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Technical Section

A human cognition framework for information visualization ☆

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ABSTRACT

We present a human cognition framework for information visualization. This framework emphasizes how top-down cognitive processing enables the induction of insight, reasoning, and understanding, which are key goals of the visual analytics community. Specifically, we present a set of six leverage points that can be exploited by visualization designers in order to measurably influence certain aspects of human cognition: (1) exogenous attention; (2) endogenous attention; (3) chunking; (4) reasoning with mental models; (5) analogical reasoning; and (6) implicit learning.

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1. Introduction

Information visualization refers to the interdisciplinary field concerned with the visual representation of complex information in ways that enhance understanding [1]. The field draws from such disciplines as computer science, graphics, visual design, psychology, mathematics, and business. The role of information visualization is to leverage the functioning of the human visual system in an effort to provide insight about abstract information [2], to help humans resolve logical problems, to think and reason [3], and to provide help in understanding data [4]. High-level cognitive functioning, such as developing insight, reasoning, and understanding, is engaged by visualization techniques because visual perception possesses *special properties* [3], is *attuned* to visual images [2], and it performs *pattern recognition* [4].

These statements, and others like them, are likely to be true, and have been a focus of the visual analytics community. Yet they lack details and specificity in the linkage between visualizations and the induction of high-level cognitive reasoning and understanding. To articulate the mechanisms and processes supporting high-level cognition, we need to place information visualization within a detailed foundation of cognitive psychology. Accordingly, we see information visualization fundamentally as a *human cognition-augmentation* issue and propose that well-designed visualizations induce reasoning and understanding by influencing high-level cognitive processes such as retrieval from long-term memory, in addition to leveraging human visual perception capabilities.

Our focus in this paper is on a *human cognition framework for information visualization* which makes direct contact with underlying cognitive processes that enable the induction of insight, reasoning, and understanding. We specifically conjecture that there is a set of leverage points a given visualization designer might exploit in order to influence human cognition in the visual analytics process.

Patterson [5] identified a number of principles for information display design in order to shift the emphasis in much of the display community from entertainment to task-oriented representations of information. In this paper, our aim is to offer a broader framework for the visualization design process through the identification of key leverage points.

Research on human cognition has been utilized to varying degrees in interaction design and analysis by the Human–Computer Interaction (HCI) and Human Factors and Ergonomics (HFE) communities. For example, the HCI community has primarily focused on performance evaluations of two or more designs for a given task, where best performance on measures such as response time and accuracy is taken to indicate design effectiveness. Many of the design principles prominent in the HCI/HFE community are summarized as lists of Dos and Don'ts, which provide very general guidance [6–8]. The supporting rationale that connects these guidelines to perceptual/cognitive capabilities are

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not obvious, so the actual implementation of the guidance is often interpreted by the designer. More recently, a few authors have embarked on more theoretical approaches, such as Huang et al. [9] who developed a measure of cognitive load they called mental effort.

Many topics in human factors-based design have not been explored by the visualization community in much depth. Much of the current methodology for designing visualization tools and interfaces is still *ad hoc* and informal. Only a few visualization designs utilize perceptual and cognitive theories. Tory and Moller [10] suggested that, because many areas of perception and cognition research are likely not utilized to their full potential, further work in this area is promising. These authors provided a survey of possible perception and cognition support for information visualization, such as methods for improving perception of 3D shape, techniques to more easily distinguish and highlight objects, new interaction methods and input devices (e.g., real-world props), faster rendering for better interactivity, interfaces to make transfer function specification easier, and methods of reducing memory load (e.g., detail and context displays).

It is in the spirit of Tory and Moller [10] that we offer our human cognition framework for information visualization. We first present a selected review of the literature on information visualization. Next is a section that presents our human cognition framework for information visualization, which includes a theoretical perspective and an overview of human cognition. We then present a set of six leverage points with specific suggestions for assessing the design choices through human performance measurement. The leverage points we provide tie a particular design principle to human cognitive processes so the designer understands why a particular recommendation is made. We illustrate in the next section the implementation of our framework in the visualization design process and a case study. Finally, we relate our perspective to some other theoretical frameworks for human cognition which may complement the implementation and assessment of our human cognition framework for visualization.

2. Information visualization

Information visualization has several design reference models, many of which now include the users interpretation of the visualization; almost all focus on the synthesis process and present alternative taxonomies for classification or synthesis methods. For example, in a pipeline design model based on Card et al. [3] (Fig. 1) the focus is on displaying data, and the involvement of the user's cognition is left undefined.

In one early synthesis model, Bertin [11] used perceptually based graphical symbols and marks to generate the visual representations. Aspects of these symbols were position, shape, size, brightness, color, orientation, texture and motion. There are other models [3], some of which include other perceptual modalities (e.g., audio or tactile), but none offer explicit treatment of the cognitive activity engaged by the user in the visual design process [12].

Formalization marked the beginning of a change from the early models. Mackinlay [13] developed the first computational approach to rule generation with the Automatic Presentation Tool (APT). Wehrend and Lewis [14] believed that by categorizing all visualizations (or at least the large number with which they started), the catalog could be the target of an automatic visualization selector based on suitable values. Roth et al. [15] used composition to create more complex displays, including extensions to 3D. Keller and Keller [16] defined visualization goals; Shneiderman [17] used data types for classification; Ward et al. [1] added user interaction.

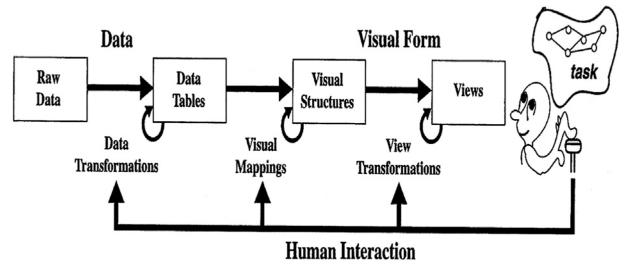

Fig. 1. Typical pipeline of information visualization design found in the visualization literature. The pipeline's focus is on displaying data, and the role played by the user's cognition is unspecified.

The incorporation of human cognition into the visualization process demarcates the modern approach. Casner [18] was one of the first to start generating perceptual task-driven displays from decision-making task descriptions. The effects of visualizations on the user's ability to mentally visualize data were examined by Zacks, Tversky and colleagues [19–22]. Finally, North [23] tried to quantify the user's insights gained through the use of visualization.

Thus, some modern theories do mention perception and cognition in their synthesis models, but most do so in a limited fashion; the connection of the visualizations to actual perceptual or cognitive processes is usually vague and leads to no or few measurable outcomes or guidelines. The approach of simply tacking on a final stage called 'User', as in Fig. 1, is very problematic because it ignores the complex nature of human cognition as the user engages with the visualizations [24,25].

The compelling need for a precise understanding of human cognition in the design of information visualizations can be appreciated by considering a study by Elting et al. [26]. In this study, participants interpreted multiple joint and conditional probabilities presented in four different graphical formats: a numerical table, a pie chart, a divided (stacked) bar chart, and an icon display. Elting et al. [26] found that the numerical table was the most preferred display format, yet it produced a lower level of decision-making accuracy relative to the icon display. The icon display was preferred by no participants and disliked by a quarter of the participants, but it produced the highest level of decision-making accuracy. The pie chart and bar graphs, which were also preferred representation techniques, yielded the lowest accuracy. Thus, visualization designers cannot rely only upon the subjective preferences of users because subjective preference may not be a reliable indicator of objective performance. Instead, designers should take the cognitive processes of the user into account in order to ensure that objectively measured performance is facilitated.

Designing an information visualization for good analytical reasoning is akin to designing graphical presentations of data for 'information extraction' rather than 'data availability' [27]. In data availability, data is displayed so that the burden of identifying, remembering, and drawing inferences from information is placed on the user. In information extraction, data is displayed to facilitate human cognitive processing, which takes advantage of graphical primitives or elementary cognitive codes, like length, angle, or area.

But we can go much deeper than such primitive codes. We can directly link information visualization with high-level cognitive processes such as reasoning and thinking. In doing so, we present a *human cognition framework for information visualization* and argue that visualizations should engage and promote high-level cognitive functioning.[1]

[1] It is important to note that we are explicitly stating that a well-designed visualization should influence high-level cognitive functioning within the environmental context *for which it was designed* but will not necessarily be effective outside of that context.