# DESIGN JUDGMENTS IN INFORMATION VISUALIZATION DESIGN

by

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# ABSTRACT

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Design form choices and information visualization outcomes remain inexhaustible, and they result from ongoing judgments about their appropriateness or effectiveness. Visualization design decision models have been widely proposed and applied. However, experts fail to explicitly study using design judgment to produce informed, professional decisions. In this dissertation, I bridge design form informational judgment gap when analyzing five studies with lab and in-situ designs individually as well as cross-case synthetically and comparably to examine the design judgments of all students working with visualization projects. The outcome stands to explain comprehensively how these student designers make judgments throughout their design process. Through analyzing several design cases, I identify the judgments enabling design moves forward and outcomes. The findings provide a robust description of designers' design judgment activities and how the design judgment methods relate to design outcomes. These findings may also help identify gaps in information visualization education.

# CHAPTER 1. **INTRODUCTION**

This chapter provides an overview of this research study and introduces important background information on persistent design judgment in a communication-oriented visualization design context. This chapter also includes a description of the study's significance, the statement of purpose, and the corresponding research questions. Furthermore, the assumptions, limitations, and delimitations of the study are included in this chapter. Finally, the chapter concludes with a preview of the dissertation's contents.

## 1.1 Background

In this information proliferation era, most people, even those who work outside of information visualization (InfoVis) and related domains, are exposed to visualization types and varieties (Fekete, Wijk, Stasko & North, 2008; Spence, 2001). With this in mind, visualization designers and researchers continue to conduct intensive design research and adopted practices to innovate and improve information visualization in many ways.

Design exemplifies an intentional activity in nature (Galle, 1999; Nelson & Stolterman, 2012). In the information visualization design context, developers and designers explore and create meaningful, reasonable, intuitive, and innovative visualizations in order to help users access and communicate insights accurately and efficiently (Card, Mackinlay, & Shneiderm, 1999; Krum, 2013). Thus, information visualization may serve two purposes: analytics and communication (Card et al., 1999). Communication-oriented visualization design encompasses artistic creation and conveys complex information in an aesthetically pleasing way. Design engenders making decisions exerting a real impact on the world we live in (Nelson & Stolterman, 2012). However, the InfoVis design space proves vast. Depending on the intended communication, data representation comprised a plethora of forms, such as a bar chart, pie chart, scatter plot, or flow diagram with different colors, sorting, filtering, and zooming (Stone, 2006; Yi, Kang, & Stasko, 2007). The possibility for designers to consider the infinite number of design forms and representations proves impossible. The challenges of visualizing data entail its diverse design purposes, rationalized visual forms, representations, and interaction approaches (Plaisant, 2004). Hence, information visualization design requires that designers learn how to make strong design judgments and use them routinely in their work. Specially, designers use design judgments to choose a form, or combine multiple forms, to achieve a particular design objective, which is the most prevalent design behavior. To date, a research dearth remains on how designers make informed design judgments, which is a central part of designers' jobs. Hence, this dissertation seeks to fill the designer void.

In information visualization courses, professors primarily teach students computing algorithms, design principles, and visualization techniques that will help them perform their work without needing to make judgments (Nelson & Stolterman, 2003). However, to create solutions with definite design choices that addresses real-world problems, designers must learn how to compare, judge, and make balanced trade-offs among design choices to apply rational design behaviors. One ideal solution would be to form a design process with methods and tools, that is, a process that is independent of the designers' ability to make judgments (Nelson & Stolterman, 2003).

To overcome design difficulties and optimize design outcomes, designers and researchers investigate and apply sound design activities. Design wisdom portrays strong design judgment with mental function (Nelson & Stolterman, 2012), which is a significant component of creativity, innovation, and rationality for any design type (Nelson & Stolterman, 2012). However, design judgment does not depict simple replication of making design decisions (Ang, 2007)., for it embodies designers' conscious and unconscious design thinking and covers diversity and divergence into focus. Simply, design conceptualizes and formulates designer ideas, making their design communicable and comprehensible in complex, real-world situations (Fraenkel, Wallen, & Hyun, 1993; Nelson & Stolterman, 2012). Improving and practicing designers' capabilities to enhance rational design judgments provide the key to obtaining access to their design wisdom (Nelson & Stolterman, 2012; Petroski, 1994).

Information visualization researchers have acknowledged the vital role of design judgment in proper visual and interactive forms that represent data. Wolf et al. (2006) described design judgment as a vehicle to inspire an informed decision with a particular visualization object and relevant context (McKenna, Mazur & Agutter, 2014; Wolf, 2006). McKenna and colleagues (2014) also illuminated prevailing empirical literature categorized decision-making into varying high-level design judgments, such as *framing, appreciate, appear, compositional,* and *navigational*, etc. (Nelson & Stolterman, 2012; Wolf, 2006). Within the visualization community, a well-cited nested design decision model, which characterizes visualization design decisions as occurring on one of four levels interpret design decision-making comprehensively (McKenna et al., 2014; Munzner, 2009). However, dominant existing literature fails to capture the comprehensive design judgment behavior of visualization designers or described how visual designers assess, appreciate, and make appropriate decisions. Because the InfoVis Research Lab in which I had developed many interactive visualization systems, we were able to reflect on personal design decision making and identify a need for a comprehensive understanding of the visualization design judgment behaviors. The research paucity sparked me to study how design judgments optimized decisions and enhanced necessary outcomes in visualization design.

Questions, if answered, would help visualization researchers and designers understand what and how design judgments occur enabling informed, professional decision-making. What design judgments do visualization designers make during their particular visualization design practice? How do design judgments form over time for each visualization design process? Which factors influence visualization designers' design judgments?

Therefore, answering these questions holds the goal of this research. Using the perspective of students working with visualization projects to identify explicitly the design judgments that enable designer moves and outcomes, I will examine the circumstances related to design judgment, methods related to design outcomes, and identify gaps in information visualization design education.

## 1.2 Significance

Design form choices and information visualization outcomes proves inexhaustible, and they result from ongoing judgments about their appropriateness or effectiveness. Experts widely propose and apply visualization design decision models. However, mavens fail to investigate explicitly using design judgment to produce informed, professional decisions. This research bridges the gap and makes a substantive contribution to the design area of the visualization design field.

By describing and explaining visualization design judgments phenomenon with qualitative research, I believe designers and developers can better understand how and why their design judgments occur particularly in visualization design contexts. They can then learn and apply the best design judgments to achieve their desired designs. This research may also help students better comprehend the complex and design nature of information visualization, so that that they can form well-crafted decisions.

## 1.3 Statement of Purpose

Considering visualization design as a series of judgments enables designers and developers to represent data insights. Visualization designers should understand, learn, and apply judgments to their design choices to construct informed, professional design decisions, actions, and outcomes. This research bridges a gap in the visualization design field and serves three main purposes:

1. To gain an overarching perspective to understand design judgments in information visualization design.
2. To summarize design judgments for producing information visualization design results.
3. To guide design judgments' methods and applications for producing information visualization design.

## 1.4 Research Questions

The research questions central to this research:

1. What are the existences of design judgments in particular information visualization design process? In other design domains, researchers have summarized eleven types of judgments move toward outcome design. This question aims to examine if and how these judgments exist in information visualization design.
2. How do design judgments occur in particular information visualization design? This question was supposed to examine and identify designers' design judgments behaviors in the key processes within specific design stages.
3. What are the factors influencing design judgments? This question aims to examine and explore how different factors, internal or external, such as design knowledge, design goal, and client's need, etc. influence designer design judgments in particular information visualization design.

## 1.5 Assumptions

The following assumptions remained inherent in the pursuit of this research:

1. The participants naturally performed the design practices without any pretense during the studies.
2. The selected participants' tasks typical represented those of student designers who worked on visualization projects.
3. The participants responded to all provided tasks to the best of their abilities.
4. The participants honestly answered the interview questions.
5. The participants understood the task instructions and the instruments stood appropriate for their abilities.
6. The background knowledge, learning, and working experience of the participants affected their design judgments, outcomes, and the final decision makers.

## 1.6 Limitations

The following limitations held inherent in the pursuit of this research:

1. The data was gathered from a limited number of volunteer participants, including individual students and student design teams.
2. The collected data reflected participants' design judgment activities for a specific design without evaluations. Visualization design is generally long-term, which accompanied by several design iterations and evaluations.
3. It would have been harder to control for extraneous variables and the scientific method in a natural environment. Also, it might have caused some irrelevant data to be collected and analyzed.

## 1.7 Delimitations

The following delimitations stood inherent in the pursuit of this research:

1. This study confined itself to observing the designers and design teams, including students from Colleges of Art and Design, Engineering, and Technology. The targeted participants represented student designers.
2. This research confined itself to typical design judgment activities, and the investigator was involved in each significant design node.

3. The research confined itself to achieving sufficient results to show the most authentic aspects of the designers' information visualizations.

## 1.8 Definitions of Key Terms

The following term definitions will assist the reader:

**Communication-oriented visualization**: to produce visually effective visualizations of their data, present stories, and thus better represent, support, and communicate their findings (Few, 2013; Spence, 2001; Wileman, 1993); thus it, remains concerned with artistic creation and conveys complex information in an aesthetically pleasing way (Few, 2013).

**Design decision (model)**: design as making decisions. For example, a well-sited (nested) model characterizes and identifies visualization design decisions occurred at one of four levels, including domain characterization, data and task abstraction, visual encoding and interaction, and algorithm (Munzner, 2009).

**Design judgment**: a key dimension of design activity describing the informed, professional decision-making process regarding a particular design objectives and contexts (Chupin, 2011; Nelson & Stolterman, 2012; Seery, 2012; Wolf, 2006).

**Design wisdom**: strong design judgments (Nelson & Stolterman, 2012) based on the "rule of rightness" that takes into account the priorities, applications, and meanings of different design domains (Vickers, 1965).

**Divergent/convergent process**: a design process typically represented as wave, for broadens and narrows until the ultimate design solution is selected (Brown, 2010; Ogilvie, 2011). Divergent means thinking widely to incorporate unusual solutions, offbeat ideas, and to expand the solution set as widely as possible before narrowing down to one decision (Brown, 2010; Ogilvie, 2011). Convergent entails using the information to narrow in on one specific facet of a problem to tackle (Brown, 2010; Ogilvie, 2011). Since brings diversity and divergence into focus, design judgment embodies a convergent process; that is, it formulates a comprehension to aspects of messy and complicated real-world situations (Nelson & Stolterman, 2012).

**Visual representation**: to encompass various visualization forms involving data selection, transformation, and presentation (Lurie & Mason, 2007). The selection of applicable graphs, charts, diagrams, and forms that can present spatial, abstract, physical and textual data represents the first step of visualization (Lurie & Mason, 2007; Mitchell, 1995). The transformational step displays transitioning from data to insights via visual techniques/graphical features such as color, size, scale, texture, orientation, and location, etc. (Horn, 1998; Bocker, 1986) In the final stage of presentation, the developers usually do their best to display data patterns and outliers when they refine the transformation process with visualization tools and techniques (Lurie & Mason, 2007). It brings diversity and divergence into focus.

**User's cognitive processing**: cognition science also affects design judgment. Cognitive processing is a major step for knowledge, understanding, and insights (Ware, 2012). Cognition encompasses the mental actions and processes in human beings, such as perception, attention, comprehension, and interpretation, memory, judgment and decision making as well as problem-solving (Neisser, 1976). In visualization studies, existing researchers have discussed users' cognitive process as reflecting four distinctive processes: providing an overview, adjusting, detecting pattern, and matching mental of obtaining insights (Yi, 2008).

## 1.9 Overview of Study

Within the visualization design domain, pundits have proposed and applied design process and decision-making studies. One prominent example depicts is a nested design decision model (Munzner, 2009), indicating that visualization design decisions generally occur during one of the four stages: including domain characterization, data and task abstraction, visual encoding and interaction, and algorithm. However, experts fail to explore how design judgment operates as a vehicle to produce informed, professional decisions. Previous researchers such as (Denzin, 2005) have undertaken qualitative methodology as an effective strategy allowed an investigation to explore and explain real-life events/complex phenomena, which never required a strict boundary between research objects and their contexts such as visualization design behaviors and their associated situations (Denzin, 2005; Kaplan, 2005; Lewis, 2015). Therefore, the qualitative research seemed to be the best method of answering the questions posed in this research and had the potential to provide a unique contribution to the visualization design domain.

The research questions addressed in this study intended to reveal how visualization design judgments developed and occurred. The purpose was to examine the design judgments of students working on design aspects of visualization projects. The findings aided to (1) identify design judgments that enable visualization designer actions and outcomes; (2) support a comprehensive description and explanation of visualization design behaviors, and the methods that relate to the design outcomes; (3) identify the gaps in design judgments in information visualization design education.

This research used the qualitative methodology to examine and describe the complex visualization design judgment phenomena and associated contexts with focused “how” and “why” questions (Denzin, 2005). I combined lab and in-situ study designs and applied analytic reporting to present the research in a way that the reader could understand (Dooley, 2002). Qualitative research provided different kinds of evidence, figures, statements, and documents that are linked together to support a strong and relevant, robust conclusion (Runeson & Host, 2009) describing visualization designers’ behaviors and judgment activities.

## 1.10 Organization

This dissertation includes eight major chapters and several appendices. Chapter 2 features a literature review of design studies in the information visualization domain and design judgments in broader design fields. It begins with a brief overview of the scientific and artistic attributes as well as existing research on the design process and decision-making (model) in information visualization design. The chapter then discusses the types, contexts, and influences of design judgments. Finally, it illuminates visualization design portrays a decision-making process and how design judgments affect the resulting design hold significant considerations.

Chapter 3 outlines an overview of the methodology used in the research. This chapter details the discussion of the qualitative research method, including data collection and combined framework and (deductive) thematic analysis procedures.

Chapter 4 explains the findings and insights of two laboratory studies using structural and ordered narratives: design judgment existence, design judgment occurrence, and design judgment influencing factors. The chapter then supports the results of study synthesis and comparisons.

Chapter 5 provides the interpretations and explanations of design judgment behaviors in three in-situ studies with the focus on research questions of occurrence and influencing factors.

Chapter 6 discusses the findings revealed Chapter 4 and 5. By linking and comparing existing research, this chapter also explains the significance of insights in this study.

Chapter 7 proposes recommendations to improve a particular design situation for novice designers and enhance visualization design education based on the highlighted patterns.

Chapter 8 concludes the study to help the reader understand why this research matters: research contributions; chapter main points; limitations of this research; and recommendations for subsequent research.

## 1.11 Summary

This chapter provided an overview of the dissertation's format. It summarized the study's background, significance, and statement of purpose. Furthermore, it includes the research questions, assumptions, limitations, delimitations, and key terms' definitions of the study were included in this chapter. The next chapter provides an overview of design studies in information visualization, and covers design judgment importance, design judgment applications in border design domains, as well as identifies the gap in design judgments in visualization design research.

# CHAPTER 2. **REVIEW OF RELEVANT LITERATURE**

Visualization design activities are intentional and either analytics or communication oriented (Card, et al., 1999). The purpose of analytics is to (1) understand the data; (2) derive the information from data; and (3) comprehend the data (Card, et al., 1999). Alternatively, communication-oriented visualization aims to (1) communicate and (2) simplify the information (Card, et al., 1999). Visualization design utilizes humans' broad visual pathways to communicate the information by providing the readers with rapid interpretation, obvious outliers, and insightful explorations (Fekete et al., 2008). For instance, one visualization "What are you going to do with that degree?" (Schmidt, 2013) applied a Sankey diagram to communicate information about how college majors relate to professions simply and effectively. Another visualization called "Where do college graduates work?" (U.S. Census Bureau, 2014), communicated to the users with (1) the relationship between college majors and occupations; (2) identified major and employment patterns by sex, race, and Hispanic origin; and (3) revealed the proportion of graduates who are employed in STEM fields based on the demographics by a modular design with a chord diagram and filter tabs. Communication-oriented visualization requires a demanding, user-friendly design for an audience with various backgrounds and knowledge, and must address a wide variety of tasks and problems (Ware, 2012). In light of this, the visualization designs that employ various decision-making and judgment strategies are particularly important.

Chapter 2 details the nature of information visualization design regarding its scientific and artistic attributes, design principles, design processes, and design decision models. The chapter examines types, contexts, and influence factors to provide an overview of design judgment studies in diverse design domains. Finally, the chapter discusses how judgments affect visualization design through design activities and behaviors, which this research will further explore and explicate.

## 2.1 Information Visualization Scientific Attributes

Information visualization depicts a science and is typically viewed as an analytical tool for data exploration, hypothesis formation, and sensemaking (Card et al., 1999; Viegas & Wattenbegr, 2007). With accurate information, communication-based visualization uses technology, utilizes computer graphics and interactions to assist humans to solve problems, detecting patterns, identifying outliers and anomalies (Few, 2009; Keim, 2008; Plaisant, 2004). In practice, many existing studies have revealed the scientific foundations of visualization design, such as data structure, perception and cognition (Card et al., 1999; Ware, 2012).

### 2.1.1 Information Visualization Data Structure

In 1996, Shneiderman (1996) discussed how researchers and designers represented detailed information with seven typical data types including 1-, 2-, 3-dimensional data, temporal and multi-dimensional data, tree and network data. Keim (2002) then added algorithms and software.

Among these data types (Keim, 2002; Shneiderman, 1996), 1-dimensional visualizations work best for linear data, such as well-organized sequential textural documents, alphabetical lists of categories, and program source code, etc. Some approaches, like bifocal display (Apperley, Tzavaras, & Spence, 1982), scrollbar-like display (Chimera, 1992), compact display (Eick, Steffen, & Summer, 1992) are often used as typical examples to explain how to present 1-dimensional data. Two-dimensional data are commonly visualized with geographic maps (Laurini & Thompson, 1992; Egenhofer, 1993), floorplans (Gao et al., 2014; Yan, Culp, & Graf, 2011), even newspaper layouts (Eden, 2009; Francisco-Revilla & Crow, 2009). Three-dimensional data often represent real-world objects, like the human bodies, buildings, and molecules. They also embody a concentrated reflection of a scientific visualization domain with famous examples such as Mayavi (Ramachandran, 2011), V3D (Peng, 2010), and Cone trees (Robertson, Mackinlay & Card, 1991). Timelines provide widely users with historical information (Andrienko, Andrienko, & Gatalasky, 2003; Viegas, Wattenberg, & Kushal, 2004), project management (Aigner & Miksch, 2006), medical records (Plaisant, Mushlin, Snyder, & Li, 2003; Wang, Giesen, McDonnell, Zollike, & Mueller, 2008), etc. The Parallel Coordinates (PCS) visualization portrays one common way to visualize and analyze multi-dimensional geometry (Inselberg & Dimsdale, 1987). Other examples include spreadsheet-like Table Lens (Rao & Card 1994), multiple linked histograms (Roberts & Tweedie, 1996), and VisDB multi-dimensional data explorations (Keim & Kriegel, 1994). Tree/hierarchical data structures present single or multiple data attributes illustrate a relationship between parents and children (Shneiderman, 1992). The node and link diagrams such as Spacetree (Plaisant, Grosjean, & Bederson, 2002), reveal global patterns of connectivity and tree map. Experts (Asahi, Turo, & Shneiderman, 1995) apply analytic hierarchies to sales data, business decision-making, and computer directories. Network visualizations with network data structures demonstrate relationships among items that cannot be conveniently captured by a tree structure (Shneiderman, 1996). For example, Breitkreutz, Stark, and Tyers (2003) developed Osprey to manipulate complex relationships between items and interaction networks. In 2013, a network visualization named BrainNet Viewer portrayed the human brain's complexity using connectomics (Xia, Wang, & He, 2013). Finally, the visualizations helping understand algorithms, for they are based on the algorithm and classes support software developement (Keim, 2002). For instance, the evolution matrix (Lanza, 2001), Javavis (Oechsle & Schmit, 2002), and Voronoi treemaps (Balzer, Deussen, & Lewerentz, 2005).

### 2.1.2 Information Visualization Cognition

Besides complex data structures, visualization helps eliminate the gray area of human perception and cognition (Ware, 2012) because it also remains scientifically rooted in preattentive visual processing (Treisman, 1986; Healey, 2007), gestalt principles of perception (Koffka, 2013; Köhler, 1967), and color perception theories (Ware, 2012; Buchsbaum, 1980) etc. Understanding perception and cognition can improve the quality and quantity of displayed information (Ware, 2012). Additionally, one crucial purpose of information visualization reflects utilizing the visual representations to illustrate abstract information and reinforce human cognition. Such visualizations help provide a clear presentation to the mind for obtaining insights (Card et al, 1999; Spence, 2001). Thus, visual representations and cognition constitute two vital concepts. The visualization design process matches designer's design cognition to the user's cognition. The designer's design cognition and design thinking reflect the ways the individual constitutes and applies the visual representations. Key empirical studies have investigated the relationship between visual representations and perception and cognition (Card et al, 1999; MacEachren, 2004; Ware, 2012), which have discussed comprehension and interpretation, memory, judgment, and decision-making.

In the following sections, I review existing research on perception and cognition as two of the most essential scientific attributes in the visualization design domain. Then, I discuss the relationship between visual representations, perception and cognition.

#### 2.1.2.1 Preattentive Processing

In 1985, vision researchers and developers discovered a limited set of visual properties that were rapidly and accurately detected with a low-level human visual system (Treisman, 1985). Five theories support these preattentive properties (Treisman, 1985): feature integration theory, texton theory, similarity theory, guided theory, and Boolean theory (Healey, 2007). Preattentive processing in visualization designs enables intuitive high-speed target detection, boundary identification, and region detection (Healey, 2007; Treisman, 1985), in which, the particular visual tasks entail target detection, boundary detection, region tracking, counting and estimation (Healey, 2007). The following image combination reflects the preattentive visual task of detecting targets. Understanding preattentive attributes help visualization researchers and designers create visuals to emphasize the most important information while ensuring other elements compete for attention (Healey, 2007).

#### 2.1.2.2 Change Blindness

Change blindness portrays a perceptual phenomenon that occurs when a change in a visual stimulus occurs and the observer fails to notice it (Simons & Levin, 1997). Since change blindness recognized major changes and ignores minor ones, it aids cognitive and perceptive science (Nowell, Hetzler, & Tanasse, 2001). Particularly, its impact on visualization reflects the importance of attracting attention solely to significant details in subsequent visuals (Nowell, et al., 2001; Ware, 2012). For instance, Nowell et al. (2001) described the cognitive science theories that accounted for change blindness using a case study, which sought to help users choose which documents and information deserved attention, so that they could perform information triage tasks. Their team also tested the solutions that for two visual analysis tools: “a dot plot” and “landscape” (Nowell et al, 2001).

#### 2.1.2.3 Cognition and Visual Representations Relationship

Using visual representations to help users see, explore, and understand large amounts of information through visual representations has always been a pertinent research topic in the information visualization domain (Ware, 2012). ***Visual representation*** encompasses various forms of visualization that involve the selection, transformation, and presentation of data (Lurie & Mason, 2007). Selection represents the first step of visualization, which aims to select the applicable graphs, charts, diagrams and forms to present data, and engenders spatial, abstract, physical and textual types of data (Lurie & Mason, 2007; Mitchell, 1995). Visualization tools demonstrates the transformational step, which transitions data into insights. Additionally, visualization tools use various algorithms to pre-process the raw data as well as the selected visual forms and graphs (Lurie & Mason, 2007). On the basis of these and other features, visualization techniques can transform data characteristics (Horn, 1998), including color, size, scale, texture, orientation, location, position, thickness, resolution, illumination, transparency, arrangement, added mark, motion, and slope to plot some dimensions. Examples include using different length, area, and volume to display the scale of a shape or using color to increase saliently categorical representation and demonstrate a shape's wood (Wang et al., 2008), as well as its density and quantity by its color hue.

These transformations exert a strong potential impact on the ultimate insights that individuals derive from the data (Bocker et al., 1986). Moreover, people use perceptual properties, including symmetry, alignment, collinearity, axis alignment and orthogonality (Marriott, Purchase, Wybrow, & Goncu, 2012) are used to create the layouts of visual representations. In the final stage of presentation, developers refine the transformation process with visualization tools and techniques to display patterns and outliers. For instance, they use marks and highlights to make some information more or less salient. Design and position layout enhance the data location information; choosing scatter plots rather than tables and parallel coordinates presents data outliers and relationships. Figure 2.1 outlies the relationships between selection, transformation and presentation.

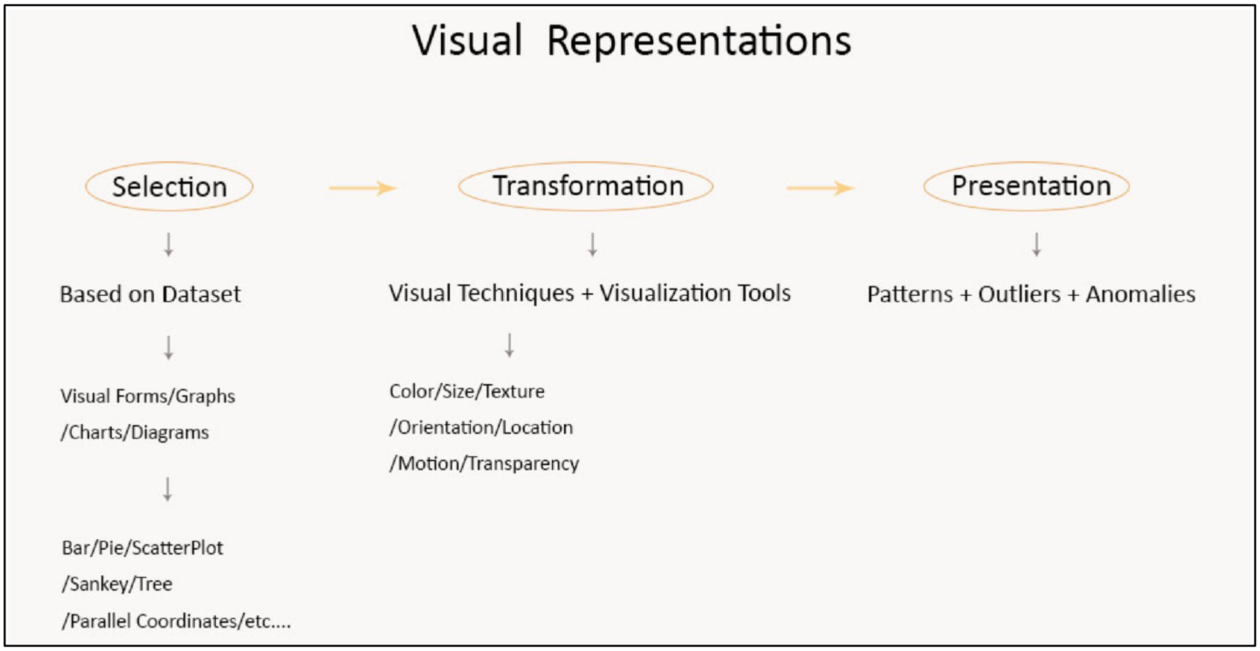



Figure 2.1 Selection, transformation, and presentation comprise visual representation.

Reinforced visual representations reduces the cognitive load and facilitates users gaining visualization insights. In addition to practicing and training their design cognition and design thinking, visualization designers need to understand the user's cognition. In other words, designers cannot successfully develop useful graphic visual representations without an understanding how humans perceive space (Tory & Moller, 2004). One example depicts knowing whether visualization holds necessary to present the relationships and correlations; therefore, designers must understand how humans make judgments and decisions about correlation (Tory & Moller, 2004).

#### 2.1.2.3.1 Perception and Visual Representations

Perception plays an important role in information visualization and information design (Healey, 2017). A thorough understanding of human perception can significantly improve both the quality and quantity of the information presented (Ware, 2012; Healey, 2017). Pre-attentive processing refers to an initial organization of the visual field based on cognitive operations, which are rapid, automatic, and spatially parallel (Healey, 2017). Pre-attentive processing applied in visualization designs and enables intuitive, high-speed target detection, boundary identification, and region detection (Healey, 2017). Gestalt principles, including the laws of figure/ground, similarity, proximity closure, and symmetry or order explain the rules of organization for complex visual fields (Ware, 2012).

Previous research has also focused on visual perceptions of visual representation, like color and size. Color perception occupied a large body of work in the visualization field (Wang et al., 2008). Color selection represents not merely an aesthetic choice but also a crucial tool to convey quantitative information (Wang et al, 2008). Perceptual portrays constantly perceiving familiar objects as possessing a standard shape, size, color, and location regardless of changes in perspective, distance, and transition, illustrates another significant concept in visual perception science (Walsh & Kulikowski, 1998). Vatavu, Anthony, and Wobbrock (2014) studied gesture performance with colorful visualizations and demonstrated gray-scale heat maps could result in perception errors. Pundits have also discussed the influence size exerts perception. Heer, Kong, and Agrawala (2009) revealed the effects of chart size on graphical perception in time series visualizations. Their results uncovered estimation error stayed stable with larger chart sizes, but smaller sizes could result in faster estimations (Heer et al., 2009). The research also elaborated on size perceptions by comparing visual representations on tabletops with multi-surface environments (Wigdor, Shen, Forlines, & Balakrishnan, 2007). They separately concluded positional perception held more accurate than the angle in the tabletop view. But in mixed display visualization, the angle stood more accurate than position (Wigdor et al., 2007). In addition, Bezerianos and Isenberg (2012) contended visual variables perception, including angles, areas, and lengths on tiled wall-sized displays impacted accuracy when viewers stood close to the wall but the result of each element were different (Bezerianos & Isenberg, 2012).

Empirical studies focus on visual forms, such as curves and rectangles, depicted how those forms improved object recognition. Bar and Neta (2006) After testing likes or dislikes based on 140 pairs of real objects (e.g., circular watch vs. rectangular watch), the authors explored why humans preferred curved visual objects. They concluded the sharpness of an object exerted a critical influence on a participant attitude (Bar & Neta, 2006). These results extended to other research on information visualization designs. This research investigated how people perceived rectangular visualizations, such as bar graphs. Bar charts can be used to complete the perceptual task of recognizing (Elzer, Green, Carberry, Sandra, & Hoffman, 2006), but bar graphs with extraneous depth cues affect readability (Zacks, Levy, Tversky, & Schiano, 1998).

#### 2.1.2.3.2 Comprehension and Interpretation and Visual Representations

Apart from perceiving the visual information, comprehending and interpreting the visual information exemplify the crucial steps. Visual Literacy (VL) represents defined usage of visual images to enhance the comprehensions and interpretations. John Debes first proposed VL in 1969 (Burmark, Visual literacy: Learn to see, see to Learn, 2002) elaborates as "the ability to understand (read) and use (write) images and to think and learn in terms of images, i.e. to think visually" (Avgerinou & Ericson, 1997). Kwon and Lee (2016) described VL as

> "a group of vision-competencies, a human-being can develop by seeing, and at the same time having and integrating other sensory experiences. The development of these competencies is fundamental to a normal human learning. When developed, they enable a visually literate person to discriminate and interpret the visible actions, objects, and symbols, either natural or man-made, that he encounters in his environment" (Avgerinou & Ericson, 1997).

Both Avgerinou (1997) and Sinatra (1986) proposed that virtual literacy illustrates a prerequisite to human thinking. In 2014 and 2015, Boy and colleagues (2014) used various research methods to investigate and assess visualization literacy. Boy et al. focused on building visualization literacy tests for line graphs, bar charts, and scatter plots. They developed the method based on "Item Response Theory" (IRT) and conducted six specific tasks to obtain participant scores. Based on 20 information visualizations and 273 visitors of science museums, Börner et al. (2016) illuminated people were more familiar with charts, maps, and graphs, but a very few were familiar with networks. In addition, in 2017, Lee (2017) sought to measure visual literacy and developed a test specifically for non-expert users in data visualization. Findings from the new measure indicated a positive correlation between users' visualization literacy and aptitude for learning an unfamiliar visualization.

#### 2.1.2.3.3 Attention and Visual Representations

Attention remains a major area of investigation within information and data visualization. Visual attention portrays the human behavioral and cognitive process of selectively concentrating on a discrete aspect of visual information (Healey & Enns, 2012). Prevailing studies have explored how visual representations affect attention.

In 1988, Ware explored how to display data dimensions in such a way to attract users' attention (Ware & Beatty, 1988). Ware et al. compared cluster resolution in both color and space, and found that color held an effective space extension for conveying information about data dimensions and also helped to draw users' attention (Ware & Beatty, 1988). In 2004, Wolfe and Horowitz found that guiding representations such as color, size, orientation, and line termination can be used to control attention (Wolfe, 2004). Moreover, Haroz and Whitney (2012) discussed how limits of individuals' attention capacity influence the effectiveness of information visualizations. Their experiments tested how visual features such as color versus motion, layout, and variety of other visual elements created an impact on user performance, and they then elucidated severe capacity attention limits strongly modulate information visualizations effectiveness (Haroz & Whitney, 2012). Moreover, Humphrey et al. (1994) showed that attention cueing effects to either the left or right side held specific to particular forms of visual representations. Furthermore, spatial spatially selective cues activated independently the within-object and between-object spatial representations (Humphreys & Riddoch, 1994).

##### 2.1.2.3.4 Memory and Visual Representations

Dominant trends in research has demonstrated visualization with particular visual representations possess the power to make items more memorable. By selecting different visual forms, Borkin et al., (2013) used 2,070 single-panel visualizations, ranging from area charts, bar charts, line graphs, and maps to diagrams, point plots, and tables to determine which visualization types and attributions stood more memorable. They asserted the diagrams such as pictograms, visual forms with more color, low-data-to-ink ratios, and high visual densities held statistically more memorable than the mere representations of the points, bars, lines, and tables (Borkin, et al., 2013). Comparing embellished charts with plain ones, Bateman et al. (2010) referenced user accuracy while describing the embellished charts held no worse than it held for plain charts, and user recall after a gap of two to three weeks was significantly better.

Empirical studies investigate the memorability of choosing and changing visual techniques as well as visual elements. Borkin et al. (2013) investigated the various ways in which the application of eye-tracking experiments with 393 visualizations, including diagrams, tree, and network diagrams enhanced visualization recognition and recall. The relationships between online visual representation and long-term scene memory remains pertinent (Holingworth, 2005). Isola et al. (2011) revealed the factors, including color, simple image features, object statistics, object semantics, and scene semantics made an image more memorable.

#### 2.1.2.3.5 Judgment & Decision Making and Visual Representations

Judgment and decision making illustrate the cognitive processes of identifying, selecting and determining the alternatives based on values and preferences (Janis & Mann, 1977). Judgment and decision making engender general processes, including recognizing the problem and the need for a decision, identifying the objective of the decision, gathering and evaluating data and diagnosing the situation, and listing and evaluating alternatives (Janis & Mann, 1977; Lurie & Mason, Visual representation: Implications for decision making, 2007). In the research of Lurie et al. (2007), they determined the visual representations displayed implications for decision making. Building upon past research, Cleveland and McGill (1984; 1985), further explained once a visual representation was created, instance size, color, shape, texture, and location, encoded information. When the decision makers saw the visual representations, decoded those factors. Only if the visual encoding is accurate and efficient are the visual representations considered workable. Conversely, the strengthened visual representations are reinforced, which improves the decoding and decision-making process.

More specifically, in visualization research, multi-variate data representation focuses on finding the relationships, such as correlative and causal. Li, Martens, and Van Wijk (2010) conducted a controlled experiment on judging the correlation from scatterplots and parallel coordinate, two different visual representations for presenting and assessing correlative relationships. By asking 25 participants to observe the correlation and analyze the accuracy and bias in the judgments, the investigator professed scatterplots stood more effective than parallel plots in supporting the visual correlations analysis (Li et al., 2010). Kay et al. (2016) also supported scatterplots held unique in combining low variance between individuals and high precision on both positively-and negatively-correlated data with the comparisons to eight visualizations and visual representations, such as doughnut, line, ordered line, parallel coordinates, radar, stacked area, stacked bar, and stacked line. Some other literature, such as the multi-task comparative experiment on scatterplots (SP) and parallel coordinates (PCS) (Kanjanabose, Abdul-Rahman, & Chen, 2015) uncovered the data table was more effective and efficient than PCS and SP for value retrieval. PCS was the best visual representation and choice for users when achieving the task of clustering. PCS was better than SP and table for outlier detection and for change detection. PCS was the best selection (Kanjanabose et al., 2015).

For only scatterplots, the variables on scatterplots held better correlations when the scales were increased (Cleveland, Diaconis, & McGill, 1982); the visual techniques of color was the optimal symbol type to help with discriminating strata in scatterplots (Lewandowsky & Spence, 1989). The selection and choice of the aspect-ratio of a scatterplot influenced the users considerably in terms of impression and their capability to recognize clusters and trends of the point data (Fink, Haunert, Spoerhase, & Wolff, 2013). The judgements failed to increase in difficulty when the sets contained more points, redundant conflicting encodings, as well as additional sets. However, judgements increased in difficulty when using less salient encodings in the tasks of judging the average value in multiclass scatterplots (Gleicher, Correll, Nothelfer, & Franconeri, 2013). In addition to the comparisons with scatterplots on correlation judgments, parallel coordinates were also being considered by some researchers. (Raidou, Eisemann, Breeuwer, Marcel, and Eisemann (2016) used the orientation-enhanced parallel coordinates to improve patterns and outliers discernibility by visually enhancing each ployline with respect to its slope. Beattie and Jones (2002) used their studies of the impact of graph slope on rate of change judgments to strengthen and support Raidou et al's (2016) clarifications. In the financial performance evaluation tasks, graph slope significantly affected both the specific conceptual used in reading the graphs impacting the accuracy of comparative judgments.

##### 2.1.2.3.6 Problem-solving and Visual Representations

Visual representation is one of the problem-solving aids that enhance a user's ability to find solutions to a problem by representing the problem with visual images, symbols, matrices, diagrams and context (Blaser, Sester, & Egenhofer, 2000; Moses, 1982; Stylianou, 2002). This applies to many fields such as mathematics, analogy, chemistry, art and design, multimedia, etc. (D'zurilla & Goldfried, 1971).

In the past literature, a lot of researchers investigated how visual representations help with mathematical problem-solving. Visual representations possess a strong relationship with mathematical activity (Stylianou & Silver, 2004). Stylianou (2002) examined the similarities and differences between the expert and novice to explore the role of visual representations in advanced mathematical problem solving. Novices indicated visual representations held useful for geometry problems, whereas the experts contended potential application to a wider variety of problems (Stylianou, 2002). Some studies combined visualization tools to scrutinize the relationship between visual representations and mathematical problem solving. Van Garderen (2006) researched how the students employed visual imagery and spatial visualization abilities to solve mathematical word problems. Their analysis revealed the gifted students performed both the spatial visualization measures more effectively than the students with learning disabilities.

Visualization researchers and designers generally employed the concept and knowledge of (user) cognition to consider design choices of different visual forms, color schemes, interactions, etc. The considerations of (user) cognition drove design judgments happen and occur in information visualization designs.

## 2.2 Information Visualization Art Attributes and Design Principles

In visualization design, the same data can be represented in different forms with different colors (Lurie & Mason, 2007), which can be considered an artistic choice rather than a scientific decision. When a visualization is presented to people, especially a general audience, people will naturally judge its art values and properties, and even aesthetics (Mitchell, 1995). In a casual environment, people simply pay less attention to unattractive visualizations (Horn, 1998). In the following sections, I discuss each of the major art attributes and design principles to synthesize the research on the artistic elements in visualization design.

### 2.2.1 Gestalt Principle in Information Visualization Design

Gestalt means "organized whole" (Perls, Hefferline, & Goodman, 1951). 1920s psychology developed the gestalt principles, which described "how human typically see objects by grouping similar elements, recognizing patterns, and simplifying complex images" (Bruce, Green, & Georgeson, 2003; Ware C. , 2012). Since the direct relationship between elements on an interface and better the communication exists (Graham, 2008), the designers utilized this to control how the design viewed; make designs more coherent and engage users. Gestalt principles include proximity, similarity, continuity, closure, and figure/ground, element connectedness (Todorovic, 2008; Wertheimer, 1923). Specifically, Han et al. in 1999 used four experiments to display the grouping by similarity of shapes in perceived slower by users the grouping by uniform connectedness (Han, Humphreys, & Chen, 1999). However, the grouping by proximity was as fast and efficient as that by uniform connectedness (Han, Humphreys, & Chen, 1999). In addition, Chang et al. (2007) hypothesized people would use touch to group display elements in the same way they group elements visually. Their findings supported their hypothesis that both proximity and similarity were equally applicable to the grouping of both visual (color) and haptic (texture) (Chang et al., 2007). Moreover, Rusu et al. (2011) presented the gestalt principle of closure as a way to alleviate the edge crossing problem and increase graph drawings.

### 2.2.2 Novel and Innovative Principles in Information Visualization Design

Infographics design practices depict visualizing data in a novel pattern, an innovative visual element usage and organization (Krum, 2013; Meyer, 1997; Smiciklas, 2012). Infographics designed fresh and appealing graphs and conducting meaningful insights to attract people's attention and interest (Siricharoen, 2013). Pop Chart Lab (Heller & Landers, 2014) used an innovative infographic to diagram and dissect the opening lines of 25 famous novels [https://www.popchartlab.com/products/a-diagrammatical-dissertation-on-opening-lines-of-notable-novels]. The developers said, "We're drawn to the idea that breaking down a sequence of sentence constituents into tiny pieces can reveal something larger and infinite about a sequence of words" (Siricharoen, 2013). This technique turned sentences into graphic structures, called parse trees, to elicit better understand the grammar and literatures of those novels.

In the book, 'Infographic Designers' Sketchbooks,' Heller (2014) gathered many innovative infographics. For example: La Lettura's infographic 'Geniuses, visualized' [https://www.behance.net/gallery/18723575/Geniuses-visualized] explored 100 geniuses of language in human history, in which each genius was designed with the shapes of growth flowers and displayed by name, historical period of activity, profession, continent of origin, number of pages dedicated in the book, visits to her pages on wikipedia.org, and relationship with other historical figures. Another one of Lettura's infographics was 'Nobels, No Degrees,' [https://www.behance.net/gallery/14159439/Nobel- no-degrees] which displayed Nobel Prizes and Laureates from 1901 to 2012 and the evolution of the six prize categories over time, as colored musicals scored along a skewed time-line. A third example was from the travel company Airbnb whose infographic, with super-idealistic concepts, explained the social contingencies of the company's novel business model (Heller & Lander, 2014) [https://kellianderson.com/blog/2012/02/06/five-new-ish-infographics-about/]. And lastly, Bloomberg Billionaires Index visualized the everyday ranking of the world's richest people with portraits with in the form of white and black stereotypes (Heller & Landers, 2014; hulman, 2012) [https://www.bloomberg.com/graphics/infographics/], in which users could view profiles for each of the world's 500 richest people, see the biggest movers, as well as compare fortunes or track returns.

As these examples reveal, many researchers have devoted a lot of time to identifying the best form, layout, and color schemes through innovations and re-combinations. These infographics fully demonstrate that designing visualizations can indeed be an art.

### 2.2.3 Informative Principle in Information Visualization Design

Another mark of successful visualizations is helping users gain knowledge (Gawain, 2016; Keim, 2002; Iliinsky, 2010). Information visualizations, especially infographic designs, also embody the informative criterion (Krum, 2013; Gawain, 2016; Smiciklas, 2012). Specifically, all information visualizations were based on valid datasets, and the primary responsibility of the designers was to convey information (Card, Mackinlay, & Shneiderm, 1999; Chen, et al., 2009). Heller and Landers (2014) also argued, "Infographics, when done well, can organize otherwise tangled bits of data for the purpose of illuminating a larger insight" [https://www.fastcodesign.com/3026864/infographic-dissecting-the-opening-lines-of-25-famous-novels].

In addition to this, Iliinsky (2010) concentrated the informative aspect on two perspectives: intended message and context of use. The primary considerations when visualizing data held to what extent was the knowledge going to be convey, what question was it going to answer, and what story was it going to tell (Chen et al., 2009; Keim, 2002; Van Wijk, 2005). In storytelling, context remained the king (Gershon & Page, 2001; Kosara & Mackinlay, 2013). Once the goal was determined, the next thought was how the visualization was going to be used, which includes the target users, the users' needs, and jargons (Iliinsky, 2010). In information visualization design, the context of use remained closely associated with storytelling (Wojtkowski, 2002). When telling a story, the insights of visualizations could be reinforced by presenting the data with more specific, research-oriented contexts in science, engineering, statistics, art, business, and other fields (Iliinsky, 2010; Wojtkowski, 2002). In these cases, the visualizations answered more specific questions, identified trends, behaviors and relationships, and even validated a hypothesis. All irrelevant information, the subjects, purposes, and insights, were rendered uninformative.

The famous visualization, Charles Mindard's map of Napolepon's disastrous Russian campaign of 1812 (Friendly, 2002; Tufte E. R., 2006) was a powerful illustration of how a designer used real context to tell a war story. Minard's flow chart aimed to show six types of information: geography, time, temperature, the course and direction of the army's movement, and the number of troops remaining (Friendly, 2002; Tufte, 2006). In order to strengthen and intensify the important events in the war, as well as to create the context, the geographical features and major battles were marked and named (Friendly, 2002; Tufte, 2006).

Another popular visualization, Hans Rosling's (2010) 200 Countries, 200 years, explored the public health data in 200 countries over 200 years using 120,000 numbers, in only four minutes. The goal of his visualization stood to plot the life expectancy against income for every country since 1810, as well as illuminate the gap between Western and non-Western countries (Rosling, 200 countries, 200 years, 2010). Clearly expressing the changes of each country in 200 years, Rosling (2010) applied an augmented reality animation and showed how the stood fundamentally different from the world most of us imagined (Rosling, 2010).

### 2.2.4 Efficient Principle in Information Visualization Design

Tufte said, "A visual design project is good if it communicates a lot with little" (Tufte E., 1989). Specifically, a good visualization design should present information as straightforwardly as possible, without any unnecessary and irrelevant complexity (Cairo, 2012; Iliinsky, 2010). The principle of efficiency was defined precisely with the Data-ink ratio (Inbar, 2007; Bateman, 2010), which is formulated as: Data-ink ratio = Ink that encodes data / Total amount of ink used to print the graphic (Cairo, 2012). In order to further show the relationship between this formula and efficiency, Cairo (2012) organized and compared three groups of charts. The results of this comparison test showed that not all "chartjunk" was junk; in fact, visualization designers simply needed to improve their understandings of design principles and the data itself.

Based on the past studies, Iliinsky (2010) identified four design principles that would improve efficiency. The principles were: (1) visually emphasizing what matters; which means, "when you have identified the critically necessary content, consider whether some portion of it—a particular relationship or data point—is especially relevant or useful;" (2) using axes to convey meaning and give free information, which is, “one excellent method for reducing visual noise and the quantity of text while retaining sufficient information is to define axes, and then use them to guide the placement of the other components of the visualization;” (3) slicing along relevant divisions, or, “the last way to reduce visual clutter and make information more accessible is to divide larger datasets into multiple similar or related visualizations;” and (4) using conventions thoughtfully, meaning, “Intentional and appropriate use of conventions will speed learning and facilitate retention on the part of your readers.”

#### 2.2.5 Aesthetic Principle in Information Visualization Design

In 2007, Lau and Moere (2007) presented “a model is to reveal information aesthetics as the conceptual link between information visualization and visualization art.” The model explained aesthetics as the artistic influence on the technical implementation and the intended purpose of a visualization technique, rather than a subjective aesthetic judgment of the visualization outcome. In reality, designers and developers have been thinking about how to learn from making a pretty picture and understand how the insights and aesthetics interact (Filonik & Baur, 2009; Iliinsky, 2010; Steele & Iliinsky, 2010). On the basis of insights, in 2005, Chen summarized the top ten unsolved information visualization problems. Among them, aesthetic has come into researchers’ focus because a successful information visualization not only sustains insight but also enhances aesthetics in terms of visual and emotional appeals (Chen, 2005; Fishwick, 2004; Moere, 2007; Viegas & Wattenberg, 2007).

Additionally, many researchers have elaborated on how visualization designs can influence and enhance visual and emotional appeals in terms of their artistic and aesthetic factors of story-based (Gershon & Page, 2001; Segel & Heer, 2010), photo-based (Chen, Weng, Jeng, & Chuang, 2008; Kang & Shneiderman, 2000), music-based (Chen, Weng, Jeng, & Chuang, 2008; Hayashi, Itoh, & Matsubara, 2013; Laurier & Herrera, 2008; Lee & Fathia, 2016), facial expression-based (Yu, Li, & Zou, 2017) and film and video-based (Nam & Tewfik, 1999), even interactive multi-touch-based (Cernea, Weber, Ebert, & Andreas, 2015) factors.

Further, Cawthon et al. (2007) elaborated on how aesthetics affects the usability of data visualizations in terms of color, typography, and layout balance, through studies of the speed of completion, accuracy rate, task abandonment, and latency of erroneous responses. Stone (2006) argued that color was a strong aesthetic component. Using color well in information display is essentially a function of what information one is trying to convey, and how and whether color could enhance it. Filonik et al. (2009) reviewed various approaches to model aesthetics using a survey, starting with Birkhoff's aesthetic measures and continuing with more recent models based on mathematical and information theoretical concepts. Overall, most of the research suggested that enhancing the artistic merit of visualization can result in a more effective and more productive visual analysis (Amar, Eagan, & Stasko, 2005).

## 2.3 Information Visualization Design Process

Apart from exploring and developing design attributes and principles, visualization researchers also conducted studies that conceptualize and operationalize visualization design processes. Fry (2007) defined seven stages of designing a visualization, which were 'acquire, parse, filter, mine, represent, refine, and interact' to design a visualization (Figure 2.2):

- Acquire – obtain the data.
- Parse – structure and order data in categories.
- Filter – filter out unnecessary data.
- Mine – analyze data by statistics or data mining.
- Represent – choose visual form, such as a bar graph, line graph, or scatter plot to represent data insights.
- Refine – improve and refine the basic representation to make the work clearer, concise, and more visually engaging.
- Interact – add methods to manipulate the data or control what characters are visible.

In most cases, visualization design processes are iterative, as shown in Figure 2.2. The "represent" stage generally leads to "acquire" and "filter." Effective and efficient interaction designs require researchers and designers to re-examine data and refine visuals concurrently. In Fry's (2007) book, he used the example of the U.S. Postal Service's zip code numbering system to illustrate how the process works. During the primary linear design process, designers refilter data to include only the contiguous 48 states because it needs to be compactly displayed on the screen (Fry, 2007).

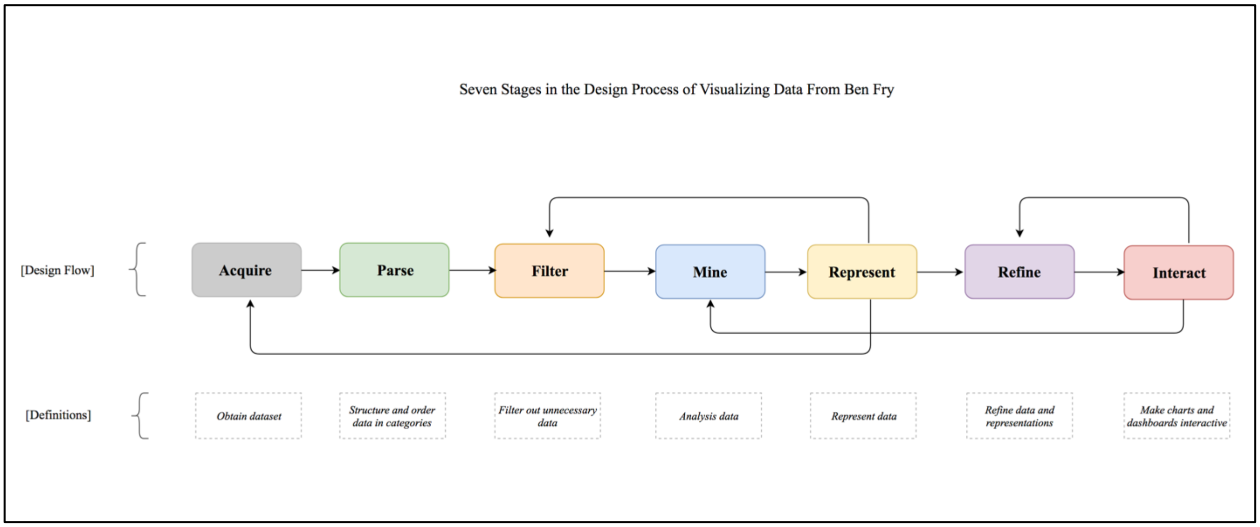



Figure 2.2 Fry's (2007) seven stages of visualization construction. Visualization designers continuously make design decisions and judgments during each design stage.

Other researchers combined both engineering and creative design processes to visualization design by probing their overlapping activities (McKenna et al., 2014; Howard, 2008). Additionally, McKenna et al. (2014) developed a framework with four activities. They were "understand, ideate, make, and deploy" for dealing with a data. For example, the "domain characterization" design task uses the "understand" component. However, design activities that overlap between "understand" and "ideate" involved dealing with data and task abstraction. Similarly, encoding and interaction also require combining "ideate" and "make."

## 2.4 Information Visualization Design Decision

Many researchers and designers have explored the role of design decisions in various domains. Chrisrtiaans et al. (2010) captured how software designers and developers make design decisions using different mindsets and strategies that are problem-driven, solution-driven, individual, team, autocratic, and autonomic. Another researcher divided software design decision into three stages in order to generate the most effective and efficient design decisions: planning, problem space, and solution space (Tang, Aleti, Burge, & van Vliet, 2010). Moreover, when making design sketches, researchers compared designers' digital and traditional decision making and developed three classes of design strategies: forward working, problem switching, and backward working (Wu, Chen & Chen, 2012).

Using existing decision models in diverse design domains, several researchers have applied them to particular visualization design processes and contexts. The well-cited nested model (Munzner, 2009; McKenna, 2014) suggests that visualization decisions occur on one of four levels: domain characterization, data and task abstraction, visual encoding and interaction, and algorithm. An extended nested blocks and guidelines model provided a more sophisticated characterization of design decisions as blocks on each level (Meyer, Sedlmair & Quinan, 2015). McKenna and colleagues (2014) argued that design judgments play an important role in visualization design processes. However, design judgment has not been exhaustively studied as an ability to assess, appreciate, and make applicable design decisions (Wolf et al., 2006).

## 2.5 Design Judgment in Diverse Design Domains

In 1965, Vickers defined the word "judgment" as a responsible choice, or an ability to discover the "rules of rightness" in any given situation (Holt, 1997; Vickers, 1965). In many other design domains—architecture design, industrial design, organizational design, product design, instructional design, social system design, interaction design, and user experience design— design judgment is central throughout the entire decision-making process (Chupin, 2011; Nelson & Stolterman, 2012; Seery, Canty, & Phelan, 2012; Wolf et al., 2006). Creating visual designs similarly relies on design judgment activities and behaviors, which need further exploration and research.

Design judgment is about making decisions in a rich, contradictory world that is full of dilemmas and insufficient knowledge (Nelson, 2003). It is about making decisions in the real world instead of a prefect ideal world. Wolf et al. (2006) argued that design judgment aided one's ability to assess, appreciate and make appropriate decisions with regard to one's own objectives and contexts. Design judgments have never blocked design inquiry, but rather stimulate informed decisions (Nelson & Stolterman, 2012; Wolf et al., 2006). Furthermore, Nelson and Stolterman (2012) postulated that design judgments were distinct from other forms of judgments (intellectual, scientific, ethical, and systemic) in that they were motivated by design volition.

### 2.5.1 Design Judgment Types

The literature review in this section traces and summarizes eleven types of design judgments across two ideologies.

Nelson and Stolterman (2012) identified two sets of design judgments: unconscious and conscious. Unconscious judgments are comprised of three types: *default* – judgments made without deliberation, *deliberated off hand* - experiential learning judgments, and *core* – judgments motivated by "why" questions (Nelson & Stolterman, 2012). Wolf et al. (2006) argued, "conscious design judgments are judgments that require a more cognizant and active relationship with the activity at hand." These judgments included *framing* - determination of boundaries and limits, *appreciative* - discernment of the background from the foreground, *quality* - determination of match between aesthetic norms, standards, and proposed design, *appearance* - determinations of style, nature, character, and experience, *connective* -judgments that make binding connections and interconnections between and among things, *compositional* - judgments that bring things together in a relational whole, *instrumental* - judgments that deal with the choice and mediation of means, and *navigational* – judgments that determine the right choices for an environment.

Nelson (2012) argued that designers generally use their design judgment in their first step to organize a more reliable and reasonable process. During the actual design process, the designer uses most, if not all, of the 10 design judgment types: default, off-hand, appreciative, appearance, quality, instrumental, navigational, compositional, connective, and core (Nelson & Stolterman, 2012; Wolf et al., 2006).

### 2.5.2 Design Judgment Activities in Variety of Design Contexts

Much of the previous literature discussed how design judgments enable designers' activities and outcomes for a particular design problem or challenge (Bazerman & Moore, 2008; Christensen & Ball, 2016; Powell, 1987; Romero, Machado, Carballal, & Correia, 2012; Seery et al., 2012; Taylor, 1994; Vinot et al., 2008). For instance, in the field of product design, Vienot and Mahler (2008) used judgments about color to grade the quality of several light-emitting diode (LED) illuminations. That study used three experiments: one was on the basis of color discrimination (character of color), and the other two employed different styles of judgment (Boothroyd, 1994; Vinot et al., 2008). Based on the color judgment, the researcher concluded that the clusters of red, green, blue, and amber LEDs impaired color discrimination (Vinot et al., 2008). Additionally, in 1987, Powell (1987) explored the relationships between buildings attributes and quality design judgments. In that project, the investigator identified 237 attributes of building designs (that ranged from simple to more complicated) through summaries of assessors' building reports (Powell, 1987).

The quality or degree of excellence—which was associated design fitness, merit, reliability, and utility—needed to be quite explicit. Moreover, researchers of computational system design projects wanted to test the average success rate of every image in a system's aesthetic properties and style. They then judged the complete aesthetic judgment system (AJS) using a heuristic (Romero et al., 2012).

#### 2.5.2.1 Design Judgment in Instructional Design

Framing and appreciative design judgments have often been used in the instructional design field. In Demiral-Uzan's dissertation (2017), the researcher used eight case studies, each with different master-level instructional design students, whose design reflections represented "framing." One of the participants decided to design instructions for undergraduate students on how to solve problems in a systematic way; he thought that designing instructions on an unfamiliar topic was an ambitious learning activity (Demiral-Uzan, 2017). Another student designer also used framing in his design judgment when he framed his design to be an instruction on something he knew about (Demiral-Uzan, 2017). Appreciative design judgments commonly accompanied framing in the instructional design field (Demiral-Uzan, 2017). In 2015, Gray et al. (2015) discussed how design judgments are productive constructs for studying instructional practice by observing eight practicing instructional designers. Their team generated a summative table to show each participant's judgment frequency and types; framing design judgments were used 47 times and appreciative judgments were used 43 (Gray et al., 2015). This evidence demonstrates the importance of both framing and appreciative design judgments in instructional design.

#### 2.5.2.2 Design Judgment in Product Design

Based on Nelson and Stolterman' s (2003; 2012) taxonomy of design judgments, appearance judgments emphasized style, nature, character, soul, and aesthesis. In the field of product design, designers followed their own design principles, such as not causing unnecessary harm, letting the function inform design, designing local, thinking global, etc. (Boothroyd, 1994). They also adhered to their own design patterns, such as scheduler scramble, context and projection hierarchy, diffuser, strategy, logo world, learning, double buffer and model-view-controller (North, 2011). This design knowledge guided designers to highlight particular attributes, including style, nature, character and soul (Nelson & Stolterman, 2003; 2012). Vienot and Mahler (2008) used color appearance judgments to grade the quality of several light-emitting diode (LED) illuminations. These judgments were tested using three experiments: one was on the basis of color discrimination (character of color) and the other two were based on appearance (style) (Vinot et al., 2008). In the color experiment, this research concluded that clusters with red, green, blue, and amber LEDs impaired color discrimination (Vinot et al., 2008). However, clusters that included white LEDs and a few correcting color LED might be a better design solution that renders the color faithfully (Vinot, 2008). Another researcher optimized food expectations by using similar color appearance judgments (Wei, 2012).

#### 2.5.2.3 Design Judgment in Computational System Design

Aesthetic properties are an important part of appearance judgments (Christensen & Ball, 2016; Romero et al., 2012; Taylor, 1994). Through learning, designers can obtain a relatively complete understanding of aesthetic properties and values, such as unity (texture, color, tone, direction, solid and void, form and shape); proportion, scale, balance, symmetry, and rhythm (Bennett, Ryall, & Spalteholz, 2007; Cawthon & Moere, 2007; De Clercq, 2005). Using experiments, researchers tested these aesthetic properties and style with an average success rate for every image in the system (AJS) and validated the heuristics of the complete aesthetic judgment system (AJS) (Romero et al., 2012). Finally, the researchers presented "the integration of learning AJS with an image generation engine to build a system designed to promote a constant search for novelty and stylistic change" (Romero et al., 2012). They also concluded that the AJS could be valuable for real-life applications such as image classification, image search engines, and online shopping (Romero et al., 2012).

#### 2.5.2.4 Design Judgment in Engineering Design

Quality design judgments focus on excellence and worth (Nelson & Stolterman, 2003; 2012). In 1987, Powell explored the relationships between a building's attributes and quality design judgments. In that project, the investigator identified 237 building attributes that ranged from simple (e.g., happy atmosphere) to more complicated (e.g., fits well into adjoining streets despite having a distinctive character of its own) by summarizing the assessors' reports of buildings (Powell, 1987). Throughout that process, quality, or degree of excellence, was associated with design fitness, merit, reliability, and utility, but it needed to be quite explicit for designers.

Also, the designers had to fully understand how to outline assessors' evaluation results using their design knowledge and their own evaluations (usability). The quality of each building was ultimately judged based on the level or degree of each attribute.

### 2.5.3 Design Judgment Influencing Factors

Previous design practice research identified that common factors—purposes, resources, research skills, ethical standards, research settings, knowledge, cognition, and manufacturing materials—significantly affected designers' choices and judgments (Eysenck, 1967; Norman, 2004; Maxwell, 2012; Rosenthal, 1987).

Gray et al. (2015) discussed the connections between judgment and instructional design practice and revealed that judgments were formed by factors unique to the firm, the role and position of the designer, and the project, client, and other external factors.

In web design and development, Rieh et al. (2002) identified that the factors that influenced quality and authority judgments. They included characteristics about objects, sources, knowledge, situations, rankings, and assumptions.

Petroski (1994) revealed that design logic and knowledge (level) can intuitively impact design judgments; however, design paradigms de-emphasized engineering design experience and judgment. Design knowledge includes design stages, design philosophies, design principles, design patterns, and design techniques. In another example, the research of "design patterns for the user interface of mobile applications," the researchers conducted and promoted a pattern of screen space utility, interaction mechanisms, and design to solve a similar problem (Nilsson, 2009). Because they encountered a commonly occurring design problem and wanted a stable design, the researchers decided to utilize a general template and a repeatable solution, in which, knowledge of design patterns was one of the most important factors.

In this research, I will explore and summarize the factors that influence visualization designers' judgments in particular contexts and processes.

## 2.6 Information Visualization Design as Making Judgments

In a broad sense, design is the result of choices (Margolin, 1989). Because the visualization design space allows for infinite design choices and situations, visualization design itself is the process of making decisions and judgments. Depending on the intended communication, a piece of data can be represented in different forms, such as a bar chart, pie chart, scatter plot, or flow diagram with different colors, sorting, filtering, and zooming (Stone, 2006; Yi et al., 2007). There is no way for designers to consider all of the vast design forms and representations. Every design is unique and inspired by its designer(s). It reflects the consequences of designers' judgments. In this research, I have defined design judgment to be the theoretical guidance to examine and explore particular the behaviors and patterns in visualization design.

## 2.7 Summary

This chapter reviewed existing visualization design research to describe how visualization design employs accurate design judgments. This chapter then provided an overview of the literature related to the design judgments in various design domains. It summarized eleven typical design judgments, design activities in several design situations, and a number of influencing factors from other design fields. This review of the literature helps investigators and readers understand existing design research in the visualization design field. By discussing the theoretical basis of design judgment and its application in various design domains, this section highlights areas of design judgment that require further exploration in visualization design.

# CHAPTER 3. METHODOLOGY

The purpose of this research was to examine and explore the design judgment behaviors of students working with visualization projects, as outlined in Chapter 1. Qualitative methodology tradition supported the best mechanism conducting this research due to the nature of the questions posed.

This chapter details what the study setting looked like. Then, it discusses how investigator gathered the data for analysis. Furthermore, it presents detailed data analysis procedures, which combined framework and (deductive) thematic analysis methods to explore student designer visualization design judgment situated upon the research question-base. Finally, this chapter provides a discussion of credibility relevant to this study with credibility of researcher and triangulation.

## 3.1 Qualitative Methodology in Design Research

Design research developed to gain understanding and improve design processes and practices (Collins, Joseph, & Bielaczyc, 2004; Roth, 1999; Teegavarapu, Summers, & Mocko, 2008), which requires a qualitative research method for local situations. Due to the essence of the research questions posed herein, a qualitative approach provided the best mechanism for conducting the research: (1) qualitative research holds effective in identifying intangible factors, such as social norms, socioeconomic status, design behaviors, ethnicity, and religion, which may not be otherwise apparent (Denzin, 2005); (2) qualitative research helps investigators and readers better comprehend the complex reality of product design and judgment behaviors in a given situation and the implications of quantitative data (Denzin, 1994; Lewis, 2015); and (3) qualitative research typically involves participant observation, in-depth interviews, or focus groups with multiple materials as supporting evidence, such that readers obtain a fuller explanation and description of a complicated phenomenon at a high level (Kaplan & Maxwell, 2005; Lewis, 2015). For instance, experiential analysis allows designers to develop theories based on their own design experiences (Reinharz, 1983; Teegavarapu et al., 2008). Investigating engineering design behaviors with a systematic approach is a popular example of experiential analysis (Pahl, Beitz, Feldhusen, & Grote, 2013). Focus group as a variation of experiential analysis continues to gain popularity among design investigators (Krueger & Casey, 2014).

Protocol analysis is also used to empirically document design problem-solving behavior employing an experimental method in which designers are observed in a controlled laboratory setting (Eckersley, 1988; Teegavarapu et al., 2008). In 1996, Galle et al. explored a site planning case by using a replication protocol analysis (RPA). By applying RPA, the investigators explained two major aspects of design: (1) how the design revolution affected chains of design decisions (2) how to elicit and extract design knowledge and apply them to design activities. In another example of engineering design, McNeill et al., (1998) used the protocol analysis method with a particular coding scheme to understand the conceptual electronic design process.

Case study methodology was used to review a design process and sought an optimum solution for a specific industrial design problem (Shahin, 1988). The designers' ten design steps, including the recognition of a need, definition of a problem, the feasibility of the study, creative designs, evaluation and decision making, detailed designs, building and testing the prototype, designing for production, product release and market analysis, and development for improvement. Another expert also discussed the different design stages in forming industrial design products; that study employed a case study titled the Flying Dutchman (Christiaans & Van Andel, 1993). Through analytical coding, that case study supported a complete presentation of a student's design process, which was defined as information, problem definition, design constraints, idea generation, description of concepts, choice of concept, materialization, user test, adjustment of prototype, and evaluation (Christiaans & Van Andel, 1993).

Phenomenological methodology generally starts with concrete descriptions of lived phenomena, often first-person accounts (Finlay, 2012; Groenewald, 2004; Moustakas, 1994). The researcher progresses by reflectively analyzing and describing as accurately as possible the phenomenon, perhaps ideographically first, then by offering a synthesized account, such as identifying general themes about the essence of the phenomenon (Finlay, 2012; Groenewald, 2004; Moustakas, 1994). Notably, some of the researchers applied a phenomenological approach to understand life experiences (Byrne, 2001). In architecture design, the experts applied a phenomenological approach to understanding a world wherein people and their environment mutually include and define each other, which focused on nature and reality as subject to human scrutiny, interaction, and creative participation (Bognar, 1985). Moreover, the researchers used a phenomenological approach to accomplish mobile interactions with the materials in romance in the information technology domain (Fallman, 2003).

This research employs qualitative phenomenological methodology with a combined framework analysis (Feller & Fitzgerald, 2000; Srivastava & Thomson, 2009) and (deductive) thematic analysis (Boyatzis, 1998; Braun & Clarke, 2006) in order to explain design judgments of student designers during their design process. This method, with two different designs, supports a more robust explanation and description for readers to synthesize how particular design judgments affect visualization outcomes. Framework analysis is an effective process for filtering and reducing data to key themes, issues, and nodes by "Familiarizing -> Identifying a thematic framework -> Indexing" (Srivastava & Thomson, 2009). Once data for the analysis is determined, "Coding," which includes initial and theme coding, provides the most intuitive way to address the research questions. Studies that use deductive thematic analysis are deductive and address specific research questions, analyzing and describing data with ideographical and synthesized accounts in mind (Braun & Clarke, 2006; Maguire & Delahunt, 2017; Mitchell, Fisher, Hastings, Silverman, & Wallen, 2010). Because this research is question-driven, with four particular research questions, a (deductive) thematic analysis is reasonable and appropriate.

## 3.2 Study Setting

The following two sections provide relevant details concerning the study environment with *section 3.2.1* and the study participants with *section 3.2.2*.

### 3.2.1 Study Environment

This research was conducted at Purdue University's campus. Two types of research designs, laboratory and in-situ studies were used to derive findings from student designers' judgment behaviors in particular visualization design contexts. It proved ideal to study real design cases, tasks and student designers. However, this approach would require a prolonged, continuous effort. To better plan the study, I started with two short, controlled lab studies, then continued with 13-week in-situ projects comprising three studies.

In the laboratory experiment, human subjects were solicited to enter a laboratory; this environment was almost entirely controlled by the research investigator (Yin, 2017). Each subject, within ethical and physical constraints, was requested to follow the researcher's instructions, which carefully prescribed the desired behavior (Yin, 2017). Any subject who did not wish to follow the prescribed behaviors was free to drop out of the experiment or survey. The lab study was a controlled environment that might result in a cleaner, but over-simplified, result (Collins et al., 2004). The in-situ study sought to provide a much more realistic data, with rich descriptions that made it possible to understand what is happening and why. Using both methodologies for the case studies diversified descriptions and provided well-founded explanations of these complex visualization design judgment. Together, they can help other researchers and designers better understand visualization design judgment activities.

#### 3.2.1.1 Laboratory Study

In the laboratory study, I observed two groups of students carry out visualization designs in a controlled, closed lab environment. Each study design was provided a dataset, a design task, and post semi-structured interview. The dataset "Flight Delay in the U.S." (https://www.data.gov/) represented multi-dimensional data that featured days, carriers, department airports, destination airports, five causes for delay, and other information. The design task was to create an innovative and intuitive visualization that would provide users with peripheral awareness of flight statuses across major airports. The interview questions were research question (RQ)-based, primarily focused on points of interest and confusion that arose from my observations. Appendix C/Semi-Structured Interview Protocol (Interview # Laboratory Studies One and Two) provides complete guides of the interview questions.

#### 3.2.1.2 In-Situ Study

The in-situ study observed designers design activities within a natural environment. I observed and noted all design judgments, including all behaviors related to the visualization design and production across a semester. This study collected a third-person observational data, as well as follow-up interviews in the middle and at the end of the academic semester with open-ended and closed questions. All interview questions [Appendix C/Semi-Structural Interview Protocol (Interview # In-situ Study 1, 2, and 3)] including the first and second sessions were compiled with the rough coding and matching, in which, I essentially mapped and adapted my participants' design judgments to Nelson and Stolterman's (2012) proposal of design judgment types.

### 3.2.2 Participants

This research scrutinized students-working visualization projects. The sample for this research was selected from students at Purdue University across various majors and educational backgrounds, including interaction design, industrial design, computer graphics technology, interior design, visual communication design, mechanical engineering design, and human factors (UX).

Specifically, two laboratory studies were conducted in an InfoVis Research Lab with four Master's students from Art and Design and Computer Graphic Technology entailing two teams to work on the design tasks. The in-situ studies observed three groups of Master and Ph.D. students working on their own course projects in a graduate level information visualization design course (CGT581 VIS Analysis, Design & Development). A total of 17 practicing visualization students in 5 teams participated in the research, 4 in the lab environment, and 13 in the coursework contexts. Selected participants were qualified on the following criteria: (1) being enrolled at the graduate levels, pursuing a Master or Ph.D. degree across a range of majors; (2) having completed at least one visualization-related course; and (3) being involved with and implementing at least one visualization design project. The following two tables (Table 3.1 and 3.2) specified participants' qualifications for the different studies.

Table 3.1 Matrix layout student designer backgrounds.

| ***Number of Participants within Each Educational Background/Major*** | | | | | |
|---|---|---|---|---|---|
| *Educational Backgrounds/Case Studies* | Lab1 | Lab2 | In-situ1 | In-situ2 | In-situ3 |
| Computer Graphics Technology | 1 | | 2 | 1 | 2 |
| Interaction Design | 1 | | 2 | | |
| Industrial Design | | 2 | | | |
| Interior Design | | | 1 | | |
| Visual Communication Design | | | | 2 | |
| Human Factors | | | | | 2 |
| Mechanical Engineering | | | | 1 | |
| *Total* | 2 | 2 | 5 | 4 | 4 |

Table 3.2 Matrix of participants' learning and working experience in visualization design.

| ***Number of Participants' with Visualization Learning and Working Experiences*** | | | |
|---|---|---|---|
| *Study* | *Participant* | Visualization Course-Related Experience (# of courses) | Visualization Project-Related Experience (# of projects) |
| Lab1 | P-SJ | 1 | 1 |
| | P-SS | 1 | 1 |
| Lab2 | P-XM | 2 | 1 |
| | P-SY | 1 | 1 |
| In-situ1 | P-JH | 1 | 2 |
| | P-ZJ | 1 | 1 |
| | P-AJ | 2 | 1 |
| | P-PR | 2 | 1 |
| | P-SD | 1 | 1 |
| In-situ2 | P-AA | 1 | 1 |
| | P-OG | 1 | 1 |
| | P-JJ | 2 | 1 |
| | P-IL | 2 | 1 |
| In-situ3 | P-KY | 1 | 1 |
| | P-KJ | 1 | 1 |
| | P-LY | 1 | 1 |
| | P-SQ | 1 | 1 |

These participants can be considered as newly trained professionals in information visualization design but without much real-world experience.

## 3.3 Data Collection

Creswell (2017), Patton (2005), Moustakas (1994), and Marshall (1995) all acknowledged that observation and in-depth interviewing are the primary data collection methods used in qualitative research. Qualitative study supports five sources of evidence collection: documents, archival records, observations (direct/participant), interviews, and physical artifacts (Palinkas et al., 2015).

As previously described, this research used purposeful samples of Master and Ph.D. student designers, relying primarily on a combination of direct observations and semi-structured interviews to gather a chain of evidence (Palinkas et al., 2015). The following sections outline the procedures used within the laboratory and in-situ studies respectively. In section 3.3.3, Table 3.3 and 3.4 summarizes the matrix to show relationships between the source of data, design studies with specific student teams, and research questions.

### 3.3.1 Data Collection Procedure – Laboratory Study

The following two sections outline how the data was gathered through observations and interviews in laboratory studies.

#### 3.3.1.1 Observations

The laboratory observations took 4 to 4.5 hours to complete and were conducted throughout participants' design processes with task controls. Each laboratory study began by providing data and assigning tasks. I sat in a corner away from designers' teams to minimize my presence. I attended participants' design meetings in an effort to observe their design judgment activities and behaviors while handling data and visualization design tasks. Witnessing each of these discussions helped me understand the current context and visualization design problems that the student designers were working on. As Denzin et al. (2005) recommend, these observations helped immerse and engage me in the participants' environment to gather data more efficiently.

During these observations, I wrote field notes with contexts, personal activities, and thoughts; I also collected all relevant design sketches and founding images, as well as conversations through audio recordings (Palinkas et al., 2015). These observational data collections: (1) were referenced during the data analysis procedures; (2) supported overall structural interpretations and explanations of design judgment activities and behaviors; (3) helped answer all research questions. These observations often reminded me of my own previous visualization design processes and design judgments.

#### 3.3.1.2 Post-observation, Semi-structured Interview

The use of semi-structured interviews with key personnel (Palinkas et al., 2015; Yin, 2017) served as another data collection vehicle for this research. After completing the design tasks in the lab, designers were requested to participate in one, 50-minute, face-to-face interview that contained six specific interview questions. All four student designers took part in the interviews. Interview questions were developed during the observations because the lab studies did not permit time gaps to read and conduct data matching or coding. During the interview, I asked participants about their backgrounds and prior design experience. I also asked them to describe how they made some particular design decisions and judgments that I identified during the observations. At the end of the session, I requested that the interviewees reflect on their complete design process and summarize the factors that influenced their design judgments. These messages provided strong supporting evidence for the third and fourth research questions.

The interview questions (Appendix C/Semi-structured Interview Protocol; Interview # Laboratory Studies 1 and 2) for both laboratory studies included, such as:

- Before the participant's (name of the person) sketching, how did you choose five variables for your visualization? Why did you select those?
- How did you decide what data attributes would be used in your final visualization? What was your judgment and decision-making process?
- How did you decide on a design idea (sketch) as a final solution for your visualization? What was your judgment and decision-making process?
- What factors drove your design judgment activities, which moved toward outcome design?

### 3.3.2 Data Collection Procedure – In-situ Study

The following two sections lay out how the data was collected through observation and interviews in in-situ studies. The student designers in each in-situ study were asked to participate in two interview sessions because their long-term visualization design projects included a number of design decisions and judgments. A midpoint interview was used to validate and collate design judgment behaviors at this time node. The endpoint interview occurred after their final group discussions/meetings. In-situ semi-structured interview sessions contained different numbers of interview questions to elaborate on designers' design judgment behaviors during the observations. I combined transcriptions from the two interviews to help me link all findings and ensured a complete overview description for readers.

#### 3.3.2.1 Observations

Each of the in-situ studies started with each group's own organization. Similar to the laboratory study, I observed participants from a corner of the room and recorded contexts and all related information. For in-situ studies One, Two, and Three, I observed and collected 13-week data. However, for the In-situ Study Three, some observations did not happen in a classroom environment because they were sponsored teams and had obligations to meet the product manager to report on their design progress. Each observation in each in-situ study took approximately 50 to 60 minutes.

#### 3.3.2.2 Midpoint Semi-structured Interview

The midpoint semi-structured interviews happened during Week 7 or 8 for in-situ studies One, Two, and Three. Each interview took 50 minutes. Two of their team members were requested to participate in interviews based on their personal willingness and motivations. I determined the interview questions by reading and re-reading observational notes, reviewing other supplementary sketches and images, as well as checking back with audio recordings. The interview questions for the midpoint session reflected how student designers filtered and reduced data, decided on the available attributes/features, and determined a design idea. Members of in-situ study One were questioned in a different pattern because their team applied a totally different design flow.

The specific interview questions (Appendix C/Semi-structured Interview Protocol; Interview Midpoint # In-situ Studies One, Two, and Three) for all in situ studies included, such as:

- How did your project go before design sketching?
- Please briefly explain why all your current designs (sketches) were the circular style-based? Also, please choose two of your design ideas (sketches) to discuss how you decided them and your judging process?
- In the same judging processes (above two), what factors drove your design judgment activities?

#### 3.3.2.3 Endpoint Semi-structured Interview

Endpoint semi-structured interviews happened during the final week, which was Week 13 for all in-situ studies. Endpoint interviews also took 50 minutes. They focused on individuals' visualization design judgments in the second half of project development. The questions included, such as:

- How did you judge a design as your final design solution for your interactive visualization? What did your decision-making process look like?
- How did you decide to switch your design strategy, refer, and adapt an online example for your final design development?

- Reflecting on your design decisions (above two), what factors drove your design forward and outcome?

The following tables (Table 3.3 and 3.4) provide a matrix of data sources, design studies, and research questions.

Table 3.3 Matrix showing the relationships between the sources of data, studies, and particular participants within each study.

***Matrix of Sources of Data Within Studies with Particular Participants***

| | | *Observations* | | | | *Interviews* |
|---|---|---|---|---|---|---|
| | *Participants* | Observational Notes | Sketches | Images/Pictures | Audio Recordings | Interviews |
| Lab1 | P-SJ | | | | | |
| | P-SS | | | | | |
| Lab2 | P-XM | | | | | |
| | P-SY | | | | | |
| In-situ1 | P-JH | | | | | |
| | P-ZJ | | | | | |
| | P-AJ | | | | | |
| | P-PR | | | | | |
| | P-SD | | | | | |
| In-situ2 | P-AA | | | | | |
| | P-OG | | | | | |
| | P-JJ | | | | | |
| | P-IL | | | | | |
| In-situ3 | P-KY | | | | | |
| | P-KJ | | | | | |
| | P-LY | | | | | |
| | P-SQ | | | | | |

Table 3.4 Table presenting the relationships between the research questions and data sources.

| ***Matrix of Research Questions and Sources of Data*** | |
|---|---|
| *Research Questions* | *Data Source* |
| 1. What are the existences of design judgments in particular information visualization design process? | Observational Notes Focused |
| 2. How do design judgments occur in particular information visualization design? | Observational Notes Focused |
| 3. What are the factors influencing design judgments? | Observational Notes and Interviews Focused<br>Interviews Focused |

### 3.3.3 Data Saturation

Data saturation is an essential principle to measure raw data acquisition throughout the research process (Fusch, 2015). Eisenhardt (1989) argued that between four and ten studies usually worked well, although there is no ideal number of studies for exploring and examining a complex phenomenon. To reach data saturation, I began with two studies that were equally distributed within laboratory and in-situ observations and interviews in order to discover the questions that could be well answered by data analysis. Reports from the first two studies provided particularly useful insight on how design judgments occurred in particular visualization designs. In total, I conducted five studies, including laboratory and in-situ methods, to produce comprehensive research findings.

## 3.4 Data Analysis

Data analysis in qualitative research generally consists of familiarizing, preparing, and organizing the data, such as transcripts and image data, for analysis, then reducing the data into themes through a process of coding and condensing the codes, and finally representing the data in figures, tables, or a discussion with a structural description (Lewis, 2015). In this research, I employed combined framework analysis (Feller & Fitzgerald&, 2000; Srivastava & Thomson, 2009) (particularly for in-situ design studies) and (deductive) thematic analysis (Braun & Clarke, 2006; Boyatzis, 1998; Maguire & Delahunt, 2017). By combining question- and theory-driven research (theories of design judgments and visualization design stages) with data driven methods (Figure 3.1), I was able to explore students' design judgment behaviors as they worked on visualization projects. The design judgment theory served as a solid foundation that directly impacted all data collection and analysis procedures. The theory of visualization design processes and stages aided the research findings, especially on "How do they occur" questions by detecting (1) patterns of design judgment (and themes) that commonly occurred during each process/stage; and (2) the connections and interactions between the design judgment (with theme), and an actionable design decision. The visualization design process is iterative, in which, theory helped me identify how individuals' design judgments interact within a design decision. I applied the analysis flow of familiarizing, identifying a thematic framework, indexing, coding, as well as charting and interpreting to learn about the meaning that participants assign to their design judgment behaviors. For the local design situations in my research, codes were categorized into types of design judgments, visualization design processes, and preconceived factors that were both question-driven and theory-driven. Data were interpreted, and results were presented in text, tabular, or figure form (Lewis, 2015).

In the following sections, I discuss why these five studies were chosen and detail the data analysis procedures used in this research.

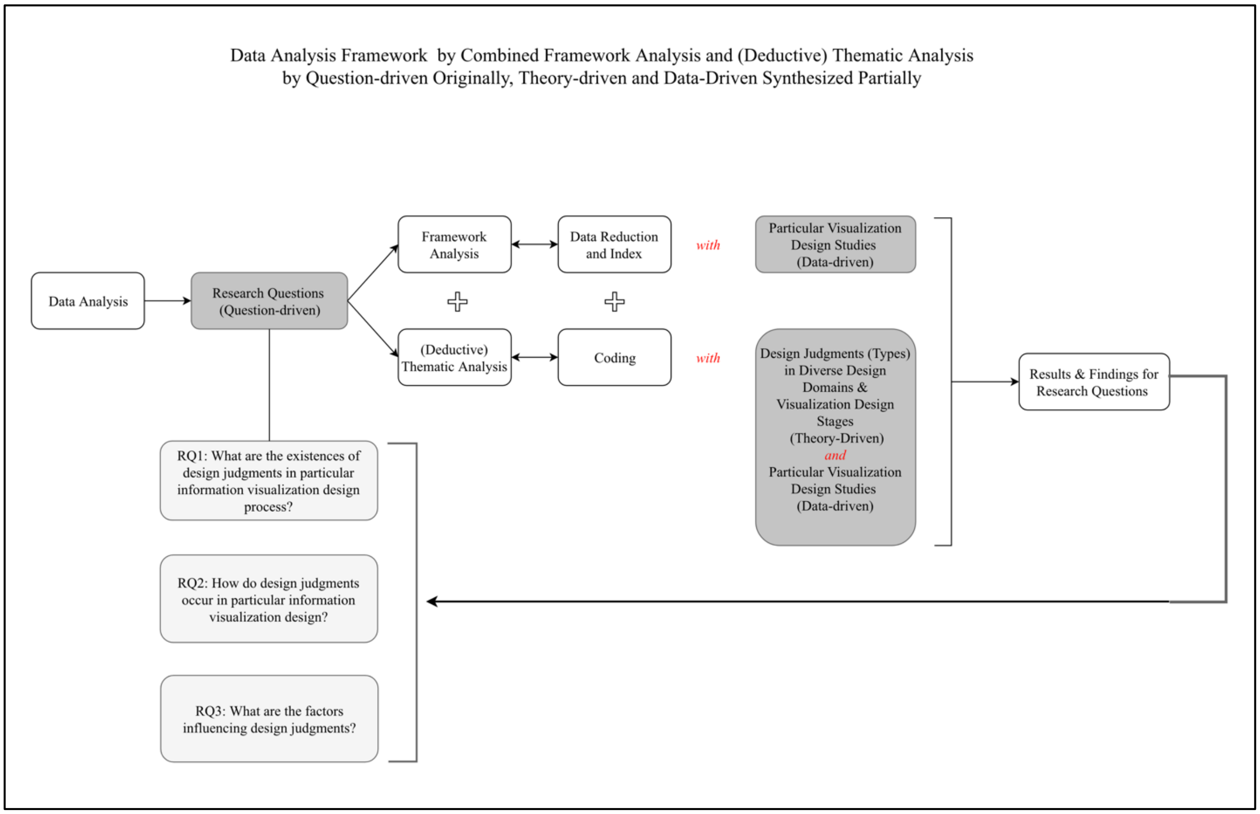



Figure 3.1 The data analysis framework using theory-driven and data-driven approaches to derive insights for the research questions that identified in Chapter 1.

### 3.4.1 Study Selection

The selection of these cases met several basic criteria (Curtis et al., 2000; Sandelowski, 1995): (1) the studies were relevant to the phenomenon and target; (2) the studies provided diversity across contexts; and (3) the studies or cases supported good chances to understand complexities in particular contexts. In my research, I applied (1) two types of study designs, laboratory and in-situ studies, to diversify data collection; (2) datasets with a similar design purpose created diversity in design activities and behaviors; (3) various groups of participants provided the opportunity to learn about complicated visualization design judgments from many different perspectives. Information about these studies and relevant contexts are presented in Table 3.5.

Table 3.5 This table shows the selected studies and their summarized contexts.

| **Cases with ID** | **Contexts** |
|---|---|
| Laboratory Study One | • Controlled by the investigator in a lab setting, 5.3 hours<br>• Integral design tasks<br>• A dataset of “Flight in the U.S.”<br>• A post semi-structured interview session<br>• Two student designers with interaction design and computer graphics technology majors were involved |
| Laboratory Study Two | • Controlled by the investigator in a lab setting, 5 hours<br>• Integral design tasks<br>• A dataset of “Flight in the U.S.”<br>• A post semi-structured interview session<br>• Two student designers with industrial design majors were involved |
| In-Situ Study One | • Naturally in participants’ working environment (a graduate level visualization design and analytics course), 13 weeks<br>• Two semi-structured interview sessions at the midpoint and the end of their designs<br>• A database of “DNA sequencing” supported by College of Biological Engineering at Purdue University<br>• Five student designers with interaction design, interior design, and computer graphics technology majors were involved |

Table 3.5 continued

| | |
|---|---|
| In-Situ Study Two | • Naturally in participants' working environment (a graduate level visualization design and analytics course), 13 weeks<br>• Two semi-structured interview sessions at the midpoint and the end of their designs<br>• A database of "Purdue PPI" provided by Polytechnic Institution, Purdue University<br>• Four student designers with computer graphics technology, mechanical engineering, and visual communication design majors were involved |
| In-Situ Study Three | • Naturally in participants' working environment (a graduate level visualization design & analytics course), 13 weeks<br>• Two semi-structured interview sessions at the midpoint and the end of their designs<br>• A database of "Relationships among different proposals" supported by Purdue Discovery Park<br>• Four student designers with computer graphics technology and human factors majors were involved |

### 3.4.2 Procedures

In the following sections, I describe how I used combined framework analysis (Feller & Fitzgerald&, 2000; Srivastava & Thomson, 2009) and (deductive) thematic analysis (Braun & Clarke, 2006; Boyatzis, 1998; Maguire & Delahunt, 2017) to filter and analyze the data. These procedures identified answers to the research questions put forward in Chapter 1 (Figure 3.2). "Coding" with the "initial coding" and "theme coding" became the main data analysis procedures to determine answers, results, and concentrated findings.

Identifying the thematic framework and indexing were not completed in the two laboratory studies because their results supported fuller descriptions of their complete design processes.

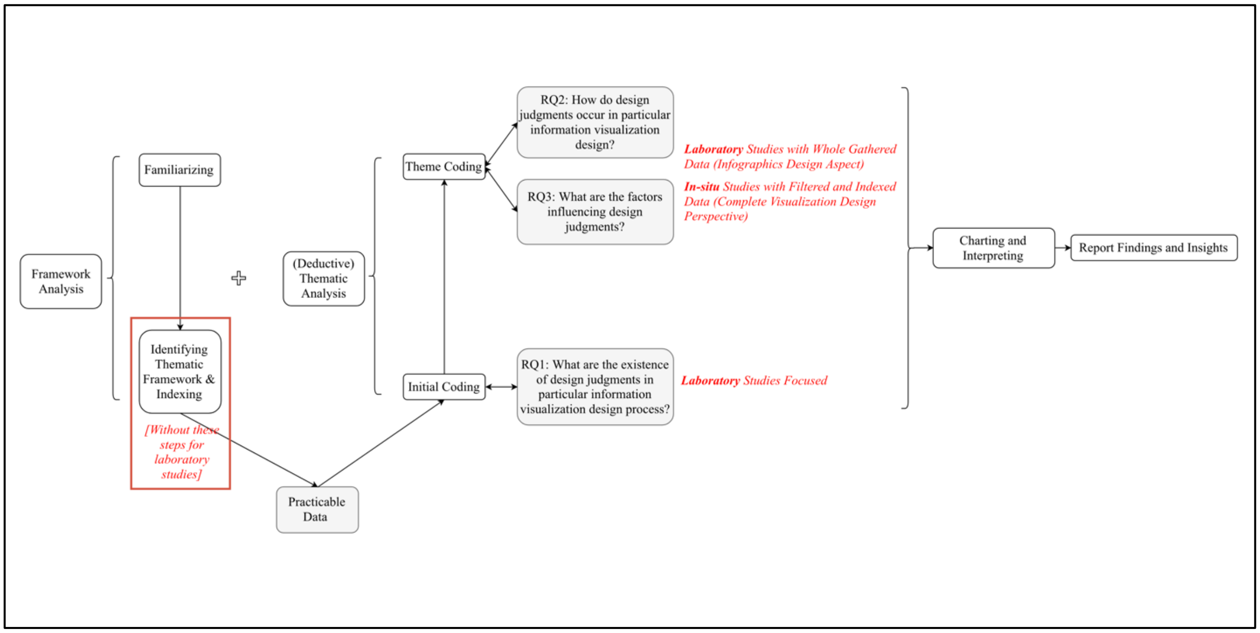



Figure 3.2 The detailed data analysis procedure using combined framework and deductive thematic analysis approaches.

3.4.2.1 Familiarizing

"Familiarizing" (Braun & Clarke, 2006; Srivastava & Thomson, 2009) refers to the process in which the researcher combs through transcripts of collected data; it occurred both in the lab and in-situ studies in this research.

Data transcriptions serve as the basis for familiarization, and they presented a big challenge in my research—especially the in-situ studies—because I gathered long-term design data. I requested help on interview transcriptions and observational notes from native English speakers on a week-by-week basis. I asked them to transcribe materials and write down the text in full statements with full stops. Four native speakers participated in the transcription process. Before the transcribers were involved, I personally edited and synthesized some audio to filter out unavailable and unrelated data (Figure 3.3), which made the process more convenient for the transcribers. Data transcriptions in this research included the field notes of observations and typing results and audio recordings of interviews.

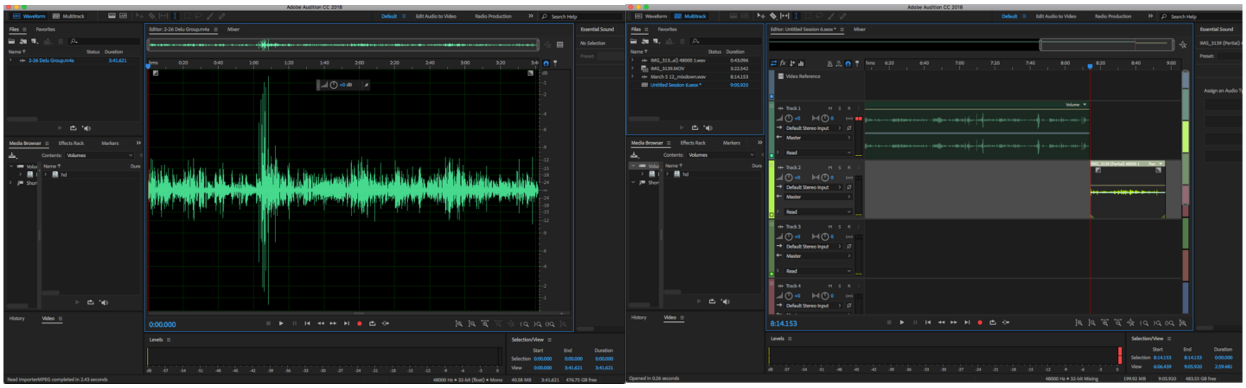


Figure 3.3 Audio editions by Adobe Audition software.

Prior to reading the transcribed data, I created a “start list” of potential codes based on theory and prior research, such as the 11 different types of design judgments, seven stages of visualization design, as well as other common predictors of design judgment making from various design domains. During reading and re-reading, I directed my attention to the critical events/nodes that shaped participants’ designs. Those potential codes helped me identify possible themes and patterns during this phase.

#### 3.4.2.2 Identifying Thematic Framework and Indexing

In framework analysis, Srivastava et al. (2009) argued that the “identifying thematic framework” stage occurs immediately after familiarizing. This is when the researcher identifies emerging themes or key events/issues. To do this, I used the notes taken during the familiarization stage to mark and record essential nodes of design decisions that impact the final design. At this point, the data segments of design decisions were coded and clearly differentiated. This process only occurred in in-situ data analysis because no selective data was captured for the laboratory studies.

“Indexing” means that one identifies portions or sections of data that correspond to a particular theme, issue, event, or node (Srivastava & Thomson, 2009). In my “indexing,” I gathered all the textual data from the transcriptions and classified a series of sub-design decisions that comprised each key node of a design decision. “Indexing” was closely related to the previous step and also occurred for the in-situ studies.

Table 3.6 is an example from In-situ Study 1 that explains how I reduced and filtered raw data based on the key issues/nodes and integrated all relevant materials into issues/nodes that would then be “Coded” (highlighted grey filling rows).

Table 3.6 How I queried key issues/nodes (highlighted in grey) for "Coding" by aligning student design team's design activities with particular design decisions.

| ***Week of Design*** | ***Design Stages*** | ***Observed Design Activities (with design decisions)*** |
| --- | --- | --- |
| Week1 | Acquire | The team brainstormed ideas of how the dataset could be visualized and fit their current term project. |
| Week2 | Acquire | The team scheduled a discussion with a TA who taught the fundamental gene biology course from Purdue's Department of Biological Sciences to acquire the raw data and define the original project's goals. The team decided to employ the biological dataset to visualize DNA sequencing. |
| Week3 | Parse | The team organized a discussion to synthesize each team member's understanding of the database. |
| Week4 | Interact, Parse, Filter, Mine | The team determined an applicable working flow using an interaction framework that paralleled database construction, and then boosted graphic design. They spent approximately two hours to resolve challenges in data explorations and time limitations. |
| Week5 | Interact | The team decided they would select, highlight, drag and drop, and use comparisons to visualize the DNA sequencing and similar/shared DNA segmentations. They arrived at these interaction design decisions by searching and referring to existing online systems and visualization applications that related to DNA information. |
| Week6 | Represent, Filter, Mine | The team spent approximately one hour collaboratively brainstorming their original design ideas with the sketches, which accompanied the filtering and mining processes. |

Table 3.6 continued

| | | |
|---|---|---|
| Week7 | Represent, Filter | The team organized about a 40-minute discussion to match team members' design ideas to the reduced data. For this process, the data filtering happened concurrently. |
| Week8 | Represent, Filter | Similar to week 7, the team scheduled a 30-minute meeting to discuss the visual representations with a new round of design sketches because no satisfactory design solutions arose during the last week. |
| Week9 | Represent | The team decided to apply a semicircle that comprised of one DNA and used different colors to lay out the similarities between different DNA. This design preserved previous circular design ideas, adapting, and referring to existing online visualization examples to a focused D3.org platform. |
| Week10 | Represent | To keep the semicircles as basic shapes, the team decided on a heap map with specific color schemes that could show "similarity" by searching and exploring the visual approaches to degree representations. |
| Week11 | Represent, Interact (programming and developing process focused) | During their group meeting, only ideas on how to improve the current design were observed. The design decisions and relevant design judgments that may have been involved in their programming progress has not recorded. During this week, the programmers designed the basic interface that laid out intensive semicircles with same colors. |

Table 3.6 continued

| | | |
|---|---|---|
| Week12 | Represent, Interact (programming and developing process focused) | Similar to week 11 my observations also focused on design enhancements to the current design. During this week's discussion, programmers tried one of early design ideas with the "clocks" metaphor as a selective visualization application. Some of their team members rejected that scheme to the final. |
| Week13 | Refine, Represent | My final observation for this team was paying attention to how they team refined "similarities" using efficient color schemes. They tried more than seven different color combinations and finally decided on a purple-green color scheme to present the values of percentages of DNA similarities. Purple was employed for their index DNA sequences and green with a different gradient was for the other seven DNA sequences. |

#### 3.4.2.3 Coding

Coding as a system of organizing and sorting data is an extreme importantly part of developing and refining explanations in collected data (Auerbach & Silverstein, 2003; Saldana, 2015). In this research, generated codes were question-driven, which combined theory-driven and data-driven analysis procedures to support my findings. The transcripts of observations and interviews were initially coded and analyzed by hand. Once all codes were agreed upon between me and my other coders, I used ATLAS.ti to review and refine the codes. Other gathered data, such as audio recordings, images, and even sketches, helped triangulate research findings and insights. During this process, "initial coding" served as the most fundamental data analysis procedure to help identify, examine and explore all research findings and insights and focused on answering the first research question of "what are the existence." For the other two questions of "how do they occur" and "why do they occur/influencing factors," "theme coding" based on the intensive codes by "initial coding" helped more on identifying results. In the following sections, I describe how the coding proceeded and how the research questions were explored.

3.4.2.3.1 Coding Team and Codebook

(Deductive) thematic analysis requires intercoders who collaboratively work with the primary investigator to improve the credibility of research results through triangulation (Burla et al., 2008; Lombard, Snyder-Duch, J., & Bracken, 2002). For coding, the codebook with specific codes serves as the underlying tool that instructs the coders on how to label, compile, and organize the raw data (Guest & MacQueen, 2008; Franklin & Ballan, 2001). Before coding started, I created a coding team and generated a codebook. The process was as follows:

*(1)* ***Coding team:*** my coding team was comprised of three Ph.D. students, including me. I acted as the primary coder and worked with the two intercoders. These two Ph.D. students are my officemates who both studied with my supervisor.

- *Reasons of Grouping Team:* The reasons why I chose to collaboratively work with my officemates were: (a) we have had a certain amount cooperation on visualization design projects; (b) we have been involved in a lot of discussions about visualization designs; (c) we have a roughly similar level of knowledge regarding the visualization design field; and (d) we knew each other well and did not have communication barriers.
- *Work Division* – During the "coding" procedure, five datasets needed to be analyzed by three coders. I trained all coders (including myself) using two datasets to reach intercoder agreement with Cohen's Kappa. After coding the second dataset, which was from Laboratory Study One, all coders similarly understood the codebook and were divided into two groups. Team A was the primary investigator with one coder (female), and Team B was the primary investigator with a different coder (male). For the remaining three datasets, Team A worked on the textual transcripts from In-situ Study Two (with longer transcriptions than the other two), and Team B was responsible for the coding assignments for Laboratory Study Two and In-situ Study Three.

(2) ***Generating a codebook with three primary labels and detailed codes*****:** The goal of the codebook was to label the 11 categories of design judgments *(Label A),* code for all 7 stages

of the visualization design process *(Label B),* and identify predictors of design judgments *(Label C)*. The categories of *Label A* and *B* with detailed sub-codes served as a pre-set list because they were theory-driven.

- *Label A* - Nelson's book (Nelson & Stolterman, 2012), which serves as the theoretical basis of design judgments applied in diverse design domains, was adapted, such that 11 types of design judgments were labeled: *Aa (Default), Ab (Deliberated off hand), Ac (Core), Ad (Framing)…Ak (Navigational).* Table 3.7 shows part of the codebook for *Label A*, its sub-codes, and related definitions.
- *Label B – Label B* was also theory-driven and adapted Fry's (2007) 7 stages for visualizing a data, which included "acquire," "parse," "filter," "mine," "represent," "refine," and "interact". Building on Fry's theory, McKenna et al. (2014) put forward a design activity framework for visualization design with four activities of "understand," "ideate," "make," and "deploy." I decided to adapt Fry's theory, which is regarded as the most fundamental and detailed set because the latter one is the application, development, even condensation of the former one. Appendix B provides each specific *Label with* example and definition, as well as how it was coded.
- *Label C – Label C* generated more emergent codes. In the codebook (Appendix B), I provided a pre-set list of known predictors within diverse design contexts. I also requested all coders to complement the emergent factors with *(C-a concrete word or phrase),* which provided evidence to support these specific influence factors in particular local visualization design situations.

Table 3.7 Operationalized types of design judgments and applicable definitions. Adapted from Nelson & Stolterman's (2012) research and from instructional design research (Gray, 2015).

| **Judgment Type *(Label A)*** | **Definition** |
|---|---|
| Default *(A-a)* | Judgments made without deliberation; an automatic response to a situation. |
| Deliberated off hand *(A-b)* | Judgments made by recalling previous judgments that have led to successful designs and adapted to the current situation. |

Table 3.7 continued

| | |
|---|---|
| Core *(A-c)* | Judgments made when one is being pushed by "why" questions concerning one's judgments and decisions. |
| Framing *(A-d)* | Judgments made for determining what is to be included within the purview of the design process, defining and embracing the space and constraints (client or tool) of assessing design outcomes. |
| Appreciative *(A-e)* | Judgments made on what is considered background and what requests more attention as foreground. |
| Quality *(A-f)* | Judgments made on effectiveness of visual and other forms of style; whether there is enough of a match between design standards, other proposed design, and aesthetic norms. |
| Appearance *(A-g)* | Judgments made on assessing overall appearance quality with style, nature, character, and aesthetic experience; relating to the entire product rather than a portion. |
| Connective *(A-h)* | Judgments made on binding connections and interconnections between and among things and various design objects to form functional assemblies that transmit their individual influences, energy, and power to one another. The connections made are not for relational whole but are particular to a design situation. |
| Compositional *(A-i)* | Judgments made on bringing various design objects together in relational who/overall design process rather than specific to a particular design situation; forming within the guiding domains of aesthetics, ethics, and reason – in the mode of synthesis. |
| Instrumental *(A-j)* | Judgments made on dealing with the choice and mediation of means – tools, concepts, and methods within the context to reach established design goal. |
| Navigational *(A-k)* | Judgments made by considering a "right rule" – a plan, flow, path, or a certain manner to make sure a right design direction and desired design state. |

### 3.4.2.3.2 Initial Coding

Initial coding resulted in comprehensive codes that revealed how the data answered the research questions and also provided supportive details on how and why codes were related, combined, and ranked for theme coding (Saldana, 2015). Table 3.8 outlined the quantity of different data sources, such as field notes of observations, interview transcriptions, sketches, audio recordings, etc., which involved in initial coding.

Table 3.8 Source of data involved in initial coding.

| | ***Source of Data*** | | | | | |
|---|---|---|---|---|---|---|
| ***Study*** | ***Field Notes (pages)*** | ***Interview Transcriptions (pages)*** | ***Images (numbers)*** | ***Sketches (numbers)*** | ***Audio Recordings (mins)*** | ***Video Recordings (mins)*** |
| Lab 1 | 6 | 3 | 1 | 20 | 320 | 280 |
| Lab 2 | 5 | 2 | 9 | 18 | 300 | 260 |
| In-situ 1 | 22 | 6 | 35 | 109 | 760 | 0 |
| In-situ 2 | 19 | 5 | 27 | 47 | 620 | 0 |
| In-situ 3 | 15 | 4 | 31 | 14 | 750 | 0 |
| ***Total*** | 67 | 20 | 103 | 208 | 2750 (approximate 45.4h) | 540 (approximate 9h) |

The results of initial coding verified that design judgment did indeed occur often in local visualization design contexts, regardless of any particular design stages. Next, theme coding was conducted by re-reading, combining, and ranking the initial codes, as well as checking back on the theoretical grounding, to prepare a well-organized finding report.

#### 3.4.2.3.2.1 *Codes on Transcriptions*

All coders were required to code quotes or conventional texts that appeared as the full statements (full stops) of a design decision-making with combined codes, *Label A, B,* and *C,* and specific marginal remarks such as *(Aa; B1; C1) OR (Aa, Ab-2, B3; B6; C6; C12) etc.* (as seen in Appendix B). Table 3.9 as an example presented what codes with three different categories outlined on data transcriptions.

Table 3.9 Table as an example that illustrates how the codes layout on the data transcriptions.

| ***Excerpt/Quotation*** | ***Types of design judgment*** | ***Information visualization design stage*** | ***Influencing factor of design judgment*** | ***Overall*** |
|---|---|---|---|---|
| *“I found that the delay time/total delay times of one specific day seems don’t make much more sense, but the total numbers for each month look more interesting, we can show this total frequency for month. Sounds like the causes connected with each variable and influenced the statistical number changes.* | framing; connective *(Ad; Ah)* | parse; filter; represent *(Bb; Bc; Be)* | design validity; design feasibility *(C design validity; C15)* | *(Ad; Ah; Bb; Bc; Be; C design validity; C15)* |
| *I think the causes should be presented with a great focus.* | appreciative; appearance *(Ae; Ag)* | filter; represent *(Bc; Be)* | clear design goal *(C14)* | *(Ae; Ag; Bc; Be; C14)* |
| *Additionally, I explored this data source from Bureau of Transportation Statistic (https://www.bts.gov/topics/airlines-and-airports) and referred several featured visualizations, in which, one of the pieces focused on the topic of the airlines and airports.* | instrumental *(Aj)* | mine *(Bd)* | capability of literature searching *(C capability of literature searching)* | *(Aj; Bd; C capability of literature searching)* |
| *In this example, see, three rings are workable to display different variables, we can use this way too, I think.”* | connective *(Ah)* | represent *(Be)* | design validity; design feasibility *(C design validity; C15)* | *(Ah; Be; C design validity; C15)* |

### 3.4.2.3.2.2 <u>*Coding for Patterns*</u>

In this section, I describe how each code examined and identified by retrieving from one of three defined codes' categories, including the types of design judgments *(Label A)*; visualization design stages *(Label B)*; and factors influence design judgments *(Label C)* with the triangulation method to compare different data source. In the following three parts, Section 3.4.2.3.2.2.1 discusses how the design judgments, such as *framing, navigational, instrumental, connective, compositional, appearance,* etc. examined and identified with supportive evidence that triangulated between different data source. Section 3.4.2.3.2.2.2 presents how seven visualization design stages identified by the same method with the previous section. Finally, section 3.4.2.3.2.2.3 outlines how the factors that influence design judgment making examined by the similar triangulation approach - the patterns of the factors that influence design judgments including the clear design goal, design validity, design feasibility, knowledge of design principles, personal life experience related to data topic, constraint of professional guidance, etc.

#### 3.4.2.3.2.2.1 <u>*Patterns of Design Judgments*</u>

<u>***Framing design judgment***</u> – I observed all design teams considered what data segments, variables, or attributes to be included or excluded within the purview of their particular design processes. They also defined and embraced the design activities' constraints (client, sponsor, manager, or tool) to assess design outcomes.

An example from the audio recording of Laboratory Study 1, Participant SJ said, "I think the total delay information is meaningless, but the delay of some particular airline or air route is more valuable. We can get rid of the total delay data. Like this website – Bureau of Transportation Statistics (https://www.bts.gov/), I don't see the total delay information at all" *(data variable).* Participant AA *(In-situ Study 2)* in the midpoint interview discussed, "We think the data variable of 'department' can be discarded because the manager from CGT needs us to focus more on the academic areas and expertise. The information of department seems unnecessary (Figure 3.4)" *(data variable; manager's requirement).* Additionally, in the early stage of In-situ Study 1, the design team made *framing* design judgment to determine the data attribute of the similarities between different DNA sequences that must be represented in their visualization design project *(data variable)*. Participant JH said (from audio recording), "Our data provider made only one request; that is, to show the similarities between different DNA sequencings, which they want to see most" *(client's needs).* In Week 6 and 7, the design team of In-situ Study 3 defined the connections and relationships between three determined variables, which to be shown further in their visualization project *(data variable with particular segments)*.

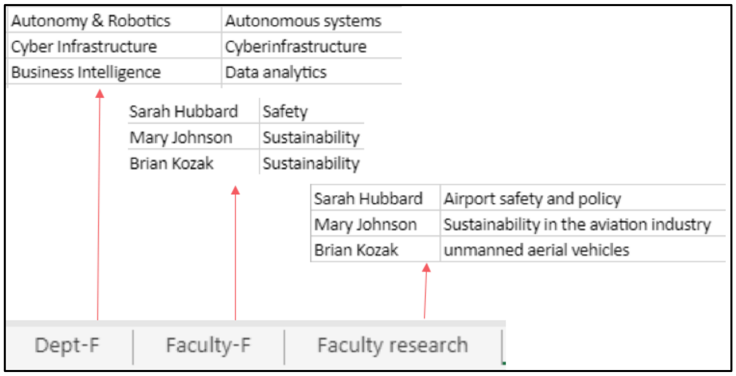
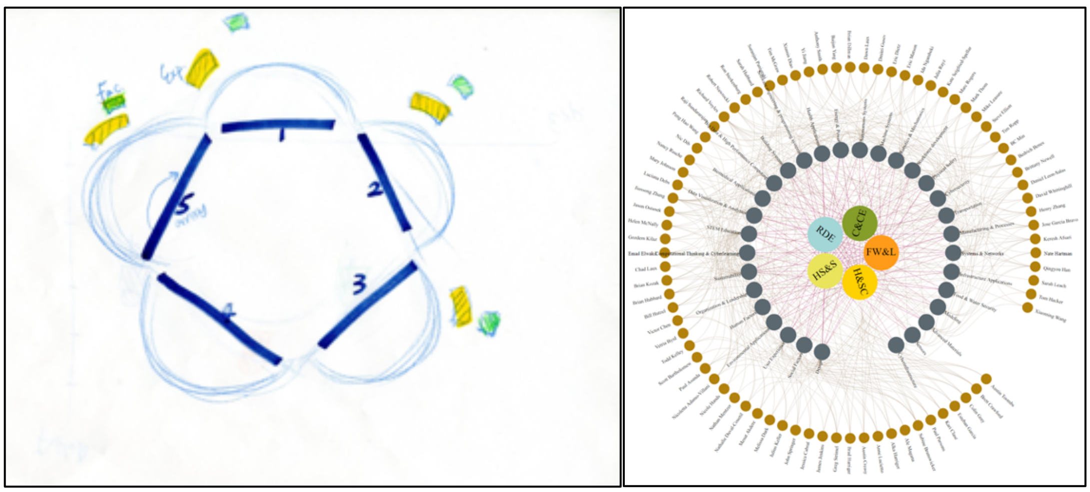



Figure 3.4 Supportive images of how code *framing* design judgment. This image premises by the designer who participated in this study.

***Navigational design judgment*** – I observed all design teams made *navigational* design judgment to define and decide a certain manner, path, or flow and employ them to process the visual representations, interactions, computing functionalities, and algorithms, etc.

The design team of In-situ Study 3 navigated their interaction ways with a certain manner of "overview, zoom, filter, details-on-demand, relate, and extract" (Schneiderman, 1996) in approaching a visualization. With audio recordings, P-KY said, "This manner is particularly in keeping with our design idea. We can give the users an overview at first, then zoom in and filter by choosing and selecting. Then, the users will see more details for the selective items by hovering and clicking. At the same time, some related information shows up and some unrelated information shows down" *(a certain manner in approaching interactions in visualization)*. In-situ Study 3's members also navigated their design by a working flow of "database re-construction and interaction paralleled firstly and graphic design then." In their midpoint interview session, Participant ZJ explained, "We are not able to build a framework for this design project through exploring database only. Data is to too hard. We have to think about another plan to help us build up a design framework. This way is reasonable for us" *(a working flow/path to building up design framework)*.

***Instrumental design judgment*** – *Instrumental* design judgments making were observed a lot in this research. The design teams made the choices of tools (i.e., DNA Analyst – *In-situ Study 1*; Bureau of Transportation Statistics – *Laboratory Study 1*, etc.), concepts (i.e., bionics design concept – *In-situ Study 2*; concept of design inclusion – *In-situ Study 2*, etc.), and methods (i.e., interaction design ways – *all studies*; computing algorithms and applications – *In-situ Studies 1 & 3*; etc.). Based on the audio recordings, Participant JH from In-situ Study 1 said, “We can use this online tool to extract the data that we really want and save to these tables. ..I think, ..we won’t design a program to filter and extract data, right? That would spend a lot of time. And unnecessary! This tool is enough!” *(an online tool for DNA analysis).* Students in In-situ Study 2 considered the bionics design concept and applied it to their in-progress design sketches and final design idea (Figure 3.5 (a) and (b)). P-JJ discussed (from endpoint interview), “We consider and attempt to apply a flower to represent five impact areas and improve the innovation and harmony of these design ideas. The bionic design is an effective way” *(bionic design concept and method).*




(a) (b)

Figure 3.5 Supportive images of how code *instrumental* design judgment. This image premises by the designer who participated in this study.

***Connective design judgment*** – I observed the participants bound connections and interconnections between various design objects (i.e., visual representations, data similarities, interaction ways, etc.) and transmit their individual influences, energy, and powers.

Some supportive evidence, such as the students in In-situ Study 2 focused on binding three main groups of visual objects between an explored online visualization example and their local design idea. Participant IL said (from audio recordings), “They have three rings with some nodes on there, right (D3 Plus Ring Network - https://bl.ocks.org/PatMartin/0fccfddf5277e01cd5024d963f0caa70)? We also have three circular shapes with some nodes. Cool, similar things. I think we only need to do a little bit revision to re-layout the nodes; then we can refer and adapt the coding examples smoothly. Then we will have an interactive visualization!" *(visual objects' connections; coding examples' transmissions).* In-situ Study 3's members also made *connective* design judgments to design interface by binding similar data segments such as the connected lines between two different data variables. In their midpoint interview, P-LY explained, "We need to show the connected lines between action and project; action and analysis; project and analysis, right? So, see… the rectangular tree, matrix, parallel coordinates, all who can help and support representing the data connections between two different variables. We then refer these examples to create our designs by outlining our specific data on there" *(data segments' connections; visual representations' transmissions).*

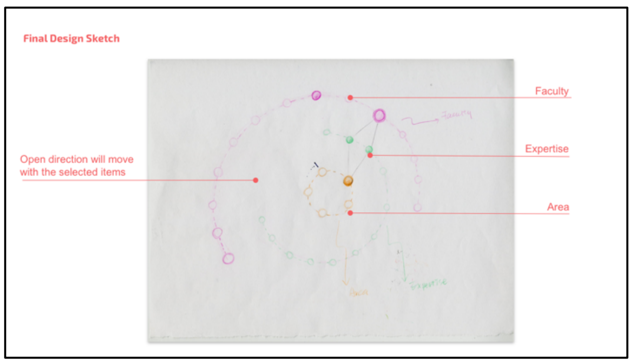
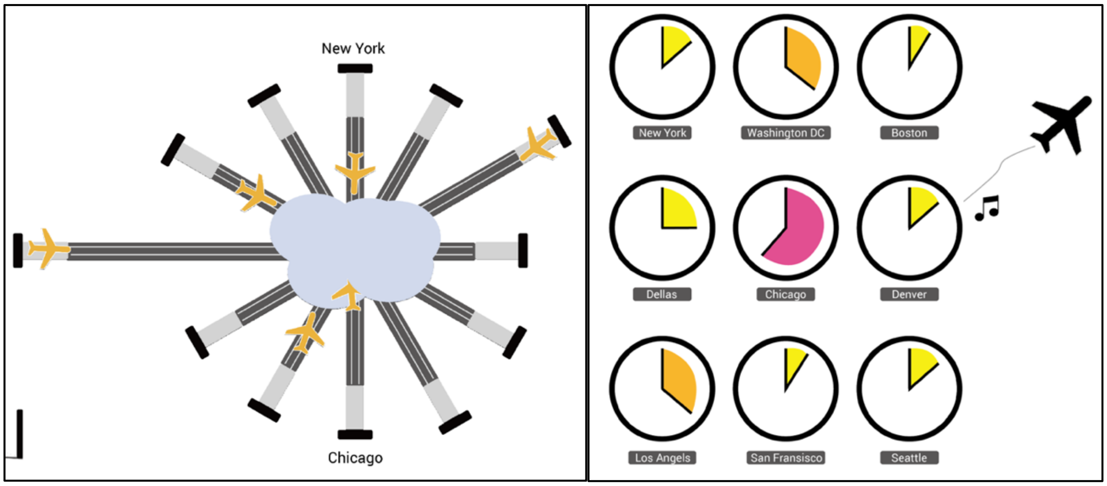



Figure 3.6 Supportive images of how code *connective* design judgment. This image premises by the designer who participated in this study.

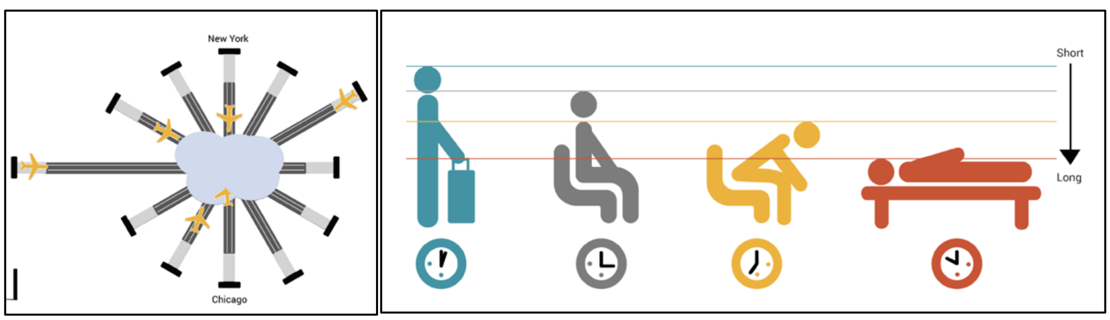
***Compositional design judgment*** – The participants made *compositional* design judgments with the considerations of combing various things or design objects together in a relational whole interface.

The student designers from Laboratory Study 2 create more than17 individual charts and graphs and then set up different combinations to make a whole design interface (Figure 3.7 (a) and (b)). P-SY discussed in their post-semi-structured interview, "We never think about creating an interface to meet all required data variables at one time. That's too hard. So, we think about defining a central diagram and combine and compose it with some small charts like pie, bar, calendar, etc. Then we will see which interface meet most of the required data attributes. That one would be the final idea" *(visual objects' compositions).* In Laboratory Study 1, P-SS also said, "The three ideas are not good. But we can keep this stacked bar chart separately. See… to combine it into this Sankey diagram would be perfect." *(visual objects' compositions).* The participants in

Laboratory Study 1 split the visual forms into separate individuals and attempted to combine and compose them into new rational wholes.




(a)




(b)

Figure 3.7 Supportive images of how code *compositional* design judgment. This image premises by the designer who participated in this study.

***<u>Appearance design judgment</u>*** – The design teams assessed overall appearance quality by making *appearance* design judgments, especially in Laboratory Study 2, In-situ Studies 1 and 2.

Participants XM and XY communicated *(Laboratory Study 2)*, “To create an aesthetic interface is critical. A beautiful design attracts people (XM). I think the overall style looks..fine, right (XY)? And we can add some visual elements to strengthen the whole design style (XY)” *(appearance of overall design style)*. The considerations of color combinations for overall interface led the students made *appearance* design judgments in In-situ Study 1. P-SD said (from audio recordings), “We need to choose a reasonable color combination to improve the whole interface. The red-blue combination is ugly, I think. The purple-green would be better, the feeling of smoother and more harmony" *(appearance of color characters of overall design style).* With the endpoint semi-structured interview of In-situ Study 2, P-AA explained, "We all think the circular shape provides the users the feelings of embracement and harmony. So, we keep this circular design all the time" *(appearance of a visual form of overall design style).*

***Quality design judgment*** – With data accuracy, the design teams also considered a lot on the visual effectiveness when creating and determining visualization design ideas.

P-SJ rejected P-SS's design idea by making *quality* design judgment. P-SJ said *(Laboratory Study 1)*, "This big pie with five small circles (Figure 3.8) never support the data representations better because some of the carriers did really good, which with few delays. So, if we have those kinds of carriers, where do you put the five circles?" *(visual effectiveness).* The students in In-situ Study 1 chose a semi-circle shape to layout one specific DNA with the similarities between two sides of DNA sequences because of the effectiveness of this semi-circle form. P-JH said (from audio recordings), "Our original goal is to represent the similarities of G-C contents between different DNA sequences, right? And we want to compare several of them concurrently, right? So, how to compare them at the same time? I think we cut a full circle into two separate parts; into two section would be a better idea. Then the left side can be used to compare to the DNA sequences on the left, and the right part for comparing with the right DNA sequencing" *(visual effectiveness).*

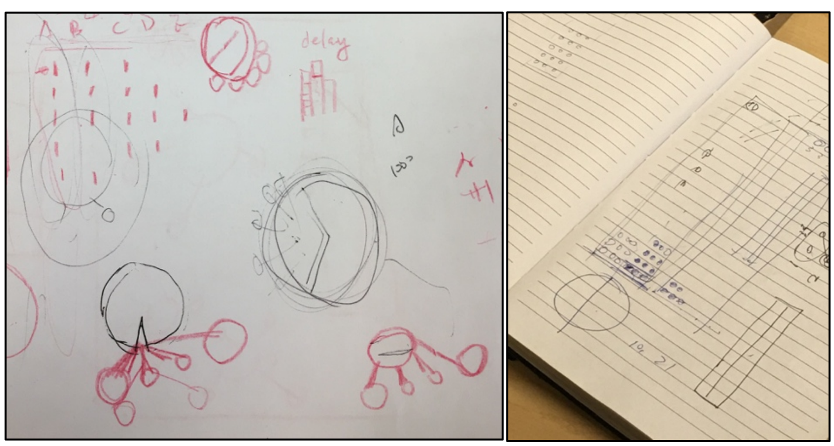
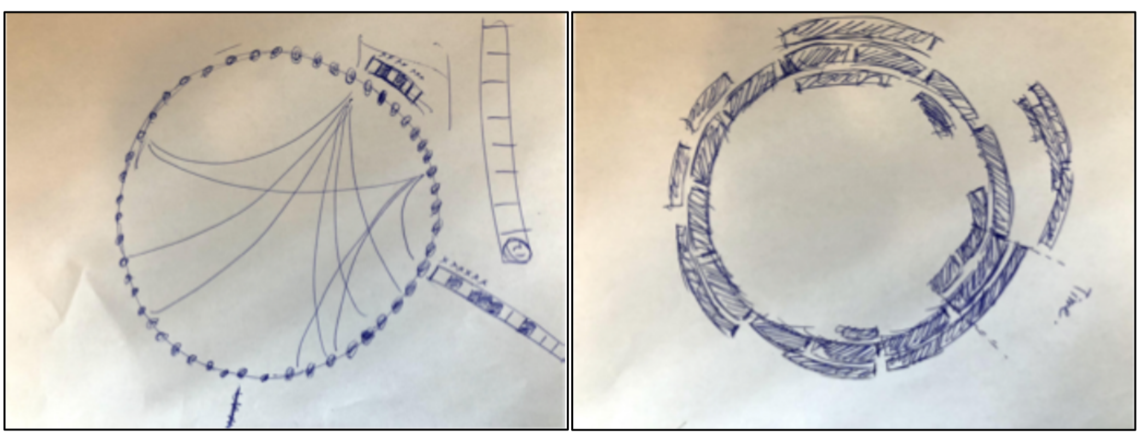



Figure 3.8 Supportive images of how code *quality* design judgment. This image premises by the designer who participated in this study.

***Appreciative design judgment*** – I observed the design teams considered to layout some design objects as foreground but the others as background.

In Laboratory Study 1, the students requested a lot of attention to represent the data variable of the causes but weaken other data segments. P-JS said (from audio recordings), “The topic of this dataset is about the reasons that led flight delays. …So, the feature of the causes would be the most focus point in this project. The other parts can be the background. Or we can regard them as the supplementary information to help explain these main contents” *(appreciating data variables)*. The participants from In-situ Study 2 and 3 also made *appreciative* design judgments when processing interaction designs. They employed the interaction ways of selecting and highlighting to appreciate the contents they would like to present as a foreground and applied the effect of fading out to weaken the information they would like to show as a background.

***Core design judgment*** **-** In my observations, the participants also made *core* design judgments, which were being pushed by “why” questions. In in-situ Study 3, the participant SQ said (from audio recordings), “Why do we put this timeline alone? I mean why it shows out of the wholeness (Figure 3.9 (a)) – the central circular chord diagram? This layout destroys the sense of wholeness. We should do a new combination to build up the sense of wholeness (Figure 3.9 (b)).” During the midpoint semi-structured interview session, the participant AA *(In-situ Study Two)* explained, “Why we always want to keep the idea of the circular shape? Circular shapes bring people more sense of harmony. It also helps us (designers) layout more information since users’ screens are fixed. A rectangular layout may cause infinite scrolling down.”

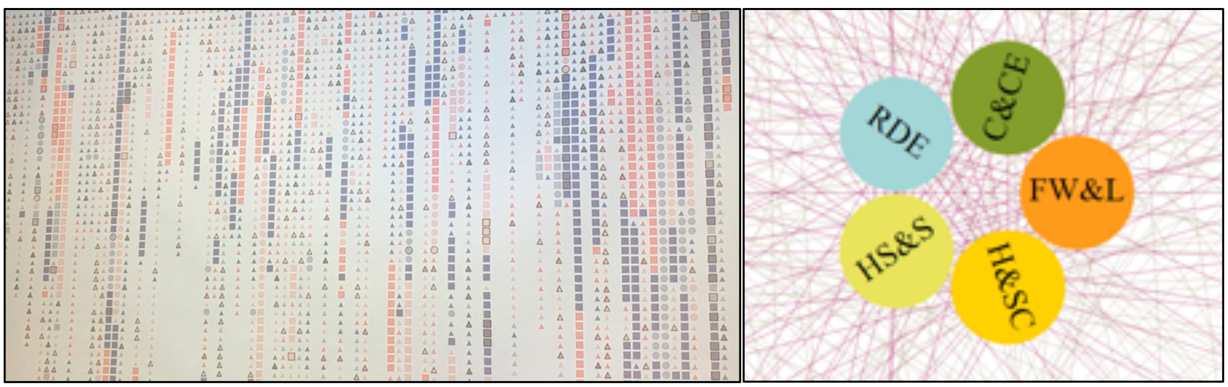


(a) (b)

Figure 3.9 Supportive images of how code *core* design judgment. This image premises by the designer who participated in this study.

***Deliberated off hand judgment*** **-** *Deliberated off hand* design judgment making was also observed in this research when the participants recall previous judgments and employed these experiences to guide current situations.

Participant JH *(In-situ Study 1)* said (from audio recordings), "You know I was in *CareerVis* project. Once we have the data from Qualtrics, I used 8 different shapes to represent 8 variables to show the data analysis results (Figure 3.10 (a)). Our users can recognize those representations. So, we can also consider applying several different shapes to outline different DNA sequences in this project. It should also be workable." In in-situ Study 2, the participant JJ discussed in her endpoint semi-structured interview, "Our group tries to keep the visual element of flower – the bionic design concept because my education and previous design project experiences tell me the bionic design concept is effective at catching people's attention. (Figure 3.10 (b))"




(a) (b)

Figure 3.10 Supportive images of how code *deliberated off hand* design judgment. This image premises by the designer who participated in this study.

***Default design judgment*** – Some of the participants made *default* design judgments with an automatic response to a design situation.

For example, the participant JJ *(In-situ Study 2)* said (from audio recordings), "…Right. We cannot use the color combination of red and green. The color blindness issue happens. Every designer knows that." *Default* design judgments were made based on *deliberated off hand* judgment-making experiences (Nelson, 2012). As another example from Laboratory Study 1, participant SJ explained in their post-semi-structured interview, "Based my mathematical learning, this design idea cannot be processed because data will be not supported. Not all data meet this design idea. We have to give up it without hesitation."

Table 3.10 Summary of how many codes of design judgments (types) in each study.

| ***Studies*** | ***Codes of Lab A – Design Judgments (Types) on Data Transcriptions*** |
|---|---|
| Laboratory Study 1 | 155 |
| Laboratory Study 2 | 113 |
| In-situ Study 1 | 497 |
| In-situ Study 2 | 419 |
| In-situ Study 3 | 375 |
| ***Total*** | 1559 |

Table 3.11 Summary of design judgment identifications with representative examples from the interviews and field notes of observations as supportive reasons and evidence.

| ***Patterns*** | | ***Reasons*** | |
|---|---|---|---|
| ***Design Judgments (Types)*** | ***Applicable Definitions of Operationalized Types of Design Judgments (Nelson 2012; Gray 2015)*** | ***Representative Examples from Interview Data*** | ***Representative Examples from Field Notes of Observation*** |
| Framing | Judgments made for determining what is to be included within the purview of the design process, defining and embracing the space and constraints (client or tool) of assessing design outcomes. | "Based on the requirements of our project team, the data variables of action, project, and analysis must to be included and represented in this visualization." – *In-situ Study 3* | The design team decided to represent three data variables of action, project, and analysis in this visualization project. – *In-situ Study 3* |
| Navigational | Judgments made by considering a "right rule" – a plan, flow, path, or a certain manner to make sure a right design direction and desired design state. | "…So, we will re-construct the database and define interaction ways firstly and concurrently, and then considering about how to improve the graphic design since we already have a workable framework." – *In-situ Study 1* | The design team determined a working flow of "database re-construction and interaction design paralleled firstly, and then graphic enhancements." – *In-situ Study 1* |

Table 3.11 continued

| | | | |
|---|---|---|---|
| Instrumental | Judgments made on dealing with the choice and mediation of means – tools, concepts, and methods within the context to reach established design goal. | "We use this existing tool to extract data; compare the DNA sequences in pairs and find out the similarities of G-C contents between them." – *In-situ Study 2* | The design team explored an existing online tool – *DNA Analyst* to help define the similarities between different DNA sequences. – *In-situ Study 2* |
| Connective | Judgments made on binding connections and interconnections between and among things and various design objects to form functional assemblies that transmit their individual influences, energy, and power to one another. The connections made are not for relational whole but are particular to a design situation. | "…So, we can directly adapt this section with code example and apply it to represent our data variables because the data structure is the same between the both designs." – *In-situ Study 2* | The design team attempted to adapt an online visualization example – *D3 Plus Ring Network* with code references and transmit the technical force for achieving an interactive visualization design based on their personal design idea. – *In-situ Study 2* |
| Compositional | Judgments made on bringing various design objects together in relational who/overall design process rather than specific to a particular design situation; forming within the guiding domains of aesthetics, ethics, and reason – in the mode of synthesis. | "Now, we have a number of ideas based on some data segments. We can try to define a graph as a central diagram and combine it to some complementary charts like the pie, bar, calendar, or fig to compose a complete interface." – *Laboratory Study 2* | The design team composed individual design ideas into several design combinations as whole interfaces to represent and strengthen data theme. – *Laboratory Study 2* |

Table 3.11 continued

| | | | |
|---|---|---|---|
| Appearance | Judgments made on assessing overall appearance quality with style, nature, character, and aesthetic experience; relating to the entire product rather than a portion. | "I think information visualization should support users aesthetic experience. Also, designers can add appropriate visual elements to enhance the overall theme although they never represent some particular data segments." - *Laboratory Study 2* | The design team considered the overall layout and color construction from aesthetic perspective and added several visual elements, which without essential data insights to enhance the aesthetic of the whole interface. – *Laboratory Study 2* |
| Quality | Judgments made on effectiveness of visual and other forms of style; whether there is enough of a match between design standards, other proposed design, and aesthetic norms. | "To layout five circles on the edge of this big pie is ineffective because not all carries support an enough space with more airlines' delays." – *Laboratory Study 1* | The design team attempted to give up an idea of "a big pie with 5 circles on the edge" because of the considerations of design effectiveness on data insights. – *Laboratory Study 1* |
| Appreciative | Judgments made on what is considered background and what requests more attention as foreground. | "…So, we determine to focus on representing the similarities of G-C contents among different DNA sequences, right? We may also present the differentials between ones but won't be the concentrated tasks." – *In-situ Study 1* | The design team focused on representing the similarities between different DNA sequences and regard the other data variables, such as the differentials as background. – *In-situ Study 1* |
| Core | Judgments made when one is being pushed by "why" questions concerning one's judgments and decisions. | "Why do we put this timeline alone? This layout destroys the sense of wholeness. We should do a new combination to build a wholeness." – *In-situ Study 3* | The design team attempted to combine the circular chord diagram and timeline chart into a rational whole with "why" questions and considerations. – *In-situ Study 3* |

Table 3.11 continued

| | | | |
|---|---|---|---|
| Deliberated off hand | Judgments made by recalling previous judgments that have led to successful designs and adapted to the current situation. | "I used 8 different shapes to represent 8 variables in showing data analysis results for *CareerVis* project. Our users can recognize those representations. So, we can consider using the same design method in this project. It should also be workable." – *In-situ Study 1* | The design team selected several different shapes to represent and distinguish total 8 different DNA sequences. – *In-situ Study 1* |
| Default | Judgments made without deliberation; an automatic response to a situation. | "…Right. We cannot use the color combination of red and green. The color blindness issue will be happened. Every designer knows that." – *In-situ Study 2* | The design team gave up the color combination of red and green to avoid color blindness issue. – *In-situ Study 2* |

3.4.2.3.2.2.2 Patterns of Visualization Design Stages

***Acquire*** – "obtain the data, whether from a file on a disk or a source over a network" (Fry, 2007). All the in-situ studies concentratedly reflected the design activities in the *acquire* phase. For instance, the participants from In-situ Study 1 asked, "You know…. we come to talk where we can download the full dataset. Or could you please point out how we can get the whole dataset from this website? Where we can see the detailed introduction of this data on this website?" (Figure 3.11) when they met the data provider at their early design stage. The participant AA reviewed in their midpoint semi-structured interview, "Firstly, we came by the CGT main office and communicated with the manager to ask if we can copy the PPI dataset to a disk. Or if someone can send out the data to all of us."

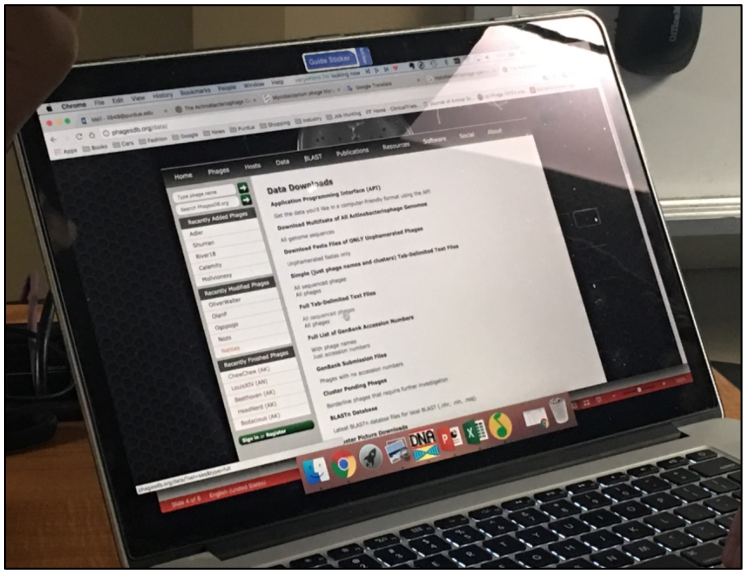


Figure 3.11 Supportive images of how code *acquire* visualization design stage. This image premises by the designer who participated in this study.

***Parse*** – "provide some structure for the data's meaning and order it into categories" (Fry, 2007). Once getting the data, the participants JH and ZJ *(In-situ Study 1)* focused on indexing their data into the categories and saved the extract data into different tables for navigating their design with database re-construction. They explained, "We try to understand the meaning of the data. But, it seems too hard. So, our idea is to split the data into segments, which would be better for us to make more sense of it." The participant SJ from Laboratory Study 1 discussed how he parsed the supported dataset of 'Flight Delays in the U.S.' He said, "I try to categorize these data attributes. I divide the data variables, such as causes, times, locations, etc. into different clusters. Then I attempt to synthesize each partial data into a whole."

***Filter*** – "remove all but the data of interest" (Fry, 2007). The participants in In-situ Study 2 removed the data feature of 'department' but kept the variables of 'impact areas,' 'expertise,' and 'faculty members.' Participant OG explained (from midpoint interview), "The main topic of this dataset is really about the impact area and expertise. Showing the variable of department seems not to be necessary. So, we determined to discard department variable." As another example, participant SJ from Laboratory Study 1 persuaded his team member to give up displaying the variable of 'total delay time' because of meaningless on data insights' deliveries.

***Mine*** – "apply methods from statistic or data mining as way to discern patterns or place the data in mathematical context" (Fry, 2007). In in-situ Study 1, the participants considered employing an existing online tool to understand the patterns of data. Participant ZJ said (from audio recordings), "This tool as a data mining approach supports us the complete functions to statistics, extract, and cluster data." The team of In-situ Study 3 applied computing algorithms of input, output, clustering, and extracting to discern the connections and interconnections between determined data variables.

***Represent*** – "choose a basic visual model, such as a bar graph, list, or tree" (Fry, 2007). Information visualization researchers and designers focus on employing visual representations of abstract data to reinforce human cognition. All the participants reflected design activities in *represent* stage. For example, the participants in Laboratory Study 2 created a number of design ideas with different visual forms, such as geographic map, bar chart, pie chart, calendar chart, timeline, etc. to represent different data segments. In in-situ Study 3, these team members communicated, "It seems a lot of visual forms can be used to represent the connections and relationships between two or multiple variables. Currently, we have this Sankey flow, matrix, treemap, and circular chord diagram. The chord diagram can be the best idea I think."

***Refine*** – "improve the basic representation to make it clearer and more visually engaging" (Fry, 2007). For instance, participant SJ *(Laboratory Study 1)* proposed to refine the No. 12 design idea for more effective data representations with the reorganization and coordination of visual elements. Participant AA from In-situ Study 2 said (from audio recordings), "I think…we need to set up clustering to group these nodes, right? Then the connected lines would be displayed clearer. For now, the intensive and overlapped lines make the whole interface super busy."

***Interact*** – "add methods for manipulating the data or controlling what features are visible" (Fry, 2007). The participants from In-situ Study 1 focused on employing the interactions to construct the framework of their project. They communicated, "We can rely on interactions to build up our framework. Then we can import the data segments to the supportive interactions. To do so, we can ensure that we have a complete design framework, at least." In in-situ Study 3, the participants applied the interaction ways of selecting, highlighting, filtering, etc. to help the users query the information and data insights that they indeed want to explore.

Table 3.12 Summary of how many codes of information visualization design stages in each study.

| ***Studies*** | ***Codes of Lab B – Information Visualization Design Stages on Data Transcriptions*** |
|---|---|
| Laboratory Study 1 | 87 |
| Laboratory Study 2 | 70 |
| In-situ Study 1 | 401 |
| In-situ Study 2 | 367 |
| In-situ Study 3 | 320 |
| ***Total*** | 1245 |

Table 3.13 Summary of the identifications of information visualization design stages with representative examples from the interviews and field notes of observations as supportive reasons and evidence.

| ***Patterns*** | | ***Reasons*** | |
|---|---|---|---|
| ***Information Visualization Design Stages*** | ***Applicable Definitions of Visualization Design Stages (Fry, 2007)*** | ***Representative Examples from Interview Data*** | ***Representative Examples from Field Notes of Observation*** |
| Acquire | "obtain the data, whether from a file on a disk or a source over a network." | "We schedule this meeting to get the raw data. Could you please provide the website that we can see and download the raw database?" – *In-situ Study 1* | This team attempted to acquire raw database from a teaching assistant who come from the data team. – *In-situ Study 1* |
| Parse | "provide some structure for the data's meaning and order it into categories." | "We can create several tables to make our raw data into categories, such as contrast two, contrast three, different G-C contents, similarities, differentials, etc." – *In-situ Study 1* | The design team set up several tables to save data in the way they could make sense with different categories of comparisons in pairs, in three, different G-C contents, similarities and differentials between different DNA sequences. – *In-situ Study 1* |

Table 3.13 continued

| | | | |
|---|---|---|---|
| Filter | "remove all but the data of interest." | "…So, I think we don't need to show the variable of department because the design purpose concentrated on the expertise and academic areas." – *In-situ Study 2* | The design team filtered out the data variable of department and kept the attributes of impact areas, faculty members, and expertise to represent. – *In-situ Study 2* |
| Mine | "apply methods from statistic or data mining as way to discern patterns or place the data in mathematical context." | "We can use this function to explore how many the exact connected lines between two different variables for the statistical results." – *In-situ Study 3* | The design team a computing function – *extract and return* to identify how many connected lines they have exactly between the determined variables. – *In-situ Study 3* |
| Represent | "choose a basic visual model, such as a bar graph, list, or tree." | "…So, for now, we will try to compose these ideas for a whole interface to represent all determined data variables." – *Laboratory Study 2* | The design team composed the separate design ideas to represent determined data attributes and examine which rational whole meet all the requirements. – *Laboratory Study 2* |
| Refine | "improve the basic representation to make it clearer and more visually engaging." | "We choose the idea of No.12, right? But we need to refine some visual elements like these 5 circles. It currently affects accurate data expressions." – *Laboratory Study 1* | The design team attempted to refine the No.12 design idea to ensure more reasonable and accurate data presentation. – - *Laboratory Study 1* |

Table 3.13 continued

| | | | |
|---|---|---|---|
| Interact | "add methods for manipulating the data or controlling what features are visible." | "We need to design interactions at our early design stage with database re-construction. | The design team explored interaction ways to help construct the overall |

| | | | |
|---|---|---|---|
| | | Interaction is a good way to help us build the whole design framework." – *In-situ Study 1* | framework for the project. – *In-situ Study 1* |

3.4.2.3.2.2.3 *Patterns of Factors Influence Design Judgments*

***Clear design goal*** – The factor of clear design goal that influences the design judgment making was observed concentratedly based on the participants' design activities from laboratory studies. Participant SJ *(Laboratory Study 1)* said (from audio recordings), "Our design goal aims to represent the causes that influence the flight delays, right? So, my opinion is that all designs should serve this goal and data theme. … Like, why I try to use a U.S. map? Because the flight delay is really related to the specific air routes with points to points from departure to destination" *(framing, quality, appearance, core design judgments).* The participants in Laboratory Study 2 communicated, "Our primary goal is to show air flight delays within an airport setting, right? To be honest, we add some other visual elements without essential meanings in order to strengthen the data topic and design goal, right?" *(appearance design judgment).*

***Design validity*** – Design judgment making was also influenced by the factor of design validity. While processing data mining, visual representations, and interactions, the participants made design judgments, which were being pushed by the consideration of design validity. For example, participant SJ rejected his teammate's design idea because of design validity factor. Participant SJ explained in the post-semi-structured interview, "This idea is ineffective to present the data because not all carriers did badly with the flight delays. Some of the carries did great jobs with few flight delays. So, where we can outline these five circles, see?" *(quality design judgment).* Based on the audio recordings, the participants from In-situ Study 1 discussed, "The wiper one may be an easier way and effective to achieve the comparisons between different DNA sequences because of a valid oscillation and displacement" *(quality and core design judgments).*

***Knowledge of design principles*** – A number of design judgments-making were affected by the factor of knowledge of design principles. The participants in Laboratory Study 2 made *quality* and *appearance* design judgments through the knowledge of design principles of color usage, concept of visual center, etc. They explained in their post-semi-structured interview, "What we learned is about each interface should support a visual center to attract users' attention quickly. ….Right! The other thing is one interface cannot include more than 6 colors, otherwise, it will cause visual conflict.” In in-situ Study 2, the participants’ design judgments-making were also influenced by the factor of knowledge of design principles. Based on the audio recordings, they discussed, “This flower is great, a bionic design. I think this design will attract a lot of attention from people. …It’s also reasonable and effective since we use the petals to represent different impact areas, right? This idea is super cool, and we can keep that” *(instrumental, quality, and appearance design judgments).*

***<u>Personal life experience related to data topic</u>*** **–** This code was examined and identified by the concentrated observations of Laboratory Study 2’s design activities. With personal life experiences, the participants firstly assumed a list of causes, such as weather, airport management, carrier management, etc. that influenced flight delays. And then they double checked if the provided dataset supported these assumptions with Tableau results. Participant SY explained (from post-semi-structured interview), “Each of us has the personal experience to take a flight, right? We first considered what causes affect the flight delays in general; that is, in our common sense. We summarized several important factors in our mind. But they are real in the provided data? We don’t know. Adequate statistical calculations are challenged for us. But we both can use Tableau to run some simple charts. We use Tableau results to do backcheck and confirm what variables to be included, for sure” *(framing, instrumental, and navigational design judgments).*

***<u>Constraints of professional guidance, development technology, design innovation and creativity</u>*** **–** The constraint of professional guidance influenced the participants made design judgments, especially in In-situ Study 1. Participant JH said (from audio recordings), “The big challenge for us is that data is too hard, but we don’t have professional guidance. We don’t have a clue. We don’t know where to start to deal with the data.” Participant SD said, “Right! If we continue working on data only, I don’t think we can submit and show something for final.” Participant ZJ said, “So.. we are thinking about another way of applying this *DNA Analyst* to re-construct our database and processing interactions to build framework. I think this would be a better way to help us release the challenges of data” *(navigational and instrumental design judgments).*

The participants in In-situ Study 2 made concentrated design judgments of *connective, framing, quality, appearance*, which influenced by the constraint of development technology. All members in In-situ Study 2 came from the design backgrounds, including visual communication design, game design, and mechanical design. They have challenged to skill the web-based programming with particular D3 functionalities and accomplish a completed interactive information visualization system in a short academic semester. Participant AA said, “How can we release this? D3 is hard, and no one in our group can master this programming. I think what we can do is to explore an online example; refer and adapt their existing code examples.”

In in-situ Study 3, the participants also made a series of *connective, framing, quality, appearance, instrumental* design judgments with the influencing factor of the constraint of design innovation and creativity. The group of In-situ Study 3 comprised of two students from Computer Graphics Technology and two other students from the Human Factors program. Without a solid design background, it was challenged for this team to brainstorm a lot of design ideas and choose a most appropriate one for next design procedures. Participant SQ said (from audio recordings), “LY and I came from the UX program. We can do design sketches, but 30 or 50 ideas are super hard for us. So… I think we can refer some example to do the sketches, and then request the manager to pick up his preference among these several ideas. Haha! This is the only way I can think of.”

***Limited time with an expected outcome*** – All the participants who involved in In-situ Studies made different types of design judgments with an influencing factor of limited time with an expected outcome. Participant ZJ said (from audio recordings), “10 weeks to accomplish a complete interactive information visualization system is really challenged since data cannot be directly used. But the time is limited. We need to submit and show a result for final. So, this flexible design thinking may help us” *(instrumental design judgment).* Participant AA from In-situ Study 2 discussed (from endpoint semi-structured interview), “What we can do to make an interactive information visualization application within the 4 weeks left. It seems other groups already have something to show, but we don’t have. Crying… So, we can try to find online examples and refer the coding. That would be a good idea” *(connective design judgment).*

***Client/sponsor’s requirement*** – The client/sponsor’s requirements influenced the participants’ design judgment activities a lot. Participant KY from In-situ Study 3 discussed (from audio recordings), “Our product manager pointed out what variables, such as action, project, and analysis must be included in our project. We don’t need a lot of discussions to framework our project” *(framing design judgment).* The product manager also put forward design ideas like adding on a timeline and requested the students to make design refinements during their representing procedures *(quality, appearance, etc. design judgments)*. The participants from in In-situ Study 2 attempted to obtain clients' needs at their early design stage. The manager from CGT Department clarified the data topic and helped the design team determine what data attributes, such as impact areas and expertise have to be represented emphatically and concentratedly in their visualization project *(framing design judgment)*.

Table 3.14 Summary of how many codes of factors influence design judgments in each study.

| ***Studies*** | ***Codes of Lab C – Factors Influence Design Judgments on Data Transcriptions*** |
|---|---|
| Laboratory Study 1 | 120 |
| Laboratory Study 2 | 85 |
| In-situ Study 1 | 403 |
| In-situ Study 2 | 301 |
| In-situ Study 3 | 298 |
| ***Total*** | 1207 |

Table 3.15 Summary of the identifications of factors influence design judgments with representative examples from the interviews and field notes of observations as supportive reasons and evidence.

| ***Patterns*** | ***Reasons*** | |
|---|---|---|
| ***Factors Influence Design Judgments*** | ***Representative Examples from Interview Data*** | ***Representative Examples from Field Notes of Observation*** |
| Clear design goal | "… I think our design goal focuses on representing the causes that make flight delays, right? So, all design ideas should revolve around this purpose." – *Laboratory Study 1* | The design team considered different visual representations based on a clear design goal of showing and presenting the causes that influenced the delays of air flights. – *Laboratory Study 1* |
| Design validity | "If I'm a user, I may cannot make sense of this graph. This design is not easy for me to find out the information." – *In-situ Study 2* | The design team refined the visual representations and interactions by reflecting the design validity and effectiveness. – *In-situ Study 2* |

Table 3.15 continued

| | | |
|---|---|---|
| Knowledge of design principles | "No more colors, I think. What we learn is one interface cannot include too many colors, no more than six." – *Laboratory Study 2* | The design team employed the knowledge of visual color theory and design principle to refine visuals of the interface. – *Laboratory Study 2* |
| Personal life experience related to data topic | "We can assume some variables, such as weather, airport management, carrier management, etc. to be appeared in this piece of data and to be included in this visualization design project." *-Laboratory Study 2* | The design team firstly put forward several assumptions when determining data variables based on their personal flying experiences. – *Laboratory Study 2* |
| Constraint of professional guidance | "…We cannot focus on data explorations all the time. We don't have the ability to understand everything about this database. We need to think about some other ways to build up a reasonable project framework." – *In-situ Study 1* | The design team decided a working flow of "database re-construction and interaction paralleled, then graphic design" to ensure an acceptable design outcome for final submission and presentation since data was professional and challenged to make sense. Blindly studying and exploring database might lead a poor design result. – *In-situ Study 1* |
| Constraint of development technology | "…I think what we can do is to find an online example with coding examples. Then we can try to refer the codes to do our design idea. To become a D3 expert is impossible for us in this short semester." – *In-situ Study 2* | The design team attempted to explore an online visualization design with coding and programming examples to refer and adapt because becoming a skilled programmer was super challenged for all members in their team within a short semester with only 14 weeks' learning. – *In-situ Study 2* |
| Constraint of design innovation and creativity | "We can focus on introducing and updating this circular diagram to the manager. We don't have many design ideas and sketches now. So, we can talk one in detail." – *In-situ Study 3* | The design team considered introducing and updating to the product manager about the idea of circular chord diagram concentratedly because they had no many sketches. To do brainstorming was challenged for this team. – *In-situ Study 3* |

Table 3.15 continued

| | | |
|---|---|---|
| Limited time with an expected outcome | "I think we have to go with next step. Data is hard, which is true. But we need something to show for final. I agree to apply this working flow for building up the framework of design." – *In-situ Study 1* | The design team gave up continues data explorations and created a workable working flow since the limited time framework. – *In-situ Study 1* |
| Client/sponsor's requirement | "…We have to represent these three variables because of the manager's requirements. We have no choice." – *In-situ Study 3* | The design team determined three data variables of action, project, analysis to be included and represented in the project because of the manager/sponsor's clear needs and requirements. – *In-situ Study 3* |

The following table (Table 3.16) summarized the total quantity of codes with each of the categories in each of laboratory or in-situ studies.

Table 3.16 Summary of how many codes on each coding categories in each study.

| ***Studies*** | ***Codes of Lab A – Design Judgments (Types) on Data Transcriptions*** | ***Codes of Lab B – Information Visualization Design Stages on Data Transcriptions*** | ***Codes of Lab C – Factors Influence Design Judgments on Data Transcriptions*** | ***Total*** |
|---|---|---|---|---|
| Laboratory Study 1 | 155 | 87 | 120 | 362 |
| Laboratory Study 2 | 113 | 70 | 85 | 268 |
| In-situ Study 1 | 497 | 401 | 403 | 1301 |
| In-situ Study 2 | 419 | 367 | 301 | 1087 |
| In-situ Study 3 | 375 | 320 | 298 | 993 |
| ***Total*** | 1559 | 1245 | 1207 | 4011 |

#### 3.4.2.3.3 Theme Coding

Theme coding helped provide coherence among theme patterns in order to tell an accurate story about the data (Saldana, 2015). The theme coding procedure proceeded with the following steps:

(1) Checking back with each chosen key design event/node (in-situ study focused) that changed or affected the design teams' designs with a specific (final) design decision-making statement during the framework analysis step;

(2) Re-reading the transcripts (observational notes and interviews) of the above key design events with codes from the initial coding; merging design decision-making statements that presented a similar topic with the final design activity into a theme. Themes with relevant design determinations were regarded as sub-themes that characterized in-progress design decisions. They helped explain the design decision-making flow for chosen design nodes;

(3) Combining and calculating the *Label (A)* codes *(types of design judgments)* in each sub-theme with in-progress design decisions (mentioned in (2)) to decide on a theme, such as "*instrumenting the design*;" combining and calculating all available codes of *Label (A)* to provide an overview theme on design judgment such as "*instrumenting and navigating the design"* for the first hierarchical design event/node;

(4) Combing and ranking the codes with *Label (B) (7 visualization design stages)* to determine the specific design stages where sub-decisions are made; combing and ranking all design stages based on all sub-decisions throughout the process to determine the design stage for the first level key design event/node;

(5) Using the same method as point 4 to identify major predictors for each critical design event; combing and ranking all the factors from each key node of the design to summarize design teams' top three determinants of the complete design process.

Theme coding of the laboratory study data followed the same process but left out selective critical design events/nodes because the laboratory findings were based on all design processes.

***Theme Coding with Research Questions 2 (How do they occur) and 3 (What are the influencing factors)*** – Based on supportive initial coding results, I highlighted how the theme coding procedure helped answer the research questions, especially for 2 and 3. The results and findings of Research Questions 2 reflected the critical design activities and their design decision-making flows with the sub-design decisions; the themes of the design judgments; visualization design stages where these design decisions, and where corresponding design judgments appeared. The insights of Research Question 3 embodied in the three top influencing factors and how they affected design teams' judgment behaviors.

#### 3.4.2.4 Describing and Interpreting

Coding identified themes, patterns, connections, and relationships. The final step in the data analysis was to describe the data and interpret these findings by developing lists of key ideas, creating diagrams/charts, and applying structural models (Dey, 2003). To arrive at these identifications, I organized the storytelling structures based on research questions to interpret the laboratory and in-situ data.

*(1) Laboratory Study –*

- *Research Question 1 – "What are the existences:"* In the initial coding phase, a large number of marked codes showed that design judgment does indeed exist in local visualization design contexts and situations. A separate section was used to describe the frequency results that showed patterns and themes of design judgments from a focused infographic design perspective. Because these two laboratory studies were controlled within a time slot, "How often/frequency" insights will help the investigator and other readers understand patterns in design judgments.
- *Research Question 2 – "How do they occur:"* Two controlled laboratory studies were provided the same dataset, time schedule, and design task (design context) and employed the same design process. By adapting Fry's (2007) theory of visualization design stages, I focused on interpreting and explaining similarities and differentials between both.
- *Research Question 3 – "What are the influencing factors:"* A separate part was needed to explain the top three predictors of design judgments, which were identified in the theme coding stage for both laboratory studies. The relationships between these factors and design judgments will help infographic designers and researchers organize better design situations and avoid adverse factors.

*(2) In-situ Study –*

- *Research Questions 2 – "How do they occur:"* The result of frequency calculation on design judgment as a supplementary explanation within *Research Question 2* helped interpret and describe how design judgments occur during particular visualization design stages using themes and patterns. Because these insights were identified based on selective key design events/nodes, it was not appropriate for "How often/frequency" to appear in its own section. In different design contexts, *Research Questions 2* could be answered with their own in-situ studies.
- *Research Question 3* – The influence factors were presented by the same method with *Laboratory Study*. The differences were: (a) to discuss it separately in each in-situ study; (2) to detailly compare the similarities and differences across studies after individual studies.

The bar charts and scatter plots help explain these findings, particularly in showing the frequency of design judgment utilization and supplementing an explanation of that design judgment theme. For example, a design decision-making with the theme *"framing the design"* used a structural description and a large square that corresponds to the type of framing to the X-axis. All charts used for finding reports were made using Tableau (Murray, 2013) (Figure 3.5).

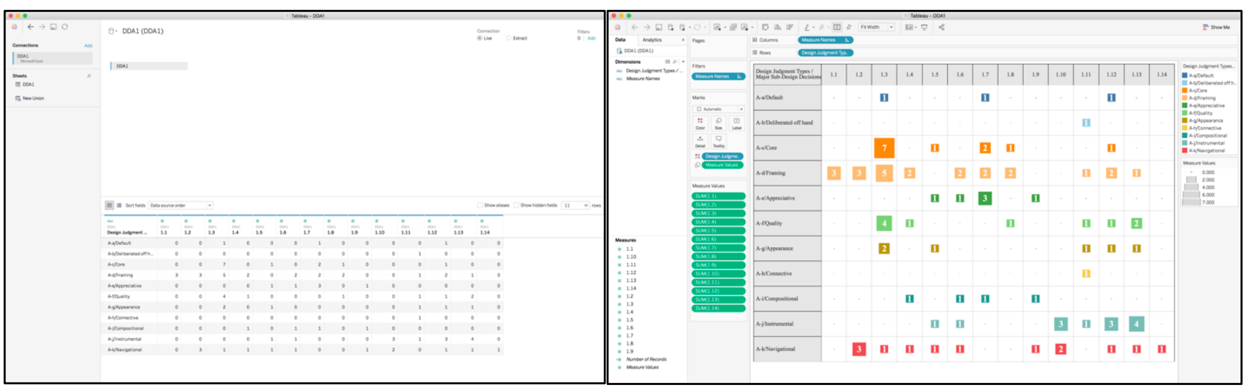


Figure 3.12 Explanatory charts produced by Tableau.

## 3.5 Credibility

Credibility is seen as the most important criterion in establishing trustworthiness in qualitative research (Patton, 2002; Golafshani, 2003). In 2002, Patton acknowledged that the credibility of qualitative research depends on the rigorous methods, a researcher's credibility, member checking, and triangulations, which include data triangulation, investigator triangulation, theory triangulation, and methodological triangulation.

I conclude Chapter 3 by discussing the credibility of this research in terms of credibility of the researcher and triangulation.

#### 3.5.1.1 Credibility of Researcher

I believe I had the requisite perceptivity (researcher credibility) for this research due to my prior experiences of: (1) being a Research Assistant who created and conducted visualization design; (2) attending courses with visualization design and analytics design topics; (3) and publishing scholarship based on personal visualization projects. As the first chapter acknowledges, the design reflections that arose out of Vis Lab sparked my curiosity on this subject and led to the questions posed in this research. Additionally, I used Chapter 1 to provide an exhaustive review of visualization design research, design judgment studies in diverse design domains, and the relationships between them. My previous experience, combined with this comprehensive literature review, makes me well equipped to investigate this important design behavior.

#### 3.5.1.2 Triangulation

As early as 1994, Denzin et al. (1994) identified four different ways' triangulation can occur in qualitative research. These include: (1) data triangulation, which is the use of a variety of data sources; (2) investigator triangulation, which is the use of multiple investigators for collection and analysis; (3) theory triangulation, which uses multiple perspectives to interpret a single dataset; and (4) methodological triangulation, where multiple methods are used. All of these approaches augment the research's credibility and trustworthiness. In my research, all approaches were employed.

(1) *Data triangulation*– Because different data sources reveal different empirical realities in qualitative studies (Denzin & Lincoln, 1994; Patton, 2002), I used multiple data sources, including observational notes, sketches, images, audio recordings, and interviews to paint a clear picture of the visualization design phenomenon under examination, and hence, trust in the findings. Data traigulation also emphasizes using different data collection techiniques (Denzin & Lincoln, 1994; Patton, 2002). This research triangulated the information via the observations and interviews.

(2) *Investigator triangulation*– The coding procedure employed in this research involved three investigators who collaboratively worked on the textual materials (observations and

interview notes and transcriptions). I divided three coders into two groups to work on four of the datasets once intercoder agreement was reached (McHugh, 2012). These groups engaged in (a) two training sessions with two arbitrarily chosen datasets (In-situ Study One and Laboratory Study One); (b) a 2-hour discussion for each session to ensure on unanimous agreement. Cohen's Kappa is frequently used to test intercoder reality (McHugh, 2012), and a Kappa value is 0.60 – 0.79 is typically considered to be moderate, acceptable, and satisfactory. I processed the Kappa for each *Label (A, B, or C)* codes for each session using SPSS (Valiquette et al., 1994). By the end of the second training, intercoder reality was satisfactory (Figure 3.6). Although intercoder agreement was met, the coders also spent a lot of time discussing the materials and seeing how we could agree to a more reasonable data analysis results during coding the remaining datasets.

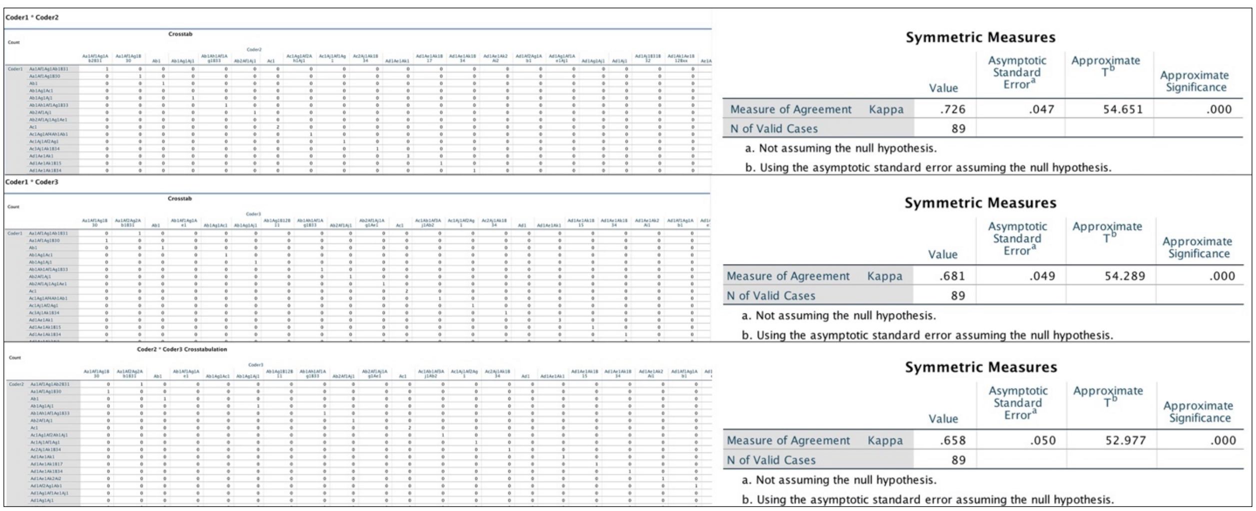



Figure 3.13 A screenshot of SPSS, which shows how the Kappa values for intercoder reliability.

*(3) Theory triangulation*– With the research-based questions, I interpreted the data using focused questions: "what are the existence," "how do they occur," and "what are the influencing factors." I provided a detailed description of study context before answering the questions. I often applied theories of design judgments and visualization design stages to my explanation of findings.

(4) *Methodological triangulation*– Methodological triangulation was practiced by executing two types of study designs: laboratory and in-situ. These methodologies improved the internal validity of this research and enhaced my understanding of how designers make judgments.

## 3.6 Summary

This chapter provided an overview of the qualitative methodology utilized in this research. In this chapter, I also described purposeful sampling strategies, research contexts, data collection using two study designs, and data analysis with the combined framework and (deductive) thematic analysis. The initial coding phase addressed research question 1; and the theme coding phase provided insights for research questions 2 and 3.

# CHAPTER 4. DESIGN JUDGMENTS IN LABORATORY STUDY

As described in prior chapters, the purpose of this research was to examine students' design judgments as they worked on visualization projects, identify judgments that enable designer decisions and outcomes, encourage a comprehensive description of the activities of visualization designers, and discuss the ways in which they relate to design outcomes, identify gaps in information visualization education and attempt to answer the question, "How and why do judgments occur and progress in visualization design contexts?" The questions central to this research were (1) What are the existence of design judgments in particular information visualization design process? (2) How do design judgments occur in particular information visualization design? (3) What are the influencing factors influencing design judgments?

Observations and interviews with combined framework and (deductive) thematic analysis were used to deduce design judgment behaviors, specifically: what, how, and why design judgments occur in particular visualization design contexts. Data sources included observational notes, sketches, images, audio recordings, as well as interview transcripts.

This chapter aims to interpret and explain student design teams' visualization design judgment behaviors in two laboratory studies. Because the two studies were uniform, I presented the findings and insights of them together. Structural and ordered narratives help the readers to (1) fully understand visualization design judgment behaviors under a particular design process using step-by-step explanations with research-driven questions; (2) quickly locate answers to the most interesting research questions and view the detailed insights; and (3) easily compare or synthesize across the cases to understand their similarities and differences.

## 4.1 Study Context

The lab studies were conducted among two groups of graduate student design teams. Two participants on Team One came from the Colleges of Art and Design and Technology, majoring in Interaction Design and Computer Graphics Technology. Team Two included two Master's students with Industrial Design majors. All participants were provided with the "Flight Delay in the U.S." dataset, which included statistics of 13 carriers, 10 departure airports, and a number of destination airports under the influence of 5 major causes. I also provided a design task for each group member, which required creating an innovative and intuitive visualization that provided users with a peripheral awareness of meaningful information from the complex dataset. I asked them to start the design process by collaborating. Additionally, I supplied each group with two laptops, 30 pieces of paper, a dozen post-it notes, and colored pencils to document their visualizations. Each lab study was controlled to complete the design task within 5-5.5 hours, which included the 50-minute semi-structured interviews.

The qualitative data collection for Team One lasted approximately 5 hours and 20 minutes (5.3 hours) of observations and interviews. Four hours and 40 minutes were used to complete the design task and 40 minutes for the post-semi structured interview session. Out of this session emerged six pages of textual descriptions and 12 pages of design sketches. Team Two allocated roughly the same amount of time: a total of 5 hours, with 4 hours and 10 minutes for the design task and 40 minutes for interviews after completing the design. The data gathered from Team Two amounted to 5 pages of notes and 18 design sketches.

Detailed findings of these lab studies are presented and analyzed in the following sections. I originally organized the findings according to the order of research questions, then synthesized and compared the results for insights of visualization design judgment methods and applications. Additionally, I summarized unexpected findings during the analysis stage, which is customary in qualitative research (Lindlof, 2017).

## 4.2 Design Judgments in Laboratory Studies

The lab visualization design focused on the infographic design aspects without attention to the actual development processes. The students' designs were executed by determining a feasible design idea and conceptualizing its visual representations and interactions. The interpretations and explanations of laboratory study findings contributed: (1) to verify the existence of design judgment in visualization design and specify the themes and patterns that occurred within; I calculated frequencies to determine the data attributes and visuals – *Section 4.2.1*; (2) to detail the occurrences of (3) segmented themes and patterns as they appeared in the process of design judgment-making and the visualization design stage in which they were located – *Section 4.2.2*; and (4) to describe the key factors (top two) that influenced the designers' decision-making and judgment making – *Section 4.2.3*. By comparing and synthesizing these findings across two laboratory studies, all summative themes and patterns for the visualization design judgments were generalized and used in the infographic visualization by checking and adapting the design contexts and team situations –S*ection 4.3*. This qualitative research produced unexpected findings because its research questions were open ended (Onwuegbuzie, 2007). *Section 4.4* explains the unexpected findings in addition to the research questions while analyzing the data.

### 4.2.1 Design Judgment Existence

The initial coding data analysis procedure helped verify that designers do make judgments in visualization designs, as can be seen from the intensive marked codes in the textual materials. The results of coding also identified no other forms of design judgment occurred both laboratory studies. While interviewing, P-SS (Participant SS) from Team One stated:

> …I am not pretty sure the terminologies about each of the different judgments, but we are constantly judging, which is true. Since this is a team project, so we communicate a lot each other about how to decide one thing such as we want to present a total 15 variables in this project. Definitely, we didn't decide all of them at once. It was comprised of several sub-design activities. Determining each sub-problem also takes a process because we usually think about some things or factors like why choose this variable? Make sense of users or not? Or, which variables should be focused and layout to the central location in our interface? These processes can be the design judgments making, I assume.

***Frequency -*** It is meaningful to calculate and rank the frequency of the design judgments because (1) both teams demonstrated a more complete infographic design (process); (2) all gathered data underwent coding; and (3) the ranked frequency serves as effective evidence that helps explore and identify themes and patterns of design judgments.

The results of the design judgment frequency were obtained from theme coding by statistically calculating the codes from initial coding. Before charting, I back checked and prepared design behaviors based on moveable design nodes in each lab study. For Laboratory Study One, theme coding helped identify four design decision-making processes as the key design nodes; however, a total of three design behaviors were examined in the Laboratory Study Two materials.

Using Tableau, I created bar graphs to present categorical data of different types of design judgments with heights/lengths proportional to the values that they represented (Figures 4.1 and

4.2). Tableau also allowed me to rank the occurrences of design judgment from most to least. On the top of each graph, I highlighted the type based on the total frequency, such as *appearance* design judgment with 16 for the Laboratory One study, and *framing* design judgment with 27 in the Laboratory 2 study. On the bottom of each diagram, I showed the ranking results for each design decision. The highlights in this section helps me and the readers refine major types of design judgments to each particular design decision. The designers used *framing design judgment* in their first two interesting design behaviors, and *compositional, appearance,* and *instrumental* for their third and fourth design behaviors. Each of explorable design activities in Laboratory study Two embodied in a lot of design judgment making on the types of *framing, compositional,* and *appearance* respectively.

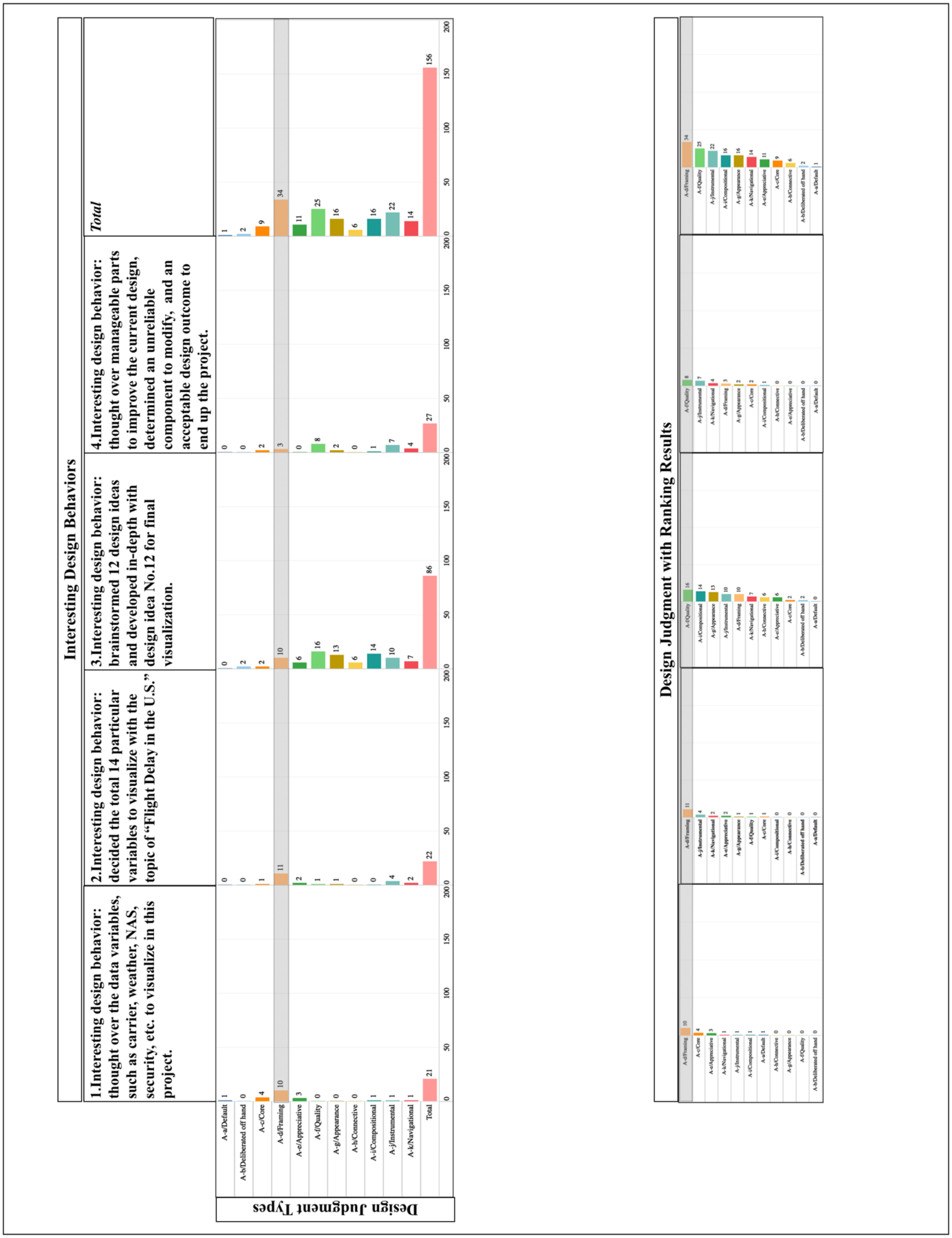



Figure 4.1 A frequency ranking of students' design judgments (Laboratory Study One).

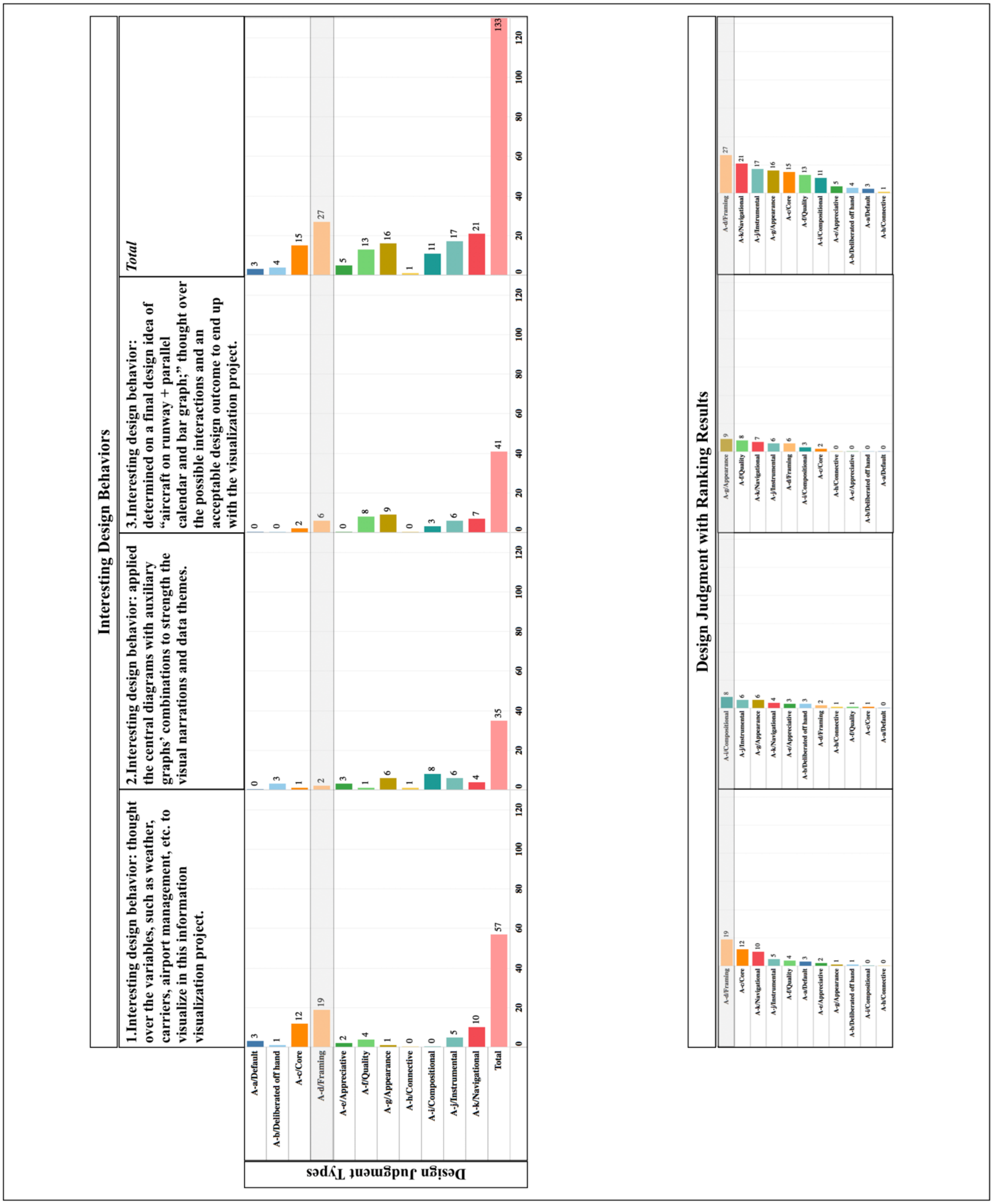



Figure 4.2 A frequency ranking of students' design judgments (Laboratory Study Two).

### 4.2.2 Design Judgment Occurrence

As described in Section 3.4/Data Analysis, all visualization design activities occurred within one or more design stages (Fry, 2007) (Figure 4.3). The coding procedures detailed seven design stages that used *Label B*, which helped me identify the particular design path of each study.

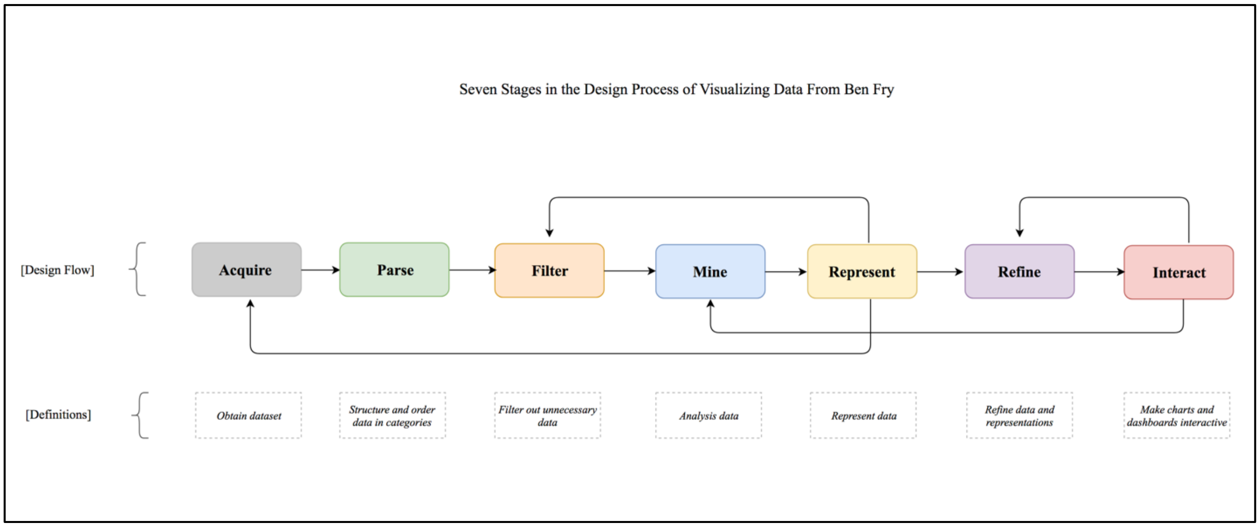



Figure 4.3 Seven stages of the design process of visualizing data from Fry (2007).

Taking advantage of visualization design stages' theory, this section aided the research findings with: (1) overviews of how designers' visualizations (infographics) accomplished an outcome using design decision-making and informed design judgments (Figure 4.4); (2) detailed information of the composition of each of explorable and valuable design activities with particular design judgment methods (Tables 4.1 and 4.2).

***(1) Overviews*** – I diagramed the findings of the two laboratory studies in one chart because both teams used similar design processes/stages to visualize the data (infographic perspective). The information in Figure 4.4 included: (a) specific design behaviors; (b) (sub)design activities that comprised of each design decision; (c) informed design judgments of each design behavior and total frequencies; (d) design judgment theme(s) of each design decision; (e) a legend of different types of design judgments; and (f) design behaviors in design stages. Among them, I determined the judgment theme of each interesting design behavior based on their frequency and semantics.

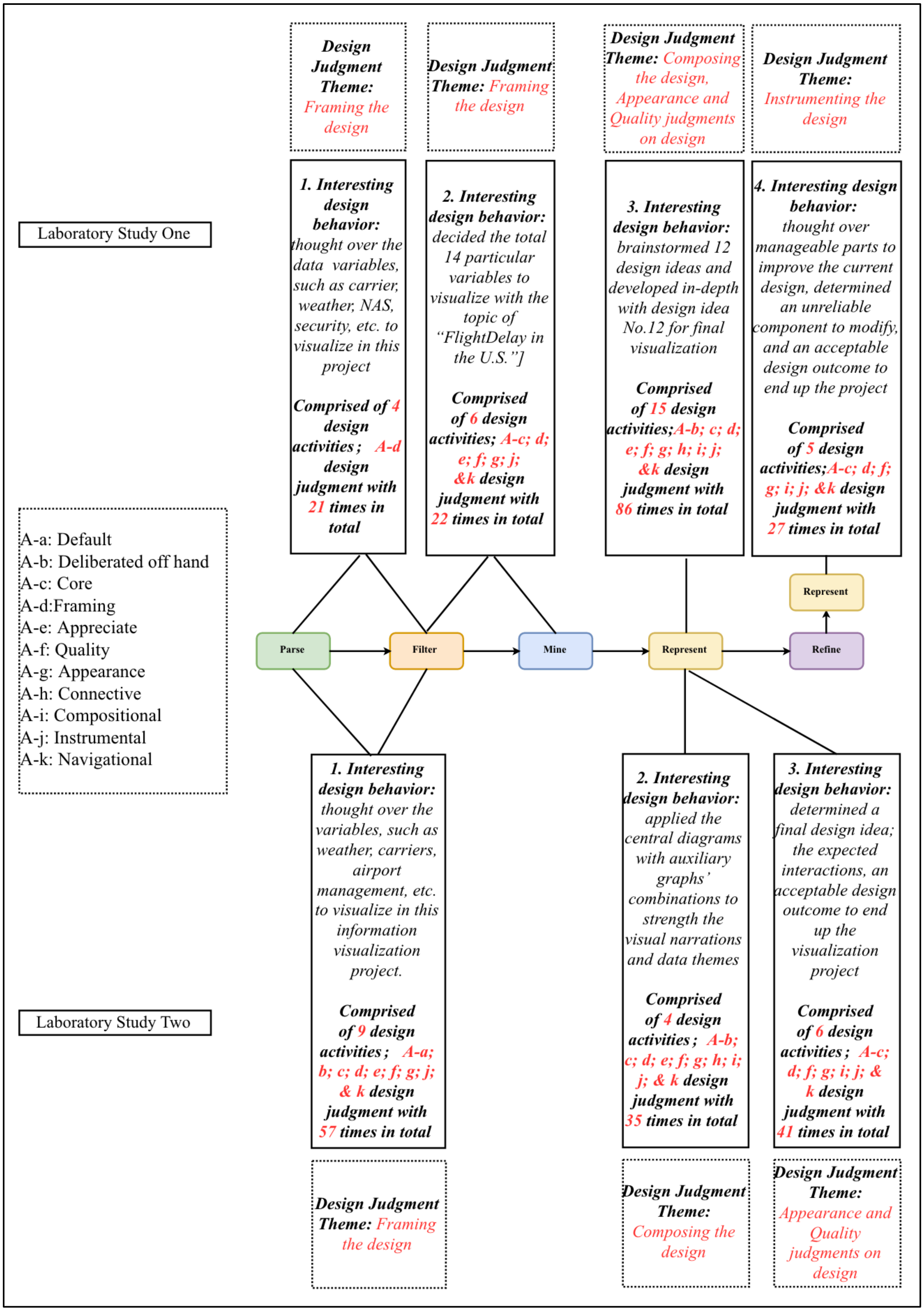



Figure 4.4 How designers from two laboratory studies accomplished their infographic designs with essential design behaviors and informed design judgments.

***(2) Details*** - Determining a workable design decision was not a one-off; instead, the designers' thoughts and actions presented a flow of (sub)design decision-making progresses. Table 4.1 (Laboratory One) and 4.2 (Laboratory Two) outlined each key design behavior and their corresponding (sub)design decision-making procedures and judgments. Here, I identified what design judgments (themes and combinations) moved the design forward within specific design situations (team situation, design requirement, design style, etc.)

***(2.1) Laboratory Study One*** –

***<u>Theme 1</u>: framing the design (a set of design activities with the design considerations on what data variables to be included in the project) -*** Throughout this project, this design team made a lot of *framing* design judgments when considering which data attributes to be represented, especially in the early stages (1 and 2 Interesting design behaviors in Table 4.1). By parsing, filtering, and mining, their team used a total of 13 variables to present their final visualization at the end of their second design behavior (bullet 2. Interesting design behavior in Table 4.1). *Framing* a design accompanied judgments of *core, appreciative, instrumental, navigational* in their first two design behaviors. For instance, they determined the variable causes (e.g., carriers, weather, NAS, etc.) should be intensively visualized due to the subjectivity of the data (*framing* and *appreciative* design judgments' concurrently).

In order to validate their initial thoughts (bullet 2.2 in Table 4.1), one participant (P-SJ) explored an online tool – Bureau of Transportation Statistics to lend support to retaining the variable total delay frequencies. To do so, they used an effective filter interaction design that could be applied to help users query the information of total delay frequencies with different categories for day, month, and quarter. (*framing, instrumental*, and *navigational* design judgments' concurrently)

***<u>Theme 2:</u> composing the design; quality and appearance judgments on design (a set of design activities with brainstorming procedures for design ideas) -*** Once the team had 14 variables (bullet 2.4 in Table 4.1), they brainstormed 12 design sketches to lay them out. Based on my observations, they spent approximately 1.5 hours creating different visual representations with various visual forms and visual techniques (size, color, shape, etc.). By the end of their third design decision, they selected the No.12 design sketch as the most innovative and creative using a series of *appearance* design judgments (bullet 3.15 in Table 4.1).

Across the activities of bullets 3.1 to 3.14 (Table 4.1), *compositional* design judgments-making were prominent. The design team spent many efforts composing visual objects to assess (all or partial) data characters by a complete interface accompanying *quality* and *appearance* judging. As an example of bullet 3.1 (Table 4.1), designers composed a circular layout of a wool ball (Figure 4.5) and a U.S. map because data charterers organized the presentation of segment information with point-to-point air routes (*quality* design judgment), which overall design appearance conformed to data theme and features (*appearance* design judgment). Concurrently, the design team made *deliberated offhand* judgment to decide the idea of "wool ball," was proposed during the 2017 VAST challenge competition (Visual Analytics Community), and the committee noted its beauty and novelty. They also made *appreciative* design judgment to set the wool ball as foreground and the U.S. map as background when visualizing.

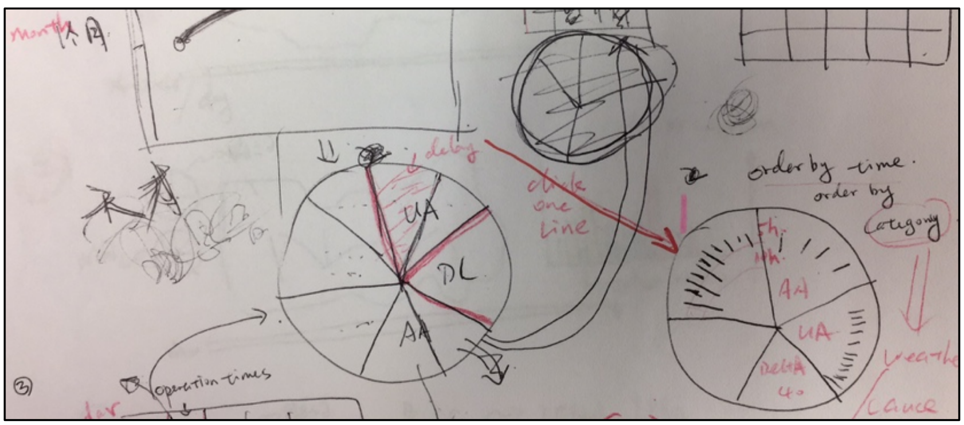



Figure 4.5 Design judgments made in designers' third key design decision. This image premises by the designer who participated in this study.

Due to all the design compositions failed to represent all determined 14 variables, they switched and decided to in-depth develop No.12 idea, which identified as the most innovative and creative to meet all decided data characters. During a post-interview, Participant P-SS said:

> …We try to combine several visual forms since we have 14 variables to show. It seems we cannot represent all of them by only one integrated interface. Thus, we consider choosing the most innovative or creative one, No. 12s at the end of this phase; and then go in-depth with it to add visual elements gradually and meet all determined data attributes.

(*compositional* (prominent); *quality, appearance* design judgments; *navigational* accompanied in this statement)

Other types of design judgments, such as *framing, connective, instrumental, and navigational* also worked concurrently. Across 3.9-3.11 design activities (Table 4.1), designers made *connective* design judgments to transmit the energies of an effective pop-up staked bar and apply to other design interfaces. During the connecting, designers defined the constraints of data variables, goal compliance, etc. (*framing* design judgment) in the current design. Moreover, designers made *instrumental* design judgment to construct a visualization with multiple charts by exploring a design concept of repetition is powerful, during which, they furtherly followed a certain rule (*navigational* design judgment) to organize individual charts to form a small-multiple visualization design.

***<u>Theme 3:</u>* *instrumenting the design, quality judgment on design (a set of design activities on design improvements of the idea No.12) -*** A refined process was observed during the end of the project while the team was trying to modify partial visuals of the selective design idea, and *instrumental* design judgment-making was prominent (bullet 4. Interesting design behavior in Table 4.1). With a focus on data accuracy, the designers double checked the data and applied statistical ways to validate the mean and median values. They also distinguished "amount" from "relationship." Once some accurate data had been explored, they appended refined data segments and modified the relevant visuals, including connecting lines, sizes of outer circles, and colors by *quality* design judgments to further improve the effectiveness of visual forms for more effective information delivery. In addition to the *instrumental* and *quality* design judgments, their final design behavior was also informed by *core, framing, appearance, compositional,* and *navigational* design judgments, for instance, designers re-filtered the data attributes while composing the visual objects for reasonable design changes to the interface. (bullet 4.2 in Table 4.1)

Table 4.1 Design judgments' occurrences in each key design behavior and the involved design activities in Laboratory Study One.

**Design Judgment Occurrences in [1. Interesting design behavior: thought over the data variables, such as carrier, weather, NAS, security, etc. to visualize in this project]**

**(*Theme - Framing the design in "Parse" "Filter" visualization design stages*)**

| Design Judgment Types / Major Sub-Design Activities | 1.1 | 1.2 | 1.3 | 1.4 |
|---|---|---|---|---|
| A-a/Default | | | 1 | |
| A-b/Deliberated off hand | | | | |
| A-c/Core | | 1 | 2 | 1 |
| A-d/Framing | 6 | 2 | 1 | 1 |
| A-e/Appreciative | | 1 | 2 | |
| A-f/Quality | | | | |
| A-g/Appearance | | | | |
| A-h/Connective | | | | |
| A-i/Compositional | | | 1 | |
| A-j/Instrumental | | | 1 | |
| A-k/Navigational | | | | 1 |

Design Activities Comprised of [1. Interesting design behavior: thought over the data variables, such as carrier, weather, NAS, security, etc. to visualize in this project]

| | |
|---|---|
| 1.1 Considered the cause(s) variable, including carriers, weather, NAS, security, and late-aircraft to be represented in the visualization. | 1.3 Considered creating the visualization with a focus on the cause(s) variable; the relationship with other variables such as total delay frequencies of each air route, total number of flights, flight dates, etc. as the supplementary and assistants to compose and interpret the data. |
| 1.2 Considered how to visualize the total delay frequencies of each particular airline/air route. | 1.4 Discussed a working path to visualize the data. |

Table 4.1 continued

**Design Judgment Occurrences in [2. Interesting design behavior: decided the total 14 particular variables to visualize with the topic of "Flight Delay in the U.S."]**
**(*Theme - Framing the design in "Filter" "Mine" visualization design stages*)**

| Design Judgment Types / Major Sub-Design Activities | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 |
|---|---|---|---|---|---|---|
| A-a/Default | | | | | | |
| A-b/Deliberated off hand | | | | | | |
| A-c/Core | | | 1 | | | |
| A-d/Framing | 1 | 2 | 1 | 4 | 1 | 2 |
| A-e/Appreciative | | | | | 1 | 1 |
| A-f/Quality | | | 1 | | | |
| A-g/Appearance | | | 1 | | | |
| A-h/Connective | | | | | | |
| A-i/Compositional | | | | | | |
| A-j/Instrumental | | 1 | | | | 3 |
| A-k/Navigational | | 2 | | | | |

| Design Activities Comprised of [2. Interesting design behavior: decided the total 14 particular variables to visualize with the topic of "Flight Delay in the U.S."] | |
|---|---|
| 2.1 Considered keeping the causes variable with five specific categories for visualization. | 2.4 Determined to visualize a total of 14 specific variables including (1) quarter measurement, (2) month measurement, (3) day measurement, (4) air route, (5) departure airport, (6) destination airport, (7) delay frequency of air route (total), (8) number of air route (total), (9) date of air route, (10) carriers, (11) weather, (12) NAS, (13) security, (14) late-aircraft in the project. |
| 2.2 Considered keeping and visualizing the total delay frequencies variable which filtered by the variables of day, month, and quarter. | 2.5 Consider keeping the determined design goal that focused on visualizing the causes variable. |
| 2.3 Thought about keeping and visualizing the total delay frequencies variable, which combined with the air route variable that represented on a U.S. map. | 2.6 Considered adding one and visualize one more (15) variable of extreme values of the delay hours for a better comparison between each air route. |

Table 4.1 continued

**Design Judgment Occurrences in [3. Interesting design behavior: brainstormed 12 design ideas and developed in-depth with design idea No.12 for final visualization]**

***(Theme - Composing the design, Appearance and Quality judgments on design in "Represent" visualization design stage)***

| Design Judgment Types/Major Sub-Design Activities | 3.1 | 3.2 | 3.3 | 3.4 | 3.5 | 3.6 | 3.7 | 3.8 | 3.9 | 3.10 | 3.11 | 3.12 | 3.13 | 3.14 | 3.15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A-a/Default | · | · | · | · | · | · | · | · | · | · | · | · | · | · | · |
| A-b/Deliberated off hand | 1 | · | · | · | · | · | 1 | · | · | · | · | · | · | · | · |
| A-c/Core | · | 1 | · | 1 | · | · | · | · | · | · | · | · | · | · | · |
| A-d/Framing | · | 1 | 1 | 1 | 1 | · | 1 | · | 1 | 1 | 1 | · | 1 | 1 | · |
| A-e/Appreciative | 1 | · | · | · | 1 | 1 | · | 1 | 1 | · | · | · | 1 | · | · |
| A-f/Quality | 1 | 2 | · | · | · | 2 | 3 | 1 | 2 | 1 | · | 1 | 1 | 1 | 1 |
| A-g/Appearance | · | · | · | 1 | 2 | 1 | · | 1 | · | 1 | 1 | 2 | · | 1 | 3 |
| A-h/Connective | 1 | · | · | · | · | 1 | · | · | 1 | 1 | 1 | 1 | · | · | · |
| A-i/Compositional | 1 | · | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | · |
| A-j/Instrumental | 1 | 2 | · | · | 1 | · | · | 2 | · | · | 1 | 1 | 2 | · | · |
| A-k/Navigational | · | 1 | · | · | · | 1 | 1 | · | 1 | · | 1 | · | · | 1 | 1 |

Design Activities Comprised of [3. Interesting design behavior: brainstormed 12 design ideas and developed in-depth with design idea No.12 for final visualization]

| | |
|---|---|
| 3.1 Created a "wool ball" diagram as the central diagram and a U.S. map to additionally visualize all determined variables. | 3.9 Created a horizontal bar chart with the pop-up stacked bars as a central diagram and a U.S. map as a supplementary to visualize all determined variables except the variable (8). |
| 3.2 Created a pie chart with multiple divided slices as well as the sub-slices from original divided slices to visualize all determined variables except the variables (1-6). | 3.10 Created an idea that composed of a chord diagram with the pop-up stacked bar charts to visualize all determined variables except the variables (7)(8). |
| 3.3 Created the 12 calendars with pop-up pie charts to visualize all determined variables except the variables (4-6). | 3.11 Created an idea that composed of a rectangular chord diagram with the pop-up stacked bar charts outsider to visualize all determined variables except the variables (7)(8). |

Table 4.1 continued

| | |
|---|---|
| 3.4 Considered to abandon previous design idea of the 12 calendars. | 3.12 Created an idea that composed of a chord diagram and insider multiple pie charts to visualize all determined variables. |
| 3.5 Created an idea that composed of two heat maps and a stacked bar chart as a central diagram and a U.S. map as the supplementary to visualize all determined variables. | 3.13 Created an idea that composed of a U.S. map with a pop-up 12*13 gird, which included a bar chart in each cell to visualize all determined variables except the variable (8). |
| 3.6 Created an idea that was composed of two heat maps and a transformative bar chart as a central diagram and a U.S. map as the supplementary to visualize all determined variables. | 3.14 Created a small-multiple design layout, in which, each segment composed of a central pie chart with four outsider circles to visualize all determined variables except the variables (1-6). |
| 3.7 Created a chord diagram with the pop-up pie charts to visualize all determined variables except the variables of (7)(8). | 3.15 Design decision: decided to go deeper with the design idea/sketch No.12 for the ultimate visualization. |
| 3.8 Created a U.S. map with a pop-up stacked bar to visualize all determined variables except the variable (8). | |

Table 4.1 continued

**Design Judgment Occurrences in [4. Interesting design behavior: thought over manageable parts to improve the current design, determined an unreliable component to modify, and an acceptable design outcome to end up the project]**

***(Theme - Instrumenting the design, Quality judgment on design in "Refine" "Represent" visualization design stages)***

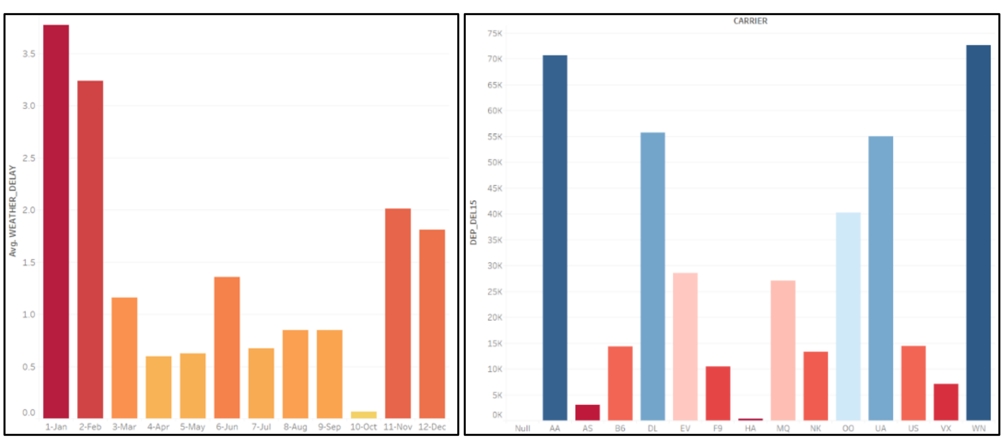
| Design Judgment Types / Major Sub-Design Activities | 4.1 | 4.2 | 4.3 | 4.4 | 4.5 |
|---|---|---|---|---|---|
| A-a/Default | | | | | |
| A-b/Deliberated off hand | | | | | |
| A-c/Core | | | 1 | | 1 |
| A-d/Framing | | | 1 | | 2 |
| A-e/Appreciative | | | | | |
| A-f/Quality | 2 | 2 | 2 | 1 | 1 |
| A-g/Appearance | | | 1 | 1 | |
| A-h/Connective | | | | | |
| A-i/Compositional | 1 | | | | |
| A-j/Instrumental | 2 | 1 | 4 | | |
| A-k/Navigational | | | 3 | 1 | |

Design Activities Comprised of [4. Interesting design behavior: thought over manageable parts to improve the current design, determined an unreliable component to modify, and an acceptable design outcome to end up the project]

| | |
|---|---|
| 4.1 Considered to add a pie chart on the left upper corner as a filter to query quarter, month, and day information to improve the design idea No.12. | 4.4 Processed the color scheme designs for the whole layout. |
| 4.2 Thought about adding an air route selector on the bottom to improve the design idea No.12. | 4.5 Figured out an unreliable component of the current design and summarized an acceptable design outcome to end up the visualization project. |
| 4.3 Considered to conduct the connection lines between the central pies and outsider circles with different lengths; the outsider circles with equal sizes to represent the accurate relationship between the carriers and other related causes. | |

***(2.2) Laboratory Study Two –***

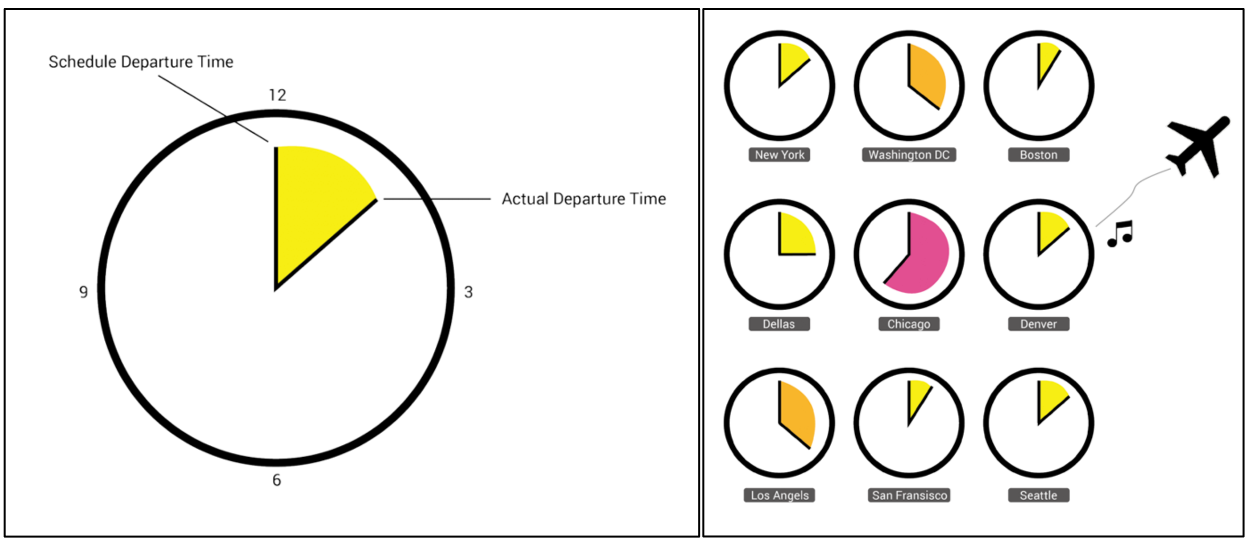
***<u>Theme 1:</u> framing the design (a set of design activities with the design considerations on what data variables to be included in the project) -*** Three key design behaviors influenced Lab Two's project (Table 4.2). Designers often used *framing* design judgments to determine which data attributes should be retained and visualized in their first step. While judging the variables, this team frequently considered how to match the design variables to their original design goals, so *core* design judgment-making was also involved and combined. Before brainstorming design ideas, they put forward several hypotheses, such as a direct correlation between weather and delay time with clear distinction among each month; delay time should be different among various carriers; etc. In order to validate these hypotheses and ensure relatively accurate data for visualization, they set up Tableau and imported some data segmentations for exploring and understanding data (*instrumental* design judgment) (Figure 4.6 a and b). In addition, this group made efforts to figure out an effective working plan (bullet 1.9 in Table 4.2) with manageable parts (*navigational* design judgment). Many other factors were also taken into consideration while splitting workable parts. For example, the team discussed if they could produce and apply one complete infographic to meet all data variables they wanted (*framing* design judgment). If this was not possible, the causes variable would be used as foreground, and all other variables were flexible and could be added back later or discarded altogether (*framing* and *appreciative* design judgments). Moreover, this team tried to explore design sketches and immediately transitioned them into high-fidelity versions using Illustrators for unambiguous layouts. This ensured visual forms and design styles were available for design innovation and reasonableness. (*quality, appearance*, and *instrumental* design judgments occur concurrently)




(a) (b)

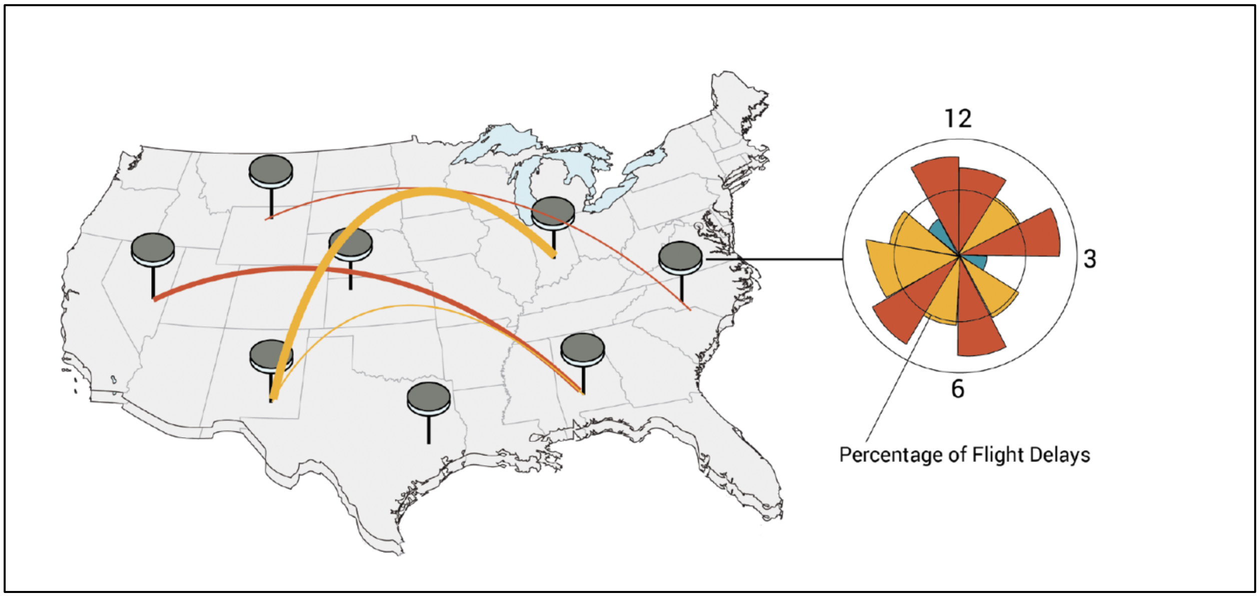
Figure 4.6 Designers making *instrumental* design judgement while developing design ideas.

***<u>Theme 2:</u> composing the design (a set of design activities with the design considerations on what data variables to be included in the project) -*** In the second step, this team focused on integrating separate design ideas into an effective whole, in order to best fulfill and match all wanted data variables (*compositional* design judgment). For instance, in bullet 2.4 (Table 4.2), this team tried eight different design combinations using a central graph and supplementary charts, as shown in Figure 4.7a/b and Figure 4.8a/b (*compositional* design judgment). While composing design ideas, the team used Gestalt Principles to enhance the layout (*instrumental* design judgment). They also incorporated specific steps, such as adding more visual elements to the central diagram and enriching color coding, to highlight foreground data variables (*appreciative* and *navigational* design judgments). Designers' discussions, such as: "why are we composing like this?" (*core* design judgment) and "some good things we did before…" (*deliberated off hand* design judgment) were also observed during bullet 2.4 (Table 4.2).




(a) (b)

Figure 4.7 Evidence to explain how the designers used *compositional* design judgment. This image premises by the designer who participated in this study.




(a) (b)

Figure 4.8 Evidence to explain how the designers used *compositional* design judgment. This image premises by the designer who participated in this study.

***<u>Theme 3:</u> appearance and quality judgments on design -*** A final design idea was decided concentratedly based on *appearance* and *quality* design judgments-making progresses. During their post-interview session, P-XM and P-SY explained:

> …Making a composition is a common thing during the design process because we usually brainstormed a plenty of design ideas. We consider the compositions of visual elements should serve an overall design topic or theme by our received education. A synthesis fails if it cannot strengthen an overall theme style of design. For us, design composition must follow some design principles like no conflicts, no more six colors in total; highlighting significant sections, consistency, etc. We used tools like Adobe Color to select appropriate colors and plan how to modify and embrace each visual parts step by step. The additional visual elements are also added for effectively servicing the project topic. Sometimes, some data variable will be discarded because of the mismatching with some of the visual designs. (*appearance* and *quality* (prominent); *core, framing, compositional, instrumental*, and *navigational* design judgments happen concurrently)

Table 4.2 Design judgments in each key design behavior and the involved design activities in Laboratory Study Two.

**Design Judgment Occurrences in [1. Interesting design behavior: thought over the variables, such as weather, carriers, airport management, etc. to visualize in this information visualization project]**

***(Theme - Framing the design in "Parse" "Filter" visualization design stages)***

| Design Judgment Types / Major Sub-Design Activities | 1.1 | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 |
|---|---|---|---|---|---|---|---|---|---|
| A-a/Default | 2 | · | 1 | · | · | · | · | · | · |
| A-b/Deliberated off hand | · | · | · | · | 1 | · | · | · | · |
| A-c/Core | 2 | · | 2 | 2 | · | 1 | · | 1 | 4 |
| A-d/Framing | 2 | 1 | 5 | 3 | 3 | 1 | 2 | 1 | 1 |
| A-e/Appreciative | · | 1 | · | · | · | · | · | · | 1 |
| A-f/Quality | · | · | 1 | · | · | · | · | · | 2 |
| A-g/Appearance | · | · | 1 | · | · | · | · | · | 1 |
| A-h/Connective | · | · | · | · | · | · | · | · | · |
| A-i/Compositional | · | · | · | · | · | · | · | · | · |
| A-j/Instrumental | · | · | 3 | · | · | · | 1 | · | 1 |
| A-k/Navigational | 2 | · | 2 | 1 | · | · | 1 | · | 4 |

Design Activities Comprised of [1. Interesting design behavior: thought over the variables, such as weather, carriers, airport management, etc. to visualize in this information visualization project]

| | |
|---|---|
| 1.1 Discussed to visualize two variables of airport and weather. | 1.6 Thought about visualizing the time slot variable as a supplement to the design goal. |
| 1.2 Determined a design goal that requested the variable of top 10 airports that cause most delays as foreground and the other attributes as the backgrounds/supplementary. | 1.7 Applied a Tableau statistical validation to ensure an accurate correspondence between the original dataset and previous hypotheses. |
| 1.3 Communicated about focusing on visualizing the variable of top 10 airports that cause most delays with particular departure delay frequencies information. | 1.8 Gave up representing the variable of carrier. |

Table 4.2 continued

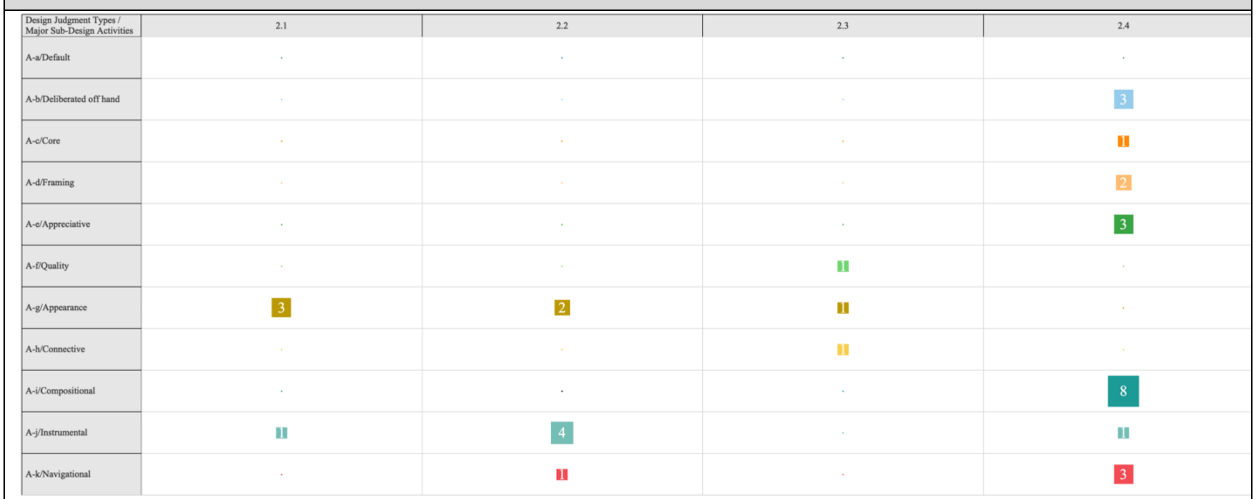
| | |
|---|---|
| 1.4 Thought about visualizing the variable of air route as a supplementary of the design goal. | 1.9 Considered to split the design problem into several manageable parts of (1) re-running accurate data values in statistical ways and combining the results into the future design sketches; (2) working on the design sketches and high-fidelity versions with the focuses of innovation and reasonableness; and (3) working on the design sketches without the consideration of involving all determined variables in each of individual design sketches/ideas. |
| 1.5 Considered visualizing the variable of carrier as a supplementary of the design goal. | |
| **Design Judgment Occurrences in [2. Interesting design behavior: applied the central diagrams with auxiliary graphs' combinations to strength the visual narrations and data themes]** *(Theme - Composing the design in "Represent" visualization design stage)* | |
|  | |
| Design Activities Comprised of [2. Interesting design behavior: applied the central diagrams with auxiliary graphs' combinations to strength the visual narrations and data themes] | |
| 2.1 Applied the visual representations of airport, aircraft, and hourglass as the central diagrams to layout the foreground variable of top 10 airports with relevant delay time. | 2.3 Used the multiple clock visual representation as the central diagram to layout the foreground variable of top 10 airports with relevant delay time. |

Table 4.2 continued

| | |
|---|---|
| 2.2 Employed the visual representation of multiple people postures with fatigues as the central diagrams to layout the foreground variable of top 10 airports with relevant delay time. | 2.4 Explored a number of different design combinations of the central diagrams with auxiliary charts to strength a visual narrative thinking of “topic + explanation” and reach the design goals. |

**Design Judgment Occurrences in [3. Interesting design behavior: determined on a final design idea of “aircraft on runway + parallel calendar and bar graph;” thought over the possible interactions and an acceptable design outcome to end up the visualization project]**

***(Theme - Appearance and Quality judgments on design in “Represent” visualization design stage)***

| Design Judgment Types / Major Sub-Design Activities | 3.1 | 3.2 | 3.3 | 3.4 | 3.5 | 3.6 |
|---|---|---|---|---|---|---|
| A-a/Default | · | · | · | · | · | · |
| A-b/Deliberated off hand | · | · | · | · | · | · |
| A-c/Core | 1 | 1 | · | · | · | · |
| A-d/Framing | · | · | · | 1 | 2 | 3 |
| A-e/Appreciative | · | · | · | · | · | · |
| A-f/Quality | 3 | 2 | 1 | 1 | 1 | · |
| A-g/Appearance | 1 | 3 | 1 | 1 | 3 | · |
| A-h/Connective | · | · | · | · | · | · |
| A-i/Compositional | · | 2 | · | · | 1 | · |
| A-j/Instrumental | · | 2 | 1 | · | 3 | · |
| A-k/Navigational | · | 1 | 1 | 1 | 3 | 1 |

Design Activities Comprised of [3. Interesting design behavior: determined on a final design idea of “aircraft on runway + parallel calendar and bar graph;” thought over the expected interactions and an acceptable design outcome to end up the visualization project]

| | |
|---|---|
| 3.1 Applied the visual representation of “aircraft on runway” as the central diagram. | 3.4 Revised the layout by referring to and matching the airport’s guide map design standard for thematic reinforcement; apply the new design to an official airport website. |
| 3.2 Synthesized the auxiliary charts of parallel calendar and bar graph on the right side of the central diagram; adapt and match the interface to an official airport plan to layout the overall design topic. | 3.5 Communicated and described several expected interaction ways that might be added on and compose an idea of high-fidelity interactive infographic design. |

Table 4.2 continued

| | |
|---|---|
| 3.3 Added the extra visual elements such as gates, clouds, etc., which never showed a connection with the data for strengthening the overall design topic. | 3.6 Determined an acceptable design outcome with (1) high-fidelity interactive infographic; (2) reasonable interaction ways; and (3) flexible changes in visual elements and styles to end up the visualization project. |

### 4.2.3 Design Judgment Influencing Factors

Factors, such as clear design goals, data accuracy, literature searchability, knowledge of design principles, design feasibility, personal life experience related to data topic, and others have been distilled based on observations and interviews of both laboratory studies.

***Laboratory Study One*** – The top three factors identified during observations and interviews were clear design goals, design validity, and design feasibility for Lab Study One. Designers determined the design goals of presenting and interpreting what caused the flight delays. Keeping that in mind, designers made prominent *framing* design judgments; combining *appreciative, instrumental, navigational, core, deliberated off hand, even quality* and *appearance* design judgments to filter and reduce data, recall and refer proposed design, replace visual elements, apply color coding method, schedule step-by-step procedure to enhance visual representations, etc. All of these design activities served above design goal. (*framing* (prominent), *appreciative, instrumental, navigational, core, deliberated off hand, quality, and appearance* design judgments concurrently with factor of clear design goal) (1 and 2 Interesting design behaviors in Table 4.1)

Information accuracy and efficiency are extremely important while visualizing data, regardless of the type. In Lab Study One, design judgments, such as *compositional, quality, instrumental, navigational,* etc. were driven by an accurate result of data representations with visual design validity. During a post-semi-structured interview, P-SJ explained:

> …Maybe because my background is Computer Graphics Technology, web design. I'm working on a lot of programming things with numeric data. I think data accuracy is most important because we create visualizations for delivering accurate information for users, right? We create design compositions for better data representations. Helplessly, we choose

> the idea No.12 because no design composition helps us to express all decided variables. We select the most creative one and go in-depth to add visuals and meet all variable, which is our primary goal. All visuals such as forms, colors, shapes, etc. should also serve data. If some of the visuals are barriers to accurate data expression, they should be replaced even discarded. Just a fancy interface or layout doesn't make any sense. (*compositional* and *quality* (prominent); *appearance, instrumental, navigational, framing,* and *core* design judgments occur concurrently with factor of design validity) (3 and 4 Interesting design behaviors in Table 4.1)

Designers from Lab Study One often considered design feasibility, especially in their final design decision-making stage. Although there was no development process in this project, this team discussed unreliable design components, and even predicted difficulties. They attempted to modify and improve them at the current step for a smoother development in the future. P-SS explained:

> …Some data will be available through statistics. Visuals may not be worked once data is imported. We've seen this happen when we were collaborating for VAST challenge. So, we find out some tools and methods to do front-end data analysis. If there is a conflict between data and visual, we can change the visual or re-filter to replace some data segments. (*instrumental* and *quality* (prominent); *framing, navigational,* and *appearance* design judgments happen concurrently with factor of design feasibility) (bullet 4. Interesting design behavior in Table 4.1)

***Laboratory Study Two*** – The top three factors identified during observation and interviews were clear design goals, knowledge of design principles, and personal life experience related to data topic for Lab Study Two. Similar to Lab Study One, designers made prominent *framing, compositional, and appearance* design judgments aimed at strengthening the design goal and data theme. P-XM said during an interview:

…I think a good visual design should serve its topic or theme. All design activities and judgments on visuals should be closely relevant to its topic (*framing, composing,* and *appearance* design judgments with factor of design goal).

P-SY also explained:

…We are not good at data analytics, to be honest. We don't like to study data all the time. In our stage, we put forward several hypotheses only based on our personal life experiences. Fortunately, we all have experience with flight delays. After these hypotheses, we find tools and software to validate if they are true in the provided data. If some conflicts occur, we think about some segments of data or parts of visuals retained or discarded. (*instrumenting* (prominent); *framing, quality, appearance, navigational* design judgments happen concurrently with factor of personal life experience related to data topic).

Student designers from art and design majors took many courses that related to design foundations, design principles, etc. They are required to follow a number of design principles while creating designs. In Lab Study Two, the designers composed eight different interfaces to adapt the determined data variables. While composing, they were guided by several observable design principles, such as strengthening visual center; consistency of colors; adding thematic visual elements, etc. to modify the visual elements; re-filter data, re-code color, etc. (*compositional* (prominent); *framing, quality, appearance, instrumental, navigational* design judgments occur concurrently with factor of knowledge of design principles).

## 4.3 Studies Synthesis and Comparisons

The activities in both laboratory studies showed that *framing* and *appearance* design judgments were essential. Although both laboratory studies used the same design context, some important differences have been identified. Table 4.3 synthesizes the studies synthesis to show how various design judgment methods affected the final design.

Table 4.3 This table supports the information of laboratory studies' synthesis and comparisons.

| ***Laboratory Study/Design Judgment (Theme)*** | ***Design Judgment (Theme)*** | ***Representative Examples from Interview Data*** | ***Influencing Factors*** |
|---|---|---|---|
| Laboratory One | *Framing, compositional, appearance, quality, and instrumental* | "I think the total delay information is meaningless, but the delay of some particular airline or air route is more valuable. We can get rid of the total delay data. Like this website, I don't see the total delay information at all." – *framing design judgment*<br>"The three ideas are not good. But we can keep this staked bar chart separately. See… to combine it to this Sankey diagram would be perfect." – *compositional design judgment*<br>"With my education, the overall experience, especially aesthetic is really important for a design work. A good interface will attract people." – *appearance design judgment*<br>"This big pie with five small circles never supports the data representations better because some of the carriers did really good, which without many delays. So, if we have those kinds of carriers, where do you put the five circles?" – *quality design judgment*<br>"We can use this tool - Bureau of Transportation Statistics to double check if our project includes all the necessary data variables." – *instrumental design judgment* | Clear design goals; design validity; and design feasibility |

Table 4.3 continued

| | | | |
|---|---|---|---|
| Laboratory Two | *Framing, compositional, appearance, and quality* | "Most of our assumptions can be found in this provided data set. So, we will firstly determine to show the carriers, weather, airport management in the current design stage, right?" – *framing design judgment*<br>"We never think about creating an interface to meet all required data variables at one time. That's too hard. So, we think about defining a central diagram and combine and compose it with some small charts like pie, bar, calendar, etc. Then we will see which interface meet most of the required data attributes. That one would be the final idea." – *compositional design judgment*<br>"To create an aesthetic interface is really important. A beautiful design attracts people. I think the overall style looks..fine, right? And we can add some visual elements to strengthen the whole design style." – *appearance design judgment*<br>"I think calendar chart can be better than the bar chart." – *quality design judgment* | Clear design goals; knowledge of design principles; and personal life experience |
| *Synthesis* | *Framing, appearance, quality, instrumental, and compositional* judgments-making cannot be excluded in visualization design, especially for a focused infographic design process. | | Clear design goals; design validity; design feasibility; knowledge of design principles; and personal life experience |

Table 4.3 continued

| | | | |
|---|---|---|---|
| *Comparisons* | ***[Visualization design - Infographic perspective]*** *With experienced data exploration and analytics as well as well-determined data variables (Laboratory Study One),* designs judgment combination of appearance and instrumental may help a lot on design movements and outcome. *With inexperienced data exploration and analytics as well as not well-decided data variables (Laboratory Study Two),* design judgment combination of compositional and appearance may help many on design movements and outcome, especially for the local design situations, in which, designers employ their design work to back match what data (segments) can be imported and presented well. | | *With instrumentations for design validity; with knowledge of design feasibility* *With solid Knowledge of design principle (especially for the compositional principle); with clear design goal of achieving a thematic visualization* |

## 4.4 Unexpected Findings

Qualitative research supported unexpected findings (Merriam S. B., 2015). An interesting insight from Laboratory Study One was P-SS's judging activities followed P-SJ's in many situations. P-SS said:

> …P-SJ is good at data explorations, but I'm not. Sometimes I don't know what the exact data we can use and import. I sketched these design ideas based on some blur concept, actually, like I understand weather, carrier may influence the delay of air routes and the dataset do support both variables. For me, that's enough. During our commutations, my partner pointed out some conflicts or inappropriateness on visuals. Those happened actually because of error or inaccuracy in data. I don't know many about data, so in many times, I have to follow his decisions to modify and revise my design. I always follow him to do judgments.

A team member becomes the final decision maker for many reasons. P-SJ in Lab Study One appears to be a key decision maker because he had better data exploration capabilities than another member. When a conflict occurred between data accuracy and aesthetic vision, almost all designers choose to do a right thing for the sake of aesthetics. This finding can be regarded as a subsequent research question that can be used to explain patterns of design judgment activities from the designers' perspectives.

Additionally, design methods of brainstorming and analogizing are used centrally in both laboratory studies while creating and conducting design ideas with *framing* and *instrumental* design judgment methods. In my observations, I also identified two participants of Laboratory Study One also applied literature searching to explore online proposed designs for validating their determined variables with *framing, instrumental,* and *navigational* judgments-making. Additionally, they utilized the approach of scales of measurements selecting to improve the effectiveness of visual forms and corresponding graphical features during determining a final design idea. (*instrumental* and *navigational* design judgments)

These unexpected findings could not be fully interpreted and explained in this dissertation; however, they provide valuable research ideas in subsequent studies.

## 4.5 Summary

Laboratory studies were employed in this research for two main purposes: (1) to identify and examine the existence of design judgment behaviors in a visualization design domain; and (2) to interpret and explain student design teams' judgment behaviors in particular visualization design processes with a focus on infographics. The limitations of laboratory studies included: (1) a shorter study time frame, which resulted in a smaller data collection; (2) infographic design procedure as one step of visualization design could not reflect holistic and comprehensive design judgments. Hence, in-situ studies in the next chapter provide more detailed interpretations and explanations to help resolve these limitations.

# CHAPTER 5. **DESIGN JUDGMENTS IN IN-SITU STUDY**

The long-term, 13-week in-situ studies supported more abundant data sources than laboratory studies, for they employed observations with several complete visualization projects. In this section, I organized three in-situ studies and parallelly interpreted and explained student design team design judgment behaviors within their particular visualization design procedures.

The differences with laboratory studies embodied in:

(1) Design judgments' descriptions, interpretations, and explanations were based on the interesting and explorable design activities that moved toward outcome designs. Thirteen-week data sources supported a plethora of information, in which, no all activities moved their design projects forward.

(2) In richer design situations within complete design processes, designer design judgment behaviors reflected more comprehensive results than laboratory studies.

Additionally, Tableau scatterplots, diagramed the frequency of occurrence of design judgment types in similar interesting and explorable design activities and helped readers understand.

In the following sections, designer design judgment activities were interpreted and explained based on two categories: design judgment occurrence and design judgment influencing factors. Then I synthesized and compared the findings and insights across three in-situ studies. Next, I discussed the unexpected findings occurring during observations and data analysis. Finally, I summarized the chapter.

## 5.1 In-situ Study One

In this section, I introduce the study context at first to present the study results and findings, and then interprets and explains designer design judgment activities by following the design judgment "occurrence" and "influencing factors."

### 5.1.1 Study Context

In in-situ settings, student design teams worked on several semester-long course projects in a graduate information visualization design course. In this course, all students selected a data and used it to create innovative and intuitive visualization solutions that provide users with peripheral awareness of meaningful information from complex data.

The group; labeled In-situ Study One chose the topic of Bioinformatics— DNA sequences from https://seaphagesbioinformatics.helpdocsonline.com/home (Pope, 2017) to visualize the similarities and differences, as well as sub-similarities/differentials between different DNA sequences. This student group, comprised of five graduate students from the majors of computer graphics technology, interaction design, and interior design; met once a week for well-organized the meetings. I participated in their discussions for the full project period of 13 weeks.

This DNA Sequence data visualization research project focused on the needs of bioengineers with comparative genomic analysis of 60 mycobacteriophage genomes: genome clustering, gene acquisition, and gene size. Through analyzing the genetic data, the design team explored the comparison logic similarity and difference and the possibility of adding multiple comparisons to the visualization process. The goal of this visualization project goal held to support a visual analytic tool for professional users, such as biological scholars, professors, students, and other related personnel to effectively explore, compare, and gain accurate information of similarities and differences between various DNA sequences. A primary question for this project stood: How do visualization and information design affect comparative genomic analysis outcomes? The team drew on their research from computer graphic technology and visualization design based on environmental psychology for data visualization, accessible design, and user-friendly design to offer a unique perspective on how to maximize the efficiency of genomic analysis. Their primary task was to interact validly with the effective visual representations to compare reasonably the genetics.

Their solution, DNA sequence heat map, compared the similarities and differences among sequencings through visualizing G-C content highlighting: (1) processed data to obtain G-C content comparisons among the DNA sequencings; (2) encoded differences in each cell to downsize the long sequencings; (3) utilized different color saturation to represent proportions; (4) colored basic sequencings identically; (5) animated the processing to indicate order.

In the following sections, I focused on questions of design judgment occurrence and influencing factors to interpret and describe the team's design judgment activities with patterns and themes.

### 5.1.2 Design Judgments in In-situ Study One

Two laboratory studies, verified the existence of design judgments with limited design processes (focused infographic design perspective) and data sources, reflecting the 11 design judgments. In this in-situ study, design judgments existed in a richer and more comprehensive form. Through referring and adapting Nelson's theory (Nelson & Stolterman, 2012), the results of coding identified no other forms of design judgment in In-Situ Study One's visualization design process. This design team's design judgment behaviors will be presented in detail with the focused research questions of "occurrence" and "influencing factors."

#### 5.1.2.1 Design Judgment Occurrence

In-situ Study One supported thirteen-week data sources, engendered design activities as key design nodes that made their visualization project progress toward an outcome. However, some behaviors embodied as in-progress actions, which failed to assist design movement. Through framework analysis, I indexed designers' key design actions with highlighted grey areas. Table 5.1 outlines the observed designer design activities within 13-week visualization design course, as well as how the investigator identified key design nodes (highlighted grey areas) that moved toward an outcome the project by framework analysis (Table 3.6 provides details), presented comprehensively with interesting design behavior and informed design judgments.

Table 5.1 An overview of observed designers' design activities in In-situ Study One, as well as how investigator identified key design nodes that moved toward and outcome the project.

| **Week of Design** | **Design Stages** | **Observed Designer Design Activities** |
|---|---|---|
| Week1 | Acquire | Brainstormed ideas of …(reference Table 3.6) |
| Week2 | Acquire | Team scheduled a discussion with a TA who taught the fundamental gene biology course from Purdue Department of Biological Sciences to acquire raw data and the original project goals. Team decided to employ the biological dataset to visualize DNA sequencing. |
| Week3 | Parse | Team organized a discussion to synthesize … (reference Table 3.6) |

Table 5.1 continued

| | | |
|---|---|---|
| Week4 | Interact, Parse, Filter, Mine | Team determined an applicable working flow with interaction framework and database construction paralleled firstly, and then boosted graphic design. They spent approximate 2 hours to resolve the challenged data explorations and be compatible with time limitations. |
| Week5 | Interact | Team decided selecting, highlighting, dragging and dropping, as well as comparing as the major interaction ways to visualize the information of DNA sequencing and similar/shared DNA segmentations. They determined an interaction design manner after searching and referring to existing online systems and visualization applications that related to DNA information. |
| Week6 | Represent, Filter, Mine | Team spent approximate 1 hour collaboratively brainstorming …(reference Table 3.6) |
| Week7 | Represent, Filter | Team organized probably 40-min discussion to …(reference Table 3.6) |
| Week8 | Represent, Filter | Similar to week 7, their team scheduled the 30-min meeting to discuss …(reference Table 3.6) |
| Week9 | Represent | Team decided to apply a shape of semicircle comprised of one DNA and used different colors to layout the similarities between different DNAs. This design movement was led by preserving their previous circular design ideas, adapting, and referring to existing online visualization examples with a focused D3.org platform. |

Table 5.1 continued

| | | |
|---|---|---|
| Week10 | Represent | To keep the semicircles as the basic shapes, their team figured a heat map with specific color schemes that could help on "similarity" presentations by searching and exploring the visual approaches to degree representations. |
| Week11 | Represent, Interact (programming and developing process focused) | During their group meeting, only the communications of the ideas on how to …(reference Table 3.6) |
| Week12 | Represent, Interact (programming and developing process focused) | Similar to week 12, what the team focused on how …(reference Table 3.6) |
| Week13 | Refine, Represent | Team was paying much attention to how their team refined the "similarities" representations by efficient color schemes. They tried more than seven different color combinations and finally decided a purple-green color scheme to layout the values of percentages of DNA similarities. Employed purple for their index DNA sequences and green with different color gradient was for the other seven DNA sequences. |

Before delving into each particular set of design activity and corresponding design judgment methods, an overview (Figure 5.1), adapted Fry's (2007) theory to this team's complete design process with the information of design behaviors and design judgments and supported the investigators and readers overall concept about the question about how design judgments occur in In-situ Study One.

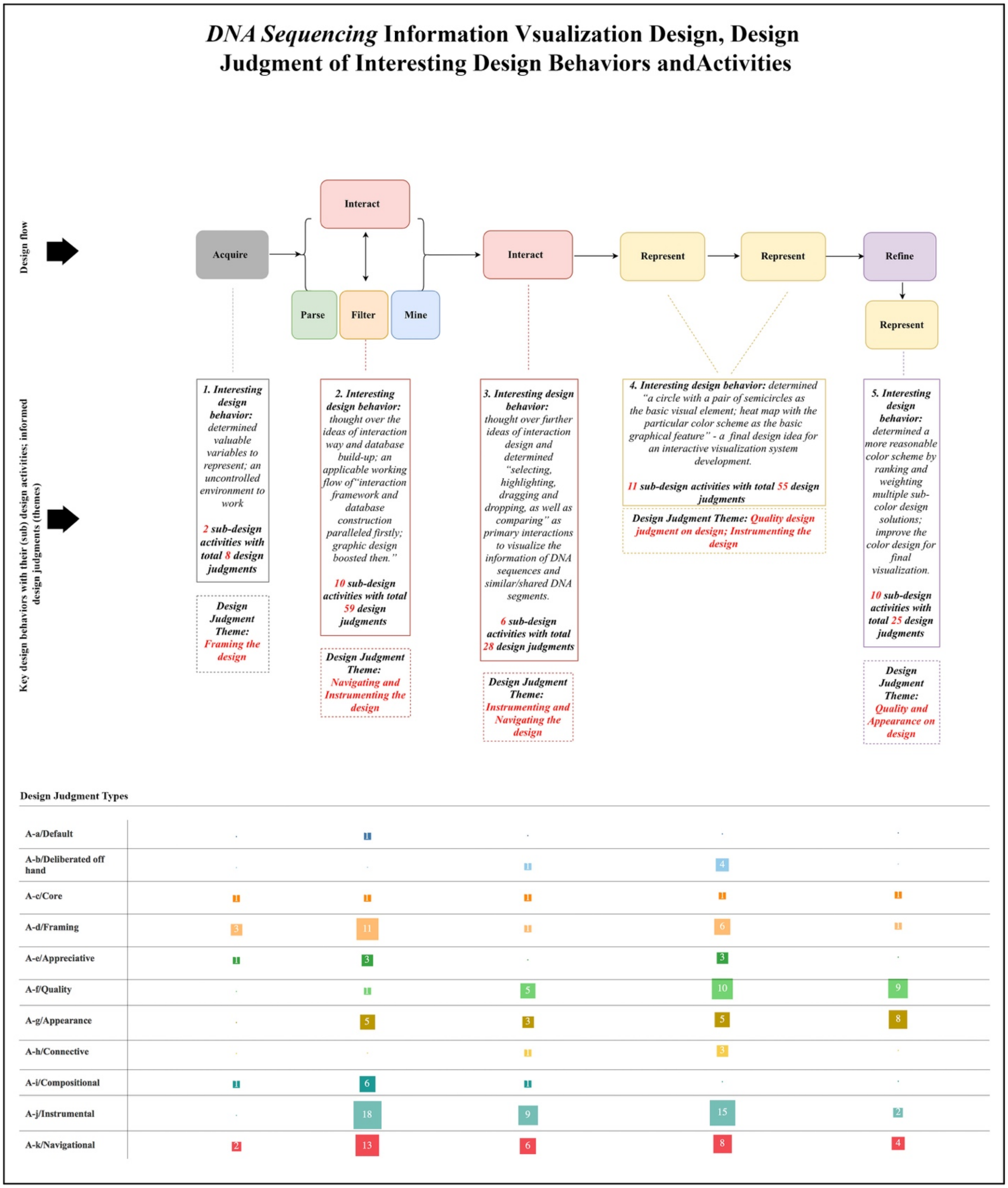



Figure 5.1 This image provides an overview of design judgment activities occurred in In-situ Study One and involved design stages.

Table 5.2 This table comprised of five (sub) tables showing key design behaviors and informed design judgments in In-situ Study One.

**(1)**

| **Design Judgment Occurrences in [1. Interesting design behavior: determined valuable variables to represent; an uncontrolled environment to work]** ***[Theme - Framing the design in "acquire" visualization design stage]*** | | |
|---|---|---|
| Design Judgment Types / Major Sub-Design Activities | 1.1 | 1.2 |
| A-a/Default | | |
| A-b/Deliberated off hand | | |
| A-c/Core | | 1 |
| A-d/Framing | 2 | 1 |
| A-e/Appreciative | 1 | |
| A-f/Quality | | |
| A-g/Appearance | | |
| A-h/Connective | | |
| A-i/Compositional | 1 | |
| A-j/Instrumental | | |
| A-k/Navigational | 1 | 1 |

| Design Activities Comprised of [1. Interesting design behavior: determined valuable variables to represent; an uncontrolled environment to work.] | |
|---|---|
| 1.1 Determined two variables of DNA sequences and similar/shared segments between DNA sequences to best represent in this visualization. | 1.2 Applied any available means to mine and represent topic-related information; helped the data team and their users (i.e., professors and students in a class) comprehend the knowledge of DNA. |

***<u>Theme 1:</u> framing the design (a set of design activities with the design considerations on what data variables to be included in the project)*** **–** This team acquired a database and defined data variables to make their first design progress. This team scheduled an appointment with data providers who came from a biology course team at Department of Biological Sciences and collected data meeting the team's needs and requirements. While defining and deciding to represent two data attributes of similarities and differences among DNA sequences, they made *framing* design judgments. Based on the suggestions from data providers, this team determined to highlight the attributes of similarities and differences, representing the foreground in their visualization design by making *appreciative* design judgments. They also made *framing* design judgments to define a relatively free space to process their project because data team's original expectation was to make sense of data insights through visualization using a visualization tool or application (*core* design judgment). During their discussion, they also made design judgments, such as *compositional* and *navigational* to decide their preliminary thoughts on visuals and design procedures.

**(2)**

**Design Judgment Occurrences in [2. Interesting design behavior: thought over the ideas of interaction way and database build-up; an applicable working flow of "interaction framework and database construction paralleled firstly; graphic design boosted then"]** ***(Theme - Navigating and Instrumenting the design in "Interact" "Parse" "Filter" "Mine" visualization design stages)***

| Design Judgment Types / Major Sub-Design Activities | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 2.10 |
|---|---|---|---|---|---|---|---|---|---|---|
| A-a/Default | 1 | | | | | | | | | |
| A-b/Deliberated off hand | | | | | | | | | | |
| A-c/Core | | 1 | | | | | | | | |
| A-d/Framing | 1 | | 1 | 1 | 2 | | 1 | 1 | 2 | 2 |
| A-e/Appreciative | 1 | | | | | 1 | | | | 1 |
| A-f/Quality | | 1 | | | | | | | | |
| A-g/Appearance | 3 | 1 | | | 1 | | | | | |
| A-h/Connective | | | | | | | | | | |
| A-i/Compositional | | 1 | 1 | | 1 | | 1 | 1 | | 1 |
| A-j/Instrumental | 3 | 2 | 2 | 2 | 3 | | 1 | 3 | 2 | |
| A-k/Navigational | 1 | 1 | 1 | 1 | | 1 | 1 | 1 | 3 | 3 |

Design Activities Comprised of [2. Interesting design behavior: thought over the ideas of interaction way and database build-up; an applicable working flow of "interaction framework and database construction paralleled firstly; graphic design boosted then"]

| | |
|---|---|
| 2.1 Considered to layout DNA sequences; applied the "blocks" to represent the similar/shared segments between the sequences by squeezing the segments' lengths. | 2.6 Considered the interactive functionalities required more attention as foreground and moved graphic design to background; implemented the interactive functionalities first, then graphic design. |
| 2.2 Determined a hierarchical layout with semantic zoom in interaction to represent all DNA sequences and similar/shared segments between the sequences. | 2.7 Aligned DNA strings by calculating from 0; extract available data for effective integration with existing interaction ways. |

Table 5.2 (2) continued

| | |
|---|---|
| 2.3 Employed a "drag and drop + compare" interaction to represent all DNA sequences and similar/shared segments between the sequences. | 2.8 Created three tables to save (1) DNA sequences with No.s; (2) segments and how many DNA sequences shared these segments; and (3) dissimilar segments. |
| 2.4 Determined to use on a "zoom in/out" interaction to represent all DNA sequences and similar/shared segments between these sequences. | 2.9 Determined the concept of "similar," defined with two consecutive similar strings, applied for an existing tool/program to obtain the similar/shared DNA segments based on "similar" principle. |
| 2.5 Synthesized previously determined interaction, tried to transform them to iPad development environment to improve user enjoyments. | 2.10 Thought over an applicable flow of working within the interaction framework and database construction first and paralleled, graphic design then; present DNA knowledge by synthesizing the main design objectives of accurate data representations and effective interactions. |

***<u>Theme 2:</u> navigating and instrumenting the design (a set of design activities with the considerations on how to navigate and move forward the project)*** – The second set of design activity with a flow, included ten (sub) design activities and provided a basis for this design team to achieve an acceptable design outcome for final submission (focused alternates between *navigational and instrumental* design judgments-making). At their discussion inception, this team decided to abandon the constant data explorations and focused on designing interactions to compile a complete design frame for this visualization (*navigational* → *instrumental* → *navigational* design judgment). Bullets 2.1-2.6 (Table 5.2 (2)) reflected how this team made a series of *instrumental* design judgments to determine the practicable interactions, such as drag and drop, compare, as well as zoom in/out. During this procedure, they also made design judgments like *compositional* and *appearance* to synthesize their decided interactive frameworks and applied them to an iPad platform for the design improvements on users' experiences. Additionally, they determined to concentrate on the design part of interactive functionalities and considered graphic design as background employing *appreciative* design judgment and a corresponding workflow with *navigational* judgment method (bullet 2.6 in Table 5.2 (2))

Due to an implementation of interaction necessitating support from the database, this team made *instrumental* and *navigational* design judgments back and forth to construct a database, so that their team members used mathematical models, statistical methods, and table establishments and corresponding specific steps and operations to gain a sense of clarify (bullets 2.7-2.9 in Table 5.2 (1)). Among determining these decisions, they composed these methods, tools, and concepts constantly to validate their assumptions utilizing *compositional* design judgments.

Finally, this team made several focused *navigational* design judgments to determine a paralleled design path of "interaction framework and database construction first and paralleled, graphic design then," (*appreciative* design judgment) which guided them to assign team member tasks reasonably and appropriately. Two members who specialized in data parsing and mining were allocated the task of maintaining database consistency, and the other three members designed interactions.

This team evidenced design judgment behaviors on "instrumenting and navigating the design" since the confronted the challenged data mining workload and time limitation. One of the most active participants from their team state:

> …We don't have any idea about how to deal with DNA sequencing database. What we only know is that what DNA is and what the role of DNA is for the human body. We have been noticed by the data supporter about visualizing everything related, which provided us with a complete freedom design environment. We didn't get too much guidance from the data team. Since all groups from this course had a hard deadline for the final project submission, we have to think about how to construct our design framework, and workflow in specific ways.

Moreover, *framing* design judgment happened continually during the complete procedure. The activities of instrumenting, navigating, composing, appreciating, even quality and appearance were accompanied the transformations of design boundaries with increased/decreased data attributes; clients' ideas; and methods' constraints.

**(3)**

| **Design Judgment Occurrences in [3. Interesting design behavior: thought over further ideas of interaction design and determined "selecting, highlighting, dragging and dropping, as well as comparing" as primary interactions to visualize the information of DNA sequences and similar/shared DNA segments]**<br>***(Theme - Instrumenting and Navigating the design in "Interact" visualization design stage)*** |
|---|

Table 5.2 (3) continued

| Design Judgment Types / Major Sub-Design Activities | 3.1 | 3.2 | 3.3 | 3.4 | 3.5 | 3.6 |
|---|---|---|---|---|---|---|
| A-a/Default | · | · | · | · | · | · |
| A-b/Deliberated off hand | · | · | 1 | · | · | · |
| A-c/Core | · | · | 1 | · | · | · |
| A-d/Framing | · | · | · | · | · | 1 |
| A-e/Appreciative | · | · | · | · | · | · |
| A-f/Quality | 1 | 1 | 1 | 1 | 1 | · |
| A-g/Appearance | · | · | 1 | 1 | 1 | · |
| A-h/Connective | · | · | · | 1 | · | · |
| A-i/Compositional | · | · | · | · | · | 1 |
| A-j/Instrumental | 3 | 2 | 1 | 1 | 1 | 1 |
| A-k/Navigational | 1 | 1 | 1 | 1 | 1 | 1 |

<table>
<tr><td colspan="2">Design Activities Comprised of [3. Interesting design behavior: thought over further ideas of interaction design and determined “selecting, highlighting, dragging and dropping, as well as comparing” as primary interactions to visualize the information of DNA sequences and similar/shared DNA segments]</td></tr>
<tr><td>3.1 Considered to display a number of similar/shared DNA segments in detail first, then whole DNA sequences by clicking, selecting, comparing; improving the interaction design innovations.</td><td>3.4 Applied a “clock” layout to present more DNA sequences; select, highlight, as well as drag and drop to switch the positions of DNA sequences within 360 degrees; compare and display the similar/shared DNA segments between DNA sequences.</td></tr>
<tr><td>3.2 Considered to display whole DNA sequences as the overview first, then information of similar/shared DNA segments in detail by clicking, selecting, highlighting, and comparing; adapted from Shneiderman’s mantra of “overview first, details and demand.”</td><td>3.5 Added a dynamic effect of tail swing while selecting and dragging a particular DNA sequence.</td></tr>
<tr><td>3.3 Applied apply a “windshield wiper” layout to present DNA sequences; select, highlight as well as drag and drop to switch the positions of DNA sequences within 180 degrees; compare and display the similar/shared DNA segments between DNA sequences.</td><td>3.6 Determined “selecting, highlighting, dragging and dropping, as well as comparing” as the main interaction ways to visualize the information of DNA sequences and similar/shared DNA segments.</td></tr>
</table>

***<u>Theme 3:</u> instrumenting and navigating the design (a set of design activities with the considerations on interaction refinements)*** – Using concentrated *instrumental* design judgment methods, this team clarified the ideas of interactive functionalities, including selecting, highlighting, dragging and dropping, as well as comparing, which provide interactive visualization tool development. A series of *navigational* design judgments were made concurrently across bullets 3.1-3.5 (Table 5.2 (3)) which helping the designers outline flows to operate the methods, tools, even concepts they chose. To support reasonable vision depending on determined interactions, they combined *appearance* and *quality* design judgment ways to decide the connections and relationships between visual elements and interactions.

**(4)**

| **Design Judgment Occurrences in [4. Interesting design behavior: determined "a circle with a pair of semicircles as basic the visual element; heat map with the particular color scheme as the basic graphical feature" - a final design idea for an interactive visualization system development]** ***(Theme - Quality judgment on design, Instrumenting the design in "Represent" visualization design stage)*** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Design Judgment Types / Major Sub-Design Activities | 4.1 | 4.2 | 4.3 | 4.4 | 4.5 | 4.6 | 4.7 | 4.8 | 4.9 | 4.10 | 4.11 |
| A-a/Default | | | | | | | | | | | |
| A-b/Deliberated off hand | | | | | | | 1 | 1 | | 2 | |
| A-c/Core | | | | | | | | | 1 | | |
| A-d/Framing | | | 2 | | 2 | 1 | | | | | 1 |
| A-e/Appreciative | | | | | 1 | | | 1 | | | 1 |
| A-f/Quality | 1 | | | | 1 | 1 | 2 | 1 | 3 | 1 | |
| A-g/Appearance | | | | | 1 | | 1 | 1 | 1 | 1 | |
| A-h/Connective | 1 | | | 1 | | | 1 | | | | |
| A-i/Compositional | | | | | | | | | | | |
| A-j/Instrumental | 1 | 1 | 1 | 2 | 2 | | 2 | 2 | 2 | | 2 |
| A-k/Navigational | 1 | | 1 | | 1 | | | 2 | 1 | 1 | 1 |

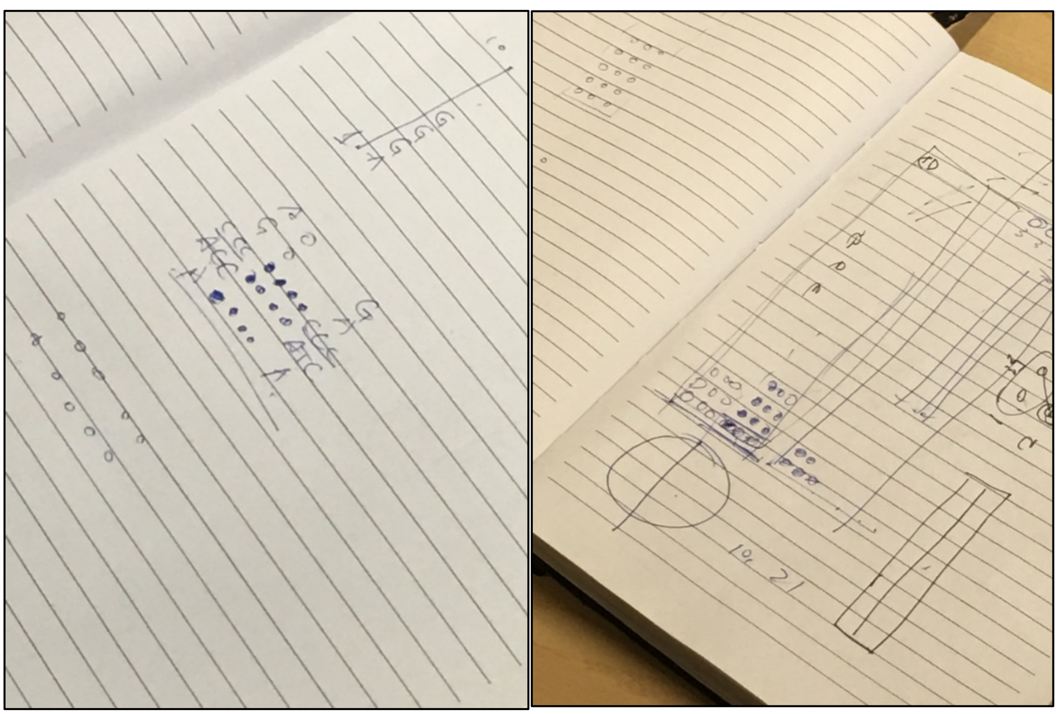
| Design Activities Comprised of [4. Interesting design behavior: determined "a circle with a pair of semicircles as the basic visual element; heat map with the particular color scheme as the basic graphical feature" - a final design idea for an interactive visualization system development] | |
|---|---|
| 4.1 Created a design sketch with the flattening version of "windshield wiper" and "clock" for discussion; to ensure reasonable visual representations and effective interactions first, then transform with more innovative interfaces. | 4.7 Applied total sixty-four different colors to represent four different DNA contents of all DNA sequences, and similarities between them; utilize color saturation to distinguish different contents and avoid Mosaic color schemes. |

Table 5.2 (4) continued

| | |
|---|---|
| 4.2 Encoded each DNA by a circle; constitute a DNA sequence by DNA circles. | 4.8 Employed color saturation with 90%, 80%, 70%, etc. to represent the similarities; define the color saturation with the percentage of similarities. |
| 4.3 Encoded a DNA group that comprises three individual DNA by a circle; form a DNA sequence by DNA groups with circles. | 4.9 Decided to further highlight and reinforce the DNA similarities between adjacent DNA sequences by (1) to define a DNA segment that comprised of three DNA groups (27 DNA in total); (2) apply a pair of semicircles side by side to represent each particular DNA segment; and (3) assign a uniform color with different color saturation to these two semicircles, each side of semicircles compares the similarities with adjacent DNA sequences. |
| 4.4 Encoded a DNA group that comprises nine individual DNA by a circle; constitute a DNA sequence by a number of DNA groups with circles. | 4.10 Assigned eight different shapes to distinguish and strength the sense of wholeness of each of the DNA sequences. |
| 4.5 Reduced data and represented a total of eight DNA sequences rather all; focus more on the design outcome achievement rather endless data exploration. | 4.11 Thought over manageable parts to work on including (1) to visualize and program the current design idea; (2) try more different permutation and combination by referring to Gestalt law principle; (3) try to revise the details such as background colors, location changes of the semicircles and look at the overall changes. |
| 4.6 Applied four different colors to represent four different DNA contents of all DNA sequences; the similar/shared DNA segments (similarities) between them. | |

***<u>Theme 4:</u>* quality judgment on design, instrumenting the design (a set of design activities with the considerations on a final design idea for an interactive information visualization)** – With time constraints (*framing* design judgment), this design team aimed to determine practicable visual forms and related graphical features, which combined as the final ideas for their interactive visualization system in their subsequent design steps. During making these design decisions, designers concentratedly made *quality* design judgments thinking of visual effectiveness; thus, all visual elements were designed for better representations of data insights. One team member argued during their interview:

> …The target users of our visualization are biological scholars and researchers, professors, students rather than the general public. Users originally want to obtain accurate data information from our visualization system. Aesthetics is important, which is true. However, based on this basic purpose, our team members decided to consider more about if the visuals like full circles or semicircles help convey data insights of the similarities and differentials of DNA G-C contents accurately and effectively first (Figure 5.2 (a)) and then thinking about how to make it aesthetic with more enjoyments for our users.  We finally applied a ring (one DNA) with two semicircles" (Figure 5.2 (b)) to represent similar G-C contents' similarities and differentials between adjacent DNA sequences because these forms supported two sides, which could be compared with the adjoining sides respectively.



(a) (b)

Figure 5.2 Designer judgment with focused *quality* on central graph visual design determinations. This image premises by the designer who participated in this study.

While making *quality* design judgments, the team applied *appearance* design judgments concurrently in many situations, such as bullets 4.7-4.9 (Table 5.2 (4)). Based on effective and efficient visual elements, designers considered improving overall design with color styles and characters by *appearance* design judgment method.

When they decided on a mosaic with semicircles, they made *deliberated offhand* design judgment. One developer P-JH recalled one of the design projects in which he was involved where designers also created similar matrix to present successfully different information flows with a particular color scheme. They assumed they could use a similar visual representation adapting to their prior experience to the current situations.

*Instrumental* design judgment activities were applied across design activities. For example, designers determined to compose nine individual DNA into a group and to represent the data using a "ring," (bullet 4.4 design activity in Table 5.2 (4)) based on the calculations and measurements of total accounts of DNA and general screen size (*instrumental* design judgment). Additionally, by connecting heat map method (*connective* design judgment), this team assigned the 64 colors (bullet 4.7 design activity in Table 5.2 (4)) and three distinguished color hues of 90%, 80%, and 70% (bullet 4.8 design activity in Table 5.2 (4)) to depict the data variable of similarities of DNA G-C contents with mathematical calculations, selections of proportions, scales, and measurements (*instrumental* design judgment). Among these procedures, *framing* design judgment re-organized design boundaries, such as design activity 4.5 (Table 5.2 (4)).

**(5)**

**Design Judgment Occurrences in [5. Interesting design behavior: determined a more reasonable color scheme by ranking and weighting multiple sub-color design solutions; improved the color design for final visualization]**
***(Theme - Quality and Appearance judgments on design in "Refine" "Represent" visualization design stages)***

Table 5.2 (5) continued

| Design Judgment Types / Major Sub-Design Activities | 5.1 | 5.2 | 5.3 | 5.4 | 5.5 | 5.6 | 5.7 | 5.8 | 5.9 | 5.10 |
|---|---|---|---|---|---|---|---|---|---|---|
| A-a/Default | | | | | | | | | | |
| A-b/Deliberated off hand | | | | | | | | | | |
| A-c/Core | | | | | 1 | | | | | |
| A-d/Framing | | | | | | | | | | 1 |
| A-e/Appreciative | | | | | | | | | | |
| A-f/Quality | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | 2 | |
| A-g/Appearance | 1 | 1 | 1 | 1 | 1 | 1 | 1 | | 1 | |
| A-h/Connective | | | | | | | | | | |
| A-i/Compositional | | | | | | | | | | |
| A-j/Instrumental | 1 | | | | | | | 1 | | |
| A-k/Navigational | | 1 | | | 1 | | | 1 | | 1 |

| Design Activities Comprised of [5. Interesting design behavior: determined a more reasonable color scheme by ranking and weighting multiple sub-color design solutions; improved the color design for final visualization] | |
|---|---|
| 5.1 Applied two different colors to distinguish the index DNA sequence and the other seven DNA sequences. | 5.6 Applied a blue gradient color scheme to layout different percentages of DNA similarities for "the other seven DNA sequences." |
| 5.2 Applied a purple-green color scheme to layout different percentages of DNA similarities for "the other seven DNA sequences." | 5.7 Applied a green gradient color scheme to layout different percentages of DNA similarities for "the other seven DNA sequences." |
| 5.3 Applied a blue-yellow color scheme to layout different percentages of DNA similarities for "the other seven DNA sequences." | 5.8 Tried and output screenshots of the visualization with different color schemes; then rank and weight to decide. |
| 5.4 Applied a red-green color scheme to layout different percentages of DNA similarities for "the other seven DNA sequences." | 5.9 Applied a purple-green color scheme as the ultimate color design determination to layout different percentages of DNA similarities for "the other seven DNA sequences;" ensured a reasonable and effective representation on the distributions and trends of DNA similarities. |
| 5.5 Design decision: decided to apply a red gradient color scheme to layout different percentages of DNA similarities for "the other seven DNA sequences." | 5.10 Decided and summarized an acceptable design outcome and some unreliable parts for further development to end up the visualization project. |

***<u>Theme 5:</u> quality and appearance judgments on design (a set of design activities with the considerations on how to navigate and move forward the project)*** – With an interactive visualization system in hand, this team attempted to enhance the effectiveness of color employing *quality* design judgments and improved overall design implementing color characters with *appearance* judgment method. For instance, designers assigned two colors for the first DNA sequence and the others to differentiate effectively between compared indexes and sequences (*quality* design judgment) (bullet 5.1 in Table 5.2 (5)). Designers constantly switched different color combinations (Figure 5.3) with two purposes (bullets 5.2-5.7 in Table 5.2 (5)): (1) representing data variables of similarities and differences with DNA G-C contents accurately and effectively using *quality* design judgment; (2) improving overall appearance quality and aesthetics of design utilizing *appearance* design judgment. During these processes, the team applied methods and tools, such as color matching and encoding to select color, combining colors, and assigning these color combinations to each semicircle.

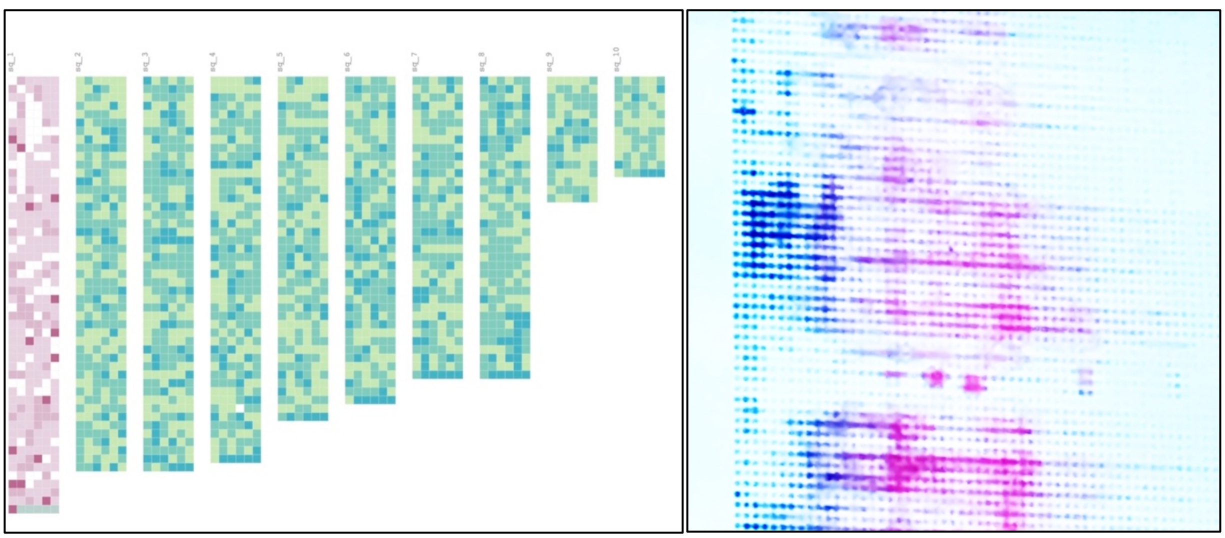


Figure 5.3 Designers' color choices for representing DNA.

5.1.2.2 <u>Design Judgment Influencing Factors</u>

I theme coded, three main factors influencing this design team's judgment activities: (1) professional guidance constraint; (2) time limitation (but needs an outcome); and (3) design validity.

In this visualization project, designers were challenged to make *framing* design judgments without professional guidance (1. Interesting design behavior in Table 5.2 (1)). Visualization designers generated the ideas of visual representations and interactions based on a defined design space with boundaries of clients' needs, constraints, and required data variables; etc. Because a professional data set with the topic of "Similarities and Differentials among DNA Sequences," was also difficult for academics to learn and understand, data providers have not supported many interpretations and explanations on data structures and specific variables. A challenging data mining made it impossible for this design team to determine a design space with defined boundaries.

Because of the lack of professional guidance, designers used other means to bypass the constraints. They considered abandoning persistent data mining; however, constructing a database relied on the explored data segmentations to make sense. Due to time limitations and coursework requirements, they decided to conduct design frameworks using reasonable interactions concurrently, move the design forward; and ensure an acceptable design outcome for final submission. During deciding a paralleled working path, this team made alternative design judgments with the instruments and navigations to constitute a rational design by the choices of means and tools with corresponding operating flows and manners and then to guide subsequent design developments. In their midpoint interview, P-ZJ explained:

> …For our group, to create tables and save data segments is easy. But, how to identify the data segmentation with compared similarities or differentials are challenged. We search a lot online and finally explored an online tool from a biology forum. This tool supports us to import data with two DNA sequences every time and extract similar data segments with G-C contents by detecting different fragments (Figure 5.4). Using this tool is another challenge for us. We looked for tutorials, word presses, and comments to figure out how to operate since we need accurate results efficiently and quickly. Our process is the exact path like to explore a tool we can apply for data analysis, and then identify how to process it. During this procedure, some news concepts may be discovered. We then create ideas to overcome new problems. This process goes back and forth. (2-3. Interesting design behaviors in Table 5.2 (b) and (c))

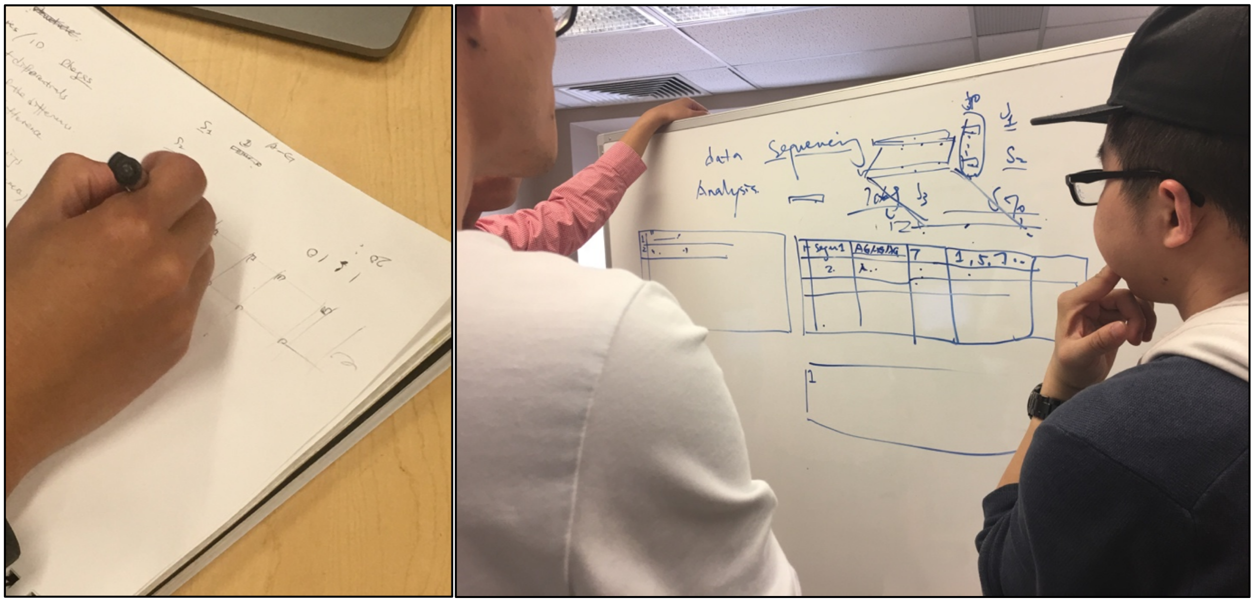



Figure 5.4 Using online tool to obtain DNA similarities.

In the section of “Study Context,” I mentioned the design goal of this visualization project held to represent accurately and effectively the data insights of the similarities and differences among different DNA sequencings with G-C contents. Data providers were supposed to obtain and understand DNA knowledge using developed visual analytics application. Based on these purposes, designers focused on design validity; that was, visual design should serve effective data insights’ deliveries by concentrated *quality* design judgment activities, especially for their design activities happened in “Represent” stage (4. Interesting design behavior in Table 5.2 (4)). For instance, designers decided a shape of ring inside two semicircles to layout a DNA group with nine individuals DNA and apply each pair to compare with adjacent DNA groups (*quality* design judgment) to highlight similarities (degrees) with different color saturations (*quality* design judgment) (bullets 4.2-4.9 in Table 5.2 (4)). P-JH supplemented:

> …Our clients want our team to develop an analytics tool for seeking and exploring data insights. So, if our visual designs, such as these semicircles, colors can help users obtain information, which is extremely significant, I think. We have a lot of design ideas previously, i.e., the ‘windshield wiper,’ ‘clock,’ ‘highway -like,’ etc. These ideas are

creative and innovative, but not effective to deliver data information. We have to give up them.

In addition, to focus on effectiveness (*quality* design judgment), this team expended efforts to design colors for the overall interface, especially in their final design phase with a series of *appearance* design judgments (5. Interesting design behavior in Table 5.2 (5)). Designers followed their decided workflows in the early stage with "database construction + interaction first; graphic design then" to improve overall appearance quality of design by concentrated combining and replacing color schemes (across all design activities of 5. Interesting design behavior in Table 5.2 (5)) for more users' engagements and enjoyments.

## 5.2 In-situ Study Two

Just as In-situ Study One, I organized this section with 5.2.1 for presenting study context and 5.2.2 for interpreting and explaining design judgment behaviors in "PPI Strategic Research Impact Areas" visualization project with research questions of "design judgment occurrence and relevant influencing factors."

### 5.2.1 Study Context

This in-situ visualization design project aimed to re-design "PPI Strategic Research Impact Areas" (https://va.tech.purdue.edu/PPI/ CGT) by resolving original design problems including: (1) lack of the whole picture; (2) confused crossing lines; (3) inappropriate colors and new colors add-on for data variable of impact areas (4) data variable of impact area needed; and (5) simple but boring. This team gathered users' needs, a process to talk and communicate with the CGT department manager to identify design problems. Then, with the primary goal of enhancing overall appearance with aesthetic experience and enjoyment, they put forward three research questions, including (1) what is the primary root to focus on; (2) how many levels are needed; and (3) how to show connections clearly so that the design answers new design creations and questions.

This team comprised of four master students, two of them came from visual communication design majors while the other two participants studied computer graphics technology (game design) and mechanical engineering (mechanical engineering design). Their judgment activities happened within 13 weeks of CGT581 visualization design and analytics in a classroom setting. I observed their design discussions entailing 30-40 minutes. I participated in their WhatsApp chatting group. Before each meeting, I was noted the topic. At course midterm (Week 9), the team scheduled an appointment with users (CGT manager and stakeholders), updated polished items, and collected further requirements.

In the following sections, I interpreted and described this team's design judgment activities with patterns and themes focusing on the questions of design judgment occurrence and influencing factors.

### 5.2.2 Design Judgments in In-situ Study Two

Nelson's theory (Nelson & Stolterman, 2012), the coding results revealed no new design judgments than discussed in In-Situ Study Two's particular visualization design process. Sections of 5.2.2.1 and 5.2.2.2 present this design team's design judgment behaviors in detail with the focus on the research questions of "occurrence" and "influencing factors."

#### 5.2.2.1 Design Judgment Occurrence

With framework analysis, I applied the same table of the structure as In-situ Study One (Table 5.1) to outline how to identify critical design behaviors that progressed the team toward the outcome visualization project of In-situ Study Two. In total, I examined five crucial design behaviors: (1) Week 2 acquiring data resource through discussing with the client (CGT manager) and applying a top-down approach to re-build a database in a sensical way employing "acquire" and "parse" design stages; (2) Weeks 4 and 5 cleaning up the data; removing all but the pertinent data (filtering); choosing basic visual forms (circular shapes) to construct project framework during the "filter" and "represent" design stages; (3) Weeks 7 and 8 selecting specific interaction ways, such as query and filter; fade in/out; and rotate to enhance overall appearance qualities on aesthetics and enjoyments of design employing "interact" and "represent" design stages; (4) Week 10 re-designing and re-organizing visual contents to improve design effectiveness implementing "refine" and "represent" design stages; and (5) Weeks 12 and 13 binding objects between local and proposed designs for releasing constrained development technology using "refine," "represent," and "filter" design stages.

The following paragraphs interpreted and explained the occurrence to support fuller descriptions of designer judgment behaviors and identify influencing factors vital design behaviors.

Before the thick descriptions, I continued the idea of In-situ Study One and employed Figure 5.5 to provide the researchers and readers an overview about designer design judgment behaviors of In-situ Study Two for PPI Strategic Research Impact Areas visualization design project with crucial design behaviors; informed design judgments (themes); and visualization design phases.

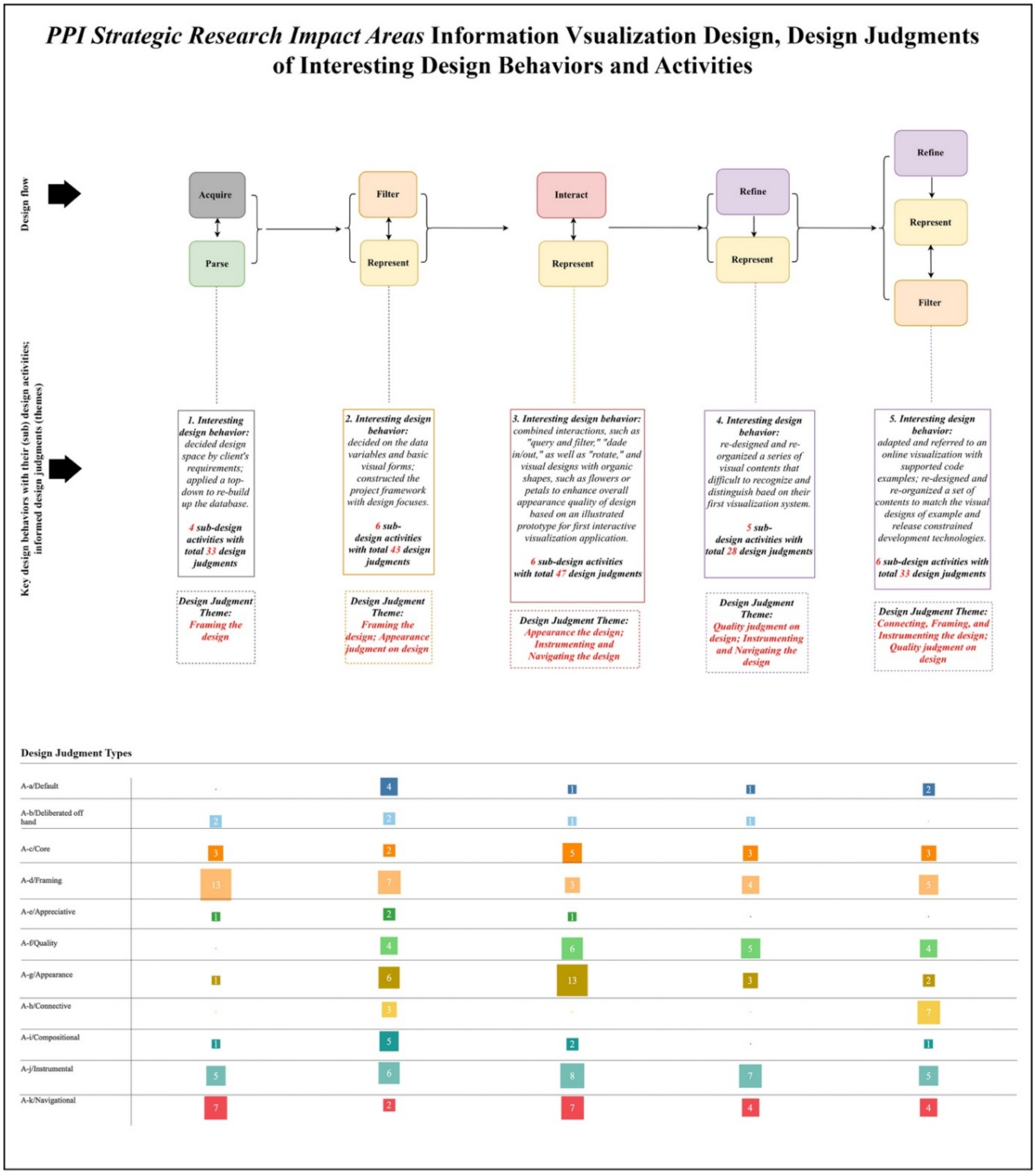



Figure 5.5 This image provides an overview of design judgment activities occurred in In-situ Study Two and involved design stages.

Table 5.3 This table comprised of five (sub) tables showing key design behaviors and informed design judgments in In-situ Study Two.

**(1)**

**Design Judgment Occurrences in [1. Interesting design behavior: decided design space by client's requirements; applied a top-down approach to re-build up the database]**
***(Theme - Framing the design in "Acquire" "Parse" visualization design stages)***

| Design Judgment Types / Major Sub-Design Activities | 1.1 | 1.2 | 1.3 | 1.4 |
|---|---|---|---|---|
| A-a/Default | | | | |
| A-b/Deliberated off hand | | | 1 | 1 |
| A-c/Core | 1 | | 2 | |
| A-d/Framing | 3 | 1 | 8 | 1 |
| A-e/Appreciative | | | | 1 |
| A-f/Quality | | | | |
| A-g/Appearance | | | | 1 |
| A-h/Connective | | | | |
| A-i/Compositional | | | 1 | |
| A-j/Instrumental | | 1 | 3 | 1 |
| A-k/Navigational | 1 | | 4 | 2 |

Design Activities Comprised of [1. Interesting design behavior: decided design space by client's requirements; applied a top-down approach to re-build up the database]

| | |
|---|---|
| 1.1 Maintained data variables of expertise and faculty member and added impact areas to represent in this visualization project. | 1.3 Thought over putting the variable expertise at the top level; sought and explored the most relevant information with expertise. |
| 1.2 Determined design criteria by summarizing design problems, such as intensive crossing lines, unreasonable colors, etc. in previous visualization. | 1.4 Thought over the manageable parts including (1) to divide the data segments into expertise; (2) to search and summarize the most relevant information with expertise; (3) to brainstorm design sketches to aid further judgments on the details of the variables as well as the connections/interconnections among variables. |

***<u>Theme 1:</u> framing the design (a set of design activities with the considerations design space)*** – In first appointment with the clients, the team gathered the users' needs. By making *framing* design judgments, designers defined what to include, such as the variable of impact areas and expertise; a whole picture; and overall aesthetics and interestingness and excluded, intensive crossing lines and ugly color schemes within the purview of the design process (bullets 1.1 and 1.2 in Table 5.3 (1)). Based on these thoughts, they decided to re-build a database using a top-down approach (*instrumental* design judgment) to append new data variables, such as impact areas and organized them more logically with distinct categories and relationships in Excel (*instrumental* design judgment) (bullet 1.3 in Table 5.3 (1)). Concurrently, the design team outlined several manageable parts (*navigational* design judgment) to implement a determined top-down method with a starting point of dividing the data segments into the variable of expertise, and then to search and summarize relevant connections on impact areas and faculties/professors (bullet 1.4 in Table 5.3 (1)).

During the procedures, several design decision-making reflected *core* design judgment due to the questions of why top-down approach and why a new database. Collaboratively making few *deliberated off hand, appreciative, appearance* design judgments, this team outlined actionable items to start the visualization project.

**(2)**

**Design Judgment Occurrences in [2. Interesting design behavior: decided on the data variables and basic visual forms; constructed the project framework with design focuses]** ***(Framing the design, Appearance judgment on design in "Filter" "Represent" visualization design stages)***

| Design Judgment Types / Major Sub-Design Activities | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 |
|---|---|---|---|---|---|---|
| A-a/Default | 2 | 1 | | | 1 | |
| A-b/Deliberated off hand | 1 | | | 1 | | |
| A-c/Core | | | 1 | | 1 | |
| A-d/Framing | 3 | 2 | | 1 | | 1 |
| A-e/Appreciative | | 1 | 1 | | | |
| A-f/Quality | | | 1 | 1 | 2 | |
| A-g/Appearance | 1 | | 1 | 3 | 1 | |
| A-h/Connective | | | | 2 | | 1 |
| A-i/Compositional | 1 | 1 | | 2 | | 1 |
| A-j/Instrumental | 1 | 1 | | 2 | 1 | 1 |
| A-k/Navigational | | | | 1 | | 1 |

Design Activities Comprised of [2. Interesting design behavior: decided on the data variables and basic visual forms; constructed the project framework with design focuses]

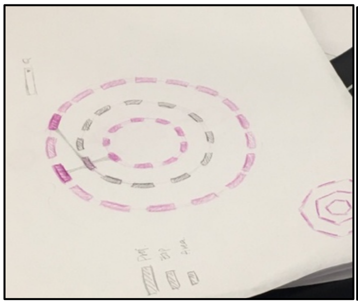
| | |
|---|---|
| 2.1 Retained the variables impact areas and faculty members most relevant to the variable areas of expertise; compose them to present and construct data theme. | 2.4 Applied a circular layout as the basic form; all design changes adhere to the circular layout. |

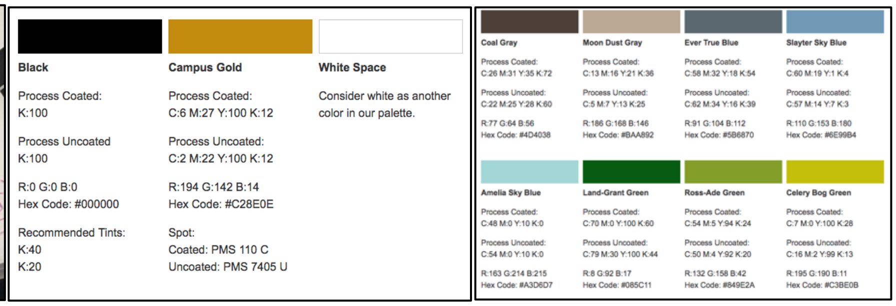
Table 5.3 (2) continued

| | |
|---|---|
| 2.2 Set “hierarchies” and “connections/interconnections” among three variables as a foreground. | 2.5 Switched the current color scheme to strengthen the data theme expression. |
| 2.3 Set “hierarchies” and “connections/interconnections” among three variables highlighting the selected items as a foreground to emphasize and deemphasize unselected/unrelated items as background. | 2.6 Thought over the manageable parts to work including (1) to connect effective design segments of sketch No.1 and 4 and compose an illustrated prototype; (2) to represent the illustrated prototype with more details of these three variables; (3) to determine a specific color scheme based on Purdue colors and apply it to the illustrated prototype. |

***Theme 2:* *framing the design, appearance judgment on design (a set of design activities with the considerations on data variables and basic visual forms)*** – With the assigned tasks of 1. Design Decision, all four members individually collected and sorted the data into Excel sheets using the determined top-down approach (*instrumental* design judgment). In this discussion, they actively synthesized and cleaned up the sheets and decided on variables of expertise, impact areas and faculty members to be visualized in their interactive visualization by making a series of *framing* design judgments (bullet 2.1 design activity in Table 5.3 (2)). Concurrently, they made concentratedly *appreciative* design judgments to determine emphasizing the connections and relationships between different data variables as the foreground of design (bullets 2.2-2.3 in Table 5.3 (2)).

One of the primary thoughts of re-designing this visualization was to improve overall aesthetics and interestingness of design, which based on client’s requirements and designers’ own wishes. Designers focused on making *appearance* design judgments across bullets 2.4-2.5 (Table 5.3 (2)) to apply a circular layout by composing design sketches No.1 and 4 (Figure 5.6 (a)) (*quality* and *compositional* design judgments happened concurrently) and University symbolic color schemes (Figure 5.6 (b)) (*instrumental* design judgment occurred concurrently) with the purposes of enhancing overall appearance quality with the harmonious design style.






(a) (b)

Figure 5.6 In this image combination: (a) designers decided a circular layout with a harmonious design style to improve overall aesthetics of design; (b) designers determined to apply University symbolic color palettes to strengthen data theme for overall design.

Close to the end of this discussion, this team scheduled a working flow to assign tasks to each of team members and focused *navigational* design judgment method, collaborating with *framing, connective, compositional, instrumental* design judgments (bullet 2.6 in Table 5.3 (2)). Furthermore, two team members in this study came from visual communication design backgrounds, their robust practical visual design experiences, and aesthetic consciousness with *default* design judgment-making also helped their designs progress.

**(3)**

**Design Judgment Occurrences in [3. Interesting design behavior: combined interactions, such as "query and filter," "fade in/out," as well as "rotate," and visual designs with organic shapes, such as flowers or petals to enhance overall appearance quality of design based on an illustrated prototype for first interactive visualization application]**
***(Theme - Appearance judgment on design, Instrumenting and Navigating the design in "Represent" "Interact" visualization design stages)***

| Design Judgment Types / Major Sub-Design Activities | 3.1 | 3.2 | 3.3 | 3.4 | 3.5 | 3.6 |
|---|---|---|---|---|---|---|
| A-a/Default | 1 | · | · | · | · | · |
| A-b/Deliberated off hand | · | · | · | 1 | · | · |
| A-c/Core | 1 | · | 1 | 2 | 1 | · |
| A-d/Framing | 2 | · | · | · | · | 1 |
| A-e/Appreciative | 1 | · | · | · | · | · |
| A-f/Quality | 1 | 1 | 1 | 2 | 1 | · |
| A-g/Appearance | 5 | 2 | 1 | 2 | 3 | · |
| A-h/Connective | · | · | · | · | · | · |
| A-i/Compositional | 1 | 1 | · | · | · | · |
| A-j/Instrumental | 5 | · | · | · | 1 | 2 |
| A-k/Navigational | 5 | · | · | · | 1 | 1 |

Table 5.3 (3) continued

| Design Activities Comprised of [3. Interesting design behavior: combined interactions, such as "query and filter," "fade in/out," as well as "rotate," and visual designs with organic shapes, such as flowers or petals to enhance overall appearance quality of design based on an illustrated prototype for first interactive visualization application] | |
|---|---|
| 3.1 Applied "query and filter" interactions with "fade in/out" animations to avoid connecting lines being displayed at the same time and highlighted the most requested information of the users. | 3.4 Changed the straight connected lines for arc/curve ones; match and keep consistent with the overall design style. |
| 3.2 Applied the rotating effect to each "ring" when selecting a particular faculty member, area of expertise, or impact area; improve design enjoyments by dynamic effects; avoid the co-linear layout and overlapped connected lines; ensure high identification of the connected lines. | 3.5 changed the sharp rectangles for organic shapes such as "flowers or petals" to enhance visual comfort and harmony. |
| 3.3 Added head portrait" of each faculty on each square to enhance the recognition of the visual elements and enlarge the space between each "ring" for the typing of names, titles, etc. | 3.6 Thought over the logic and manageable parts to program and implement their first visualization. |

***Theme 3:*** ***appearance judgment on design, instrumenting and navigating the design (a set of design activities with the considerations on how to combine the interaction with determined visual designs)*** – Designers in this design phase composed interaction ways and organic visual design ideas to aid design improvements on interestingness and enjoyments with combined *appearance, instrumental,* and *navigational* design judgments. Besides, *quality* design judgments also applied to the processes. During the interview, P-IL explained:

> …We consider that interesting interaction ways may help on improving overall quality of design. Firstly, we need to make our users to see something by highlights. So, the functions of query, filter, and fade in/out can help. They should be common ways for people to gain information, we believe. Besides, a rotating effect/dynamic animation would be great to add on for increasing enjoyments. It's a two-pronged approach. It also helps on

distinguishing overlapped connected lines. (bullets 3.1-3.2 in Table 5.3 (3)) (*instrumental, navigational, appearance, quality* design judgments)

Across bullets 3.3-3.5 (Table 5.3 (3)), designers re-organized space allocation; switched all straight connected lines to arcs/curves; and replaced monotonous rings into organic shapes of "flower/petal" *(appearance, quality, instrumental, navigational).* These design activities further enhanced the overall appearance quality of design.

*Framing* design judgments were made concurrently, especially among bullets 3.3-3.5 design activities (Table 5.3 (3)). Some changes on overall appearance directly affected information presentations. Designers actively adjusted their design boundaries, which re-defined what data segmentations to add or exclude.

**(4)**

**Design Judgment Occurrences in [4. Interesting design behavior: re-designed and re-organized a series of visual contents that difficult to recognize and distinguish based on first interactive visualization system]**
***(Theme - Quality judgment on design, Instrumenting and Navigating the design in "Refine" "Represent" visualization design stages)***

| Design Judgment Types / Major Sub-Design Activities | 4.1 | 4.2 | 4.3 | 4.4 | 4.5 |
|---|---|---|---|---|---|
| A-a/Default | · | · | 1 | · | · |
| A-b/Deliberated off hand | · | · | · | 1 | · |
| A-c/Core | 1 | · | 1 | 1 | · |
| A-d/Framing | 2 | 1 | · | · | 1 |
| A-e/Appreciative | · | · | · | · | · |
| A-f/Quality | 2 | 1 | 1 | 1 | · |
| A-g/Appearance | 1 | · | 1 | 1 | · |
| A-h/Connective | · | · | · | · | · |
| A-i/Compositional | · | · | · | · | · |
| A-j/Instrumental | 1 | 2 | 1 | 1 | 2 |
| A-k/Navigational | 1 | 1 | · | 1 | 1 |

Design Activities Comprised of [4. Interesting design behavior: re-designed and re-organized a series of visual contents that difficult to recognize and distinguish based on first interactive visualization system]

| | |
|---|---|
| 4.1 Broke down the current strict tree structure for the co-linear and indistinguishable connecting lines and relationships between variables. | 4.4 Switched the full circle/ring to unclosed one to strengthen the sense of growing. |

Table 5.3 (4) continued

| | |
|---|---|
| 4.2 Set the "bar" zoom out a little bit to show textual descriptions and relevant information when clicking and selecting a particular "bar" (faculty member/area of expertise/impact area). | 4.5 Thought over the manageable parts to work including (1) to re-illustrate the interface based on above amendments; (2) cut and separate all visual elements as individual ones for next-step of programming; (3) seek and search the example visualizations with similar data topics and explore their programming logic to eliminate technical weaknesses. |
| 4.3 Put the abbreviations rather than full titles on each "bar." | |

***<u>Theme 4:</u> quality judgment on design, instrumenting and navigating the design (a set of design activities with the considerations on design improvements and refinements)*** – With a good appearance of design, designers attempted to refine visual content that confused the users, which aimed to convey data insights more effectively and efficiently. They understood users by scheduling a discussion with the clients (CGT manager) and updated what parts accomplished in Week 8. Among their refinements, designers made *quality* design judgments on the modifications of visual forms of style, for example, they broke the current rigorous tree structure for more distinguishable connected lines; enlarge the selected "bar" to showing textual descriptions; switched full titles to abbreviations, etc., (bullets 4.1-4.3 design activities in Table 5.3 (4)) during which, *Instrumental* design judgments occurred. Developers explored clustering method with scales and measurements to break down current hierarchies (*instrumental* design judgment) (bullet 4.1 design activity in Table 5.3 (4)). They also extracted abbreviations by functions with a set of inputs and outputs (*instrumental* design judgment) (bullet 4.3 in Table 5.3 (4)). In the refinements, *framing* design judgments accompanied the re-defining design space and boundaries and guiding designers to align data to maintain visuals effectiveness (especially bullets 4.3 and 4.4 design activities in Table 5.3(4)).

In In-situ Study Two, *navigational* design judgments occurred. Design behavior of this team reflected splitting design into several manageable parts and assigning each member like 4.5 design activity (Table 5.3 (4)) with three steps of (1) re-illustrate the interface; (2) cut all visual elements; and (3) search and explore online examples for adaptation. Each subsequent discussion was based on the preciously decided working path.

**(5)**

**Design Judgment Occurrences in [5. Interesting design behavior: adapted and referred to an online visualization with supported code examples; re-designed and re-organized a set of contents to match the visual designs of example and release constrained development technologies]**

***(Theme - Connecting, Framing, and Instrumenting the design, Quality judgment on design in "Refine" "Represent" "Filter" visualization design stages)***

| Design Judgment Types / Major Sub-Design Activities | 5.1 | 5.2 | 5.3 | 5.4 | 5.5 | 5.6 |
|---|---|---|---|---|---|---|
| A-a/Default | | | | 1 | 1 | |
| A-b/Deliberated off hand | | | | | | |
| A-c/Core | 1 | | 1 | | 1 | |
| A-d/Framing | 3 | | | | 1 | 1 |
| A-e/Appreciative | | | | | | |
| A-f/Quality | | 1 | 1 | 1 | 1 | |
| A-g/Appearance | | | 1 | | 1 | |
| A-h/Connective | 1 | 5 | 1 | | | |
| A-i/Compositional | | | 1 | | | |
| A-j/Instrumental | 3 | 1 | | 1 | | |
| A-k/Navigational | | 1 | | 1 | 2 | |

Design Activities Comprised of [5. Interesting design behavior: adapted and referred to an online visualization with supported code examples; re-designed and re-organized a set of contents to match the visual designs of example and release constrained development technologies]

| | |
|---|---|
| 5.1 Adapted and referred to on an existing online visualization with a similar data structure to do development. | 5.4 Applied a tooltip technique to resolve further the design issue of displaying textual descriptions. |
| 5.2 Used a set of specific procedures to bind and adapt each visual segment between their design and explored example. | 5.5 Thought over the manageable parts to work including (1) to re-organize the layout to match and fit the design framework of the example; (2) to make the texts such as names and titles shorter by replacing them with abbreviations; and (3) to play with the found example, familiar with the structure, refer to the programming logic. |
| 5.3 Changed the central circle in the example for an independent "flower" layout for maintaining an innovation of overall design. | 5.6 Decided and described an acceptable design outcome for final course submission; as well as an evaluation plan for future work. |

***<u>Theme 5:</u>* connecting, framing, and instrumenting the design, quality judgment on design (a set of design activities with the considerations on how to adapt and refer an online example to accomplish an interactive visualization system)** – Development technology was most laborious for this team. To release this, designers considered to switch design strategy and adapt proposed design with supported code examples to ensure an acceptable design result for updating with clients and submitting for coursework assignment. Their design activities reflected the concentrated *connective, framing, instrumental,* and *quality* design judgments-making within "refine," "represent," and "filter" design processes. For example, designers attempted to bind the central circles between local design ("flower" in the middle) (Figure 5.7 (a)) and proposed design (purple area in the middle) (D3 Plus Ring Network - https://bl.ocks.org/PatMartin/0fccfddf5277e01cd5024d963f0caa70) and replace the "purple area" into a "flower" (*connective* design judgment) (bullet 5.3 in Table 5.3 (5)). Then, the development of web programming techniques came to fruition directly and efficiently. One team member P-JJ from visual communication major claimed:

> …Most of our team members came from Art & Design background, even Game Design and Mechanical Engineering Design. We all have no any idea about HTML, CSS, and JavaScript. Everything is new and needs to learn. Hence, we have to continually refine our visuals, filter, even discard some data attributes or features to match the constrained technical development. Because of the primary purpose, we have to switch strategy to adapt ideas from on online existing visualization tool to make sure we have something that can be presented and updated to our clients and also for coursework submissions. But I think this may be a good point for those student designers who have no solid programming knowledge foundation but still want to create excellent visualization design.

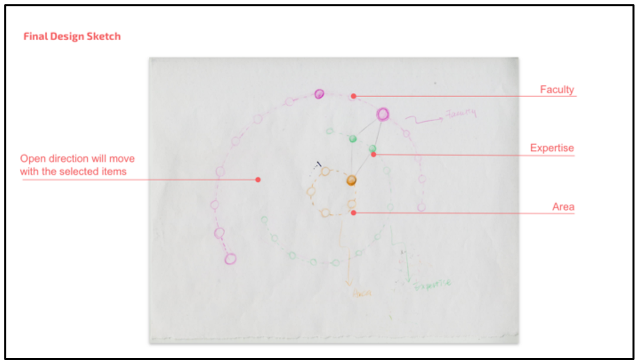



Figure 5.7 Figure (a) in this image combination shows the final design idea of this design team; figure (b) displays an explored online visualization example (https://bl.ocks.org/PatMartin/0fccfddf5277e01cd5024d963f0caa70) that this team referred and connected for resolving technical issues.

Among these steps, *framing* design judgments identified and defined constraints representing a mismatch between two designs. Concurrently, *instrumental* design judgment method resolved these limitations, such as conducting a tooltip to modify unreasonable displays of textual descriptions (5.4 Design decision). Additionally, designers made *quality* design judgments to maintain effective functionalities after binding and connecting (bullets 5.2-5.4 in Table 5.3 (5)).

5.2.2.2 <u>Design Judgment Influencing Factors</u>

Three primary reasons, including client/sponsor's requirement, time limitation with an outcome, and educational background with development technology constraint influenced designer design judgments in In-situ Study Two.

In the early stages (1 and 2 Interesting design behaviors in Table 5.3 (1) and (2)), the design team focused on utilizing the *framing* design judgment method to define a design space with precise boundaries by collecting client's requirements and summarizing design problems based on existing visualization application. Two factors drove motivated such behaviors: (1) client/sponsor's requirement; and (2) designers' ideas and expectations. The design team also collaboratively applied *instrumental* and *navigational* judgments to reconstruct the database, especially when clarifying the included variables, as well as their connections and interconnections to define an accessible environment. During their midpoint semi-structured interview, P-AA clarified:

> …We consider that a good starting will lead to a good outcome, which is a general rule of design. We have to determine an appropriative design context at the beginning, especially for visualization design with what data dimensions needed to be included; what designs should be modified; and what parts can remain because our work is about re-designing. We can refer the previous one and keep the good partials. We collected some information when chatting with our client; actually, she is the data provider. We also hold our own ideas about how to improve it when seeing and discussing the existing design. To clean up the data and re-build the database can be the first steps. We do not think we have the ability to make active changes to the data at later stage, which may lead all design chaos. This is a coursework assignment. We have to make sure a result for final submission. (*framing, instrumental,* and *navigational* design judgments) (1 and 2 Interesting design behaviors in Table 5.3 (1) and (2))

Both client's needs and team members' educational backgrounds influenced their judgment making. Thus, they employed *appearance* category (bullet 3. Interesting design behavior in Table 5.3 (3)). The client suggested design alterations enhance overall design appearance, especially, the form selection and color style should be modified to elicit a more aesthetic appeal. In addition to following the user requirements, the design team also set high standards on design style and appearance. P-IL explained:

> …All members in our team come from design backgrounds no matter game design or mechanical engineering design. Especially for P-JJ and me, we are the students in Visual Communication Design majors. In the education that we received, the overall appearance is super important. Almost all users' liking, interesting, engagement, and enjoyment are based on the appearance of a product. It provides a first expression for users. To assume I'm a user to play with this visualization (the existing one), I have no desire to play it continually so that it is also hard for me to reveal accurate data insights. (*appearance* design judgment) (bullet 3. Interesting design behavior in Table 5.3 (3))

Development technology remained a constraint for this design team. Combined with the time limitation of an expected outcome, the design team made concentrated *connective* design judgments to bind design objects and transmit internal energies to achieve a final design. Since connecting, *framing, instrumental,* and *quality* design judgment methods occurred concurrently. P-AA also explained:

> …I try to learn something about coding and programming in this project. Honestly, I'm interested in web programing. But D3 with JavaScript is really hard for me. I can learn and understand it better if I have one or two years. But I cannot make it within one semester and meet the deadline. In our team, only me is interested in programming. I do not have a helper at all. We had no choice. But maybe this strategy can help the design team like us. At least we have a result for final submission and presentation.

## 5.3 In-situ Study Three

Like the previous two studies, I organized this section with 5.3.1 for presenting study context and 5.3.2 for interpreting and explaining design team's judgment activities in "C4E" visualization project with research questions of "occurrence" and "influencing factors."

### 5.3.1 Study Context

The student design team involved in a joint project, which partnered among UNSA (Universidad Nacional de San Agustin in Arequipa, Peru), Purdue University (in Indiana), and C4E (Discovery Park's Center for the Environment). These institutions work collaboratively on challenges to ensuring a sustainable future, such as the food, energy, water, and environment for the people of Arequipa. Under this background, students in In-situ Study Three were required to focus on visualizing the relationships among proposals with the gathered information, such as soil maps, contamination maps, and bedrock geology in an organized and efficient way. The provided data structured five categories, including action, information gathered, proposal (people), time (F, W, S, U), and infrastructure (Figure 5.8). Due to the fact the proposed design showed a visualization of intensive network with a bunch of unclear crossing lines, the new tasks for this group entailed: (1) to change the layout and represent the relationships in an organized manner; (2) to allow users access to detailed information of each proposal; and (3) to demonstrate the duration of each proposal.

Most of my observations occurred off-classroom because the design team scheduled the weekly meetings with their project manager (sponsor) who works as Co-Director and Acting Director at Nexus Institute. A couple of times, their meetings involved the other stakeholders, such as primary data collectors who joined their discussions to clarify data constructions and suggest design improvements. I collected the data during 13-week of observations, in which each session took lasted 40-50 minutes and the interviews, which happened at midpoint (Week 7) and endpoint (Week 13). In each communication, the whole team focused on three things: (1) to update what have been accomplished (the student design team); (2) to guide and suggest what needed polishing (the product manager); and (3) to discuss the details for implementations of proposed ideas in the second item in this list.

With three rounds of brainstorming, the team determined their final design idea of "A Framework for Sustainable Water Management in the Arequipa Region" with several outcomes. At Week 13, I observed the team defined two major design issues of scalability and timeline and attempted to alleviate these challenges with several proposed improvements in subsequent developments.

| Project Aspects | | | | |
|---|---|---|---|---|
| Action | Information Gathered | Proposal | Time (F,W,S,U) | Infrastructure |
| Data Mining | soil maps | Filley | s u f w s u f w s u f w | model |
| Data Mining | contamination maps | Filley | s u f w s u f w s u f w | model |
| Data Mining | bedrock geology | Filley | s u f w s u f w s u f w | model |
| Data Mining | land use/ land cover maps | Filley | s u f w s u f w s u f w | model |
| Data Mining | digital elevation maps | Filley | s u f w s u f w s u f w | model |
| Workshop | course development | Sheffield | s u f w s u f w s u f w | academic course |
| Workshop | assesment | Sheffield | s u f w s u f w s u f w | academic course |
| Data Mining | contamination maps | Elwakil | s u f w s u f w s u f w | model |
| Data Mining | contamination risk factors | Elwakil | s u f w s u f w s u f w | model |
| Workshop | food security | Ejeta | s u f w s u f w s u f w | center/program |
| Workshop | proposal preparation | Ejeta | s u f w s u f w s u f w | center/program |
| Workshop | energy audit | Sheffield and Flores Larico | s u f w s u f w s u f w | academic course |
| Workshop | course development | Sheffield and Flores Larico | s u f w s u f w s u f w | academic course |
| Data Mining | soil maps | Ebert | s u f w s u f w s u f w | vizualization system |
| Data Mining | water data | Ebert | s u f w s u f w s u f w | vizualization system |
| Data Mining | soil health info | Ebert | s u f w s u f w s u f w | vizualization system |
| Data Mining | survey | Ebert | s u f w s u f w s u f w | vizualization system |
| Workshop | infrastucture planning | Martin and Chaubey | s u f w s u f w s u f w | research/field station |
| Data Mining | weather | Bowling | s u f w s u f w s u f w | framework |
| Data Mining | soil maps | Bowling | s u f w s u f w s u f w | framework |
| Data Mining | land use/ land cover maps | Bowling | s u f w s u f w s u f w | framework |
| Data Mining | water data | Bowling | s u f w s u f w s u f w | framework |
| Data Mining | social institutions | Bowling | s u f w s u f w s u f w | framework |

Key | Field Sampling based projects | Data, Building Based Projects | +

Figure 5.8 Data segments in C4E project of In-situ Study Three.

### 5.3.2 Design Judgments in In-situ Study Three

The initial coding results, adapted to Nelson's (2012) theory, yielded no new design judgment categories revealed in the specific visualization design process of In-situ Study Three. The following sections of 5.3.2.1 and 5.3.2.2 interpret and explain the design team's design judgment activities comprehensively with the focus on the research questions of "occurrence" and "influencing factors."

#### 5.3.2.1 Design Judgment Occurrence

The design team's activities also happened during 13 weeks within a course semester although most formal discussions occurred in an off-classroom context. In total, I examined five vital design activities: (1) Week 2 acquiring data resource through discussing with the product manager (sponsor - Co-Director and Acting Director at Nexus Institute); scheduling three initial tasks employing "acquire" and "parse" design stages; (2) Weeks 4 and 5 brainstorming and sketchign ideas; updating design thinking with their product manager within the "represent" design stage; (3) Weeks 6 and 7 detailing relationships and connections between variables; adding visual elements with corresponding interactive approach to enrich data representations employing "filter," "mine," "represent" and "interact" design stages; (4) Week 9 revising the design content; deciding a final design idea for interactive visualization development implementing "refine" and "represent" design stages; and (5) Weeks 11 and 12 determining the new design scheme to improve "time-associated" visual block with reasonable interactions; taking out confusing textual descriptions to improve design using "refine," "represent," and "interact" design stages.

The following parts interpreted and explained the occurrence to support fuller descriptions of designer judgment behaviors and identify influencing factors key to design activities. Before the thick descriptions, I continued the idea of previous two studies and employed Figure 5.9 to provide the readers an overview about designer design judgment behaviors of In-situ Study Three for C4E visualization design project with vital design activities; informed design judgments (themes); and visualization design stages.

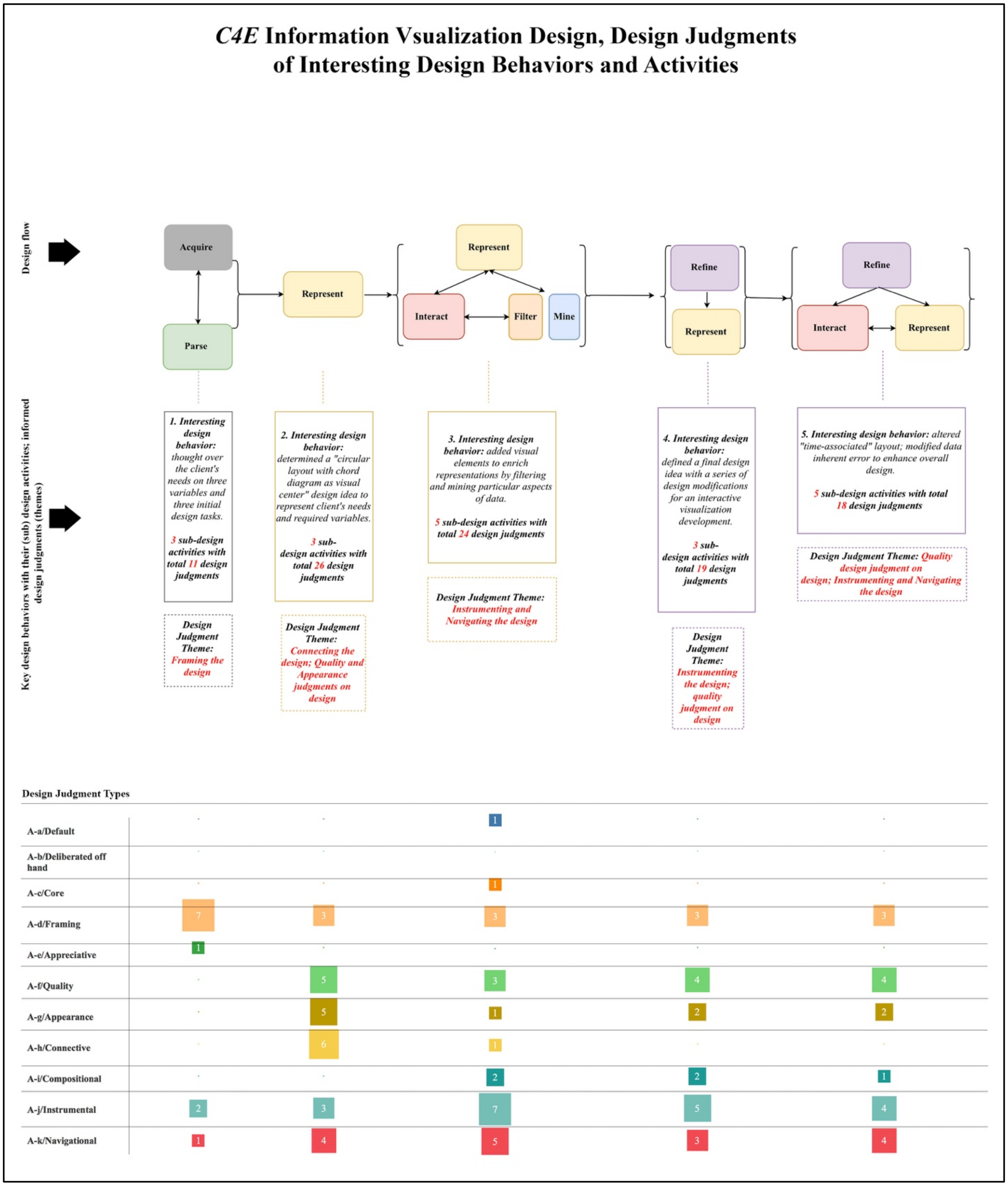



Figure 5.9 This image provides an overview of design judgment activities occurred in In-situ Study Three and involved design stages.

Table 5.4 This table comprised of five (sub) tables showing key design activities and informed design judgments in In-situ Study Three.

**(1)**

**Design Judgment Occurrences in [1. Interesting design behavior: thought over the client's needs on three variables and three initial design tasks]**

***(Theme - Framing the design in "Acquire" "Parse" visualization design stages)***

| Design Judgment Types / Major Sub-Design Activities | 1.1 | 1.2 | 1.3 |
|---|---|---|---|
| A-a/Default | · | · | · |
| A-b/Deliberated off hand | · | · | · |
| A-c/Core | · | · | · |
| A-d/Framing | 3 | 4 | · |
| A-e/Appreciative | · | · | 1 |
| A-f/Quality | · | · | · |
| A-g/Appearance | · | · | · |
| A-h/Connective | · | · | · |
| A-i/Compositional | · | · | · |
| A-j/Instrumental | · | · | 2 |
| A-k/Navigational | · | · | 1 |

Design Activities Comprised of [1. Interesting design behavior: thought over the client's needs on three variables and three initial design tasks]

| | |
|---|---|
| 1.1 Discussed three user needs. | 1.3 Thought over several initial design tasks as a starting point. |
| 1.2 Discussed three variables of action, project, analysis represented in the project. | |

***Theme 1:* framing the design (a set of design activities with the considerations on the client's needs, data variables, and design tasks)** – In Week 2, the design team joined the C4E project, the first opportunity for the students to chat with the product manager. During the meeting, the students made a series of *framing* design judgments to define three variables, including action, project, and analysis must be represented and three detailed missions presented in section of study context as design boundaries (bullets 1.1 and 1.2 in Table 5.4 (a)). The manager clarified his requirements, which also reflecting the needs of the entire project team. He then interpreted and explained the information about the provided database. These activities facilitated student judgment.

Adhering to user needs, the students decided several initial tasks to start the project (bullet 1.3 in Table 5.4 (1)) (*navigational* design judgment): (1) to represent the data segments most relevant to the subject (*appreciative* design judgment) using data filters (*instrumental* design judgments); (2) to implement a basic clickable button and test if information could be displayed by triggering it; and (3) to brainstorm (*instrumental* design judgment) visual design ideas and sketch the ideas to discuss in next weekly meeting. In their first design progress, *framing, appreciative, instrumental,* and *navigational* design judgments occurred concurrently.

**(2)**

**Design Judgment Occurrences in [2. Interesting design behavior: determined a “circular layout with chord diagram as visual center” design idea to represent client’s needs and required variables]**
***(Theme - Connecting the design, Quality and Appearance judgments on design in “Represent” visualization design stage)***

| Design Judgment Types / Major Sub-Design Activities | 2.1 | 2.2 | 2.3 |
|---|---|---|---|
| A-a/Default | | | |
| A-b/Deliberated off hand | | | |
| A-c/Core | | | |
| A-d/Framing | | | 3 |
| A-e/Appreciative | | | |
| A-f/Quality | 1 | 3 | 1 |
| A-g/Appearance | 1 | 3 | 1 |
| A-h/Connective | 1 | 3 | 2 |
| A-i/Compositional | | | |
| A-j/Instrumental | 1 | 2 | |
| A-k/Navigational | 1 | 2 | 1 |

| Design Activities Comprised of [2. Interesting design behavior: determined a “circular layout with chord diagram as visual center” design idea to represent client’s needs and required variables] | |
|---|---|
| 2.1 Determined a rectangular flow layout as the design idea after referring to and adapting from an online example. | 2.3 Considered to (1) apply a circular layout with a central chord diagram; (2) go more in-depth and improve the “circular layout” above; (3) program with the “circular layout” above; (4) abandon rectangular design ideas; and (5) present all design ideas but with a focus on the “circular layout” to their sponsor. |

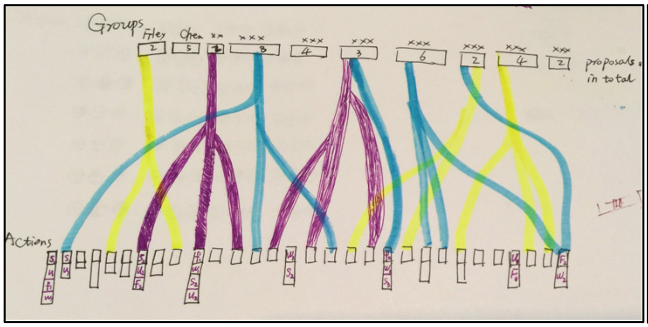
Table 5.4 (2) continued

| | |
|---|---|
| 2.2 Created three rectangular layouts of the matrix, flow map, and parallel coordinates (preference) as the broader design ideas. | |

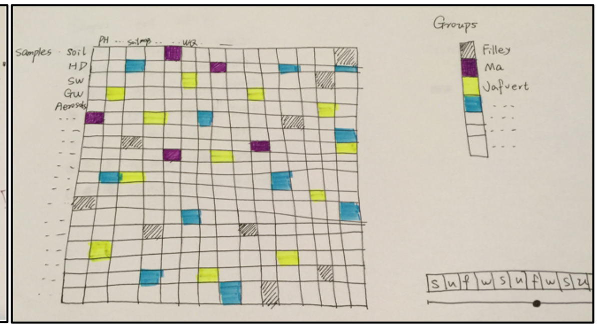
***<u>Theme 2:</u>* *connecting the design, quality and appearance judgments on design (a set of design activities on defining a reasonable design idea)*** – The involvement of management helped the design team quickly progress into the phase of "represent." The determined design missions primarily required efforts on both appearance and effectiveness when processing the visual representations. The constraint of design inspiration impeded the design team achieve these design missions. To overcome this limitation, the design team attempted to refer to the searchable online examples that fully demonstrate design requirements using several designs; and choose one in a limited capacity as a final idea. To achieve these attempts, the students (1) made *instrumental* judgment when searching and choosing the proposed tools and applications, such as "Rectangular Flow Visualization/Sankey Diagram" (https://beta.observablehq.com/@mbostock/d3-sankey-diagram); (2) applied a number of *connective* design judgments binding visual objects and relevant concepts to guide their local design creations with the ideas presented of rectangular flow (Figure 5.10 (a)), matrix (Figure 5.10 (b)), parallel coordinates (Figure 5.10 (c)), and circular chord diagram (Figure 5.10 (d)) (across all design activities in Table 5.4 (2)). During the process, the design team utilized *navigational* judgment to organize how to implement a systematic interface to create the relationships between members of a flow; and then achieve full relationship map with one command (across all bullets of design activities in Table 5.4 (2)).

*Appearance* and *quality* judgments-making accompanied *connective* all through to outline the connecting lines effectively and alleviate a crowded appearance style, in which, both aspects were mutually reinforcing (across all bullets of design activities in Table 5.4 (2)).

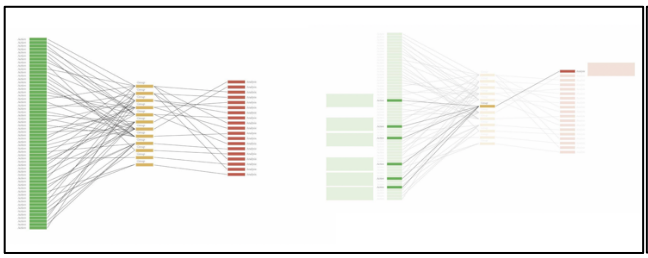
*Framing* judgment-making also happened during the process, especially for bullet 2.3 design activity. The design team determined to exclude all sketches except the circular chord diagram due to team member preference.



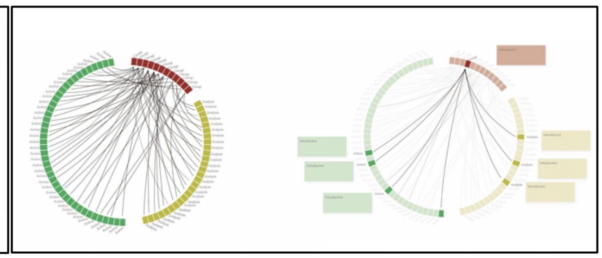

(a)




(b)



(c)



(d)

Figure 5.10 The design team created four ideas and presented to their product manager. These figures premises by the designer who participated in this study.

**(3)**

**Design Judgment Occurrences in [3. Interesting design behavior: added visual elements to enrich representations by filtering and mining particular aspects of data]**
***(Theme - Instrumenting and Navigating the design in "Filter" "Mine" "Represent" "Interact" visualization design stages)***

| Design Judgment Types / Major Sub-Design Activities | 3.1 | 3.2 | 3.3 | 3.4 | 3.5 |
|---|---|---|---|---|---|
| A-a/Default | | | | | 1 |
| A-b/Deliberated off hand | | | | | |
| A-c/Core | | | | 1 | |
| A-d/Framing | 1 | | | | 2 |
| A-e/Appreciative | | | | | |
| A-f/Quality | | | 1 | 1 | 1 |
| A-g/Appearance | | | | 1 | |
| A-h/Connective | | 1 | | | |
| A-i/Compositional | | | 1 | | 1 |
| A-j/Instrumental | | 1 | 2 | 1 | 3 |
| A-k/Navigational | | 1 | 2 | 1 | 1 |

Design Activities Comprised of [3. Interesting design behavior: added visual elements visual elements to enrich representations by filtering and mining particular aspects of data]

Table 5.4 (3) continued

| | |
|---|---|
| 3.1 Detailed relationships between the determined variables. | 3.4 Remove the "un-toggle" lines in the central part of the current chord diagram. |
| 3.2 Sought and referred to an existing online example to program the visualization. | 3.5 Considered to (1) add time-associated variable; (2) add one more interaction way based on time-association to help the users receive the same data insights about the relationships between the variables. |
| 3.3 Approached two interaction ways of "querying" and "highlighting;" help the users obtain the data insights with similar structures about the relationships between the variables. | |

***Theme 3:* instrumenting and navigating the design (a set of design activities on defining a reasonable design idea)** – After updating and determining the idea of circular chord diagram, the product manager detailed the connections and relationships between the variables. He also required the design team to represent these connections or interconnections accurately and helped the users grasp the data insights effectively and efficiently (*quality* design judgment) employing reasonable interactive approaches (*instrumental* design judgment). With the guidance of the manager, the design team formulated the connections one-to-one among three determined variables (*instrumental* design judgment) to define practicable data segments, which could be included (*framing* design judgment) to organize a relationship map. (bullet 3.1 design activity in Table 5.4 (3))

To realize effective data transmissions, the design team determined two interactive methods of "querying" and "highlighting" to help the users query wanted data categories, and then clearly see the relationships between the selected species and related categories (*instrumental* design judgment; *navigational* accompanied) (bullet 3.3 design activity in Table 5.4 (3)). Furthermore, students made *quality* design judgment while removing the "un-toggle" connecting line, so that all presented links were valid (bullet 3.4 design activity in Table 5.4 (3)). To strengthen the visual effectiveness, the team decided to include the time-associated variable (*framing* design judgment) and one more interaction of "dragging and dropping" (*instrumental* design judgment) with the working flow of (1) adding the corresponding data segments to database; (2) extracting them to display on the interface; and (3) conducting interactions to manipulate the add-on data segments and combine the representations into the whole (*navigational* accompanied) (bullet 3.5 design activity in Table 5.4 (3)).

**(4)**

**Design Judgment Occurrences in [4. Interesting design behavior: defined a final design idea with a series of design modifications for an interactive visualization development]**
***(Theme - Instrumenting the design, Quality judgment on design in "Refine" "Represent" visualization design stages)***

| Design Judgment Types / Major Sub-Design Activities | 4.1 | 4.2 | 4.3 |
|---|---|---|---|
| A-a/Default | | | |
| A-b/Deliberated off hand | | | |
| A-c/Core | | | |
| A-d/Framing | 1 | 1 | 1 |
| A-e/Appreciative | | | |
| A-f/Quality | 3 | | 1 |
| A-g/Appearance | 1 | | 1 |
| A-h/Connective | | | |
| A-i/Compositional | | 2 | |
| A-j/Instrumental | 3 | 1 | 1 |
| A-k/Navigational | 2 | 1 | |

| Design Activities Comprised of [4. Interesting design behavior: defined a final design idea with a series of design modifications for an interactive visualization development] | |
|---|---|
| 4.1 Considered the specific method and path to modify redundant lines in the center of the chord diagram. | 4.3 Applied the color dimension to enhance the differentiation and identification among variables. |
| 4.2 Considered the specific method and path to add on the time-associated variable and synthesize it with the centered-chord diagram layout. | |

***<u>Theme 4:</u> instrumenting the design, quality judgment on design (a set of design activities on defining a final design idea with visual modifications)*** **–** The design team focused on refining visual elements to improve the effectiveness of design at this step. In my observations, the design pattern activities in In-situ Study Three concentratedly reflected in how to organize reasonable visual representations for the effective information delivery and appropriative overall appearance of design. The product manager, collaborated with other stakeholders, like the data collector, to interpret the data and explain requirements when the design team got confused about the database.

In their third critical set of design activity (3. Interesting design behavior in Table 5.4 (3)), a circular chord diagram embodied an inclusive and harmonious visual perception that met their requirement of overall aesthetically pleasing design appearance.

In the process of continuously improving the design effectiveness, the design team consciously made *instrumental* design judgment using particular choices of means and *quality* design judgments to enhance visual effectiveness. Concurrently, the team formed *framing* and *navigational* judgments. For instance, the team in bullet 4.1 design activity (Table 5.4 (4)) chose a logic algorithm (*instrumental* design judgment) to filter out redundant lines in the systematic computing progress (*navigational* accompanied). By this filter, each connecting line shown was refined (*quality* design judgment).

In design activity 4.2 (Table 5.4 (4)), the design team combined the data segments of the time-associated variable into the table on a server (*instrumental* and *compositional* design judgments) and applied SQL statements to invoke the data used in the representations (*instrumental* and *navigational* design judgments). The team composed a "time-associated" visual block as a supplementary aim to increase the effectiveness of the circular chord diagram in the visual center (*compositional* and *quality* design judgments).

In their final sub-design activity (bullet 4.3 design activity in Table 5.4 (4)), the design team applied *instrumental* judgment while processing color coding to improve visual differences among various data variables (*quality* design judgment). During the progress, the color re-design also enhanced the overall design appearance with the nature of data (*appearance* design judgment). A *framing* design judgment was also made at the same time.

**(5)**

| **Design Judgment Occurrences in [5. Interesting design behavior: altered "time-associated" layout; modified data inherent error to enhance overall design]** <br> ***(Theme - Quality judgment on design, Instrumenting and Navigating the design in "Refine" "Represent" "Interact" visualization design stages)*** |
|---|

| Design Judgment Types / Major Sub-Design Activities | 5.1 | 5.2 | 5.3 | 5.4 | 5.5 |
|---|---|---|---|---|---|
| A-a/Default | | | | | |
| A-b/Deliberated off hand | | | | | |
| A-c/Core | | | | | |
| A-d/Framing | | 1 | | 1 | 1 |
| A-e/Appreciative | | | | | |
| A-f/Quality | 1 | 1 | 1 | 1 | |
| A-g/Appearance | 1 | | | 1 | |
| A-h/Connective | | | | | |
| A-i/Compositional | 1 | | | | |
| A-j/Instrumental | | 1 | 2 | 1 | |
| A-k/Navigational | | 1 | 1 | 1 | 1 |

| Design Activities Comprised of [5. Interesting design behavior: altered "time-associated" layout; modified data inherent error to enhance overall design] | |
|---|---|
| 5.1 Synthesized the "time-associated" layout to the central chord diagram as a perfect whole. | 5.4 Changed the proper nouns for the undecided items in the database. |
| 5.2 Represented the time-associated variable with a circular bar layout and a mouseover/out interaction way. | 5.5 Decided on an acceptable design outcome and a future work plan. |
| 5.3 Represented the time-associated variable with an "integral, closed/unclosed" circular bar layout and the "mouseover/out + highlighting" interaction way. | |

***<u>Theme 5:</u> quality judgment on design, instrumenting and navigating the design (a set of design activities on design refinements and improvements)*** – Just as in 4. Interesting design behavior, the design team continuously focused on improving the effectiveness of visual representations to strengthen the validity of data presentations in this step. During the process, students concurrently utilized the design judgments of *quality, instrumental,* and *navigational* (*framing* accompanied). The design team in bullet 5.1 design activity (Table 5.4 (5)) also made the *compositional* judgment to synthesize two visual blocks for a perfect overview of design and *appearance* design judgment to assess the overall appearance quality with consistency.

Across bullets 5.2-5.3 design activities (Table 5.4 (5)), students attempted to replace visual elements, such as a circular bar or an "integral, closed/unclosed" circular bar to improve the visual effectiveness; in turn, it helped to present data insights (*quality* design judgment) effectively. *Instrumental* and *navigational* design judgments were used concurrently due to the interactive approaches manipulated data, which helped the users obtain the information more efficiently.

The *framing* judgment was made in bullet 5.4 design activity (Table 5.4 (5)) while excluding undefined descriptions in the database, which aimed to enhance overall design appearance without confusing data and information (*appearance* design judgment) and improve the effectiveness of visual representations (*quality* design judgment).

Finally, the design team decided two usability problems of scalability and timeline exist that would require more focus in subsequent development employing the *framing* design judgment-making. They also applied *navigational* design judgment to conduct a workflow to alleviate these two usability issues (bullet 5.5 design activity in Table 5.4 (5)).

#### 5.3.2.2 Design Judgment Influencing Factors

In my observations and interviews, the client requirements (sponsors and other stakeholders) represented the most critical factor driving the design team to make design judgments, especially with *framing* method. The student P-KY in their midpoint interview said:

> … Our team never encounter many difficulties to define what data variables to be represented because our product manager directly points out what attributes must be shown. The manager helps us to explore and understand the database so that we save a lot of time on data analytics. It is like working at a company, the manager also defines several missions during our very first meetings. We'll just do what he wants. (*framing* design judgment) (1 and 3. Interesting design behavior in Table 5.4 (1) and (3))

This factor also influenced students making design judgments with focused *quality, appearance, instrumental* and *navigational* categories. P-KY also explained:

> … I remember once we determine a circular chord diagram as a final idea, the manager leads us to further clarify the relationships and connections between the variables. We also

> applied mathematical calculations by Excel and computing functionalities to identify what exact of each connected line. He requires us to visualize these connecting lines clearly for (1) a good look on overall appearance of design; (2) accurate and effective data representations, particularly for the relationships between three determined variables. He also suggested to add interactions with step-by-step path for enhancing the user experience. Using interactions to perform data is also about making visual representations more effective. (*quality, appearance, instrumental,* and *navigational* design judgments occur concurrently) (bullets 2-5. design activities in Table 5.4 (2-5))

The design team made a series of *connective, instrumental,* and *navigational* design judgments (*quality* and *appearance* accompanied) due to the limited design innovation and creativity. During the midpoint interview, P-LY explained:

> … You know… Actually, we don't have visual designers in our team. P-SQ and I come from UX background. We can do some sketches, but we are not good at sketching, especially for creating like 50 or more ideas… We want our design look good as well as effective on data presentations. What we can do is to search and explore online examples, tools, or applications, which hold similar concepts and data topics; refer and adapt from the examples with step by step binding and connecting for our local designs. (*instrumental, connective, navigational, quality* and *appearance* design judgments happened concurrently) (2. Interesting design behavior in Table 5.4 (2))

Design feasibility was the third important factor influencing students design judgments-making based on my observations and interviews. Because of a scheduled conference deadline, the design team considered the design feasibilities while deciding and determining visual representations and interactions. P-KJ in their endpoint interview said:

> …Although I act as a programmer in our group, I'm actually in favor of a breakthrough in design. I agree that we should spent more time improving design on the aspects of innovations and effectiveness. But when my mission becomes urgent of accomplishing a complete interactive system to catch a conference deadline, I will request to modify, even

discard partial designs to match my development and implementation. If some part of design is difficult to accomplish in web programming, we will discuss to discard or make it simplify. (*framing, quality, instrumental,* and *navigational* design judgments made concurrently) (bullets 4-5. design activities in Table 5.4 (4) and (5))

## 5.4 Studies Synthesis and Comparisons

The complex design processes with various situations diversified design judgment behaviors and corresponding influencing factors. The following table (Table 5.2) clarified the results of synthesis and comparisons across all three in-situ studies, which helped the investigators and other readers understand and learn design judgments (methods) and related influencing factors in a holistic perspective; identified matched conditions with local design situations and improved designs by adapting supportive design patterns.

Table 5.5 This table supports the information of in-situ studies' synthesis and comparisons.

| ***In-situ Study/Design Judgment (Theme)*** | ***Design Judgment (Themes)*** | ***Representative Examples from Interview Data*** | ***Influencing Factors*** |
|---|---|---|---|
| In-situ Study One | *Framing, navigational, instrumental, quality*, and *appearance* | "Our data provider made only one request; that is, to show the similarities between different DNA sequencings, which they want to see most" – framing design judgment<br>"We navigate our design by a working flow of "database re-construction and interaction paralleled firstly and graphic design then" – navigational design judgment<br>"We can use this online tool (DNA Analyst) to extract the data that we really want and save to these tables. ..I think, ..we won't design a program to filter and extract data, right? That would spend a lot of time. And unnecessary! This tool is enough!" – *instrumental design judgment*<br>"Our original goal is to represent the similarities of G-C contents between different DNA sequences, right? And we want to compare several of them | Constraint of professional guidance; limited time with an expected outcome; and design validity |

Table 5.5 continued

| | | | |
|---|---|---|---|
| | | concurrently, right? So, how to compare them at the same time? I think cut a full circle into two separate parts; into two section would be a better idea. Then the left side can be used to compare to the DNA sequences on the left, and the right part for comparing with the right DNA sequencing" – <u>*quality design judgment*</u><br>"We need to choose a reasonable color combination to improve the whole interface. The red-blue combination is ugly, I think. The purple-green would be better, the feeling of smoother and more harmony" – <u>*appearance design judgment*</u> | |
| In-situ Study Two | *Framing, appearance, instrumental, quality*, and *connective* | "With CGT manager's requirements, we have to include the data variables of impact areas, expertise, and faculty members." – <u>*framing design judgment*</u><br>"We all think the circular shape provide the users the feelings of embracement and harmony. So, we keep this circular design all the time" – <u>*appearance design judgment*</u><br>"We consider and attempt to apply a flower to represent five impact areas and improve the innovation and harmony of these design ideas. Bionic design is an effective way" – <u>*instrumental design judgment*</u><br>"I think we can cluster the nodes, which would be more effective for showing the connected lines." – <u>*quality design judgment*</u><br>"They have three rings with some nodes on there, right? We also have three circular shapes with some nodes. Cool, the similar things. I think we only need to do a little bit revision to re-layout the nodes, then we can refer and adapt the coding examples smoothly. Then we will have an interactive visualization!" – <u>*connective design judgment*</u> | Client/sponsor's requirement; educational background (with development technology constraint); limited time with an expected outcome |

Table 5.5 continued

| | | | |
|---|---|---|---|
| In-situ Study Three | *Framing, connective, quality, appearance, instrumental*, and *navigational* | "The connections and relationships between three determined variables, have to be shown further in our visualization project based on project manager's requirements." – *framing design judgment*<br>"We need to show the connected lines between action and project; action and analysis; project and analysis, right? So, see… the rectangular tree, matrix, parallel coordinates, all which can help and support representing the data connections between two different variables. We then refer these examples to create our designs by outlining our specific data on there." – *connective design judgment*<br>"I think we can outline the timeline as a circular shape to the outside edge of the chord diagram. It can help on the continuity of information." – *quality design judgment*<br>"We prefer the circular chord diagram, which is the most aesthetic one." – *appearance design judgment*<br>"I think… we need to use the function of input, output, and extract to determine the data segments of DNA similarities between different DNA sequences." – *instrumental design judgment*<br>"This manner is particularly in keeping with our design idea. We can give the users an overview at first, then zoom in and filter by choosing and selecting. Then, the users will see more details for the selective items by hovering and clicking. At the same time, some related information shows up and some unrelated information shows down" – *navigational design judgment* | Client/sponsor's requirement; limited design innovation and creativity; design feasibility |

Table 5.5 continued

| | | | |
|---|---|---|---|
| *Synthesis* | Design judgments with *framing, navigational, instrumental, quality, appearance*, and *connective* were applied to move and an outcome (complete) visualization designs. | | The internal and external factors, such as constraints of professional guidance and development technology; limited time with an expected outcome; limited design innovation and creativity; design validity and feasibility; client/sponsor's requirement; and educational background greatly influenced design teams' design judgments in visualization projects |
| *Comparisons* | *With challenged design activities of defining and identifying design spaces and boundaries (In-situ Study One with primary goal of design effectiveness),* transformational judgment-making by collaborative *navigational* and *instrumental* types supported a reasonable mean to constitute design framework; *quality* design judgment activities helped with a design for professions and academic users with primary purpose of accurate data (insights) representations.<br>*With challenged activities of design developments (In-situ Study Two with primary goal of aesthetics and interestingness's enhancements of design),* *connective* design judgment method helped on remitting technical shortages by referring and adapting proposed design.<br>*Appearance* design | | *With constraint of time and professional guidance; with explicit requirements of design validity*<br>*With constraint of development technology; but good educational background on visual design field; with explicit client's requirements* |

Table 5.5 continued

| | | | |
|---|---|---|---|
| | judgment-making helped on assessing overall appearance with aesthetic experience and enhanced the feelings of engagements and enjoyments.<br>*With challenged activities of design innovations and creations (In-situ Study Three with primary goal of reasonable visual representations),* combined *framing, connective, quality, instrumental,* and *navigational* design judgments-making aided a team to establish and polish a design idea. | | <br><br><br><br><br><br>*With constraints of design innovations and creations; but superiority of an experienced guidance (product manager)* |

## 5.5 Unexpected Findings

In laboratory studies, design behaviors of individuals in a team affected the design judgment activities of other members. In in-situ studies, the most active member influenced team member judgment activities, especially in a multiplayer collaborative design team. In this research, each in-situ study consisted of at least four members. For instance, five students composed a team to visualize data of Similarities and Differentials among DNA Sequences in In-situ Study One. One member, P-JH was specialized in data explorations but remained actively involved in the discussions of every design phase. During determining what visual representations, i.e., a reasonable color scheme was required for assigning the index DNA sequence and the others, P-JH followed designers' ideas because he lacked knowledge of color design standards and principles. However, he actively explored relevant online examples and documents and helped his team expand design ideas. In my observations, other members' design judgment activities (i.e., focused *quality* and *appearance* design judgments in "represent" design stage) were transformed and transferred by P-SH's continuous comments and suggestions. A similar situation also occurred in In-situ Study Two. P-AA, a game design major was adept at visual design nor development techniques. Despite this lack of knowledge, she helped her team make meaningful design judgment because she actively sought solutions and participating in discussions.

While making judgments to inform design ideas, designers in laboratory studies applied de deliberate design methods, such as identified brainstorming, analogizing, literature searching, and selection of scales of measurements. With complete visualization design processes of in-situ studies, they utilized design methods more extensively. For example, designers in In-situ Study Two not only organized several rounds of brainstorming and analogizing but also processed the meaning of investigating user behaviors when making *framing, instrumental, appearance,* and *quality* design judgments in “acquire” and “represent” design phases. By strategy changing design way, this design team made a series of judgments with concentrated *connective* type to bind connections between design objects; transmit powers of adapted examples and valid a submittal design for their coursework’s final presentation. The design team of In-situ Study Three used a series of literature searches to layout and enhance their design interface with *appreciative, quality, appearance,* and *framing* judgments. Designers involved in In-situ Study One applied the design methods of ranking and weighting while making *quality* and *appearance* judgments and classifications of design information when making *navigational* and *instrumental* judgments.

These unexpected findings could not be described comprehensively in this dissertation; however, they provide valuable research directions in subsequent academic studies.

## 5.6 Summary

With in-situ studies’ results and findings, this chapter presented the holistic answers to the primary questions with the focused of “occurrence” and “influencing factors” proposed in Chapter 1. For each in-situ study, I introduced the design context and then detailed design judgment phenomenon highlighting particular design behaviors, identified as key nodes progressed toward outcome designs. Besides, across-study synthesis and comparison helped summarize the generalized design judgments (methods) that progress outcome designs with particular situations at a high level. Finally, this chapter also presented unexpected findings regarded as the subsequent research directions to examine and explore.

# CHAPTER 6. **DISCUSSION**

This research examined and explored design judgment behaviors, in particular, the visualization design processes of five student working projects that occurred in the lab or natural environments. In this chapter, I will discuss the synthetic findings and insights of visualization design judgment-making behaviors using cross studies from five different aspects. Secondly, I linked the results with findings of prevailing empirical literature, theory, and practice to highlight the significance of this study.

## 6.1 Discussion of Findings

This research aimed to examine and explore visualization design judgment behaviors with focused student design teams. The research questions included: (1) What are the existences of design judgments in particular information visualization design process? (2) How do design judgments occur in particular information visualization design? and (3) What are the factors influencing design judgments? In the following sections, I stated and discussed the significant findings of this study.

### 6.1.1 Design Judgments Happen Overtime in InfoVis Design

From a theoretical perspective, Nelson and Stolterman (2012) argued design judgments continuously occur. Experts have proposed the applied design decision models for visualizing a data (Meyer, Sedlmair, & Quinan, 2015; McKenna, Mazur, & Agutter, 2014; Munzner, 2009). Mavens also have broken decision-making into design judgments at a high level, they have explicitly examined the existences and achievement processes in various design areas, such as product design, instructional design, and engineering design (McKenna et al., 2014). Driven by the first research question, coding the results initially verified design judgments intensively existed, and student design teams made design judgments continuously during their design processes whether they were in the lab or natural working environments.

#### 6.1.1.1 Framing Design Judgments Are Made Throughout Design

Making *framing* design judgments represented a way to pass visualization design. By observations and interviews, the investigators identified that *framing* design judgments were made throughout the entire design process even if it was not their role. The research employed coding to triangulate this phenomenon. In-situ Study two revealed this pattern, which involved five key design behaviors, and a thematic design judgment informed each design decision. Figure 6.1 shows how concurrently and constantly *framing* design judgment accompanied thematic design judgment when designers propelled design.

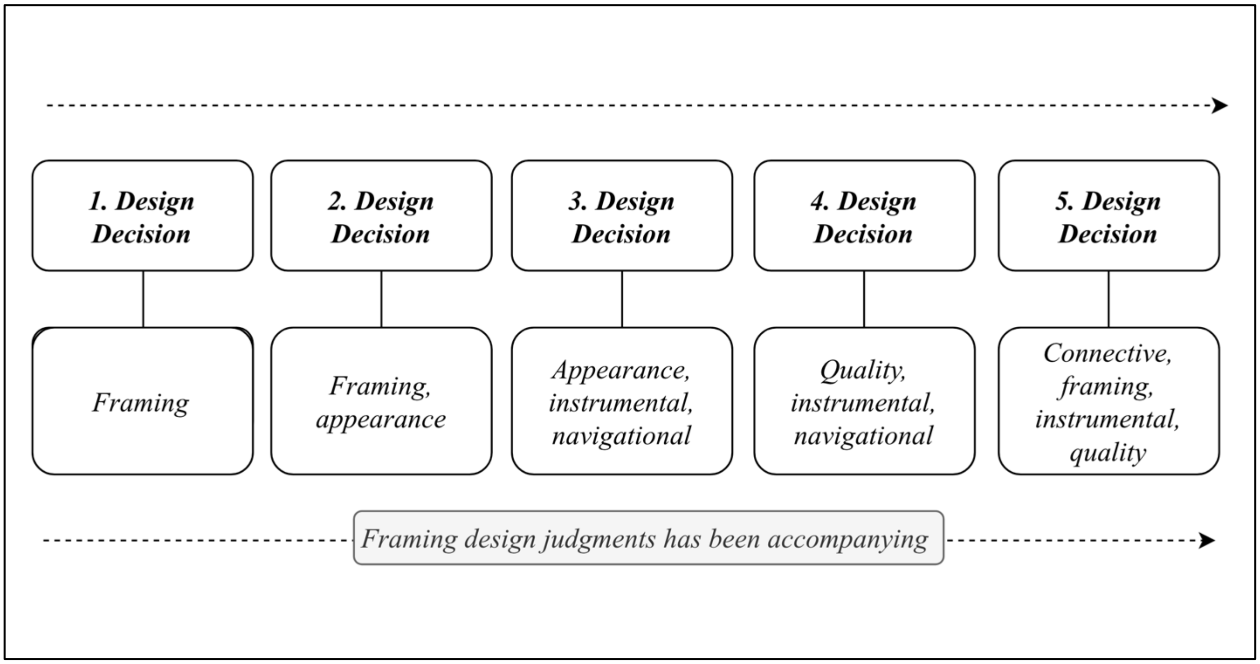



Figure 6.1 This figure shows how *framing* design judgment was accompanied with thematic design judgment to make design move forward.

Notably, this team originally determined to include database re-building within the purview of their design process *(framing design judgment)* due to: (1) current data structure led to visual problems; (2) sponsors provided new requirements, such as including variable impact areas; and (3) constructing a database to help them acquire data insights more quickly and accurately. For these purposes, they applied a top-down approach with the variable expertise for a broader concept, which provides the first level to build networks and hierarchies. after gathering the explored data and copying it into one shared Google Sheet, the participants cleaned the data. Concurrently, they communicated with the sponsor and manager at Department of Computer Graphics Technology at Purdue University (CGT); decided what data variables and segments to represent and which parts to ignore to depict *framing* design judgment. Based on discussing with their sponsor (CGT Department), the design team ascertained to present the variables of expertise, faculty, area and their relationships to engender *framing* design judgment. While creating design ideas and revising prototypes represented *appearance* judgment on design*,* quality judgment on design*, and instrumenting* the design, the design team also formed *framing* design judgments to determine what variables and visual representations to incorporate in the design when gradually updating the model and reporting to their sponsor. Due to the technical limitations of web programming constraint and *framing* design judgment, the design team altered their design strategy; referred and adapted an existing online visualization project (refer back Figure 5.7 (b)) to resolve technical issues for an acceptable design outcome. While binding connections between design objects from their final design idea (refer back Figure 5.7 (a)) and found example (refer back Figure 5.7 (b)) *(connecting the design)*, they defined the functional constraints, such as non-rotatable circular shape/ring in this example, which split the overlapped lines *(framing design judgment)*. Due to this obstacle, they chose to reduce and re-filter the data, cleaned the data segments to fit the supported technicians *(framing design judgment)*.

### 6.1.2 Design Judgments Happen Concurrently in InfoVis Design

Student design teams made concurrent design judgments while designing and creating visualizations, consistent with what other researchers have observed and discussed. In 2012, Nelson and Stolterman contended design judgments overlap, for interconnections and interrelationships exist among them. Instructional design pundits also observed consistent conclusions when exploring how students design instructions (Gray, Dagli, & Demiral-Uzan, 2015).

Chapter 4 and 5 primarily highlighted design judgment themes to interpret and explain student design team behavior when making design judgments. The findings illuminated design judgments occurred concurrently. Also, concurrent design judgments constituted a combination of *quality & appearance; navigational & instrumental; connective & framing.*

#### 6.1.2.1 Quality and Appearance

Communicated-visualization design entails two primary purposes (Card et al., 1999): (1) innovative and aesthetic visuals; and (2) accurate data or information insights to communications efficiently with users. While designing overall style, nature, character, even aesthetic experience *(appearance design judgment)*, visualization designers also considered if the visual forms or graphical features effectively reflect the data insights *(quality design judgment)*. Theories of data science, computing technique, cognition, and perception science influence empirical visualization development research. These factors require designers and developers to focus on scientific accuracy in the process when creating visuals. [Laboratory Study One – 3. Interesting design behavior (Table 4.1); In-situ Study Three – 2. Interesting design behavior in Table 5.4]

#### 6.1.2.2 Navigational and Instrumental

Visualization design includes, (1) data exploration and understanding; (2) visual design; (3) interaction design; and (4) development and implementation (Card, Mackinlay, & Shneiderm, 1999). During design, especially in the early stages, designers discuss and choose a reasonable overall workflow according to a right rule or a specific manner (*navigational* design judgment). In design progress, designers plan design to optimize each in-process section (*navigational* design judgment). Each task in the plan requires a corresponding method, concept, or tool for implementation (*instrumental* design judgment). For instance, designers from In-situ Study One selected reasonable interactive ways of selecting, highlighting, dragging and dropping, as well as comparing to achieve apt comparisons for similarities and differences between two DNA sequences (*instrumental* design judgment). Among developing, designers also explored online JavaScript libraries as tools to guide their coding and programming procedures (*instrumental* design judgment). [In-situ Study One – 2. Interesting design behavior (Table 5.2); In-situ Study Three – 4. Interesting design behavior in Table 5.4]

#### 6.1.2.3 Connective and Framing

A design pattern provides a template, or repeatable, reusable solution to a common design problem (Gamma, 1995; Gangemi, 2005), visual designers frequently apply. Visualization design libraries, such as Data-Drive Documents (Bostock, 2017) and FlowingData (2007) portrayed design examples to which designers could refer to help resolve local design challenges.

Information insights within a hierarchical data structure represent a general design visualization problem, and it manifests differently in various localities, In-situ Study Two (PPI Strategic Research Impact Areas Project) due to a nuanced variable data structure typified such situational variability. The visualization design adaptations connect and transmit individual functions and influences, including visual forms; graphical features even if code between two or more design ideas achieve efficient partials (*connective* design judgment) forming an effective whole. Based on local design differentials, designers usually realize and identify constraints (from client's requirements, e.g., CGT's needs; data structures, or tools (*framing* design judgment), leading to unsmooth connection's binding and bridging between design objects. Under this circumstance, designers choose to revise design boundaries, for example, re-filtering to add to or discard some of data variables, to explore a new tool, or to switch design focus (*framing* design judgment). Then designers employ the available energy to solve their local design problems. In-situ Study Two, I observed that designers attempt to discard several expertise and associated connections between faculty and impact area and then fit available functionalities (fixed and irritational rings) with coding examples from an explored online visualization. [In-situ Two – 5. Interesting design behavior (Table 5.3)]

### 6.1.3 InfoVis Design Judgments Are Influenced by Internal and External Factors

With observations and interviews, I saw how internal factors, such as designers' academic background, project experience, life experience; and external factors like design environment within the controlled time and limited resources, client, sponsor, and coursework requirements shape design judgments. Many situations transcended categories and acted simultaneously on visualization design judgments. Moreover, one designer's ideas influenced other designers' design judgment.

#### 6.1.3.1 Internal Factors of Academic Backgrounds and Project Experiences

In collaborative student-working projects, each member's academic background and project experience affects team design judgment. A team of In-situ Study Two comprised four designers with various academic backgrounds: visual communication design, computer graphic technology (game visual design), and mechanical engineering (mechanical design). Each designer had also taken at least one visualization design course and participated in one visualization project before participating in this study. The team made design judgments focusing on appearance, quality, connective, and framing because universities train students from design majors and backgrounds to form a relatively higher level of design literacy than students from other majors. With solid design practices, the design judgments of these design majors centered on creating more innovative and aesthetic works.

The design team In-situ Study One constituted five students from the CGT (with former architecture and digital media design and development experiences), interaction design, industrial design, and interior design. Two of the team members specialized in at data constructions, and the other three specialized in visual and interaction designs. Designer academic strengths and project experiences led the team to decide on a parallel working flow of "paralleled database construction (two of team members) + interaction design (three of team members)" to make a series of *navigational* and *instrumental* design judgments to process and start their design.

From another angle, lack of academic backgrounds and project inexperience also influenced design judgments. In-situ Study One's on DNA sequences held more challenges for the team to visualize due to the complex data structures and insights. No team member in In-situ Study One specialized in DNA so that this topic challenged them to explore and understand the data from a thoroughly professional perspective. For this reason, this team determined to use *core, framing, instrumental*, and *navigational* design judgments rather continuously data mining to construct an understandable database.

***Academic and Project Experiential Influences–*** In collaborative visualization projects, designers actively participating in design activities generally surface as a team leader. The decision-making and judgments from leaders frequently influence other design team member's judgments. For example, in Laboratory Study One, P-JS, a graduate level student with a computer graphics technology major, specialized in data analysis and web programming. However, P-SS possessed superior visual design skills but lacked knowledge of data explorations concepts. Markedly, the member who knows data explorations with better searchability took the lead in this team. I observed P-SS brainstorm more than ten design sketches visualizing the determined data attributes, but P-SJ only created two ideas. While communicating these sketches, P-SS followed P-SJ's decision-making and judgments to form judgments. For instance, P-SS attempted to design five circles with five different colors as representations for five causes influencing flight delays. She also tries to make these circles closely fit the big pie (carrier) with the segment for "delays" (Figure 6.3).

According to the results of mathematical calculations, P-SJ rejected P-SS's idea with the statements "carriers" cannot support an available area to accommodate the five circles because some pies illustrate a smaller scale and smaller segmentations of "delays." After this, P-SS made additional judgments and tried to improve such design defects.

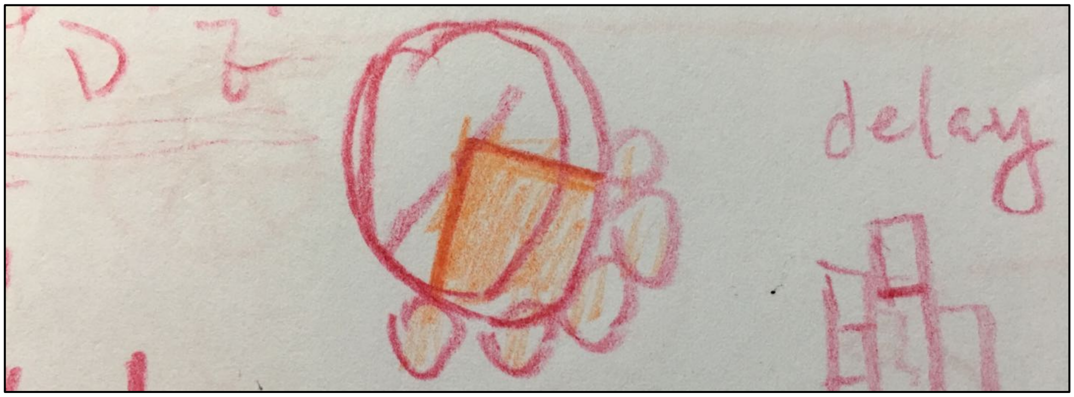



Figure 6.2 This figure shows how designer visualizes data variables of carrier and related causes in Laboratory Study One. This image premises by the designer who participated in this study.

6.1.3.2 Internal Factors of Life Experiences

Datasets with specific topics in visualization projects closely related to daily life, such as flight delays in the US People experience flight delays, like the student designers in Laboratory Study One and Two. The teams defined variables without persistent data mining when starting their design. They made design judgments with a focused *framing* type to decide what data segments to retain or discarded; therefore, they recalled their personal flying experiences to determine variables. To validate their hypotheses, designers in Laboratory Study One chose running statistics and explored existing online tools and proposed design with focused *instrumental* and *navigational* design judgments to backcheck. However, designers in Laboratory Study Two applied Tableau results with same focused *instrumental* and *navigational* design judgments to re-filter data variables and re-define design boundaries.

Designers in In-situ Study Two choose a data set with the topic of "PPI Strategic Research Impact Areas" the CGT supported. Purdue University. Studying and living in a university environment makes designers understand collegiate data variables (e.g., expertise, faculty, and impact), relationships between variables; identify general data inadequacy and structural reasonableness. Combined new requirements from Client (CGT), this team made *framing* design judgments in the early design stages to re-gather data and re-build data structure using a top-down approach, which motivated them engage more actively in the project.

***Life Experience Influence on Design Judgments*** – The provided dataset of "DNA sequences" in In-situ Study One came from biology. A conceptual knowledge base of designers held insufficient to support work on an in-depth data analysis and exploration. A team member, P-

JH, discussed the project with relatives who specialized in genetic research and pointed out the unreasonable and unprofessional ways they were exploring and understanding the data; thus, he expounded upon the risks if the team continued on their path. To ensure an acceptable design outcome for final submission and presentation, they abandoned data mining and reconstructed the data so that they could understand it.

#### 6.1.3.3 External Factors of Clients, Sponsors, and Coursework

All design judgment activities occurred in a university environment. The data sets were primarily derived from course assignments (e.g., all in-situ studies), laboratory research projects (e.g., In-situ Study One and Three), or special needs of a department (e.g., In-situ Study Two). Some labs or departments supported sponsorships for student design teams while providing data. They also generally sent a project manager to join the student team and manage the entire project, which notably includes, such as (1) indicating the data variables and functionalities to present; (2) deciding all visual designs related to the projects; (3) scheduling time frames for final submissions, presentations, even deliveries for a particular academic conference or journal. Students formed *framing, quality, appearance*, and *core* design judgments, especially in In-situ Study Three (C4E project), substantially based on sponsor requirements. In-situ Study Two's designers made navigational and instrumental design judgments to inform a parallel design workflow of "paralleled working path of database construction + interaction design" due to a coursework assignment need of an acceptable design outcome for final submission and presentation. Designers' persistent focus on data mining increased the burden of having an acceptable design result.

#### 6.1.3.4 External Factors of Resources Constraints

***Student Resource Limitations -*** Although the participants in this research came from diverse academic backgrounds, constructing a fully staffed team according to the study parameters represented a struggle. In-situ Study Two included four student designers whose majors were all related to design. Due to the lack of developer, this team switches design strategy with *connective* design judgment method to bind the objects between their local designs and explored online example for releasing development technology constraint. A skills superiority such as strong visual design skill depicted a distinctly inferior position in completing the visualization design process. Without a team member who specializes in the visual design, students in In-situ Study Three were challenged to make *quality* and *appearance* design judgments for innovative and creative interfaces.

***Professional Guidance Limitations***– In visualization design, researchers and designers attempted to visualize data, in which, not all datasets prove easy to analyze and understand. Making framing design judgments to define data variables and project boundaries challenged the student design team. Specifically, In-situ Study One's data represented complex data for designers unfamiliar with biology. Without professional guidance, this team gave up persistent data mining and employed *navigational*, *instrumental, framing*, and *core* design judgments to reconstruct the database in a way they could comprehend the data.

A remarkable difference in *framing* design judgment between design teams existed, which may not have surfaced if professional guidance were available. C4E project (In-situ Study Three) included a sponsor who came from C4E the data management team. He worked at Purdue Discovery Park and participated in collecting, exploring, and mining the provided database. The sponsor fully understood the data nuances, so that the design team of In-situ Study Three determined data variables and designed boundaries more smoothly while *framing* design judgment.

As a summary section of Design Judgments in Laboratory Studies, designers who do not specialize in data analysis and data mining can also achieve an effective design scheme through making *compositional* design judgments and employ each design combination to match what and how many data (segments) were effectively imported and well presented.

#### 6.1.3.5 Internal and External Factors Influence InfoVis Design Judgments Conjointly

By observations and interviews, internal and external factors concurrently influence student design teams made design judgments. Designers used their knowledge and experiences to make judgments. However, they could not escape a design environment with certain unavoidable limitations and constraints, such as client, sponsor, design goal or inadequate team formation. Markedly, the three top influencing factors that drove the student designers from In-situ Study Two to make design judgments held academic background, poor team formation, and client need. Without the help from the data provider and professional guidance, designers from In-situ Study One applied their academic knowledge and personal life experiences to form design judgments and decision-making and achieved an acceptable design result in a limited time.

### 6.1.4 Design Judgments Are Connected with InfoVis Design Stages

With observations and focused data analysis, design judgments are closely connected and interconnected with visualization design stages. By the following sections, I discussed why they tightly connected based on a more theoretical perspective with visualization stages' theory (Fry, 2007) and three identified patterns.

#### 6.1.4.1 Framing Judgment in "Parse" "Filter" Design Stages

Fry's (2007) seven stages of visualizing a data outline represented what the designers primarily employed at each design step. As a summarized result, designers "parse" and "filter" visualization stages and made *framing* design judgments. In visualization design, designers defined design boundaries, which mostly aimed to determine what data variables to include and represent based on client and sponsor requirements, design goals, and personal ideas and understandings. These activities ordered the data into categories ("parse") and removed all but the data of interest ("filter") (Fry, 2007).

#### 6.1.4.2 Quality & Appearance Judgments in "Represent" Design Stage

The "represent" stage in visualization design means choosing a basic visual form, such as a pie chart, a line graph, or a tree to represent data structures, and using effective graphical features like color with red-to-blue, shape with rectangle, and a scale with 0% -100% to display data values (Fry, 2007). Generally, a visualization employs one visual form; no matter if multiple ones prove pertinent. While choosing and arranging visual forms, designers make *appearance* design judgments to assess the overall *appearance* design quality with visual representation style, nature, character, and aesthetic experience, which helps create an aesthetically harmonious and acceptable visualization. Concurrently, *quality* design judgment occurs at the "represent" design stage. To reach the second goal of communicated-visualization design for effective information transmission, designers considered how effectively the visual forms, which primarily focused on if the particular visual forms and graphical features represented the data insights effectively and efficiently. For example, designers in In-situ Study Three initially considered and selected a circular layout with three separate arcs to portray three determined variables because circular shapes elicit harmonious feelings, unlike sharp shapes. They also thought circular layout supported representing more data items without raising concerns with screen dimensions. Based on this circular form, they considered the node-link connections outlined inside the circular shape, which conclusively shows the relationships between different data categories and variables. This team made *appearance* and *quality* design judgments with the considerations of visual aesthetic and effectiveness on data presentation to determine a circular chord diagram as their final design idea.

#### 6.1.4.3 Instrumental & Navigational Judgments in "Mine" "Interact" Design Stages

The "mine" stage in visualization design applies approaches from statistics or data mining as a way to identify patterns and place the data in a mathematical context (Fry, 2007). Designers select the means of tools, concepts, and methods to make *instrumental* design judgments to reach established design goals. For example, students in In-situ Study One applied an online mathematical library to extract the DNA segments to compare similarities by exploring differentials (*instrumental* design judgment). Using this online tool, this team referred to tutorials to ensure the right direction of data analysis and a relatively accurate result (*navigational* design judgment).

Designers' activities in "interact" visualization design stage reflected more *instrumental* and *navigational* design judgments making. Designers in the "interact" stage focus on adding methods for manipulating the data or controlling what features the visibility features with detailed interaction design ways, such as selecting, connecting, highlighting, sorting, filtering, zooming, reconfiguring, etc. (Fry; Yi, Kang, & Stasko, 2007) (*instrumental* design judgment). Once designers apply one or more interaction, they follow the right rule to manipulate the data step-by-step (*navigational* design judgment). For instance, In-situ Study Two's designers used a ring with three layers to layout three data variables of expertise, faculty, and impact area. Most importantly, they designed connections and relationships between different data categories and related specific items with the concept of showing the related items. The connect interaction method (*instrumental* design judgment) (Yi, Kang, & Stasko, 2008) helps determine a reasonable workflow of (*navigational* design judgment) (1) highlight associations and relationships between data items selected and represented; and (2) show hidden data items relevant to a specified item. What these designers mainly do is: (1) achieve user clicks on one faculty members, and then highlight linked areas and expertise; and (2) achieve user hovers on selected expertise, then related expertise nodes add to the display.

## 6.2 References to Previous Research

Linking and comparing existing research, this section aims to interpret and discuss the significance of findings and insights in this research. After comparing the findings in this study and previous empirical studies and explaining the rationality of insights in this research, this section supports why this topic was chosen, and then highlights the study's vital contributions to the research base.

### 6.2.1 Comparision with Previous Research

By analogizing with similar design situations and comparing the findings with previous research, the explanations in this section verify the generalizability and rationality of the research findings and insights of this research.

#### 6.2.1.1 Design Judgment Occurrence

Various design judgment activities widely examined design domains, such as product design, engineering design, architecture design, computational system design, and instructional design.

Burdek (2005) stated that product design expression stems from the combined effects of all elements with entities and visions in a product. Color tone, size, and shape direct a person's thoughts towards buying a product. Similar to visualization, product designers consider two design aspects of overall aesthetics and effectiveness when making an *appearance* and *quality* design judgments. For instance, Vienot and Mahler (2008) applied *color appearance* and *quality* design judgments to grade the characters of several light-emitting (LED) illuminations. Additionally, product design for manufacture and assembly focuses on making *quality* design judgment with product design standards, such as not causing unnecessary harm and letting the function inform design (Boothroyd, Dewhurst, & Knight, 2001). To achieve aesthetics and effectiveness, visualization designers make a focused *appearance*, and *quality* design judgments mostly in "represent" design stage.

Instructional designers make *framing* design judgments when defining their instructional design boundaries, such as identifying a topic for the student project; designing instruction on printing a specific object; and deciding to focus only on the educational piece in instruction. (Demiral-Uzan, 2017). Gray et al. (2015) also purported design judgment type, most frequently used in instructional design exemplified framing, for it observed eight practicing instructional designers' activities in two consulting situations. In this research, framing design judgment also occurred throughout overall designs. Research findings revealed it frequently collaborates with *connective, appearance, quality*, and *core* types of design judgments to propel designs.

Visualization designers make *instrumental* and *navigational* design judgments due to data needed manipulated by adding methods (i.e., interactive ways) with the reasonable implementation paths to make sense to the users. In cross-cultural user research, designers also apply *instrumental* and *navigational* design judgments to understand (Chinese) users and aid the result of new product for the market by a set of planning, execution, and debriefing sessions (Gray & Boling, 2018). Gray and Boling (2018) unveiled their design team's *instrumental* judgments as they shifted from the design phase to the debriefing phase. In visualization design, *instrumental* design judgments with reasonable navigations also moved over time to the "mine," "interact," and even "refine" design stages to help designers transmit data insights with methods.

#### 6.2.1.2 Design Judgment Influencing Factors

Many design areas have addressed most of the internal and external influencing factors discussed in this dissertation. Specifically, for example, instructional researchers and designers display the role and position of the designer, and the project, client, and other external factors influencing instructional design practice (Gray, Dagli, & Demiral-Uzan, 2015). In web design and development, Rieh (2002) presented the factors affecting quality judgment and authority, like the characteristics of information objects, sources, knowledge, situations, rankings, and assumptions. Designer's design knowledge level depicts a significant internal factor impacting designers' design judgment in engineering design (Petroski, 1994).

### 6.2.2 Research Significance

Design elements remain present in the decision-making and judgments made both before and during the process (Nelson & Stolterman, 2012; Norman, 2013). Designers make design decisions and informed judgments with particular methods and procedures to accomplish visualization as one type of design (Lurie & Mason, 2007).

Diverse design domains, like the visualization design field, widely discuss design decision-making. Munzner (2009) asserted visualization design decisions occurred at one of four layers, including domain characterization, data and task abstraction, visual encoding and interaction, and algorithm. In 2015, Meyer et al. added a finer grained layer structure to polish the visualization design decision model and detailed characterization of individual design decisions. In visualization, design decision making happens continually with informed design judgments; that is, visualization design entails forming judgments. McKenna et al. (2014) elucidated design decision-making breaks down into different high-level design judgments based on Nelson's (2012) theory, extensively applied in other design domains, but not in visualization design field. In this research, I processed five laboratory and in-situ studies to bridge this research gap and support particular design judgments and related methods to capture specific explorable and interesting design beahviors that visualization researchers and designers face while representing and encoding data insights.

The developments of visualization remains based on theories from many disciplines, such as graphic design, data science, computing technique, cognition, and perception science. By exploring designer judgment behaviors, the interpretations and explanations in this research also reflect how visualization designers applied the knowledge of (graphic) design, data science, cognition and perception science and techniques of computing and programming to deal with complex data structures, create innovative and effective visual representations, and program these visuals into the interactive visualization systems. Combined with judgment-making, these methods vigorously promote design moves and outcome.

# CHAPTER 7. **RECOMMENDATIONS**

This chapter is an extension of Chapter 6, which aims at proposing recommendations to improve a particular design situation and enhance visualization design education based on the highlighted patterns.

## 7.1 Recommendations for Novice Designers

To improve problem-solving in difficult design situations, remedial actions must re-organize the design. In this section, I recommend two solutions to improve particular visualization design situations and promote a smooth design movement and outcome.

### 7.1.1 Professional Guidance Design Project Involvement

Through observations, the activities of making framing design judgments show a sharp contrast to methods and procedures between design teams, such as In-situ Study One versus In-situ Study Three if professional guidance were involved in design processes, which discussed in *section 6.1.3.4*. Designers of In-situ Study One acquired a data set with the topic of "DNA Sequences— Similarities and Differentials"— which embodied professional biological expertise. Information was obtained on data insights and design boundaries while communicating with the data providers. This team made sense of the data but struggled with the methods and procedures to complete the task. With such a complex data set, the design process should include guidance from data management. Designers from In-situ Study Three easily made *framing* design judgments because their sponsor sent a product manager, who was the data collector and organizer and intimately familiar with the data insights, to join and manage this design project. Design activities of In-situ Study Three's designers focused more on visual representations and published within a controlled time rather than data mining their designs. Therefore, requesting and involving professional guidance in a design project remains highly recommended, especially when working with an intricate dataset.

### 7.1.2 Collaboration with Group Diversity in Design Project

University environments stand limited for researchers and designers match ideal personnel distribution to comprise at least one data explorer, one visual designer, and one developer in visualization teams for better design movements and outcomes (refer back to *section 6.1.3.4*). Varied composition holds strongly recommended to achieve necessary allocations when forming a team. Compared to In-situ Study One, the database presented to designers in In-situ Study Two proved more straightforward to explore and understand. However, In-situ Study One supported a more acceptable design outcome with an interactive visualization system because of a relatively effective team allocation, which included two developers and three designers. Design results of In-situ Study Two lacked a few basic functionalities until their final submission. During their final design phase, designers attempted to refer and adapt from an existing online example to resolve technical challenges with *connective* design judgment. However, the solid fundamental programming skills and practical experiences enabled them to employ better problem-solving techniques. Just as In-situ Study Two, the design team in In-situ Study Three also made *connective* design judgment to form design ideas due to the lack of visual designers with the constraint of innovations and creativities.

## 7.2 Recommendations for Visualization Design Education

Understanding and learning visualization design originates in academia, especially for university students. Taking topic-related classes and accomplishing coursework assignments, students practice visualizing data. Educational methods help student design teams and individual designers or developers improve visualization design judgment capabilities. In the following sections, I discusses the recommendations with three perspectives: (1) awareness of judgment in nature of visualization design; and (2) practicing to develop judgment in visualization design.

### 7.2.1 Awareness of Judgment in Visualization Design

In this research, I observed many immature or inappropriate design judgments. For example, in Laboratory Study One, P-SS presented significant insights using an integral graph rather than several individual pieces. He then created a chord diagram with some crossing lines, which represented the flight airlines. He then placed multiple pie charts overlapping on the chord one. The team elected to create and develop this prototype because an innovative design might enhance user aesthetic experience (*appearance* design judgment). However, such intensive structure might confuse people.

Information visualization engenders artistic and scientific foundations from art, psychology to computing. Based on such foundations, people summarize design principles and proposed technologies toward specific problems. Students have learned these science, technologies, and principles from various sources (Card et al., 1999; Ware, 2012). However, while facing real design tasks, students may experience difficulty in making sound design judgments. Some solutions stand appropriate for a small local problem. However, when implementing an integrated complex visualization, the narrow local solution may conflict with other aspects in the broader context. Other than letting students learn visualization design from trial and error, the educator should pay attention to help the student better understand the complex design nature of information visualization to make informed decisions.

Design movements and outcomes need effective design judgments (Nelson & Stolterman, 2012), not a new concept in diverse design domains. Visualization designers centrally engaged in design activities propose and create effective visual representations to reinforce human cognition (Ware, 2012). Among visualization design activities, design judgment remains central to designers' capabilities. I identified the design judgments that enable designers to progress toward an outcome, described the design methods that relate to design outcomes, and composed a model to generalize design judgments applicable to various visualization design behaviors; thus, this study increased awareness of design judgments in the visualization design field. The reflections on design judgment activities in this research also inspired the designers to strengthen their awareness of design judgment, practice, and improve the design judgment formation.

By employing a qualitative approach, I realized and examined primary design judgment patterns and behaviors for each step in the visualization design process using distinct design topics. In this dissertation, I combined the qualitative and quantitative evidence to answer the research. After reflecting on several major design judgment activities, I helped visualization researchers, designers, educators, and relevant readers to improve awareness of design judgments. The educators who have read this dissertation will be expected to increase design judgment awareness, and then instruct and deliver to their students on how designers apply their judgments while visualizing. Two methods to reach this would be:

(1) To request the experienced instructors who have already taught theme-related courses to reflect on their teachings, which may include curriculum resources and strategies, project designs and management, and instructional ways. Specifically, designing

course instructions or syllabi to incorporate real-world projects providing learners with an excellent opportunity to gain experience to use design judgment and realize how judgments occur. When disseminating course materials, instructors may think aloud to demonstrate how the design judgment process unfolds in self-designed course projects. Instructors also can encourage students to emulate the illustrated process– reflect and think aloud and work on design projects in classrooms. During which, learners will to observe their design judgments. Instructors can collect and highlight some common design judgments that students make and draw attention to their activities. When students become aware of their design judgments, the instructor may easily encourage them to continue development.

(2) To require the doctoral students in visualization research and design fields, who aspire to instruct, to gain practice in design, for instructors share their ideas, thoughts, and experiences with their students. In addition to focusing on how to broaden doctoral students' horizons, instructors must think about how to act to make students better designers and involve learners in coursework design projects. Students may engage in design projects and help instructors teach how to use design judgments in particular design situations. Professors can also work with students in their programs and practice how to help them develop their design judgments.

#### 7.2.2 Visualization Design Judgment Development

*Deliberated offhand* judgment is rarely made because most of the students in this research lack involvement in design projects with continuous accumulations and developments on design decision-making and judgment progress. Generally, involving one or two short-term visualization design projects could not help students accumulate and develop design judgment experience. To support student judgment development in visualization design:

(1) Educators can consistently encourage students to work on design projects and continue to seek and explore interesting data sources, and motivate active students to participant in design projects. As early as 1997, Holt suggested students should be given open-ended design tasks and commanded to design judgment for design creations. Based on the compiled data, educators may need to provide students relative freedom and make them explore their ways of design thinking, decision, and judgment making to see

judgment occurrences and gain insights from their personal choices. Students can construct their repositories about the judgment making methods, which can be applied in the future when doing decision-making and judgments in other design situations with more, such as *deliberated offhand* design judgment type.

(2) Lawson and Dorst (2013) argued development designers should be assigned a list of design projects increasing in complexity. Educators also can provide a series of design projects with gradually increased complexity to help student designers develop judgment making in visualization design. However, a classroom setting lasting three to four months may not help visualization students develop their design judgments enough. A two-year master's program, working a project across three to four semesters may help the student to develop sound design judgment. Students should seek opportunities to engage in various design situations with varying levels of complex design thinking. This exploratory approach may enhance student design judgment development.

# CHAPTER 8. **CONCLUSION**

To conclude this document, this chapter supports an overview of significant contributions of this research; the main points of various chapters, limitations of this research; and recommendations for subsequent research.

## 8.1 Research Contributions

Design as decision-making and informed judgments enables designers and developers to represent data insights in visualization domain. Knowing its nature to improve design means visualization designers should understand, learn, and apply judgments to their design choices to construct informed, professional design determinations, actions, and outcomes. With four research questions and three main purposes clarified in Chapter 1, this research has delved into examining and exploring design judgment behaviors in students working visualization design projects. By conducting and processing five studies with laboratory and in-situ types, the findings and insights contributed to:

(1) Bridge a gap in visualization design field; interpret and explain to visualization researchers, designers, and other relevant readers on a holistic level about how design judgments occur and develop, as well as how internal and external factors influence designer judgments;

(2) Summarize and guide design judgments with methods and applications for producing visualization design results and outcomes;

(3) Make recommendations for improving particular visualization design situations and visualization education programs.

## 8.2 Chapter Main Points

By involving seventeen students divided into five groups, this research applied the qualitative methodology and processed two laboratory and three in-situ studies to construct sufficient data sources with quantitative and qualitative evidence for data analysis. This research then approached the combined framework and (deductive) thematic analysis methods to obtain the findings with themes and patterns. Conducting and processing two types of study designs supported fuller explanations for visualization researchers and designers about design judgment behaviors at a holistic view. The results of laboratory studies described and explained the design judgment methods in infographic design, a form of visualization and a vital phase in visualizing a data with focused (visual) design perspective. According to the explorations from laboratory studies, in-situ studies interpreted student design team decision-making and judgment methods comprehensively with complete visualization design processes.

I compared and synthesized the study results to generalize the research findings and discussed some highlighted insights to guide designers. By linking to previous research, I elucidated the research significance since other design areas already reflect many of these conclusions. Moreover, I detailed recommendations to extend the finding and discussion to improve particular design situations and visualization education programs.

## 8.3 Limitations of this Research

Chapter 1 outlines several limitations:

1. The data comprised a limited number of volunteer participants, including individual students and student design teams at Purdue University.
2. The collected data reflected participant design judgment activities for a short-term without evaluations while visualization generally reflects a long-term process encompassing several design iterations and evaluations.
3. It would have been harder to control for extraneous variables and the scientific methods within a more natural environment, and it might cause some irrelevant data to be collected and analyzed.

Complementary, visualization judgment patterns with student designers may be different from professional designers and developers immersed in various industries. Working and designing in a university environment with constrained data sources limited research findings generalization. Besides, the identified behaviors and patterns in this research were based on design teams within the collaborative design processes, which might reveal a limitation for explaining and presenting design judgment activities with individual designers and developers.

## 8.4 Recommendations for Subsequent Research

The research will never truly reach culmination, which opens the doors for other experts to further this study. With a qualitative research methodology, some unexpected findings were identified, and recommendations for the following research directions stand as follows:

(1) Earlier than Fry's (2007) theory, Jones (1992) asserted the design process breaks down into three stages of divergence, transformation, and convergence with detailed design methods, such as interviewing users, synectics, removing mental blocks, checklists, ranking, and weighting. In this author's observations, visualization designers and developers created visualizations by applying particular design methods like brainstorming, investigating user behavior, and selecting scales of measurement. In future research, to explore the relationship between design judgments and design methods is highly recommended.

(2) During observations, I found different types of design judgments occurred concurrently and influenced each other. For example, designers from In-situ Study One made *instrumental* and *navigational* design judgments to inform a "parallel working flow with data construction + interaction design" design decision; and move the design forward. Within this process, two kinds of design judgments were used interchangeably and interacted with each other. It is challenging to describe and explain this phenomenon in detail. Hence, to examine and explore how the design judgments influence each other for design decision-making is also recommended.

(3) A design team consisted of several individuals whose role directly affected the team motivation. Due to the fact limitations of design judgment behaviors of individual designers were rarely mentioned in this research, identifying and describing each designer's judgment activities would be recommended although they were involved in collaborative work.

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# APPENDIX A. IRB DOCUMENTS

## Approval Memo

PURDUE
UNIVERSITY

HUMAN RESEARCH PROTECTION PROGRAM
INSTITUTIONAL REVIEW BOARDS

| | |
|---|---|
| **To:** | YINGJIE CHEN<br>KNOY |
| **From:** | JEANNIE DICLEMENTI, Chair<br>Social Science IRB |
| **Date:** | 12/11/2017 |
| **Committee Action:** | **Expedited Approval - Category**(6) (7) |
| **IRB Approval Date** | 12/08/2017 |
| **IRB Protocol #** | 1711019930 |
| **Study Title** | Exploring Comprehensive Design Judgments in Visualization Design |
| **Expiration Date** | 12/07/2018 |
| **Subjects Approved:** | |

The above-referenced protocol has been approved by the Purdue IRB. This approval permits the recruitment of subjects up to the number indicated on the application and the conduct of the research as it is approved.

The IRB approved and dated consent, assent, and information form(s) for this protocol are in the Attachments section of this protocol in CoeusLite. Subjects who sign a consent form must be given a signed copy to take home with them. Information forms should not be signed.

Record Keeping: The PI is responsible for keeping all regulated documents, including IRB correspondence such as this letter, approved study documents, and signed consent forms for at least three (3) years following protocol closure for audit purposes. Documents regulated by HIPAA, such as Authorizations, must be maintained for six (6) years. If the PI leaves Purdue during this time, a copy of the regulatory file must be left with a designated records custodian, and the identity of this custodian must be communicated to the IRB.

Change of Institutions: If the PI leaves Purdue, the study must be closed or the PI must be replaced on the study through the Amendment process. If the PI wants to transfer the study to another institution, please contact the IRB to make arrangements for the transfer.

Changes to the approved protocol: A change to any aspect of this protocol must be approved by the IRB before it is implemented, except when necessary to eliminate apparent immediate hazards to the subject. In such situations, the IRB should be notified immediately. To request a change, submit an Amendment to the IRB through CoeusLite.

Continuing Review/Study Closure: No human subject research may be conducted without IRB approval. IRB approval for this study expires on the expiration date set out above. The study must be close or re-reviewed (aka continuing review) and approved by the IRB before the expiration date passes. Both Continuing Review and Closure may be requested through CoeusLite.

Unanticipated Problems/Adverse Events: Unanticipated problems involving risks to subjects or others, serious adverse events, and serious noncompliance with the approved protocol must be reported to the IRB immediately through CoeusLite. All other adverse events and minor protocol deviations should be reported at the time of Continuing Review.

Ernest C. Young Hall, 10th Floor - 155 S. Grant St. - West Lafayette, IN 47907-2114 - (765) 494-5942 - Fax: (765) 494-9911

# Consent Form

Purdue IRB Protocol #: 1711019930 - Expires on: 07-DEC-2018

**RESEARCH PARTICIPANT CONSENT FORM**
Exploring Comprehensive Design Judgments in Visualization Design
Principal Investigator: Yingjie Chen
Computer Graphics Technology
Purdue University

**What is the purpose of this study?**
The goals of this research are to identify and elaborate 1) "what and what types" of design judgments to be made when visualizing data; 2) "what" factors (i.e., design goals, design knowledge [with different levels], design cognition application & understanding, etc.) influence designers design judgments; 3) "how" the factors influence designers' design judgments; 4) "why and what cause" a designer becomes ultimate decision makers. The protocols of data analysis from the step-by-step design judgments of two targeted groups of visualization designers should support my development of a comprehensive list of decisions and detailed descriptions. My minute-to-minute observations and interviews should clarify the influence factors, casualties, even situations, which will help to answer and explain the questions of "how," "why," and "what cause."

**What will I do if I choose to be in this study?**
If you choose to be in this study, either laboratory or in situ, you will sign this consent form. You will be given a brief introduction about the steps of this study, either laboratory or in situ, and what information will be collected. You will fill in a demographic survey about your age, gender, learning experience, and working experience. For laboratory study, you will be provided four tasks and twelve interview questions. For either study, the gathered data will be primarily based on qualitative data of verbalization, sketches, audio-visual recordings of participants' overt behaviors, performances and actions and relevant text or word descriptions.

**How long will I be in the study?**
The laboratory observational study will take 2 – 2.5 hours, and the in situ observational study will take place depending on individual designers' working time. You are under no obligation to participate in the study. You do not have to answer all the questions if you do not want to answer it but we ask that you answer as many questions as you can. You may terminate the interview at any point without any consequences.

**What are the possible risks or discomforts?**
This is a minimal risk user study. You will show me your visualization design process. The risk is no greater than what you would encounter in daily life. Exposure of personal information is a potential risk. We have established safeguards to maintain confidentiality. We are not requiring any personal identifiable information for this study. All the data from this study will be stored in the computer used for this study in a locked room only for the main investigator of this study. The data will remain in the computer until they are analyzed. After we complete the data analysis, we will burn all the data to a DVD and store the DVD in the principal investigator's office for record keeping purpose for at least three years.

**Are there any potential benefits?**
As a designer, you may get a better understanding of how to process design judgments in visualization design. Also, the process will help you review and reflect your previous designs.

**Will I receive payment or other incentive?**
You will receive $15 per hour as the compensation.

**Will information about me and my participation be kept confidential?**
The project's research records may be reviewed by departments at Purdue University responsible for regulatory and research oversight.
The data of this study will not contain any personal identifiable information like your name. The research team of this study will have access to the data of this study only for data analysis purposes. The data will be stored in the computer for this study in a locked room. Only the principal investigator has access to the room and can log into the computer. After the data are analyzed, we will burn the data into a DVD and store the DVD in the principal investigator's office for record keeping purpose for at least three years.
The results of this study may be published in academia research papers. However, neither individual information nor identifiable information will be included in the publication.

**What are my rights if I take part in this study?**
Your participation in this study is voluntary. You may choose not to participate or, if you agree to participate, you can withdraw your participation at any time without penalty or loss of benefits to which you are otherwise entitled. If you withdraw from the study, you have the right to request that the data already collected are destroyed.

**Who can I contact if I have questions about the study?**
If you have questions, comments or concerns about this research project, you can talk to the researcher, Mingran Li (li1940@purdue.edu). Please contact Yingjie Chen at 765-494-1454 (first point of contact).

If you have questions about your rights while taking part in the study or have concerns about the treatment of research participants, please call the Human Research Protection Program at (765) 494-5942, email (irb@purdue.edu)or write to:

Human Research Protection Program - Purdue University
Ernest C. Young Hall, Room 1032
155 S. Grant St.,
West Lafayette, IN 47907-2114

**Documentation of Informed Consent**

I have had the opportunity to read this consent form and have the research study explained. I have had the opportunity to ask questions about the research study, and my questions have been answered. I am prepared to participate in the research study described above. I will be offered a copy of this consent form after I sign it.

______________________________ ______________
Participant's Signature Date

______________________________
Participant's Name

______________________________ ______________
Researcher's Signature Date

# APPENDIX B. CODEBOOK

The research questions central to this research:

1. What are the existences of design judgments in particular information visualization design process? In other design domains, researchers have summarized eleven types of judgments move toward outcome design. This question aims to examine if and how these judgments exist in information visualization design.
2. How do design judgments occur in particular information visualization design? This question was supposed to examine and identify designers' design judgments behaviors in the key processes within specific design stages.
3. What are the factors influencing design judgments? This question aims to examine and explore how different factors, internal or external, such as design knowledge, design goal, and client's need, etc. influence designer design judgments in particular information visualization design.

Table 1 Detailed definitions, examples, and contexts for code collections, which are research question-driven, theory-driven, and data-driven.

| ***Codes and Coding*** | |
|---|---|
| ***Codes with label category*** | ***(Label A)*** |
| *Particular Codes under Label A* | *Design judgment types [Label (A-lowercase)]* |
| Definition | 11 categories of design judgments that have been commonly applied in various design domains (Nelson & Stolterman, 2012; Gray, 2015) [details and definitions of each particular kind by checking [Extensional Table of Table 1- For *Label (A)*]] |
| Example | • Default *(Aa)*<br>• Deliberated off hand *(Ab)*<br>• Core *(Ac)*<br>• Framing *(Ad)*<br>• Appreciative *(Ae)*<br>• Quality *(Af)*<br>• Appearance *(Ag)*<br>• Connective *(Ah)*<br>• Compositional *(Ai)*<br>• Instrumental *(Aj)*<br>• Navigational *(Ak)* |

| | |
|---|---|
| Example in context | "I saw one of my officemates applied seven different shapes to distinguish seven different variables for presenting Qualtrics user evaluation results. For that meeting, it was OK for readers to explore the patterns and insights of the messages. It should also work in our case if we apply various shapes to represent each of different DNA sequences. Additionally, we can combine a heat map, which succeeds in matrix presentations. If we choose a heat map, the color ladders will be naturally used." (A-b; A-j; A-h)<br>*Note: a quote may contain more than one design judgment type. You may explore additional design judgment type, which adapts to some particular visualization design. Add the extra ones while coding. |
| *Particular Codes under Label A with quantity* | *Design judgment frequencies [Label of (A lowercase letter-quantity)]* |
| Definition | The quantity (Arabic number) of usage for each design judgment type |
| Example | • Default *(Aa-quantity)*<br>• Deliberated off hand *(Ab-quantity)*<br>• Core *(Ac-quantity)*<br>• Framing *(Ad-quantity)*<br>• …until…<br>• Navigational *(Ak-quantity)* |
| Example in context | "I saw one of my officemates [a name] applied seven different shapes to distinguish seven different variables for presenting Qualtrics user evaluation results. For that meeting, it was OK for readers to explore the patterns and insights of the messages. It should also work in our case if we apply various shapes to represent each of different DNA sequences. Additionally, we can combine a heat map, which succeeds in matrix presentations. If we choose a heat map, the color ladders will be naturally used. Also, once a time, I created a heat map to show a result of the cluster analysis, I mean a matrix. The heat map was really useful." (A-b-2; A-j-1; A-h-1)<br>*Note: a quote may contain more than one quantity of each design judgment type. |
| *Coding method for category Label A* | *Directly coding by (Ab2) OR (Ab2; Aa1) OR (Ab2; Aa1; etc.)* |
| | |
| ***Codes with label category*** | ***(Label B)*** |
| *Particular Codes under Label B* | *Visualization Design stages [Label (B-lowercase)]* |
| Definition | • A brief history of design argues that visualization design process breaks down into 7 stages of "acquire," "parse," "filter," "mine," "represent," "refine," and "interact" (Fry, 2007). |

| | |
|---|---|
| | • Acquire – "obtain the data, whether from a file on a disk or a source over a network."<br>• Parse – "provide some structure for the data's meaning and order it into categories."<br>• Filter – "remove all but the data of interest."<br>• Mine – "apply methods from statistics or data mining as way to discern patterns or place the data in mathematical context."<br>• Represent – "choose a basic visual model, such as a bar graph, list, or tree."<br>• Refine - "improve the basic representation to make it clearer and more visually engaging."<br>• Interact – "add methods for manipulating the data or controlling what features are visible." |
| Example | Acquire *(Ba)*<br>Parse *(Bb)*<br>Filter *(Bc)*<br>Mine *(Bd)*<br>Represent *(Be)*<br>Refine *(Bf)*<br>Interact *(Bg)* |
| *Coding method for category Label B* | *Coding by (B1) OR (B5; B3) OR (B7; B5; etc.)* |
| | |
| ***Codes with label category*** | ***(Label C)*** |
| *Particular Codes under Label C* | *Influenced factors of visualization design judgments [Label (C-Arabic)]* |
| Definition | The factors that influence visualization designers' design judgments and impact visualization design processes and outcomes. |
| Example | • Interests (C1)<br>• Creativity (C2)<br>• Design experience (C3)<br>• Professional guidance (C4)<br>• More sketch practice (C5)<br>• Access to accurate and valuable data (C6)<br>• Life experience (C7)<br>• Design knowledge and levels (C8)<br>• User cognition knowledge and levels (C9)<br>• Professional knowledge (e.g., DNA sequencing) (C10)<br>• Technology (C11)<br>• Time limitations (C12)<br>• Clients' requirements (C13)<br>• Design goals (C14)<br>• Design feasibility (C15) |

| | |
|---|---|
| | • Design behaviors (C16)<br>• Design methods (e.g., parallel design method) (C17)<br>• …etc.… |
| Example in context | "Because I'm interested in information visualization design. I want to learn more, so I actively took part in each of the design steps, and actively discussed each of design ideas. I think it's a fascinating process that we can talk about the solutions to get the results." (C1)<br>*Note: each quote may contain more than one factors. Also, you may explore extra factors while coding, please add them by (C description, which will be defined by yourself) |
| *Coding method for category Label C* | *Coding by (C1) OR (C1; C10) OR C1; C10; etc.) OR (C1; C10; C description)* |

Table 2 Two cycles of coding, adapted from (Saldana, 2015). Coding step-by-step supports the data analysis of individual-studies and helps with researcher understanding.

| **Two Cycles of Coding** | |
|---|---|
| **Initial Coding** | |
| **Purpose** | • *Generating detailed codes on textual transcripts of observational notes and interviews;*<br>• *Supporting answers of research questions 1, 2 and 3 – with the focus on the question of "What are the existence?"* |
| **Method** | Initial coding by ***Coding with Label (A)(B)(C) combinations – For each of the quotes (from interviews)/Statements (observational notes) in transcriptions; i.e., (Aa; B1; C1) OR (Ab2, B3; B6; C6; C12) etc.*** |
| **Theme Coding** | |
| **Purpose** | • *Combining and composing themes to accurately depict the data;*<br>• *Supporting answers of research question the focuses of 2 – "How do they occur?" and 3 – "What are the influencing factors?"* |
| **Method** | Theme coding by ***Re-reading the transcripts; combing the codes; ranking the codes; checking back of theoretical foundations; as well as summarizing and preparing the themes for reports.*** |

Extensional Table of Table 1 – For *Label A*

11 types of design judgments and applicable definitions, adapted from Nelson and Stolterman (2012) and referred from instructional design research (Gray, 2015).

| **Types of Design Judgment** | **Definition** |
|---|---|
| Default<br>*(A-a)* | Judgments made without deliberation, automatic response to a situation/circumstance. |
| Deliberated off hand<br>*(A-b)* | Judgments made by recalling previous judgments that have led to successful design and adapting to current situations. |

| | |
|---|---|
| Core<br>*(A-c)* | Judgments made when one is pushed by "why" questions concerning one's judgments and decisions. |
| Framing<br>*(A-d)* | Judgments made for determining what is to be included within the purview of the design process, defining and embracing the design activities' space and constraints (client or tool) or ways of assessing design outcomes; occurs across multiple design levels. |
| Appreciative<br>*(A-e)* | Judgments made on what is background and what requests more attention as foreground. |
| Quality<br>*(A-f)* | Judgments made on effectiveness of visual and other forms of style; whether there is enough of a match between design standards, other proposed design, and aesthetic norms of a design situation. |
| Appearance<br>*(A-g)* | Judgments made on assessing overall appearance quality with style; in relation to a concrete design artifact, nature, character, and aesthetic experience; relating to the entire product rather than a portion. |
| Connective<br>*(A-h)* | Judgments made on binding connections and interconnections between and among things between/among various design objects to form functional assemblies transmitting their individual influences, energy, and power to one another. The connections made are not for relational whole but particular to a design situation. |
| Compositional<br>*(A-i)* | Judgments made on bringing various things or design objects together in relational who/overall design process rather than specific to a particular design situation; forming within the guiding domains of aesthetics, ethics, and reason – in the mode of synthesis. |
| Instrumental<br>*(A-j)* | Judgments made on dealing with the choice and mediation of means – tools, concepts, and methods within the context to reach established design goal. |
| Navigational<br>*(A-k)* | Judgments made by considering a "rule" – a plan, flow, path, or a certain manner to in approaching a design direction, task, or challenge to reach to a desired design state. |

# APPENDIX C. INTERVIEW PROTOCOLS

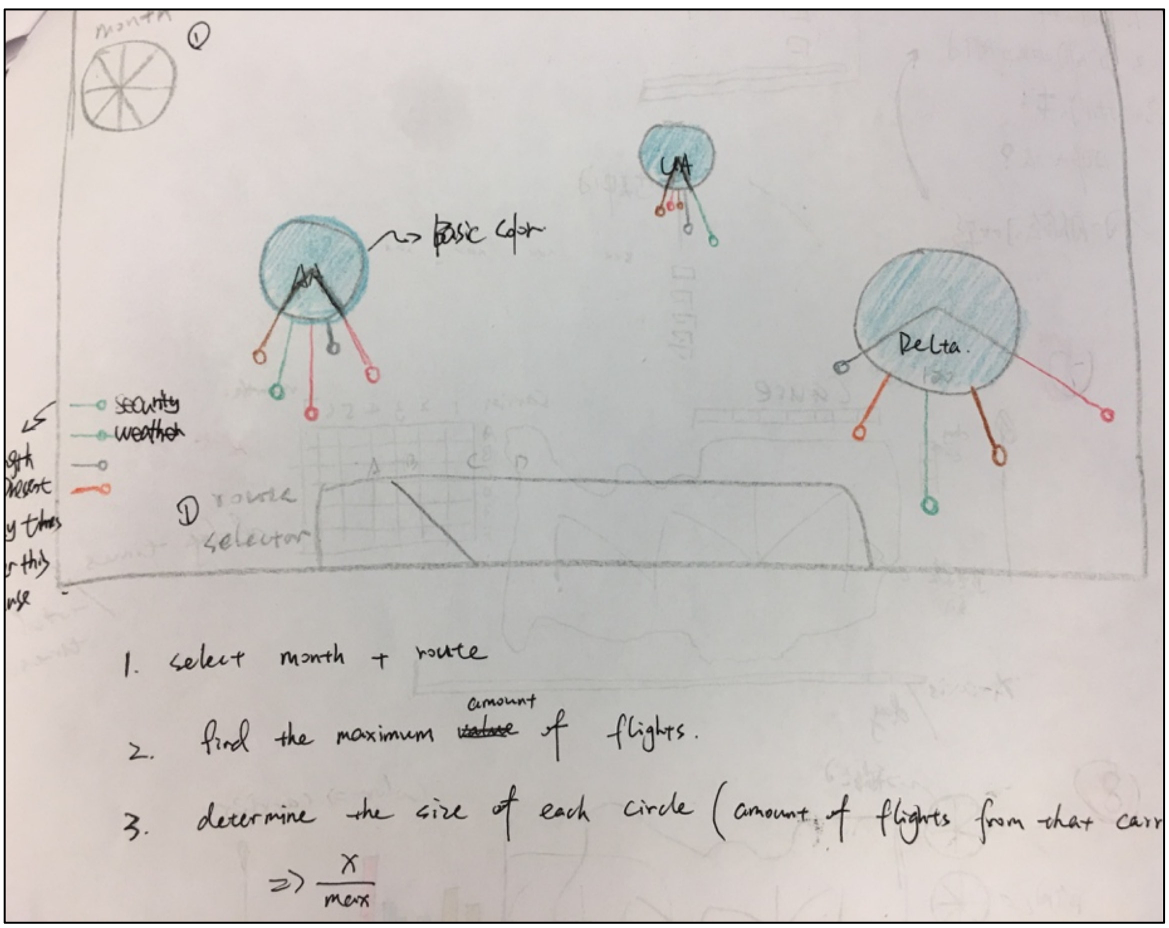
**Semi-Structured Interview Protocol (Interview # Laboratory Study One)**

*Background Questions*

1. Please tell about your background.
2. Have you had any visualization design experiences, including learning experience and project involvement experience? If so, please tell about your experiences.

*Decision-making and Judgment-making Related Questions*

3. Before the participant's (name of the person, i.e., P-SS) sketching, how did you choose five variables for your visualization? Why did you select those?
4. How did you decide what data attributes would be used in your final visualization? What was your judgment and decision-making process?
5. How did you decide on a design idea (sketch) as a final solution for your visualization? What was your judgment and decision-making process?



(Figure)

6. What factors drove your design judgment activities that moved toward design outcome?

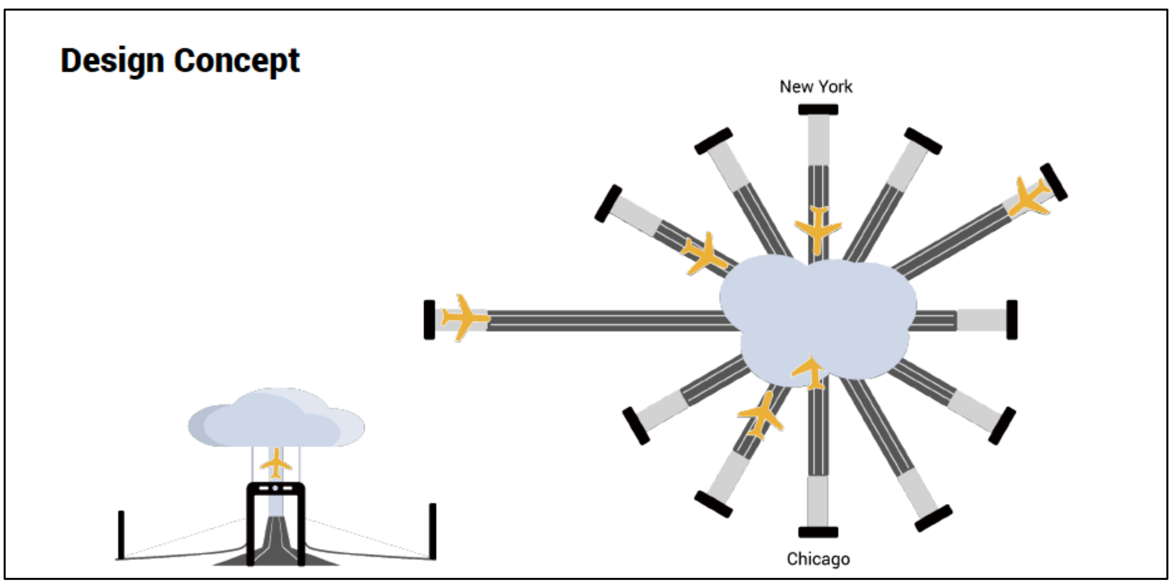
**Semi-Structured Interview Protocol (Interview # Laboratory Study Two)**

*Background Questions*

1. Please tell about your background.
2. Have you had any visualization design experiences, including learning experience and project involvement experience? If so, please tell about your experiences.

*Decision-making and Judgment-making Related Questions*

3. How did you choose five variables of location, delay (times), time frame, air route, and cause for your visualization?
4. How did you match your raw data to your design concepts (sketches)? Please choose two or three design concepts to describe your decision-making process.
5. How did you decide a design idea (sketch) as a final solution (Figure) for your visualization? How the process looks like of doing judgment and decision-making?




(Figure)

6. What factors drove your design judgment activities that moved toward design outcome?

**Semi-Structured Interview Protocol (Interview Midpoint # In-Situ Study One)**

*Background Questions*

1. Please tell about your background.
2. Have you had any visualization design experiences, including learning experience and project involvement experience? If so, please tell about your experiences.

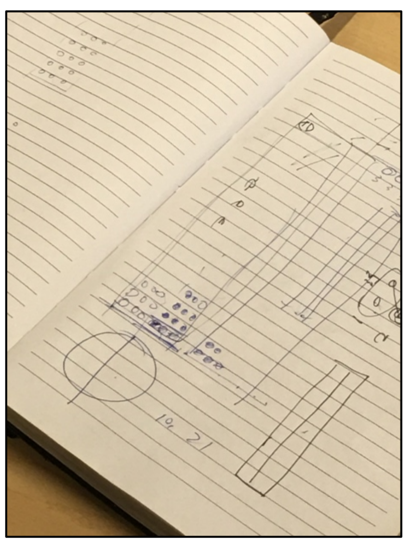
*Decision-making and Judgment-making Related Questions*

3. Your group spent approximately two hours to discuss your design flow. Please explain how you decided on a parallel working flow to make data construction and interaction design happen concurrently?
4. Please explain how you and your group decided on visualizing your data using interactions.
5. In the same judgment processes (Q3, 4 above), what factors drove your design judgment activities?

**Semi-Structured Interview Protocol (Interview Endpoint # In-Situ Study One)**

*Decision-making and Judgment-making Related Questions*

6. Your group made a lot of effort to compare, compose, even abandon some designs with the process of data re-explorations and re-definitions. Please select two examples of design activities to show why you kept or left some designs and how did you make these judgments?
7. Your group selected the layout of "bar + heat map" (Figures) as your final graphical design decision. How did you make these judgments and what factors influenced your judgments?



(Figures)

8. Your group put forward a variety of color scheme combinations during color design modifications. Please explain your design decision-making process.

9. Reflecting on your design decisions (Q6, 7, and 8 above), what factors drove your design judgment activities that moved toward outcome design?

**Semi-Structured Interview Protocol (Interview Midpoint # In-Situ Study Two)**

*Background Questions*

1. Please tell about your background.
2. Have you had any visualization design experiences, including learning experience and project involvement experience? If so, please tell about your experiences.

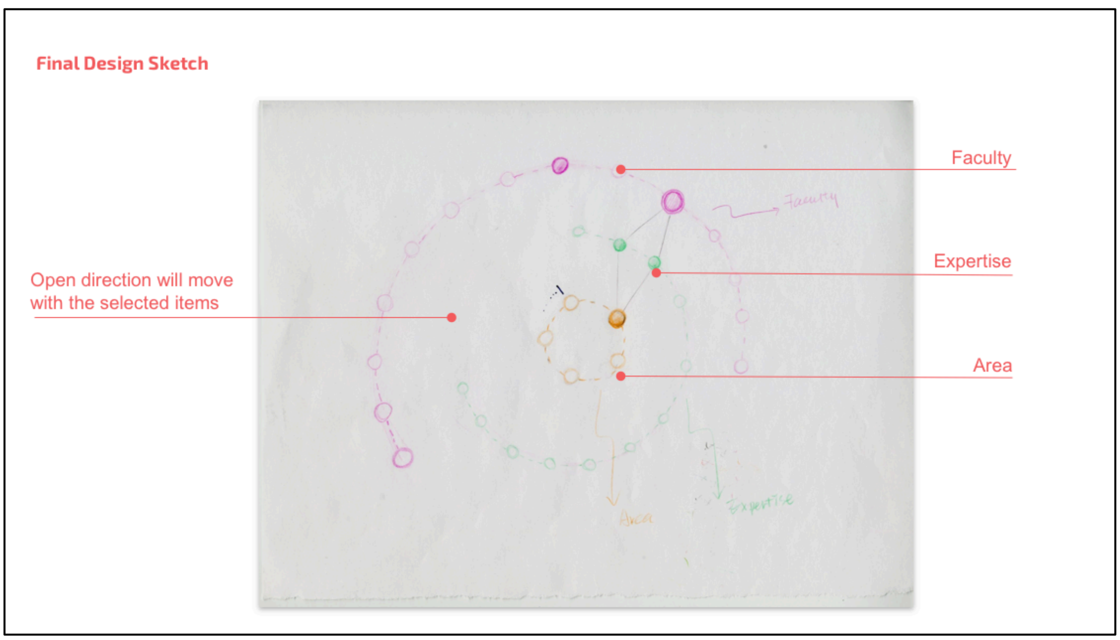
*Decision-making and Judgment-making Related Questions*

3. How did your project go before design sketching?
4. Please briefly explain why all your current designs (sketches) were circular style-based? Also, please choose two of your design ideas (sketches) to discuss how you decided them and your judging process?
5. In the same judging processes (Q3, 4 above), what factors drove your design judgment activities?

**Semi-Structured Interview Protocol (Interview Endpoint # In-Situ Study Two)**

*Decision-making and Judgment Making Related Questions*

6. How did you judge this design (Figure) as your final design solution for your interactive visualization? What did your decision-making process look like?




(Figure)

7. How did you decide to switch your design strategy, refer, and adapt an online example for your final design development?
8. Reflecting on your design decisions (Q6, 7 above), what factors drove your design process and outcome?

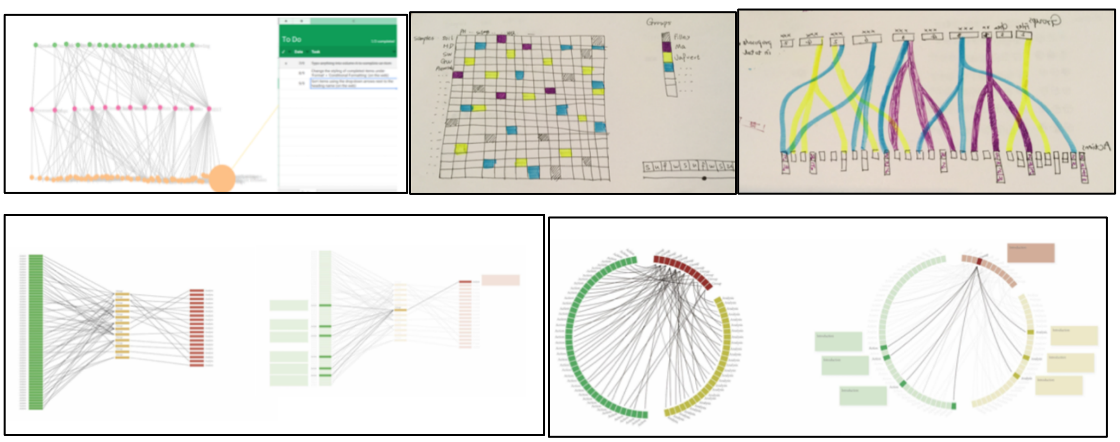
**Semi-Structured Interview Protocol (Interview Midpoint # In-Situ Study Three)**

*Background Questions*

1. Please tell about your background.
2. Have you had any visualization design experiences, including learning experience and project involvement experience? If so, please tell about your experiences.

*Decision-making and Judgment-making Related Questions*

3. Why did you decide to change your original rectangular layouts to circular layouts (Figures)? Please elaborate on your decision-making process.



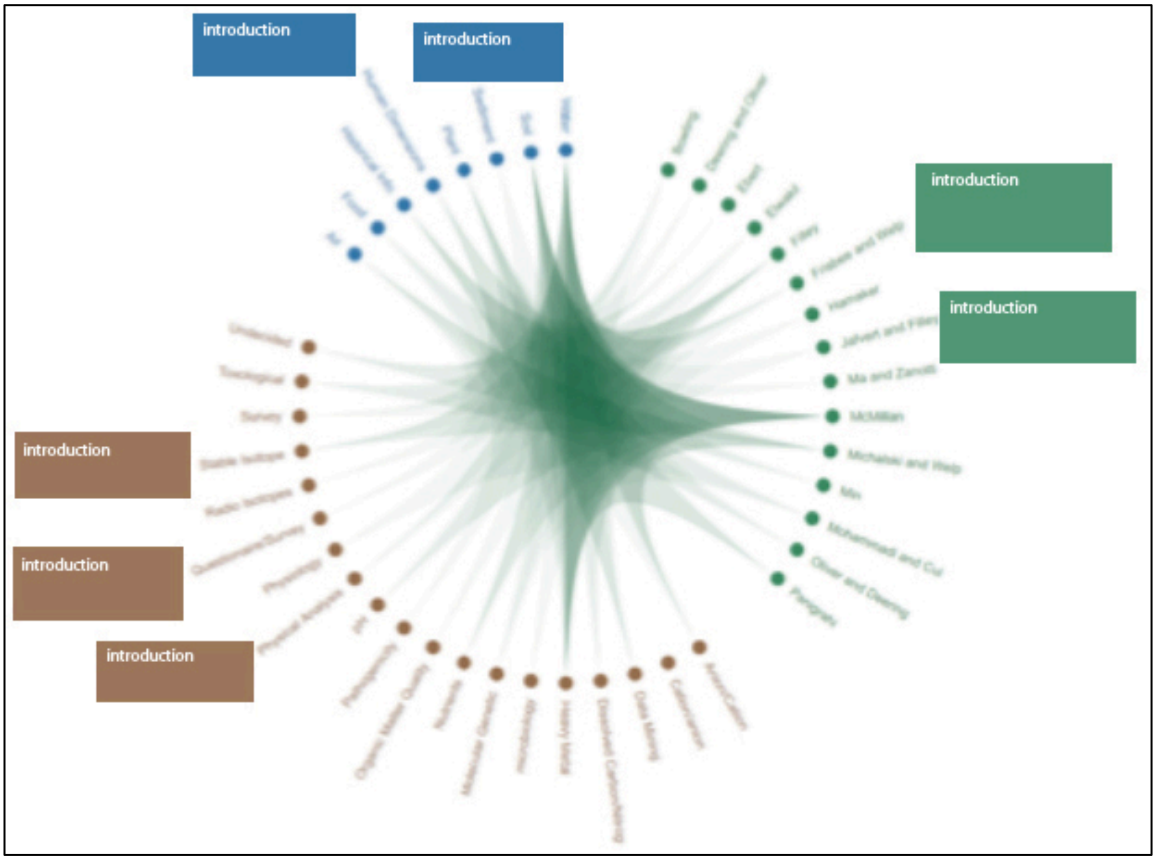
(Figures)

4. In the same judging process (Q3 above), what factors drove your design judgment activities that moved toward outcome design?

**Semi-Structured Interview Protocol (Interview Endpoint # In-Situ Study Three)**

*Decision-making and Judgment-making Related Questions*

5. How did you decide on this design (Figure) as the final solution for your interactive visualization? What did your decision-making process look like?




(Figure)

6. Reflecting your design decision (Q5 above), what factors drove your design judgment activities that moved toward outcome design?

# VITA

**Mingran Li**

West Lafayette, Indiana 47906 • li1940@purdue.edu • LinkedIn • Portfolio

## CAREER PROFILE

Dedicated IT professional with experience in Research and Design complemented by a track record of facilitating strong interpersonal relationships between businesses and their clients. Capable researcher who continues to establish ongoing success by implementing a broad range of systems and initiatives to ensure quality and due diligence is always paramount. Proven ability to utilize industry-standard software and techniques to maximize efficiency and maintain continual effectiveness in a rapidly evolving industry.

Highly skilled professional with years of experience aiding college level professors in developing and teaching post-secondary courses in a wide range of environments. Motivated, energetic, and passionate about student success. Committed to improving learning experiences for diverse student populations. Serve on various academic and extracurricular committees and excited about developing new opportunities for student engagement.

**Areas of expertise include…**

- User Experience Research
- User Experience Design
- Web Programming
- Visualization Research
- Visualization Design
- Data Analysis
- Qualitative Research
- Quantitative Research

- Student Centered Instruction
- Curricula Design
- Student Mentoring & Tutoring
- Curricula Improvements
- Study Improvement Strategies
- Academic Evaluations

**EDUCATIONAL BACKGROUND**

**Ph.D. in Computer Graphics Technology |** Purdue University, Polytechnic Institute, West Lafayette, Indiana, Expected 2018

*Coursework: Information Visualization Design Research (Design Judgements), UX Research*

**Master of Arts in Digital Art and Science |** University of Florida – Digital World Institute, Gainesville, Florida, 2014

*Coursework: Collaborative Learning in Video Games*

**Bachelor of Arts in Digital Media Arts |** Beijing Institute of Fashion Technology, Beijing, China, 2012

*Coursework: Collaborative Learning in 3D Game Play*

**AWARDS & DISTINCTIONS**

*Xi Man Color Scholarship, Trends Group Scholarship, Communication University of China Animation Award, Aimer Scholarship, National College Students' Advertising Competition – Award of Excellence, National Liberal Arts College Students' Computer Design Competition – Third Award, Honorable Mention for Quality Aesthetics – MetaCurve*

**PUBLICATIONS**

Li, M., Wu, W., Zhao, J., Zhou, K., Perkis, D., Bond, T., Mumford, K., Hummels, D., & Chen, Y. (Accepted & Being Published at Nov 2018). *CareerVis: Hierarchical Visualization of Career Pathway Data.* IEEE Computer Graphics and Applications.

Li, M., Gao, R., Hu, X., & Chen, Y. (2017). *Comparing infovis designs with different information architecture for communicating complex information.* Communication Design Quarterly Review, 5(1), 43-56.

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Gao, R., Li, M., Chen, Y. (2016). *A Hierarchical Interaction Design for Multi-dimensional Flow Datasets.* IEEE Visual Analytics Science and Technology. IEEE.

Guo, C., Wei, S., Li, M., Qian, Z. C., & Chen, Y. V. (2017, July). *Comparison of Circle and Dodecagon Clock Designs for Visualizing 24-Hour Cyclical Data*. In International Conference of Design, User Experience, and Usability (pp. 54-62). Springer, Cham.

Tang, H., Zhou, Z., Wei, S., Li, M., Liu, S., Wu, H., ...&Qian, Z. C. (2016, October). *Meta Curve: A Method for Discovering Patterns, Identifying Anomalies, and Summarizing of Periodical Time Series Datasets.* Paper Presented at 2016 IEEE Conference on Visual Analytics Science and Technology (VAST), Baltimore, USA

Tang, H., Pan, C., Yu, B., Du, W., Wei, S., Li, M., ...& Li, X. (2015, October). *[COMM] greater: A toolset for temporal communication patterns and dynamic network structure.* In 2016 IEEE Conference on Visual Analytics Science and Technology (VAST) (pp. 173-174). IEEE. doi: 10.1109/VAST.2015.7347666

Wei, S., Hu, K., Cheng, L., Tang, H., Du, W., Guo, C., Pan, C., Li, M., …& Zhu, Y. (2015, October). *CrowdAnalyzer: A Collaborative Visual Analytic System.* In 2016 IEEE Conference on Visual Analytics Science and Technology (VAST) (pp. 177-178). IEEE.

Li, M., Wei, S., Tang, H., Gray, C., Bendito, P., Mohler, J., & Chen, Y. (Submitted to Review). *Exploring Design Judgments in Visualization Design.* ACM CHI Conference 2019.

## EXPERIENCE HIGHLIGHTS

<u>Lilly Endowment Inc.</u>, Indianapolis, Indiana | <u>Purdue University</u>, West Lafayette, Indiana

**User Experience Researcher,** 1/2015 – Present

*Technologies: User Experience Research & Design Techniques, Visualization Research & Design Techniques, Web Programming*

Construct and deliver UX research studies, customer interviews, competitive analyses, usability tests, and surveys. Analyze findings and develop actionable trends to increase business and improve academic decisions. Facilitate strong interpersonal communications between programmers and stakeholders to ensure an effective and collaborative atmosphere. Conduct UX design research programs and identify opportunities to improve design interactions on the Career Mapping visualization system.

**Key Contribution:**

- Acted as the primary UX Researcher for four years including responsibilities such as balancing, organizing, and delegating tasks within a team of highly-skilled professionals.
- Authored all publications resulting from the research, including an SCI, journal, and IEEE paper poster.

Purdue University, West Lafayette, Indiana

**Graduate Teaching Assistant,** 1/2016 – Present

*Technologies: Student-centered Instruction, Student Mentoring & Tutoring, Curricula Design and Improvements*

Provided essential mentoring and tutoring services to students in need and evaluated the academic status of visiting students during office hours in order to re-educate and instill healthier study habits moving forward. Aided teaching staff and used the experience to improve academic knowledge, teaching experience, and communications. Utilized industry-standard software and languages and performed essential job functions such as supportive responsibilities for both server and mobility infrastructures, as well as web programming.

**Key Contribution:**

- Aided instructors with designing and improving course constructions.
- Introduced the world of web-based programming to countless students seeking career advice and instruction.

Grocerwise, London, England

**User Experience Researcher,** 10/2017 – 12/2017

*Technologies: Human-centered design, customer interview, persona building, journey mapping, user stories*

Spearheaded the development of detailed conducted plans aimed at assisting in the identification of themes and categories, and responsible for the creation of persona and journey maps. Interfaced with customers regularly to identify patterns and determine key insights based upon their overall shopping experience. Contributed to regular research planning sessions by providing recommendations intended to validate assumptions and improve the feedback loop.

**Key Contribution:**

- Served an integral role as a key contributor on all design stages, especially in regard to the research stage of developments.

Purdue University West Lafayette, Indiana

**User Experience Researcher & Designer/Research Assistant,** 9/2016 – 12/2016

*Technologies: user interview, persona, journey map, user stories, competitive analysis, co-design workshop, wireframing, prototyping, qualitative usability testing*

Directed a co-design workshop designed to analyze and understand the daily challenges of resettle Burmese refugees. Performed regular usability tests and accessibility evaluations to ensure product usability and improve designs. Created affinity diagrams, user personas, user scenarios, wireframes, and high-fidelity prototypes aimed at achieving design goals and decisions.

**Key Contribution:**

- Headed responsibilities for design research, secondary research, primary interviewing, solution brainstorming, wireframing, competitive analysis, and a co-design inspired workshop.

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## CERTIFICATIONS

**Customer Interview Training: How to Conduct Customer Interviews**, Grocerwise

**Advance Your Skills as a User Experience Researcher**, LinkedIn

**Design Thinking: Implementing and Understanding the Process**, LinkedIn

**UX Foundations: Research**, LinkedIn

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