart showing revenue, meaningful comparisons between the two metrics can be challenging. According to a study conducted by Cleveland and McGill,

people frequently make inaccurate judgments when comparing graphs with different scales (Cleveland & McGill, 1984).

In addition, combining two difficult-to-compare graphics with redundant visual cues or unnecessary embellishments such as colors, 3D effects, or patterns can increase cognitive load and reduce the dashboard's effectiveness. Although adding extra elements to a chart or graph may be tempting, doing so can detract from the primary message and make it more difficult for the audience to focus on the essential information. Tufte discovered that adding unnecessary visual cues to a graph decreases its effectiveness because viewers are more likely to focus on the embellishments rather than the data (Edward R. Tufte, 1985). Dashboards are cognitive tools that should be used to improve understanding of data and help people visually find relationships, trends, patterns, and outliers.

Most importantly, dashboards should leverage people's visual and cognitive capabilities.

These principles are based on cognitive psychology and understanding how the human brain processes visual information. Cowan suggested that the average person can only hold two to six pieces of information at a time (Cowan, 2001). By applying these principles to dashboard design, designers can create visual arrangements that make it easier for viewers to understand the relationships between data elements. For example, proximity can be used to group related elements together, while symmetry can be used to create balance and harmony in the overall layout of the dashboard. At its most basic, the entire form is perceived (or emerges from our visual pathways) as opposed to its component parts. For instance, if a scatter plot and a bar chart are combined,

the resulting visualization may be difficult to interpret due to the two graphics types' incompatibility. Hullman et al. (Hullman et al., 2011) discovered that viewers had trouble understanding a visualization that included a scatter plot and a line chart, which brought attention to this issue. Moving forward, designers must navigate the delicate balance of complexity and comprehension to ensure that dashboards serve as a potent tool for conveying information succinctly and effectively, enhancing the viewer's ability to grasp and analyze the presented data seamlessly.

### 3.3 Cognitive Principles

Perception is a biological process involving sensory systems and neural mechanisms. The retina, a multi-layered tissue, lines the back of the eye and converts photons into electrical impulses that travel along the optic nerve to the brain. This process is crucial for understanding perception. Sensory modality, such as sight, hearing, and touch, has specialized receptors that convert physical stimuli into electrical signals that the brain can interpret. For instance, light enters the eye and activates photoreceptor cells in the retina, (Hubel & Wiesel, 2004).

Human perception is an essential component of data visualization that can significantly enhance both the content and quantity of displayed information (Ware, 2012). Perception refers to the organization, interpretation, and conscious experience of sensory data. Perception is also defined as “the process of recognizing (being aware of), organizing (gathering and storing), and interpreting (binding to knowledge) sensory information” (Ward et al., 2010). Ward et al. explain the notion of perception as follows: “The brain makes as-

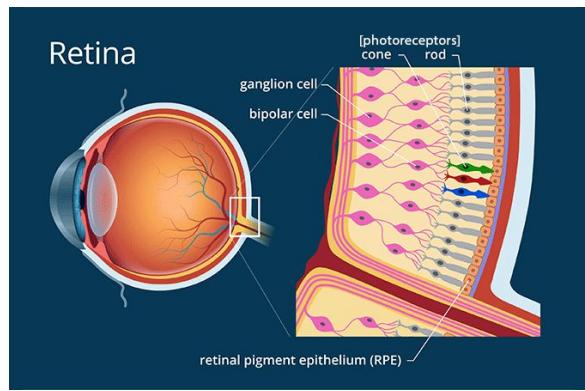


Figure 3.3: An example of how the retina signals the visual cortex

sumptions about the world to overcome the inherent ambiguity in all sensory data and in response to the task at hand.”

The principles of eye-tracking involve the investigation of eye movements and fixations during visual perception. Eye-tracking technology permits researchers to monitor and record where individuals look and how their gaze traverses a visual scene. This data can be utilized to analyze patterns of attention, gaze behavior, and the sequence of fixations. The principles of eye-tracking provide valuable information regarding how individuals allocate their attention, which elements attract their gaze, and how they visually explore and process information.

Gestalt principles, on the other hand, examine how humans perceive and organize visual elements into meaningful patterns and wholes. These principles originated in the field of Gestalt psychology, which emphasized that perception is influenced by the arrangement and grouping of its constituent parts. The Gestalt principles of proximity, similarity, closure, and continuity describe how our brains organize visual stimuli to form coherent and meaningful perceptions.

Perceptual grouping is a fundamental process in visual perception that in-

volves organizing individual graphical elements into coherent perceptual units based on their inherent properties and spatial relationships. It helps us make sense of the complex visual world by grouping elements that belong to the same object or structure and separating elements that belong to different entities. Gestalt psychologists have extensively studied the concept of perceptual grouping, proposing principles such as proximity, similarity, closure, and continuity as grouping's underlying mechanisms. These principles govern our perception of objects, edges, contours, and patterns, enabling us to perceive organized and meaningful visual information (Wertheimer, 1938), (Wagemans et al., 2012) and (Palmer, 2002).

The Gestalt principles play a crucial role in directing eye movements and cognitive processes involved in scanning scenes. The integration of scene scanning with Gestalt grouping concepts synergistically contributes to the facilitation of visual scene perception and comprehension. In the course of scene scanning, individuals frequently employ Gestalt grouping principles, such as proximity and similarity, in an unconscious manner to arrange diverse visual elements into cohesive groups. This process facilitates the rapid and efficient interpretation of intricate scenes (WERTHEIMER, 1923) and (Wertheimer, 1938). They facilitate the efficient assimilation and processing of visual information by emphasizing specific clusters or patterns in the visual field.

Scene scanning is the cognitive process of visually examining a given scene in order to acquire relevant information pertaining to the surrounding environment. The aforementioned procedure encompasses the utilization of both ocular motions and cognitive mechanisms to comprehend and analyze the visual data inherent in a given scenario. The subject matter is frequently ex-

amined within the framework of disciplines such as psychology, neuroscience, and computer vision.

The process of exploring visual scenes involves an intricate interaction of cognitive processes that influence an individual's perception and interaction with their surroundings. The saliency-driven focus is a key mechanism that guides scene scanning. This process involves both overt and covert shifts of visual attention, which are directed towards specific characteristics in the environment. Itti and Koch have extensively studied and explained this phenomena. Furthermore, the cognitive processes involved in perceiving scenes frequently involve a higher-level comprehension that entails a synergistic equilibrium between bottom-up processes driven by stimuli and top-down strategies driven by information (Itti & Koch, 2000). This theoretical perspective is supported by the work of Henderson and Hollingworth (Henderson & Hollingworth, 1999). The aforementioned phenomena are applicable to various cognitive processes such as reading, visual searches, and scene perception, as demonstrated by (Rayner, 2009). In this study, it was found that eye movements during these activities are notably impacted by individual cognitive processes, including linguistic comprehension and visual interpretation. Moreover, the interpretation and allocation of attention during scene scanning are influenced by the context in which visual items are encountered, as emphasized by (Bar, 2004). The significance of global features in the search for objects in real-world settings is crucial for guiding eye movements and attention within a contextual framework, (**torrableba2006?**).

By examining the complexities of scene scanning, it becomes evident that attention plays a crucial role in directing the eyes systematically as they ana-

lyze and comprehend the visual narratives present in each gaze. This process contributes to a complex cognitive framework that integrates perception and interpretation through an interactive and dynamic relationship.

Starting with Wertheimer's experiments on the perception of motion, he examined the phenomenon of apparent motion, which refers to the perception of motion when successive stationary stimuli are presented. Wertheimer investigated the principles underlying the perception of motion and provided insights into the Gestalt principles of visual perception by conducting a series of perceptual experiments.

(Wertheimer, 1912) investigated the phi motion, a type of motion in which the rapid presentation of two stationary stimuli creates the perception of movement. By manipulating the temporal and spatial arrangement of stimuli systematically, Wertheimer was able to identify critical factors that influenced the perception of motion. His experiments revealed that motion perception results from the interaction between sensory input and perceptual organization processes.

The work of Wertheimer emphasized the significance of perceptual grouping principles, such as proximity and similarity, in the perception of motion. He hypothesized that the visual system tends to group stimuli that are close in space or have similar properties, resulting in the perception of a continuous and smooth motion between them. The results of Wertheimer's experiments on the perception of motion were instrumental in developing Gestalt psychology, which emphasized the significance of holistic and organized perceptual experiences. Wertheimer's work influenced our understanding of how the brain processes visual information to create motion perception by laying

the groundwork for subsequent studies on motion perception.

According to (Goldstein & Cacciamani, 2021), preattentive processing automatically extracts and analyzes basic features such as color, shape, orientation, and motion. These features are processed in parallel across the visual field, allowing for the rapid detection and identification of salient environmental stimuli. Preattentive processing occurs effortlessly and outside conscious awareness, laying the foundation for subsequent attentional selection and more elaborate perceptual processing.

The theories of Goldstein emphasize the significance of preattentive processes in various perceptual domains. For instance, he discusses the preattentive analysis of visual features such as color and orientation, which contribute to the visual perception of objects, scenes, and graphic patterns. In the auditory domain, preattentive processes automatically extract basic acoustic features like pitch and loudness. This makes it easier to find the source of sounds and tell them apart.

By examining preattentive processing, Goldstein's theories provide a framework for comprehending the initial stages of sensory processing and the automatic extraction of fundamental perceptual features. These theories have significant implications for understanding how automatic and controlled processes shape perception.

Perception and attention are crucial cognitive processes that allow users to interpret and make sense of data visualizations. Perception refers to the manner in which we interpret and organize sensory information from our environment, whereas attention refers to the capacity to selectively focus on particular aspects of this information (McCallum, n.d.). Expectations of per-

ception and attention are important in data visualization interactions, however expertise is the in-depth knowledge and skills that come from having a lot of experience and learning over a long period of time.

In addition to perception and focus, domain-specific knowledge is essential for understanding and interacting with data visualizations. Expertise in a particular field can enable individuals to better interpret and comprehend the significance of the presented data, as well as identify potential biases or errors in the visualization. Thus, the ability to perceive and interact with data visualizations requires a combination of perceptual and attentional processes, as well as domain-specific knowledge, to interpret and comprehend the presented information. This suggests that data visualization involves the misuse of human visual perception in the visual presentation of data. Assigning meaning to visualization is not a statistical or computational step but a cognitive one. Each step in the data analysis process is part of a more extensive mental process of constructing meaning with important cognitive-based concepts.

Short-term memory (STM), which is often referred to as working memory, represents a cognitive stage characterized by the brief storage and processing of information, requiring significant cognitive resources for memory preservation. In the publication titled “Working memory: Theories, models, and controversies” authored by Alan Baddeley, it is asserted that short-term memory (STM) is a system with restricted capacity that is susceptible to both interference and decay (A. Baddeley, 2012). Selective attention plays a crucial role in the preservation of short-term memory (STM) since it enables individuals to effectively filter out extraneous information and focus on pertinent stimuli (Cowan, 2001). According to (Alvarez & Cavanagh, 2004), the utilization

tion of visual aids, such as charts and diagrams, has the potential to enhance short-term memory by facilitating more efficient encoding and retention of information. The utilization of visual aids, such as charts, has the potential to increase our short-term memory. Moreover, annotations can also serve to facilitate short-term memory. According to (Alvarez & Cavanagh, 2004), the act of incorporating annotations, such as notes or highlights, to the information we aim to retain can enhance our ability to recall the information at a later time.

According to the Feature Integration Theory (FIT), STM is composed of two stages: pre-attentive processing and focused attention (A. Treisman, 1998). Parallel and independently, the brain processes the physical characteristics of an object, such as its color, shape, and orientation, during pre-attentive processing. However, focused attention is required to bind these features into a coherent object representation in STM. STM can be improved through various strategies, such as rehearsal, chunking, and elaboration (Oberauer, 2009). For example, by repeating a phone number several times or breaking it down into chunks of two or three digits, we can increase the likelihood of it being stored in STM. Similarly, by elaborating on the information we want to remember, such as creating mental associations or visual images, we can enhance its retention in STM (Bui & Myerson, 2014).

STM is a dynamic and malleable cognitive system that is crucial to our daily lives. Understanding the mechanisms underlying STM and how to improve it can have significant implications for learning, memory, and the treatment of memory disorders. By analyzing the relationship between attention and working memory, we can gain insight into how we construct meaning from

the information in our environment.

Gestalt psychology indicates that humans actively construct meaning by organizing information into patterns and wholes (Wertheimer, 1938). Both top-down and bottom-up processing are involved in the process of meaning construction. Bottom-up processing entails analyzing sensory data from the environment and constructing perceptions based on this data. Top-down processing reflects the influence of prior knowledge, expectations, and context on the perception and interpretation of incoming sensory data.

Together, top-down and bottom-up processing facilitate the encoding and retrieval of information from STM. Selective attention, which is the ability to focus on relevant information while ignoring irrelevant information, is an example of top-down processing that aids in the encoding and retrieval of information in STM (Cowan, 2010).

According to FIT, perceiving objects involves both the bottom-up analysis of individual features and the top-down processing of higher-level features in order to form a complete perception (A. M. Treisman & Gelade, 1980).

The Gestalt principles of perception address how humans construct meaning from sensory data through both bottom-up and top-down processing. Both types of processing are involved in encoding and retrieving information, which has significant implications for understanding the mechanisms of STM.

Baddeley expanded our understanding of working memory by emphasizing its active processing nature, expanding upon the model of Atkinson and Shiffrin's Information Model developed in the 1968, which emphasizes the process of encoding, storage, and retrieval. Unless actively practiced, short-term memory has a limited capacity and a short duration of retention. If infor-

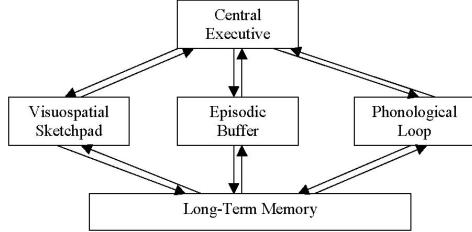


Figure 3.4: Working Memory Model created by Baddeley (left) and Information Processing Model created by Atkinson and Shiffrin (right)

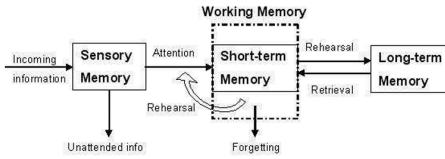


Figure 3.5: Working Memory Model created by Baddeley (left) and Information Processing Model created by Atkinson and Shiffrin (right)

mation is deemed significant or sufficiently rehearsed, it can be encoded and transferred to long-term memory, which has an almost unlimited capacity and long-term storage. The influential model developed by Baddeley, known as the working memory model, proposed a more complex structure with multiple components, (Baddeley Alan D., 1976).

The Baddeley Memory Model is an updated and influential model of working memory. It includes the phonological loop (maintenance of verbal information), the visuospatial sketchpad (maintenance of visual and spatial information), the central executive (attentional control), and the episodic buffer (integrated storage). Together, these components facilitate the active processing and temporary storage of data in working memory.

Visual and spatial information is processed and temporarily stored in the visuospatial sketchpad when individuals view statistical graphics. The central executive component facilitates the interpretation and analysis of the pre-

sented data by directing attention to pertinent aspects of the graphic. Utilizing working memory resources effectively can aid in comprehending and remembering the statistical information conveyed by the graphics.

Together, Baddeley's model of working memory provided a comprehensive framework for studying memory and cognition. They contributed to the understanding of how information is processed, encoded, stored, and retrieved in human memory systems, laying the groundwork for subsequent research and theories in cognitive psychology.

### 3.4 Ensemble Perception

Ensemble perception is the cognitive ability to quickly derive summary statistics from sets of similar items (Chong & Treisman, 2003). This component of visual cognition enables the visual system to summarize and describe collections of comparable objects or features effectively. This capability is often activated at a glance and is crucial for making sense of complex visual scenes.

David Whitney's fundamental review outlines the core principles of ensemble perception, emphasizing the extraction of summary statistical information from groups of similar objects (Whitney, Haberman, & Sweeny, 2014) and (Dakin & Watt, 1997). Ensemble perception pertains to the capacity of the human visual system to efficiently and swiftly extract statistical data from a collection of items or objects, as opposed to separately processing each item. The application of ensemble perception can be observed through the utilization of Gestalt principles of visual perception, including proximity (referring to the nearness of objects), similarity (pertaining to similar appearance), and

closure (denoting the completion of shapes). These concepts facilitate the perception of patterns and groups in visual scenes without necessitating a detailed examination of each individual piece.

Huberman et al. further discussed that individual differences exist in ensemble perception capabilities, indicating the presence of multiple, independent levels of ensemble representation (J. Haberman, Brady, & Alvarez, 2015). Recent studies have expanded on these principles.

Khayat et al.'s work explores how ensemble perception can create a unified perception from groups of similar objects and also delves into the implicit perception and memory of set statistics (Khayat, Ahissar, & Hochstein, 2023) and (Khayat, Fusi, & Hochstein, 2021). Examples of perception and memory of set statistics in visual information can best be described when you look at a field of flowers with various colors. Your perception quickly summarizes the set statistics of color, such as the overall color distribution, or in a crowd of people, your perception helps you group individuals into categories based on shared characteristics like clothing color, height, or age. In brief, the cognitive processes of perceiving and remembering statistical information in visual stimuli are crucial for efficiently comprehending and retaining the statistical characteristics of visual scenes and objects. These mechanisms play a significant role in enhancing our comprehension and analysis of the visual environment.

The study "Perceptual History Biases in Serial Ensemble Representation" by Khayat et al. focuses on ensemble perception, explicitly examining how past visual experiences influence the perception of current visual ensembles. The study investigates the serial dependence of ensemble perception when each ensemble set is presented simultaneously but spatially distributed over

the screen.

This suggests that the objects and our prior experiences with similar ensembles impact how we perceive groups of similar objects (Khayat et al., 2023).

This adds a layer of complexity to the understanding of ensemble perception, which is generally considered the visual system's ability to summarize groups of similar objects into a unified perception efficiently.

The study “Perceiving ensemble statistics of novel image sets” by Khayat et al. focuses on how the human visual system perceives summary statistics of sets of stimulus elements.

The study is particularly interested in how we perceive novel image sets and hypothesizes that our capacity to summarize statistical data from these sets affects how well we can comprehend and interpret new visual information (Khayat et al., 2021). This research contributes to the broader field of ensemble perception, which explores how the visual system can efficiently represent groups of similar objects as a unified perception.

The study implies that not only can the visual system quickly grasp the “gist” or essence of familiar visual ensembles, but it can also do so for novel sets of images.

This ability to quickly summarize statistical information from new visual stimuli could be a fundamental feature of human perception (Khayat & Hochstein, 2018).

Other research has investigated the role of ensemble perception in both high- and low-level visual information, such as emotion and brightness, and how it can even operate when scene information is incomplete (Chakrabarty & Wada, 2020) and (J. M. Haberman & Ulrich, 2019).

Furthermore, ensemble perception is not just a specialized function but a pervasive aspect of visual perception.

It has been discussed holistically to engage a general audience and has been shown to condense redundant information into summary statistical representations (Corbett, Utochkin, & Hochstein, 2023) and (Whitney & Manassi, 2022).

Stable ensemble representations have been found to facilitate visual search, even when they are not predictive of a target location (Utochkin, Choi, & Chong, 2023). The study focuses on a coding model that emphasizes the crucial role of the “pooling layer” in ensemble perception.

### **3.4.1 Ensemble Visualization**

Ensemble visualization refers to the graphical representation of ensemble data, which typically consists of multiple related datasets. It aims to provide a comprehensive view that allows for rapidly extracting visual statistics and insights about distributed information.

Ensemble visualization techniques can vary, including Ensemble Surface Slicing (ESS) to visualize regions of similarity and difference among surfaces and statistical visualization techniques to identify areas of interest quickly (Alabi et al., 2012) and (Potter et al., 2009).

The aim is to provide a comprehensive view that allows for the rapid extraction of visual statistics and insights about distributed information.

By combining various statistical visualization techniques, Potter presents the Ensemble-Vis framework in his paper as a way for scientists to identify areas of interest quickly, (Potter et al., 2009). The paper’s thorough methodology, which combines various statistical visualization techniques to build a more

helpful ensemble visualization framework, makes it noteworthy. This framework has been referenced by many other studies, leading to the development of new visualization methods.

By exploring the effects of ensemble and summary displays on data interpretation, Padilla's research adds valuable insights to the field, (Padilla, Ruginski, & Creem-Regehr, 2017). Padilla investigates how ensemble displays, which plot multiple data points on the same Cartesian coordinate plane, affect the viewer's understanding and interpretation of the data. The paper contributes to the theory by examining the cognitive aspects of ensemble visualization. However, a counterexample to the effectiveness of ensemble displays can be observed when the data points are highly overlapping and densely packed, leading to visual clutter and difficulty distinguishing individual data points. In such cases, ensemble displays may hinder the viewer's understanding and interpretation of the data rather than enhance it. This highlights the importance of considering the specific characteristics of the presented data when deciding whether to use ensemble displays. Additionally, summary displays, which provide an overview of the data, can be a helpful alternative in situations where ensemble displays may be less effective. Summary displays condense the data into crucial statistics or visual representations, allowing for more straightforward interpretation and analysis, especially when dealing with complex or dense datasets. Further research is needed to explore the optimal conditions for ensemble and summary displays to maximize their effectiveness in data interpretation.

### 3.4.2 Multidimensional Ensembles

Initial research on ensemble perception primarily focused on one-dimensional ensembles, where summary statistics are extracted from a single feature or dimension (J. Haberman et al., 2015). For example, in a study on facial expression perception, participants were presented with an ensemble of faces displaying different emotions. In this case, the pooling layer would analyze the overall emotional expression of the ensemble, summarizing the various individual facial expressions into one general emotion perception. This model allows researchers to understand how humans perceive and interpret complex emotional expressions more systematically. However, as Maule and Franklin note, real-world scenes often consist of complex, multidimensional attributes, and research has gradually shifted towards understanding how the human visual system processes these more intricate ensembles (Maule & Franklin, 2015). Research on multidimensional ensembles has explored how people simultaneously perceive summary statistics across multiple attributes, such as size and color.

Dakin and Watt were among the first to explore how orientation statistics are computed from visual textures, extending the concept of ensemble perception into a multidimensional setting, (Dakin & Watt, 1997). Haberman et al. expanded this research by showing that individual differences exist in ensemble perception capabilities, suggesting multiple, independent levels of ensemble representation exist, (J. Haberman et al., 2015). The existing literature on multidimensional ensembles in visual information covers various topics, from neuroscience to data visualization.

For instance, studies have explored the role of neuronal ensembles in control-

ling visually guided behavior and their influence on visual working memory (Carrillo-Reid, Han, Yang, Akrouh, & Yuste, 2019). Research has also delved into the use of aggregated plots for multidimensional visual analysis, although these don't explicitly mention ensembles (Fofonov & Linsen, 2018).

Fast ensemble representations have been investigated to understand high-level perceptual impressions based on visual information (Leib, Kosovicheva, & Whitney, 2016).

Additionally, the aesthetic complexity of visual information has been quantified using information theory, offering a potential framework for ensemble-based representations (Karjus, Solà, Ohm, Ahnert, & Schich, 2023). But a detailed example of why you shouldn't use aggregated plots for multidimensional visual analysis is when the individual data points in the ensemble show significant differences. Data aggregation may obscure important patterns in such scenarios and lead to misleading interpretations. Further, ensembles may fail to capture the fine-grained details and nuances present in the individual plots, compromising the overall accuracy and precision of the analysis. The long-term stability of neuronal ensembles in the visual cortex has been studied, shedding light on their potential role in visual perception (Pérez-Ortega, Alejandre-García, & Yuste, 2021). Ensemble visualization techniques, particularly in computer simulations, have also been reviewed (Afzal et al., 2019). Lastly, the structure of neural networks has been shown to affect working memory, which could have implications for visual ensembles (Leavitt, Pieper, Sachs, & Martinez-Trujillo, 2017).

## Chapter 4

### **Does Color Help?: Multidimensional Ensembles in Bland-Altman Plots: An Exploration**

#### **4.1 Introduction:**

“How can multidimensional ensembles be effectively incorporated into Bland-Altman plots to enhance the accuracy and comprehensibility of assessing agreement between multiple measurement techniques?” This research question explores the theoretical and practical implications of incorporating ensemble perception and multidimensional data into Bland-Altman plots, traditionally used for comparing two measurement methods. By doing so, the research seeks to advance the utility and interpretability of these plots in complex, real-world scenarios where multiple dimensions are often at play. The interpretation of Bland-Altman plots is conventionally one-dimensional, focusing primarily on the mean difference and limits of agreement (Bland & Altman, 1986). However, in real-world applications, the measurements under consideration often contain multiple dimensions that could contribute to interpreting the agreement or disagreement between two techniques (Chong & Treisman, 2003). A detailed counterexample of the utility and interpretabil-

ity of Bland-Altman plots in complex, real-world scenarios can be seen where two techniques are being compared for measuring blood pressure. The Bland-Altman plot may show good agreement between the mean difference and the limits of agreement, suggesting high concordance. However, when considering additional dimensions such as accuracy and precision in different subgroups (e.g., age, gender), it could reveal significant discrepancies and limitations in the interpretation of Ensemble coding, a perceptual mechanism that provides a statistical summary of a visual scene, offers a promising solution by facilitating the rapid extraction of variability information (Alvarez, 2011). The theory of ensemble perception offers a framework for understanding how these multiple dimensions could be processed simultaneously (J. Haberman et al., 2015) and (Whitney et al., 2014).

#### **4.1.1 Ensemble Perception**

Ensemble perception is the cognitive ability to quickly derive summary statistics from sets of similar items (Chong & Treisman, 2003). This component of visual cognition enables the visual system to summarize and describe collections of comparable objects or features effectively. This capability is often activated at a glance and is crucial for making sense of complex visual scenes.

David Whitney's fundamental review outlines the core principles of ensemble perception, emphasizing the extraction of summary statistical information from groups of similar objects (Whitney et al., 2014) and (Dakin & Watt, 1997).

(J. Haberman et al., 2015) further discussed that individual differences exist

in ensemble perception capabilities, indicating the presence of multiple, independent levels of ensemble representation.

Recent studies have expanded on these principles.

Khayat et al.'s work explores how ensemble perception can create a unified perception from groups of similar objects and also delves into the implicit perception and memory of set statistics (Khayat et al., 2023) and (Khayat et al., 2021).

The study "Perceptual History Biases in Serial Ensemble Representation" by Khayat et al. focuses on ensemble perception, explicitly examining how past visual experiences influence the perception of current visual ensembles.

The study investigates the serial dependence of ensemble perception when each ensemble set is presented simultaneously but spatially distributed over the screen.

This suggests that the objects and our prior experiences with similar ensembles impact how we perceive groups of similar objects (Khayat et al., 2023). This adds a layer of complexity to the understanding of ensemble perception, which is generally considered the visual system's ability to summarize groups of similar objects into a unified perception efficiently.

The study "Perceiving ensemble statistics of novel image sets" by Khayat et al. focuses on how the human visual system perceives summary statistics of sets of stimulus elements.

The study is particularly interested in how we perceive novel image sets and hypothesizes that our capacity to summarize statistical data from these sets affects how well we can comprehend and interpret new visual information (Khayat et al., 2021). This research contributes to the broader field of ensemble perception, which explores how the visual system can efficiently represent

groups of similar objects as a unified perception.

The study implies that not only can the visual system quickly grasp the “gist” or essence of familiar visual ensembles, but it can also do so for novel sets of images.

This ability to quickly summarize statistical information from new visual stimuli could be a fundamental feature of human perception (Khayat & Hochstein, 2018).

Other research has investigated the role of ensemble perception in both high- and low-level visual information, such as emotion and brightness, and how it can even operate when scene information is incomplete (Chakrabarty & Wada, 2020) and (J. M. Haberman & Ulrich, 2019).

Furthermore, ensemble perception is not just a specialized function but a pervasive aspect of visual perception.

It has been discussed holistically to engage a general audience and has been shown to condense redundant information into summary statistical representations (Corbett et al., 2023) and (Whitney & Manassi, 2022).

Lastly, stable ensemble representations have been found to facilitate visual search, even when they are not predictive of a target location (Utochkin et al., 2023). The study focuses on a coding model that emphasizes the crucial role of the “pooling layer” in ensemble perception.

Ensemble perception refers to the ability of the visual system to summarize information from a group of similar objects. The “pooling layer” in the model likely serves as a computational mechanism for aggregating or summarizing this information, potentially providing insights into how the brain processes complex visual scenes. The study aims to provide a more structured un-

derstanding of ensemble perception by introducing a model highlighting the importance of a specific computational layer, known as the “pooling layer,” in summarizing visual information.

#### 4.1.2 Multidimensional Ensembles

Initial research on ensemble perception primarily focused on one-dimensional ensembles, where summary statistics are extracted from a single feature or dimension (J. Haberman et al., 2015). For example, in a study on facial expression perception, participants were presented with an ensemble of faces displaying different emotions. In this case, the pooling layer would analyze the overall emotional expression of the ensemble, summarizing the various individual facial expressions into one general emotion perception. This model allows researchers to understand how humans perceive and interpret complex emotional expressions more systematically. However, as (Maule & Franklin, 2015) notes, real-world scenes often consist of complex, multidimensional attributes, and research has gradually shifted towards understanding how the human visual system processes these more intricate ensembles. Research on multidimensional ensembles has explored how people simultaneously perceive summary statistics across multiple attributes, such as size and color.

(Dakin & Watt, 1997) were among the first to explore how orientation statistics are computed from visual textures, extending the concept of ensemble perception into a multidimensional setting. (J. Haberman et al., 2015) expanded this research by showing that individual differences exist in ensemble perception capabilities, suggesting multiple, independent levels of ensemble

representation exist. The existing literature on multidimensional ensembles in visual information covers various topics, from neuroscience to data visualization.

For instance, studies have explored the role of neuronal ensembles in controlling visually guided behavior and their influence on visual working memory (Carrillo-Reid et al., 2019). Research has also delved into the use of aggregated plots for multidimensional visual analysis, although these don't explicitly mention ensembles (Fofonov & Linsen, 2018).

Fast ensemble representations have been investigated to understand high-level perceptual impressions based on visual information (Leib et al., 2016).

Additionally, the aesthetic complexity of visual information has been quantified using information theory, offering a potential framework for ensemble-based representations (Karjus et al., 2023). But a detailed example of why you shouldn't use aggregated plots for multidimensional visual analysis is when the individual data points in the ensemble show significant differences. Data aggregation may obscure important patterns in such scenarios and lead to misleading interpretations. Further, ensembles may fail to capture the fine-grained details and nuances present in the individual plots, compromising the overall accuracy and precision of the analysis. The long-term stability of neuronal ensembles in the visual cortex has been studied, shedding light on their potential role in visual perception (Pérez-Ortega et al., 2021). Ensemble visualization techniques, particularly in computer simulations, have also been reviewed (Afzal et al., 2019). Lastly, the structure of neural networks has been shown to affect working memory, which could have implications for visual ensembles (Leavitt et al., 2017).

#### 4.1.3 Bland-Altman Plots

The study of multidimensional ensembles has seen applications in the field of data visualization. (Szafir, 2017) showed that understanding color differences could improve the design of visualizations that require the viewer to integrate multiple pieces of information. This work suggested that effective visualization tools could be designed by leveraging the human ability to process multidimensional ensembles rapidly.

Bland-Altman Plots are widely used in clinical research for assessing the agreement between two measurement techniques by plotting the differences against the means (Bland & Altman, 1986). They offer a straightforward representation of data, making them a popular choice for visualizing measurement bias. However, the plots are conventionally one-dimensional, primarily focusing on mean differences and limits of agreement.

#### 4.1.4 The intersection of Multidimensional Ensembles and Bland-Altman Plots

The application of multidimensional ensembles in Bland-Altman Plots could potentially offer a more nuanced understanding of data. For example, integrating color coding to indicate standard deviation and shape variations to indicate skewness could offer additional layers of information in a single plot (Szafir, 2017). Such an approach could leverage our innate abilities in ensemble perception to offer a more comprehensive assessment of agreement between multiple sets of measurement techniques (Szafir, Haroz, Gleicher, & Franconeri, 2016).

#### 4.1.5 Gaps in Research

While the fields of ensemble perception and data visualization have seen significant growth, there is a lack of research focusing on the application of ensemble perception, particularly multidimensional ensembles, in Bland-Altman Plots. This gap points to the need for empirical studies designed to validate theoretical frameworks and to assess the practical utility of incorporating multidimensional ensembles into Bland-Altman Plots.

### 4.2 Methods:

Ensemble perception involves the rapid and often unconscious extraction of summary statistics from a set of similar items (Chong & Treisman, 2003), (Whitney et al., 2014). In the context of multidimensional ensembles, this would refer to the simultaneous extraction of various features such as mean, variance, and other statistical attributes across multiple dimensions (Maule & Franklin, 2015), (J. Haberman et al., 2015). Understanding this concept will provide a unique way to interpret Bland-Altman plots that contain data from multiple dimensions.

Traditionally, Bland-Altman plots present the difference between two sets of measurements against their mean, providing a graphical representation of agreement or bias. However, this one-dimensional representation might not capture the full complexity of real-world data, where measurements can often be multidimensional (Dakin & Watt, 1997). Given the human brain's ability to rapidly process multidimensional ensemble statistics (J. Haberman et al., 2015), incorporating this aspect into Bland-Altman plots might yield a more nuanced interpretation (Bauer, 2009), (Szafir et al., 2016).

One way to incorporate multidimensionality into Bland-Altman plots is by adding layers that represent different statistical attributes. For example, varying shades of color could indicate the standard deviation within each plotted point, and shape variations could indicate another dimension such as skewness or kurtosis (Szafir, 2017). This model would require human observers to simultaneously extract multiple summary statistics, leveraging the brain's capabilities in ensemble perception (Chong & Treisman, 2003).

In this proposed study, we utilize color coding to represent varying levels of variability in Bland-Altman plots. To ensure the universal interpretability of the plots (Ware, 2012), the color palette will be selected with care, taking into account potential issues such as color blindness.

For this study, two Bland-Altman plots will be generated. A traditional plot without color-coding and a plot using the color-coding technique we propose. Both plots will be presented to a group of participants that includes both experts and non-experts in data interpretation and statistics. The participants will be required to interpret the plots and complete a questionnaire to assess their comprehension and speed of interpretation.

For a layer of interactivity in our study, we will generate interactive Bland-Altman plots incorporating ensemble coding of variability through color gradations. Interactivity will be implemented via D3, providing detailed information about each data point when hovered over, as well as zoom features allowing users to zero in on areas of interest.

#### 4.2.1 Design of the User Studies

User studies will be designed to assess the effectiveness of the interactive Bland-Altman plots in conveying information about the variability of data points. The studies will consist of two parts:

**Task-based Evaluation:** Participants will be given a set of tasks to complete using both the interactive color-coded Bland-Altman plot and a traditional static Bland-Altman plot. Tasks will involve identifying specific data points, interpreting data variability, and answering questions about the overall data trend. Metrics such as task completion time, success rate, and error rate will be recorded (Rubin & Chisnell, 2008).

**Subjective Evaluation:** After completing the tasks, participants will be asked to fill out a questionnaire assessing their user experience. The questionnaire will include items related to the perceived ease of use, satisfaction, and preference between the traditional and interactive color-coded Bland-Altman plots.

### 4.3 Discussion:

We anticipate that the application of ensemble coding for variability will aid in the comprehension of Bland-Altman plots. Based on ensemble coding principles, the color-coded plot should enable faster and more accurate interpretation of data variability (J. Haberman & Whitney, 2012). This method has the potential to enhance the interpretability and utility of these graphs, making them accessible to a broader audience and facilitating more efficient data communication.

## Conclusion

If we don't want Conclusion to have a chapter number next to it, we can add the `{-}` attribute.

### More info

And here's some other random info: the first paragraph after a chapter title or section head *shouldn't be* indented, because indents are to tell the reader that you're starting a new paragraph. Since that's obvious after a chapter or section title, proper typesetting doesn't add an indent there.

## Appendix A

### The First Appendix

This first appendix includes all of the R chunks of code that were hidden throughout the document (using the `include = FALSE` chunk tag) to help with readability and/or setup.

#### In the main Rmd file

```
library(knitr)
library(palmerpenguins)
library(tidyverse)
library(nycflights13)
data(flights)

library(ggpcp)
library(ggplot2)
library(dplyr)
data(nasa)

library(scales)
library(datasets)
data("ChickWeight")
library(formatR)
```

In Chapter 4:

## Appendix B

### The Second Appendix, for Fun

## Colophon

This document is set in **EB Garamond**, **Source Code Pro** and **Lato**. The body text is set at 11pt with *lmr*.

It was written in R Markdown and *LATEX*, and rendered into PDF using **huskydown** and **bookdown**.

This document was typeset using the XeTeX typesetting system, and the **University of Washington Thesis class** class created by Jim Fox. Under the hood, the **University of Washington Thesis LaTeX template** is used to ensure that documents conform precisely to submission standards. Other elements of the document formatting source code have been taken from the **Latex**, **Knitr**, and **RMarkdown templates for UC Berkeley's graduate thesis**, and **Dissertate: a LaTeX dissertation template to support the production and typesetting of a PhD dissertation at Harvard, Princeton, and NYU**

The source files for this thesis, along with all the data files, have been organised into an R package, `xxx`, which is available at <https://github.com/xxx/xxx>. A hard copy of the thesis can be found in the University of Washington library.

This version of the thesis was generated on 2023-09-17 18:09:04. The repository is currently at this commit:

The computational environment that was used to generate this version is as follows:

```
## - Session info -----
## setting value
##   version R version 4.2.2 (2022-10-31)
##   os       macOS Big Sur ... 10.16
##   system  x86_64, darwin17.0
##   ui       X11
##   language (EN)
##   collate en_US.UTF-8
##   ctype    en_US.UTF-8
##   tz       America/Detroit
##   date     2023-09-17
##   pandoc  2.19.2 @ /Applications/RStudio.app/Contents/Resources/app/quarto/bin/tools/
##
## - Packages -----
##   package      * version date (UTC) lib source
##   assertthat     0.2.1   2019-03-21 [1] CRAN (R 4.2.0)
##   bookdown      0.33    2023-03-06 [1] CRAN (R 4.2.0)
##   cachem        1.0.7   2023-02-24 [1] CRAN (R 4.2.0)
##   callr         3.7.3   2022-11-02 [1] CRAN (R 4.2.0)
##   cli           3.6.1   2023-03-23 [1] CRAN (R 4.2.0)
##   colorspace    2.1-0   2023-01-23 [1] CRAN (R 4.2.0)
##   crayon        1.5.2   2022-09-29 [1] CRAN (R 4.2.0)
##   devtools      2.4.5   2022-10-11 [1] CRAN (R 4.2.0)
##   digest        0.6.31  2022-12-11 [1] CRAN (R 4.2.0)
##   dplyr        * 1.1.2   2023-04-20 [1] CRAN (R 4.2.0)
##   ellipsis      0.3.2   2021-04-29 [1] CRAN (R 4.2.0)
##   evaluate      0.21    2023-05-05 [1] CRAN (R 4.2.0)
##   fansi         1.0.4   2023-01-22 [1] CRAN (R 4.2.0)
```

```
## farver           2.1.1   2022-07-06 [1] CRAN (R 4.2.0)
## fastmap          1.1.1   2023-02-24 [1] CRAN (R 4.2.0)
##forcats          * 1.0.0   2023-01-29 [1] CRAN (R 4.2.0)
##formatR          * 1.14    2023-01-17 [1] CRAN (R 4.2.0)
##fs                1.6.2   2023-04-25 [1] CRAN (R 4.2.0)
##generics         0.1.3   2022-07-05 [1] CRAN (R 4.2.0)
##ggpcp            * 0.2.0   2022-11-28 [1] CRAN (R 4.2.0)
##ggplot2          * 3.4.2   2023-04-03 [1] CRAN (R 4.2.0)
##glue              1.6.2   2022-02-24 [1] CRAN (R 4.2.0)
##gtable             0.3.3   2023-03-21 [1] CRAN (R 4.2.0)
##hms                1.1.3   2023-03-21 [1] CRAN (R 4.2.0)
##htmltools         0.5.4   2022-12-07 [1] CRAN (R 4.2.0)
##htmlwidgets       1.6.2   2023-03-17 [1] CRAN (R 4.2.0)
##httpuv             1.6.9   2023-02-14 [1] CRAN (R 4.2.0)
##knitr              * 1.42    2023-01-25 [1] CRAN (R 4.2.0)
##labeling            0.4.2   2020-10-20 [1] CRAN (R 4.2.0)
##later               1.3.0   2021-08-18 [1] CRAN (R 4.2.0)
##lifecycle          1.0.3   2022-10-07 [1] CRAN (R 4.2.0)
##lubridate          * 1.9.2   2023-02-10 [1] CRAN (R 4.2.0)
##magrittr            2.0.3   2022-03-30 [1] CRAN (R 4.2.0)
##memoise             2.0.1   2021-11-26 [1] CRAN (R 4.2.0)
##mime                 0.12    2021-09-28 [1] CRAN (R 4.2.0)
##miniUI              0.1.1.1  2018-05-18 [1] CRAN (R 4.2.0)
##munsell             0.5.0   2018-06-12 [1] CRAN (R 4.2.0)
##nycflights13     * 1.0.2   2021-04-12 [1] CRAN (R 4.2.0)
##palmerpenguins    * 0.1.1   2022-08-15 [1] CRAN (R 4.2.0)
##pillar              1.9.0   2023-03-22 [1] CRAN (R 4.2.2)
##pkgbuild            1.4.0   2022-11-27 [1] CRAN (R 4.2.0)
##pkgconfig            2.0.3   2019-09-22 [1] CRAN (R 4.2.0)
##pkgload              1.3.2   2022-11-16 [1] CRAN (R 4.2.0)
##prettyunits          1.1.1   2020-01-24 [1] CRAN (R 4.2.0)
```

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## processx           3.8.1   2023-04-18 [1] CRAN (R 4.2.0)
## profvis            0.3.7   2020-11-02 [1] CRAN (R 4.2.0)
## promises           1.2.0.1  2021-02-11 [1] CRAN (R 4.2.0)
## ps                  1.7.5   2023-04-18 [1] CRAN (R 4.2.0)
## purrr               * 1.0.1   2023-01-10 [1] CRAN (R 4.2.0)
## R6                  2.5.1   2021-08-19 [1] CRAN (R 4.2.0)
## RColorBrewer        1.1-3   2022-04-03 [1] CRAN (R 4.2.0)
## Rcpp                 1.0.10  2023-01-22 [1] CRAN (R 4.2.0)
## readr                * 2.1.4   2023-02-10 [1] CRAN (R 4.2.0)
## remotes              2.4.2   2021-11-30 [1] CRAN (R 4.2.0)
## rlang                 1.1.1   2023-04-28 [1] CRAN (R 4.2.0)
## rmarkdown             2.20    2023-01-19 [1] CRAN (R 4.2.2)
## rstudioapi           0.14    2022-08-22 [1] CRAN (R 4.2.0)
## scales                * 1.2.1   2022-08-20 [1] CRAN (R 4.2.0)
## sessioninfo          1.2.2   2021-12-06 [1] CRAN (R 4.2.0)
## shiny                 1.7.4   2022-12-15 [1] CRAN (R 4.2.0)
## stringi               1.7.12  2023-01-11 [1] CRAN (R 4.2.0)
## stringr               * 1.5.0   2022-12-02 [1] CRAN (R 4.2.0)
## tibble                * 3.2.1   2023-03-20 [1] CRAN (R 4.2.0)
## tidyverse              * 2.0.0   2023-02-22 [1] CRAN (R 4.2.0)
## timechange            0.2.0   2023-01-11 [1] CRAN (R 4.2.0)
## tzdb                  0.3.0   2022-03-28 [1] CRAN (R 4.2.0)
## urlchecker            1.0.1   2021-11-30 [1] CRAN (R 4.2.0)
## usethis               2.1.6   2022-05-25 [1] CRAN (R 4.2.0)
## utf8                  1.2.3   2023-01-31 [1] CRAN (R 4.2.0)
## vctrs                  0.6.2   2023-04-19 [1] CRAN (R 4.2.0)
## withr                  2.5.0   2022-03-03 [1] CRAN (R 4.2.0)
## xfun                   0.37    2023-01-31 [1] CRAN (R 4.2.0)
## xtable                 1.8-4   2019-04-21 [1] CRAN (R 4.2.0)
```

```
## yaml           2.3.7   2023-01-23 [1] CRAN (R 4.2.0)
##
## [1] /Library/Frameworks/R.framework/Versions/4.2/Resources/library
##
## -----
```

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