Common Visualizations: Their Cognitive Utility

Paul Parsons and Kamran Sedig

Abstract Visualizations have numerous benefits for problem solving, sense making, decision making, learning, analytical reasoning, and other high-level cognitive activities. Research in cognitive science has demonstrated that visualizations fundamentally influence cognitive processing and the overall performance of such aforementioned activities. However, although researchers often suggest that visualizations support, enhance, and/or amplify cognition, little research has examined the cognitive utility of different visualizations in a systematic and comprehensive manner. Rather, visualization research is often focused only on low-level cognitive and perceptual issues. To design visualizations that effectively support high-level cognitive activities, a strong understanding of the cognitive effects of different visual forms is required. To examine this issue, this chapter draws on research from a number of relevant domains, including information and data visualization, visual analytics, cognitive and perceptual psychology, and diagrammatic reasoning. This chapter identifies and clarifies some important terms and discusses the current state of research and practice. In addition, a number of common visualizations are identified, their cognitive and perceptual influences are examined, and some implications for the performance of high-level cognitive activities are discussed. Readers from various fields in which a human-centered approach to visualization is necessary, such as health informatics, data and information visualization, visual analytics, journalism, education, and human-information interaction, will likely find this chapter a useful reference for research, design, and/or evaluation purposes.

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1 Introduction

It is well known that visualizations have numerous benefits for supporting problem solving, sense making, decision making, learning, analytical reasoning, and other high-level cognitive activities (see, e.g., [40, 45, 59, 62, 63, 77]). Because of their numerous benefits, visualizations are used in nearly all information-based domains including, but not limited to, science, engineering, journalism, education, public health, finance, medicine, and insurance [34, 37, 66, 67, 71, 77]. The term visualization can have different meanings depending on the context in which it is used—sometimes it refers to a computational tool, sometimes to the process of encoding and representing information, and sometimes to the visual representation that is displayed to users at the interface of a tool. To avoid ambiguity, the terms visualization tool (VT) and visual representation (VR) are used throughout this chapter to refer to an entire tool, and to the visual form of information that a user perceives and acts upon, respectively (see Sect. 2.1 for more detail). Unless stated otherwise, the use of the term visualization in this chapter is synonymous with VR. Examples of VRs are radial diagrams, network graphs, tables, scatterplots, parallel coordinates, geographic maps, and any other visual form that encodes and organizes information.

Research in cognitive science has demonstrated that cognitive processes are distributed across internal, mental representations of information (e.g., mental models) and external representations of information (e.g., VRs) [45, 86]. In addition, psychologists have discovered that VRs represent information (e.g., concepts, events, objects, relationships) in such a way that there is a semantic connection between the VR and the underlying information (see [11]). In other words, from the perspective of the user, there is a unity of meaning between a VR and what it represents. Consequently, VRs influence cognitive processes and the construction of mental models in a very fundamental manner. A strong understanding of human cognition is therefore necessary for proper research and design of VRs. Although such is the case, visualization researchers often place undue emphasis on VRs alone, and do not focus enough on how VRs affect internal representations (e.g., mental models) of users [45]. What often results is an assumption that VRs automatically amplify cognition, without any critical analysis of how and why this may be the case [4]. Moreover, when research does examine cognitive effects of VRs, the focus is often on perceptual and low-level cognitive processes, rather than on higher-level cognitive processes and activities [23].

Although some relevant research does exist, the scattering of pertinent research findings across numerous disciplines makes it difficult for researchers and designers to think systematically about how VRs influence the overall performance of high-level cognitive activities. In this chapter, we draw on research from information and data visualization, visual analytics, cognitive and perceptual psychology, learning sciences, and diagrammatic reasoning to identify some perceptual and cognitive effects of common VRs, and to discuss their utility for performing high-level cognitive activities. As there are countless instances of VRs, we will discuss some of their common features and cognitive effects. Where applicable, we will discuss studies that have been conducted in various contexts on the cognitive effects of VRs. We will also identify some common visualization techniques, provide some examples of existing visualizations, and discuss some of their effects on the performance of cognitive activities. In doing so, this chapter will identify and integrate research that is not often acknowledged in the visualization sciences, yet is applicable and useful. This chapter can thus serve as a point of reference for researchers and practitioners interested in visualizations that support high-level cognitive activities.

2 Background

This section will provide an overview of background concepts and terms that are necessary for understanding the rest of the chapter. Section 2.1 identifies some commonly used terms, clarifies their meanings, and sets their usage for the remainder of the chapter. Section 2.2 distinguishes between perception and cognition, suggests the necessity of viewing them as connected but distinct, and identifies some shortcomings in visualization research regarding claims about cognitive support and amplification of visualizations. Section 2.3 introduces the notion of complex cognition, contrasts it with simple cognition, and briefly characterizes some complex cognitive activities. Finally, Sect. 2.4 discusses the current state of research in light of the preceding three subsections.

2.1 Visualization Tools, Visualizations, and Visual Representations

There is no commonly agreed upon set of terms and meanings that are used in visualization research. For example, when the term 'visualization' is used, it is often not clear whether the meaning is the whole tool, the process of visually encoding (i.e., visualizing) information and data, or the visual representation that sits at the interface of a tool. To add more clarity and precision to the discussion, we make a distinction between visualization tools (VTs), visual representations (VRs), and the process of visual encoding. VTs are electronic computational tools that encode data and/or information in visually perceptible forms—i.e., VRs. Unlike static media, VTs are interactive, allowing users to perform actions upon VRs and receive reactions. Furthermore, VTs can store information, perform analytic operations on the stored information (e.g., as in visual analytics tools), and manipulate the information in numerous ways. In this manner, VTs can take on an active information-processing role to facilitate the performance of complex cognitive activities (see [57]). Figure 1 depicts the components of a VT. VTs receive or retrieve information (e.g., from

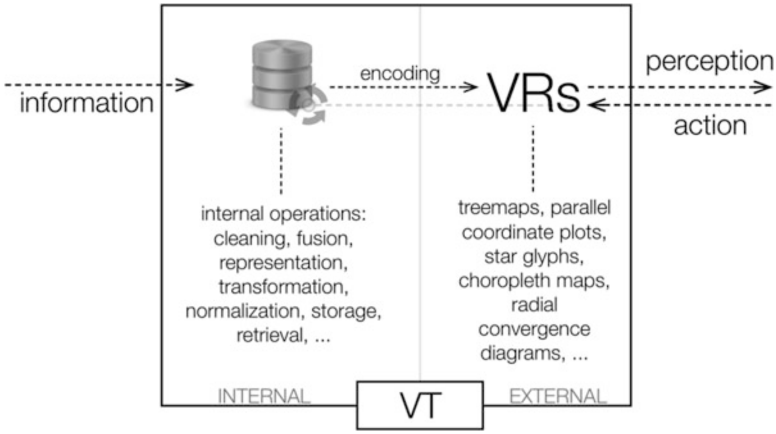

Fig. 1 Internal and external components of a visualization tool

databases, sensors, images), perform some information processing, encode the information in VRs, and allow input from users in the form of actions. The depiction in Fig. 1 is for conceptualization purposes, and does not suggest that a VT has to be an isolated artifact. A webpage, for example, could be considered a VT if it displays interactive VRs and engages in some internal information processing. In such a case, the information processing may take place on a remote server, but could still be conceptualized as the internal component of the VT. As this chapter takes a human-centric approach, the primary concern is the relationship between VRs and users—what aspects of information VRs emphasize and communicate to users, how perceptual and cognitive processes are affected, and how high-level cognitive activities are supported. Indeed, it is the focus on human mental-state changes that characterizes all research in human-centric informatics [49].

2.2 Perception and Cognition

The underlying motivation for doing visualization research is that VRs amplify human cognition. The classic definition of information visualization from Card, Mackinlay, and Shneiderman states that information visualization is “the use of computer-supported, interactive, visual representations of data to amplify cognition” ([8], p. 6). Similarly, Ware has stated that information visualization is “the use of interactive visual representations of abstract data to amplify cognition” ([81], p. xvii). More recently, Mazza has suggested that “visualization is a cognitive activity, facilitated by external visual representations from which people build an internal mental representation of the world” ([50], p. 7). Although most definitions suggest that the purpose of VRs is to amplify cognition, much of the research that is done in the visualization sciences (e.g., data visualization, information visualization, visual analytics), especially in the context of design guidelines and frameworks, focuses more on perception than it does on cognition. It is often the case that the relationship between perception and cognition is not discussed, or when discussed, it is done so in a nebulous manner. This is a likely consequence of the fact that the human perceptual system is a less complex phenomenon than the cognitive system, and its features are more easily observable and amenable to measurement and experimentation. Indeed, while research conducted throughout the past century has characterized many of the features of the human perceptual system, research findings are not as clear about cognition in general, and especially about higher-order cognition [59]. It should be noted that perception and cognition are indeed components of the overall human cognitive system, and that they cannot be entirely separated. For scientific purposes, however, it is necessary to make a clear distinction among them. As Pylyshyn notes, "visual perception does indeed merge seamlessly with reasoning and other aspects of cognition", but cautions that this view is "too broad to be of scientific value" ([59], p. 50).

This is not to say that an extensive understanding of the perceptual system, and how features of VRs affect perception, is not necessary. The human perceptual system does have its own independent characteristics that can be exploited if VRs are designed properly, and many such characteristics are important to have an awareness of in order to create effective visualizations. For example, our visual systems pre-attentively process many features within our visual field in less than 250 milliseconds—quickly, effortlessly, and in parallel—without requiring any conscious mental effort [29, 78, 79]. Such features include, among others, length, orientation, width, hue, curvature, and intersection (see [29]). Being aware of these features and their perceptual effects is therefore necessary for proper design of VRs. In addition, Harnad [27] suggests that the basic properties of our perceptual system may in fact give rise to our higher-order cognition. For instance, although colors differ only in their wavelengths, and exist along a continuum, our visual system detects qualitative changes, from red to yellow to orange, and so on. These bounded categories that are created by our pre-attentive processing may be what provides the groundwork for higher-order cognition [27]. Thus, what is important for visualization research is having the requisite knowledge to take both an analytic and a synthetic approach to perception and cognition to have a more comprehensive understanding of how VRs affect the performance of high-level cognitive activities.

2.3 Cognitive Activities and Complex Cognition

To engage in human-centric visualization research, researchers must understand the difference between simple and complex cognition. Simple cognition to low-level cognitive and perceptual processes such as recognizing objects in a visual field and identifying and comparing them. Complex cognition is emergent—that is, it results from the combination and interaction of simple processes such as perception and memory [21]—and is concerned with how humans mentally represent and think with and about information [41, 75]. When complex cognitive processes involve an active component, as in decision making and problem solving, they can be referred to as complex cognitive activities (see [57]). In this chapter, we have used the terms complex cognitive activities and high-level cognitive activities interchangeably. Although they are not technically synonymous, for the purposes of this chapter they have the same meaning.

Many of the phenomena that VTs are nowadays being applied to, such as climate change, insurance fraud, and disease outbreaks, necessarily involve the performance of complex cognitive activities. Consequently, to develop a more adequate understanding of the cognitive utility of visualizations, one of the necessary lines of research is to explicate this level of cognition in the context of the activities in which users engage. Researchers and practitioners require a sense of which cognitive activities a VT is intended to support, and what the characteristics of such an activity are, in order to effectively design and evaluate VRs. Another chapter in this volume [65] has identified a number of complex cognitive activities, characterized them, and has discussed implications for research and design of VTs. Readers are referred to this other chapter for more information (see also [63]). Also required is knowledge of what tasks can be carried out while performing an activity, and what low-level interactions are performed with visualizations to achieve the goals of such tasks. Such interaction-related concerns are beyond the scope of this paper, however, and readers are directed to other publications [57, 64, 65] that address these concerns more fully.

2.4 Current State of Research and Practice

To date, research has identified and characterized many of the pre-attentive and elementary influences that VRs have on perceptual and cognitive processing. For instance, Bertin's seminal work identifying "visual variables" [6], which have been further studied by subsequent researchers (e.g., [46, 47, 53]); Tukey's work on exploratory data analysis [80]; Cleveland and McGill's experimentation with elementary perceptual tasks [10]; and other similar work that is oft-cited in visualization literature has provided us with a good idea of how features such as color, shape, orientation, length, and texture affect simple cognitive processes. Not as well understood, however, are the effects of VRs on higher-order cognitive processes and their influence on the performance of complex cognitive activities.

Although the need for a deeper understanding of cognitive effects of VRs has been identified in the literature (see [63]), many recent research contributions still place most or all of their focus on low-level considerations, providing guidance for choosing appropriate layouts and visual encodings, focusing on position, layout, axes, color, size, proximity, gestalt laws, depth cues, and so on (e.g., [38, 50, 51, 82]). Survey-style articles (e.g., [7, 30]) also do not discuss effects on higher-order cognition. In their research and development agenda for visual analytics, while acknowledging that this aforementioned type of work is valuable, Thomas and Cook suggested that cognitive principles relevant to analytical reasoning with VRs must be "better understood", and that "we are far from having a complete, formally developed theory of visual representations" ([77], p. 71). While this was stated several years ago, other researchers have recently made similar claims, suggesting that this problem still exists. For instance, in the context of geovisual analytics, Fabrikant states that "we still know little about the effectiveness of graphic displays for space-time problem solving and behavior, exploratory data analysis, knowledge exploration, learning, and decision-making" ([17], p. 139). Green and Fisher have also recently suggested that "there is still a lack of precedent on how to conduct research into visually enabled reasoning. It is not at all clear how one might evaluate interfaces with respect to their ability to scaffold higher-order cognitive tasks." ([22], p. 45). In other words, we still know little about researching and designing VRs that effectively support complex cognitive activities.

In industry, the problem may be even worse, as there seems to be a disconnect between the research that does exist and how visualizations are typically designed. On this topic, Few [18] suggests that "products . . . promote data visualization in ways that feature superficially appealing aesthetics above useful and effective data exploration, sense-making, and communication." Even relatively recent books that are geared towards practitioners (e.g., [32, 36]) mention only perceptual concerns and do not provide any guidance for facilitating cognitive activities. The next section attempts to address some of these problems by discussing how some common visualizations influence the performance of high-level cognitive activities.

3 Common Visualizations and Their Utility

This section identifies some common visualizations—i.e., common categories in which instances of VRs can be placed—and their perceptual and cognitive influences, with a particular attempt to identify utility for complex cognitive activities. Perceptual effects are described to help give a more complete picture of the overall utility of VRs. This is especially true for perceptual effects that are not typically referenced in the visualization literature. Because research on high-level cognitive utility is not comprehensive or universal, some VRs have received more attention than others in the existing literature. Since we cannot report research that has not been conducted, some sections have more support than others. However, where appropriate, we will make inferences about the possible utility of some VRs and techniques. In addition, where applicable, we will provide empirical evidence based on studies that have been conducted in areas such as cognitive and perceptual psychology and learning sciences. Each category will be briefly characterized and then its utility discussed.

3.1 Visual Encodings and Marks

Visual encodings, also known as visual marks, are atomic visual entities such as lines, dots, and other simple shapes. Visual encodings are the building blocks of more complex VRs. Thus, their cognitive utility does not typically arise from their isolated existence and is best discussed in the context in which they are employed in more complex VRs.

3.2 Glyphs and Multidimensional Icons

Glyphs, also known as multidimensional icons, combine and integrate a number of encodings into one visual entity. Glyphs often make use of multiple visual variables such as color, shape, size, length, and orientation, to encode multiple properties of information items. In doing so, glyphs exploit the perceptual system's ability to discern finely resolved spatial relationships and differences [60]. Wickens and Carswell [83] have investigated how the integration of multiple encodings into one visual entity (e.g., a glyph) can result in emergent features that cannot be communicated with the encodings alone. While such emergent features may be detected pre-attentively by the perceptual system, Wickens and Carswell note that glyphs may engender conscious cognitive processing of information by having attention drawn to such features. That is, glyphs may demand conscious cognitive effort and facilitate higher-order cognitive processes due to the salience of their emergent features. Therefore, although some of the utility of glyphs comes from their perceptual effects that exploit the features of the human visual system, their utility for performing cognitive activities can also be considered. This may be especially true when multiple glyphs are combined within a VR. For example, consider the ClockMap technique [19] shown in Fig. 2. The empty (white) chunk of the glyph in the middle of the VR draws attention and engenders higher-level cognitive activities such as knowledge discovery and sense making. Users may pose questions, engage in exploratory analysis, drill further into the information space to look for patterns, and so on. Since glyphs allow multiple dimensions to be parsed and compared quickly by the perceptual system, they are useful for facilitating the identification of trends and patterns that can assist in high-level cognitive activities such as decision making [48]. In a decision making activity, the attention that is drawn to emergent features may facilitate the choice of one among a number of alternatives within an information space. In one study, Spence and Parr [72] found that subjects who used glyphs for a decision making activity required half the time as subjects who used other VRs.

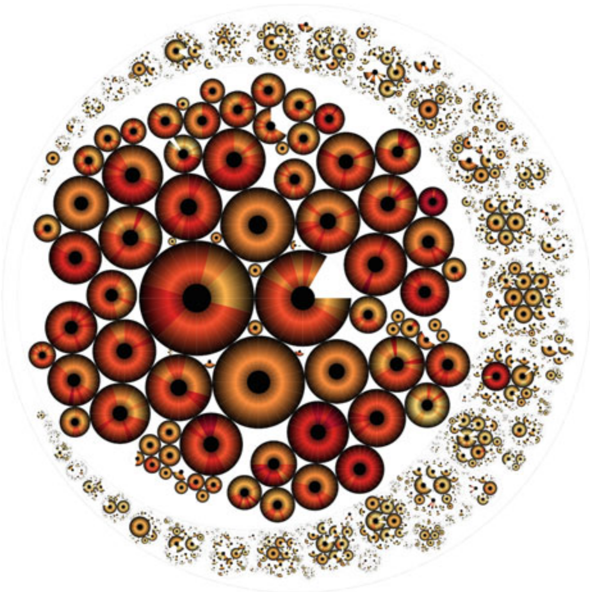

Fig. 2 A VR that uses the ClockMap technique (CC BY-SA 3.0, Fabian Fischer, http://ff.cx/clockmap/)

3.2.1 Techniques

Some common techniques are Chernoff faces [9], Clockeye glyphs [19], multidimensional icons, stick figures, star glyphs, timewheels, multicombs, spikeglyphs, stardinates, kite diagrams, and whisker glyphs. Figure 2 shows a VR that uses the ClockMap technique, which uses a number of small Clockeye glyhps.

3.3 Plots and Charts

Plots, also known as charts, map information onto coordinate systems. Plots help users to think about the distribution of information by depicting the location of information items relative to an axis. For example, plots can facilitate the perception of anomalies, deviations, and outliers, and thus facilitate the performance of cognitive activities that involve reasoning about trends and patterns within an information space [28, 33, 58]. Because of such perceptual suggestions, the solution to a problem involving linear functions, for instance, can be much more apparent when the information is encoded with a plot than with mathematical symbols [3]. For example, an equation such as $y = x2 + 5x + 3$, fails to make explicit the variation which is perceptually evident in a conceptually-equivalent plot [1]. Different types of plots serve different perceptual and cognitive functions.

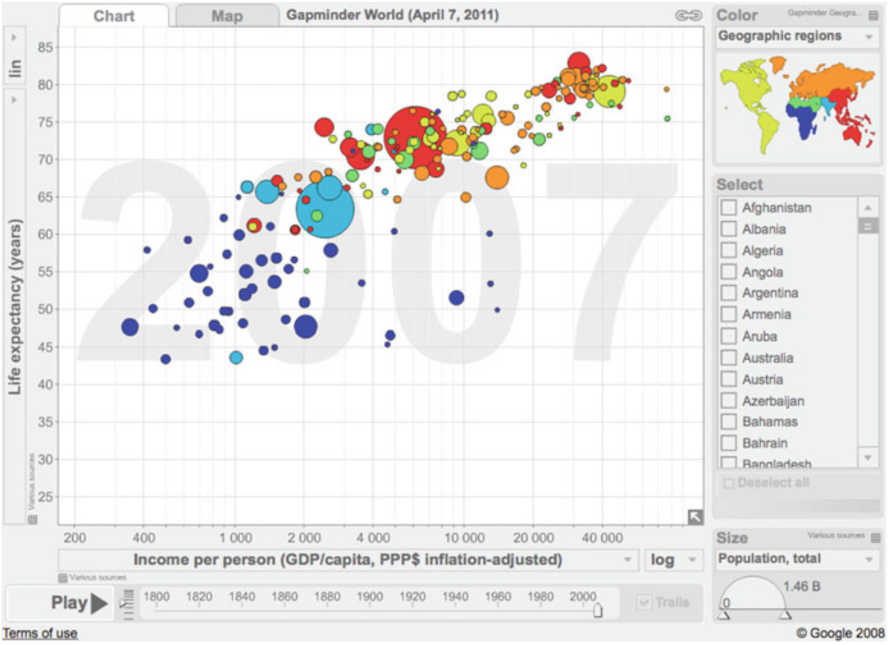

Fig. 3 A VR that uses the scatterplot technique (Used with permission from www.gapminder.org. Data from www.gapminder.org/data)

For instance, bar graphs can be used to facilitate comparisons among discrete or categorical information, whereas line graphs can be used to facilitate reasoning about trends and linear relationships [28, 68, 85].

3.3.1 Techniques

Some common techniques are scatterplots, column, line, circular, bar, area, point, trilinear, vector, radar, nomograph, contour, wireframe, and surface graphs, and parallel coordinates. Figures 3 and 4 show VRs that use scatterplot and parallel coordinate techniques respectively. By distributing the information relative to axes, users can quickly perceive outliers and anomalies within an information space. This can assist with knowledge discovery, for example, by helping users explore an information space to identify the distribution and dispersion of information items, formulate hypotheses based on observed patterns, trends, anomalies, and outliers, and discover new and unsuspected correlations and potential causal relationships.

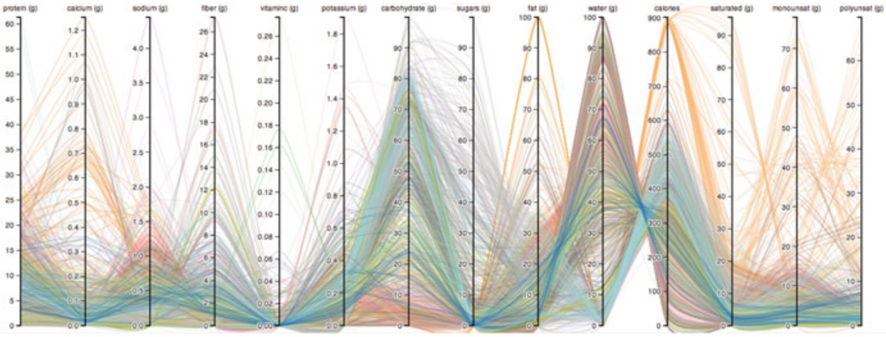

Fig. 4 A VR that uses a Parallel Coordinates technique (Created by Kai Chang, Mary Becica and Vaibhav Bhawsar, http://exposedata.com/intake/. Used with permission under GNU General Public License V3.0. Data from USDA Nutrition Database)

3.4 Maps

Maps spatially distribute information in such a manner that geometric properties of the VR correspond to geometric properties in the information space. Maps can represent both concrete and abstract information spaces. An obvious example of a concrete information space is a VR of a geographical area. In such cases geometric properties of the information space map naturally to geometric properties of the VR. In the case of abstract information, entities within an information space, such as concepts and ideas, may be encoded such that locations, relative distances, and other geometric properties depict semantic distance, categorical similarity, and so on. Representing abstract information spaces in such a way may facilitate the development of mental models of an information space, considering that research in cognitive science has demonstrated that spatial metaphors form a foundation upon which all conceptual structures are built (see [42]). Maps are effective at facilitating high-level cognitive activities requiring spatial reasoning, route planning, and spatial navigation [5, 15, 31, 44]. Consequently, maps also facilitate better decision making and problem solving regarding geographic information—while making decisions about land use, for example [54]. Likewise, maps can facilitate reasoning and higher-order thinking about spatial patterns such as the spread of disease, distribution of mortality rates, and weather patterns [2, 25]. John Snow's map of cholera, for instance, reportedly helped to identify the cause of the cholera outbreak in London in 1854. In a study, Smelcer and Carmel [70] found that for tasks that require geographic, spatial analysis, problems were more effectively solved when the information was encoded with a map than other VRs.

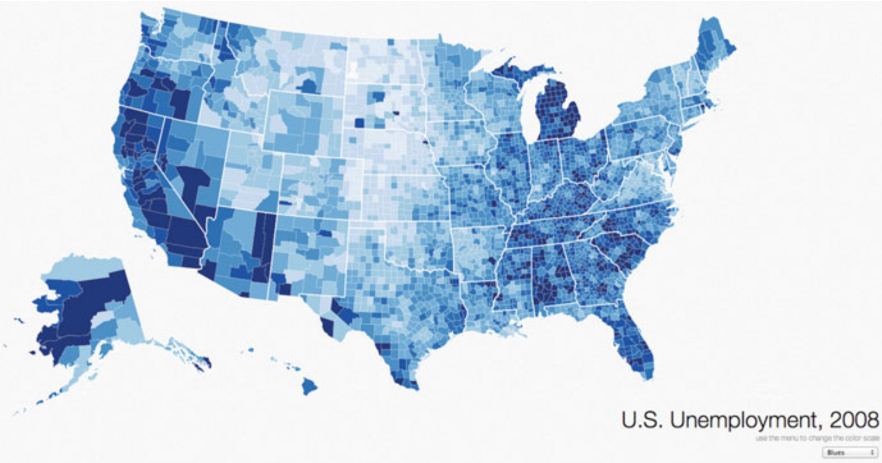

Fig. 5 A VR that uses the Choropleth technique (Created with D3.js, http://mbostock.github.com/d3/talk/20111018/choropleth.html)

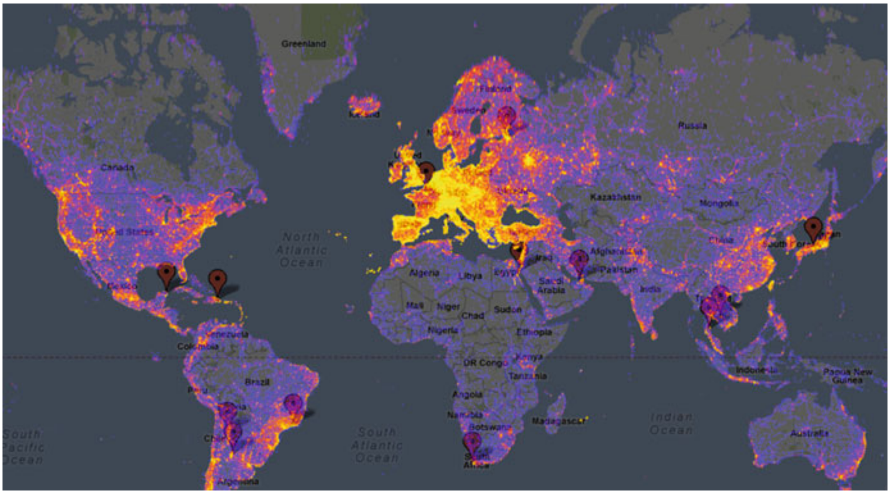

Fig. 6 A VR that uses the heatmap technique (Used with permission under CC BY 3.0 License, http://www.bluemoon.ee/~ahti/touristiness-map/)

3.4.1 Techniques

Some common techniques are thematic, nautical, weather, geologic, topographic, choropleth, and isarithmic maps, cartograms, Themescapes [84], Self Organizing Maps (e.g., [69]), and heatmaps. Figures 5 and 6 show VRs that use choropleth and heatmap techniques respectively. By representing an information space in such a way, users can quickly perceive the distribution and density of information such that cognitive activities are supported. The VR in Fig. 5, for instance, by using color to encode density, facilitates the quick processing of the distribution of information across different geographic regions. Such a VR could then help policymakers to make decisions about job growth strategies or to solve problems regarding the optimal geographic distribution of employment centers.

3.5 Graphs, Trees, and Networks

Graphs, also known as trees and networks, connect information items with lines, arrows, and other shapes. The connections that are used in graphs are readily detected by our perceptual systems at the level of Gestalt organization [56], and thus powerfully express relationships [81]. This perceptual utility can facilitate high-level cognitive activities that involve reasoning about relationships within an information space. For example, Spence [71] recounts a case of mortgage fraud investigation where eight person-years were spent identifying a perpetrator using typical linguistic representations on static, paper-based media. The same information space was later investigated with a visualization that used a radial technique to represent the relationship network among purchases, lenders, and solicitors. Using this VR, the perpetrator was found within four weeks by a single investigator—a time improvement of a factor of about 100. Spence submits that the explicit relationships depicted by the VR played a valuable role in understanding the relationships within the information space. Cognitive psychologists Novick and Hurley [52] conducted a study investigating structural features of VRs, and concluded that the structural properties of graphs facilitate inference-making about movement, transition, or relation more so than other types of VRs. Furthermore, their study indicated that the structure of graphs and networks facilitates reasoning and problem solving when subjects already mentally represent the information space in graph and network forms.

3.5.1 Techniques

Some common techniques are tree, arc, radial, network, node-link, flow, decision, layout, circuit, concept, and decision diagrams, cone trees [61], and hyperbolic trees [43]. Figures 7 and 8 show two VRs that use a typical node-link technique and a radial convergence technique respectively. The VR in Fig. 7 depicts the relationships among different classes in a java program. The connections between items, as well as encoding techniques such as color and size, exploit the user's perceptual system and thus facilitate higher-order cognition. In a sense making activity, for example, the object and string classes immediately stand out and draw attention, allowing the user to identify questions that further the activity, such as why certain classes have more connections, leading to the development of mental models that incorporate the structure and texture of the information space.

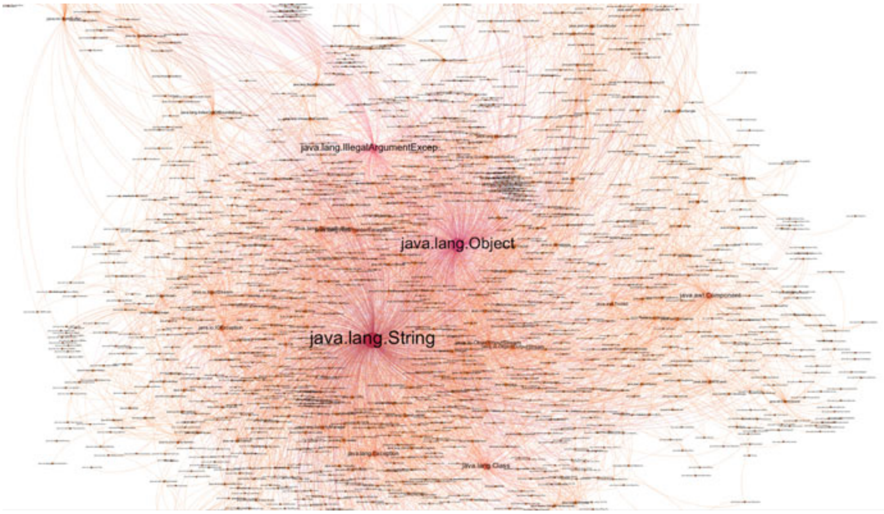

Fig. 7 A VR that uses a typical node-link technique (Created with Gephi, www.gephi.org)

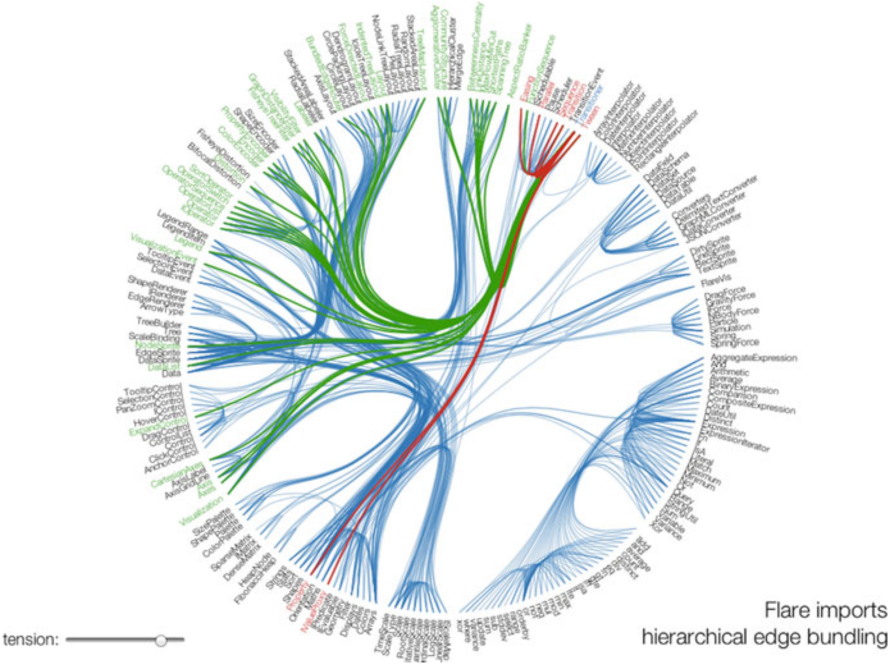

Fig. 8 A VR that uses the radial convergence technique (Created with D3, http://mbostock.github.com/d3/talk/20111116/bundle.html)

3.6 Enclosure Diagrams

Enclosure diagrams place information items in different regions of space. There is a strong perceptual tendency to see information as being inside or outside an enclosed region [81], and thus such regions perceptually suggest commonality [55]. Although VRs such as Venn diagrams exploit properties of the perceptual system, they do so in such a way as to facilitate higher-order cognition [59]. For instance, research in psychology and diagrammatic communication and reasoning suggests that techniques such as Venn and Euler diagrams, which contain or segment information, can help with reasoning about class or set membership and inclusion and exclusion of information [20, 24, 26, 76]. When their perceptual and cognitive effects are combined, enclosure diagrams can act to constrain the set of possible inferences that can be made, and thus facilitate and canalize higher-order thinking processes [14, 74]. Accordingly, such VRs can facilitate high-level cognitive activities such as decision making and problem solving by constraining the set of alternatives that one must consider during a decision making activity, and specifying paths and commonalities among different problem states within an information space.

Enclosure diagrams such as tables and various types of matrices are useful for representing precise and indexical information, both in a quantitative and qualitative manner. Their utility is due to the fact that they facilitate the extraction of exact numerical values or single bits of information, even within large sets of information [13, 25, 70]. In doing so, such VRs facilitate problem solving, by making missing information explicit (e.g., with empty cells) and directing attention to unsolved parts of a problem [14]. In Mendeleev's periodic table of elements, for example, the empty cells that the table displayed helped to predict the discovery of yet unknown elements, and the properties of known and unknown elements could be predicted from their positions within the table [39]. Such VRs also tend to support quicker and more accurate read-off, and highlight patterns and regularities across cases or sets of values [1].

3.6.1 Techniques

Some common techniques are Venn, Voronoi, and Euler diagrams, adjacency matrices, analytical, frequency, percent, contingency, time, and bidirectional tables, TreeMaps [35], SunBursts [73], and DocuBursts [12]. Figure 9 shows a VR that uses the TreeMap technique. By enclosing the different food groups, commonality is naturally suggested to the user's perceptual system. Moreover, visual variables such as size and color also make perceptual suggestions, and can facilitate high-order cognition. For example, in a sense making activity, the user must identify and reason about the structure and texture of the information space, identify the major divisions and groups within the information space, and ask important questions (e.g., why is there only one green box in the 'fats' category?), all of which are made easier due to the manner in which the VR exploits features of the user's perceptual system.

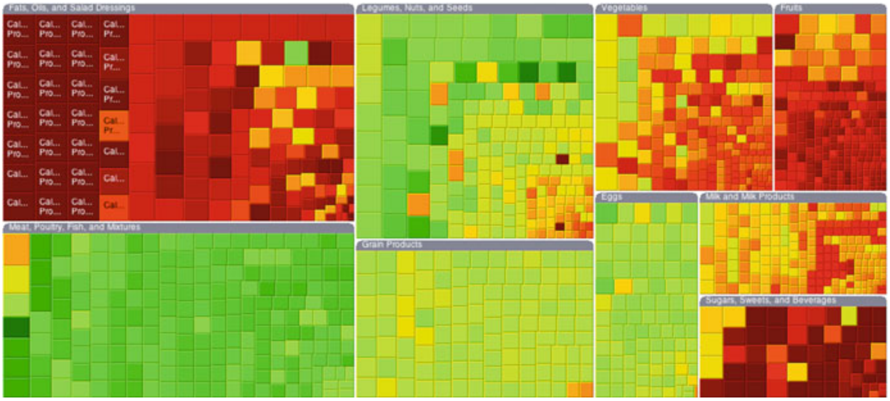

Fig. 9 A VR that uses the Treemap technique (www.hivegroup.com. Used with permission)

4 Summary and Future Research

Much of the visualization research to date has focused on low-level perceptual and cognitive effects of VRs. While important, this addresses only part of the picture. What is needed is further research into how VRs affect higher-order cognition and the performance of complex cognitive activities such as sense making, knowledge discovery, and decision making. The development of an adequate body of research in this regard requires moving beyond the familiar territory of visual variables and pre-attentive perceptual processes. What is needed is a systematic investigation of how visualizations influence cognition to, for instance, canalize and scaffold higher-order thinking processes, assist in discovering the structure and texture of an information space, and facilitate the investigation and selection of alternatives in a decision making process. Much future work is still required, and this chapter has attempted to make a contribution to this research challenge by discussing the utility of some common visualizations for performing complex cognitive activities.

As was mentioned earlier, research into the effects of VRs on the performance of complex cognitive activities is still in the early stages. As a consequence, there are many different lines of future research that can be identified. One is concerned with systematic research being done in visualization disciplines on how visualization impact higher-order cognition. Much of the support that has been provided in this chapter is from disciplines not concerned specifically with interactive VTs and/or VRs. Although in itself this is not a major problem, it would likely be beneficial for more visualization researchers to study these issues in the context of modern visualizations for at least two reasons. First, research in cognitive science and other areas does not examine the techniques particular to data visualization, visual analytics, and similar areas, and thus the application of research from such disciplines has limitations. Second, and of particular importance, is that visualizations nowadays are very often interactive and/or dynamic, which adds many new research questions and challenges that are not addressed by older research on static VRs.

This chapter has grouped a number of common VRs loosely based on some common features to discuss their utility for performing cognitive activities. Future research should develop more comprehensive and elaborate taxonomies and catalogs of VRs that bring more order and structure to the visualization landscape. Additionally, as has been previously suggested by researchers in information visualization (e.g., [16]) and visual analytics (e.g., [77]), one useful but challenging line of research is in developing a pattern language to guide and bring systematicity to the design process.

Still another area of needed research is the performance of more empirical studies that examine the effects of different VRs on high-level cognitive activities. Although some studies have been mentioned in this chapter, many are outdated and were not carried out in the context of modern visualizations. Also needed is a closer investigation of the relationship between perception and cognition and how perceptual effects of certain visualizations may naturally facilitate certain cognitive activities.

Finally, a grand challenge of such research must be to develop comprehensive descriptive and prescriptive frameworks that integrate the aforementioned lines of research. Descriptive frameworks can capture a broad range of considerations to help thinking about the utility of all kinds of visualizations for many different cognitive activities. Prescriptive frameworks can provide visualization design guidance by identifying principles for supporting cognitive activities in general, as well as for supporting particular activities, users, contexts, and domains. Carrying out these aforementioned lines of research can make a positive contribution to the visualization literature, and can help develop a more comprehensive understanding of how visualizations can and should be used to support high-level cognitive activities.

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