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Visual Representation and Cognitive Models in Information Visualization

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Abstract: As a branch of computer science, information visualization aims to help users understand and analyze complex data through graphical interfaces and interactive technologies. Information visualization primarily includes various visual structures such as time-series structures, spatial relationship structures, statistical distribution structures, and geographic map structures, each with unique functions and application scenarios. To better explain the cognitive process of visualization, researchers have proposed various cognitive models based on interaction mechanisms, visual perception steps, and novice use of visualization. These models help understand user cognition in information visualization, enhancing the effectiveness of data analysis and decision-making.

Keywords: Information visualization; Visual structures; Cognitive models; Interaction design

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1. Introduction

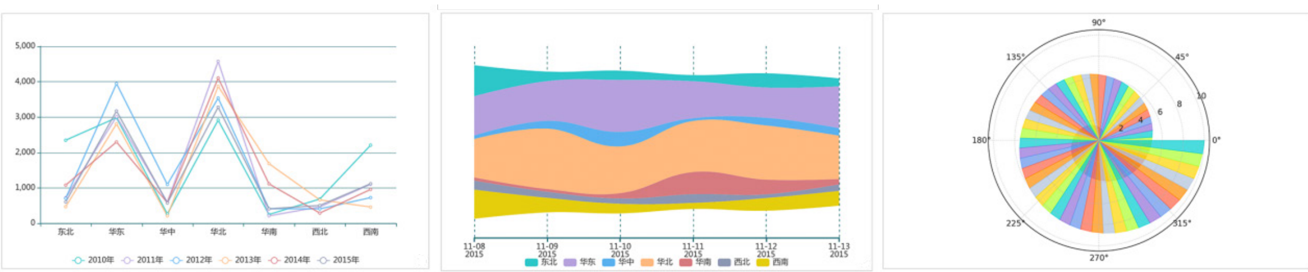
Information visualization, initially a branch of computer science, is an essential part of visualization research. It was first systematically articulated by Stuart K. Card, George G. Robertson, and Jock D. Mackinlay in 1990. They introduced a system called the "information visualizer," designed to help users process and understand large amounts of complex data through graphical interfaces and interactive technologies [1]. The paper detailed how computer graphics and user interface technologies could transform abstract data into easily understandable visual forms, enhancing users' cognitive and analytical abilities. Ben Shneiderman and Ben Bederson defined information visualization as using computers to interactively display abstract data, enhancing people's cognition of abstract information. Both Shneiderman and Bederson made significant contributions to the field of information visualization. They proposed a visualization taxonomy based on data types and tasks, designing a high-level graphical user interface framework: "Overview first, zoom and filter, then detail-on-demand" [2]. This approach helps users better understand and interact with large and complex data sets. Many scholars also believe that the information objects in information visualization include text, images, and sounds, realized through different model methods. Information visualization maps abstract data into images on computer screens, helping users quickly extract useful information from large datasets.

2. Visual structures of information visualization

Information visualization maps abstract data to visual forms for understanding through visual cognitive tasks. Designers must first consider how to present these visualizations, which generally follow a basic framework with three levels. The highest level is the visualization interface, the medium for human-computer interaction, possibly containing multiple sub-interfaces. The middle level is the visual structure, organizing data with methods like bar charts, scatter plots, and tree diagrams. The lowest level consists of visual units, the smallest components like points, lines, and text, encoded by variables such as color, shape, and size.

2.1. Time-series structures

Data sets that change over time are one of the most common forms of recorded data. Time-series data involving state changes are core to many fields, such as finance (stock prices, exchange rates), science (temperature, pollution levels, potential), and public policy (crime rates). People can often extract patterns of data changes over time from temporal phenomena, but it is difficult to quickly obtain effective information through visual observation alone. Therefore, various charts representing time-series data have emerged and have achieved outstanding results in data presentation. Common visualization visual structures based on time-series include line charts, streamgraphs, and spiral plots, as shown in Figure 1.



(a) Line chart (b) Streamgraph (c) Spiral plot

Figure 1. Time-series structures

The concept of line charts was first proposed by Scottish economist William Playfair. He used this type of chart to represent changes in economic data, such as annual changes in export and import data. William Playfair is considered the founder of graphical statistics, and his work profoundly influenced later data visualization methods. The X-axis of line charts usually represents time, while the Y-axis represents variables of other attributes, making it intuitive to see the patterns of data points changing over time.

Streamgraphs, first proposed by Lee Byron and Martin Wattenberg in 2008, were designed to better represent changes in time-series data, especially those with hierarchical structures. Streamgraphs display the flow and trends of data over time using color and shape variations, making them very suitable for showing changes in complex data sets [3]. In addition to representing information by time, streamgraphs also allow users to discover the dynamic trends of thematic events through information changes, providing an effective way to reveal internal relationships between events over time within documents.

The concept of spiral plots was first proposed by Dutch mathematician and graphic designer Gerard ’t Hooft in the 1980s. Spiral plots arrange time-series data along a spiral path, commonly used to display cyclical data, such as seasonal changes or periodic events. This chart form makes periodic patterns more apparent and intuitive by arranging data points along a spiral line [3].

2.2. Spatial relationship structures

In daily life, information is often organized by logical relationships, such as books in a library classified by themes for easy access. Similarly, in information visualization, the interface design must organize information organically, summarizing relationships and reflecting spatial structure. Most data can form natural hierarchical structures. Visualization techniques for these structures enable rapid multi-scale reasoning, allowing both micro-level observation of individual elements and macro-level observation of groups [5]. Common visual structures for spatial relationships include tree diagrams, rack diagrams, and node-link diagrams, as shown in **Figure 2**.

(a) Tree diagram (b) Rack diagram (c) Node-Link diagram

Figure 2. Spatial relationship structures

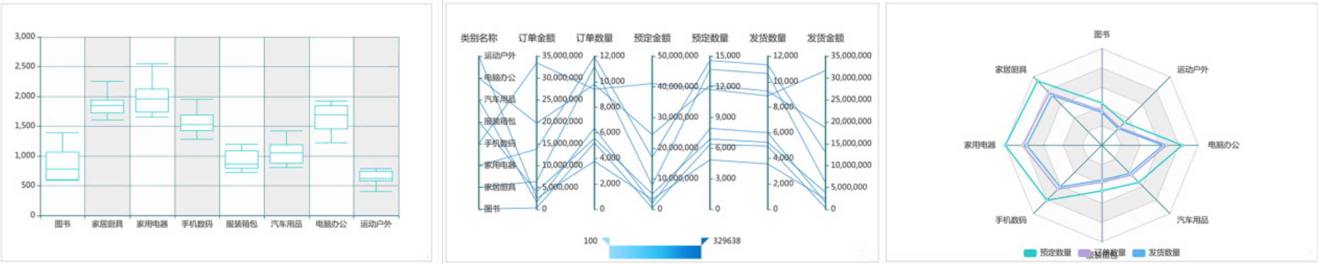
Tree diagrams were first proposed by Johann Vogel in 1661. A tree diagram is a graphical tool used to represent hierarchical structures, widely used in mathematics, computer science, organizational structure diagrams, and other fields. Tree diagrams show hierarchical relationships between pieces of information, where connected information has parent-child relationships. One child information can only correspond to one parent information, but one parent information can contain multiple child information.

Rack diagrams were first proposed by Ben Shneiderman in 1991. By editing information areas into rectangles and using different colors and size codes, rack diagrams can significantly distinguish hierarchical and associative attributes of information, with good readability and size estimation capabilities. Rack diagrams are a variant of traditional tree diagrams, where each information area is edited into a rectangle. The size of any node is quickly displayed.

The concept of node-link diagrams can be traced back to the study of graph theory. Graph theory was introduced by Swiss mathematician Leonhard Euler in 1736 when he was studying the Seven Bridges of Königsberg problem. The concepts of Eulerian graph and Eulerian circuit laid the foundation for graph theory, from which the representation method of node-link diagrams was derived. Since then, graph theory has been widely used in computer science, network science, social network analysis, and other fields. Node-link diagrams, as an intuitive graphical representation method, gradually began to be used to describe various complex relationships and network structures.

2.3. Statistical distribution structures

Visualization design aims to reveal the distribution of data, helping data analysts better understand the statistical characteristics of data. Data analysts often want to match their data with statistical models, especially in hypothesis testing or predicting the value of the next point. However, wrong model choices may lead to incorrect predictions. Therefore, one important use of visualization is exploratory data analysis, understanding how data is distributed to inform data transformation and modeling decisions. Common statistical distribution structures include box plots, parallel coordinates plots, and radar charts as shown in **Figure 3**.



(a) Box plot (b) Parallel coordinates plot (c) Radar chart

Figure 3. Statistical distribution structures

Box plots were first proposed by American statistician John Tukey in the 1970s. Box plots are statistical charts used to describe the distribution of data sets, displaying five main summaries of the data set: minimum value, first quartile, median, third quartile, and maximum value. They can also display outliers, providing an intuitive representation of data distribution and variation. Box plots are often used for numerical statistics, drawn horizontally or vertically.

Parallel coordinates plots were first proposed by French mathematician Maurice d'Ocagne in 1885. In his work, he introduced this chart as a tool for visualizing multidimensional data. Parallel coordinates plots represent each data dimension as a parallel axis and connect data points on each axis, realizing the visualization of multidimensional data. This chart has been widely used in later data analysis and visualization fields.

Radar charts were first proposed by American engineer and industrial designer Charles Joseph Minard in the 19th century. Radar charts display multivariate data in a two-dimensional chart form with three or more quantitative variables starting from the same point. They can represent multidimensional data, but the relative positions of points and the angles between coordinate axes carry no information.

3. Cognitive patterns in information visualization

3.1. Cognitive models of information visualization interaction mechanisms

Card *et al.*, as cited by Xu, proposed the information visualization reference model, which details the basic processes and interaction mechanisms of information visualization. This model explains how raw data is transformed into effective visual displays to enhance users' understanding and analytical abilities [4]. From this cognitive model, we can clearly understand the task goals that information visualization aims to solve and the steps to achieve these goals: starting from raw data, through mapping, exchange, and interaction control, and finally achieving effective visualization. In this process, there are two intermediate results between raw data and the final view: data tables and visualization structures. Through data transformation, visualization mapping, and view transformation, raw data is ultimately converted into visualization views. Users can interact with information visualization during these three transformations, adjusting data tables, visualization structures, and views, as shown in **Figure 4**.

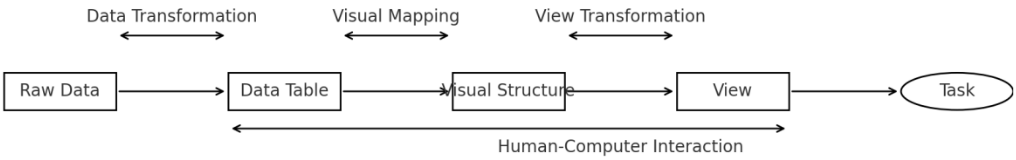


Figure 4. Cognitive models of information visualization

This model involves three stages: structuring raw data, mapping it to visual structures, and presenting it as visual charts. Proposed in 1999, it emphasizes user interaction with data to enhance understanding and analysis. The data transformation stage cleans, organizes, and filters raw data into structured tables. In the visualization mapping stage, structured data is converted into visual elements like points and lines. The view transformation stage adjusts and optimizes visual charts for better data presentation. User interaction is crucial, allowing adjustments to data tables, visualization structures, and views to explore different perspectives. This model by Card *et al.* offers a systematic framework for applying information visualization technology, improving data analysis efficiency and effectiveness.

3.2. Visual perception steps model of information visualization

Rodrigues *et al.*, as cited by Shi, Cheng, and Hof, proposed a model for the visualization expression process, detailing the steps data visualization undergoes in the visual cognitive process. The model includes four main parts: pre-attentive stimuli, analytical perception, abstract patterns, and decision support [5].

Firstly, the pre-attentive stimuli stage involves the initial neural response to light, quickly scanning visual information to identify key features and reduce cognitive load. Secondly, the analytical perception stage focuses attention on a single element for detailed analysis, using pattern matching to identify and classify visual elements. For example, in data visualization, this stage helps identify data points and trends. Thirdly, the abstract patterns stage transforms specific visual information into abstract concepts, simplifying complex data for easy understanding and memory storage. Finally, the decision support stage combines abstract patterns with long-term memory knowledge to aid decision-making, forming a dynamic cognitive process [6].

The bidirectional arrows indicate simultaneous bottom-up and top-down interactions during tasks. Low-level perceptual inputs influence high-level cognitive processing, and vice versa. For example, seeing a new data visualization chart involves initial perception shaped by existing knowledge, while new information updates our cognitive framework [7]. This process may generate new information needs, prompting redefinition of visualization through new interaction parameters. Users may seek more details or different perspectives, driving further optimization of visualization. This model describes the cognitive process from perception to complex cognition, offering a framework for designing effective and user-friendly data visualization tools.

4. Conclusion

Information visualization, a crucial branch of computer science, has evolved into a powerful tool for processing and understanding complex data. It integrates computer graphics, user interface technology, and human-computer interaction, enhancing cognitive abilities and advancing information and cognitive science. From Stuart Card and colleagues' "information visualizer" to Shneiderman and Bederson's visualization taxonomy, research has continually progressed. The core of information visualization is transforming abstract data into visual forms for intuitive understanding. Widely applied in scientific research, business, and public policy, its importance grows with increasing data complexity. Future research must explore new technologies and methods to meet these expanding needs.

Disclosure statement

The authors declare no conflict of interest.

References

[1] Zhang L, 2021, Analysis of User Interface Animation Design in Digital Media Art. Art and Design, 08: 45–48. https://doi.org/10.16824/j.cnki.issn10082832.2021.08.021

[2] Wang N, Qiu X, 2021, Simulation of UI Interface Data Visualization Transmission Based on Perceptual Feedback. Computer Simulation, 38(10): 34–36.

[3] Jason F, 2012, The Mobile Interface Theory: Embodied Space and Locative Media. Routledge, London, 2012: 56–60.

[4] Xu H, 2017, Study on the Styling Style Characteristics in Dynamic Graphic Design. Packaging World, 05: 120–121. https://doi.org/10.13337/j.cnki.packaging.world.2017.05.040

[5] Shi S, Cheng X, Hof PMJVD, 2020, Excitation Allocation for Generic Identifiability of a Single Module in Dynamic Networks: A Graphic Approach. IFAC-PapersOnLine, 53(2): 40–45.

[6] Liu Y, Zhang Y, 2022, Research on Dynamic Graphics Features in Digital Media Interface. Digital Communication World, 5: 121–123.

[7] Spiliotopoulos D, Tzoannos E, Stavropoulou P, et al., 2012, Designing User Interfaces for Social Media Driven Digital Preservation and Information Retrieval. Springer-Verlag Berlin Heidelberg, 7382: 581–584.

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