From subjectivity to objectivity in information visualization: challenges in bridging the gap between cognitive theory and information design.

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ABSTRACT

Information designers often provide information product (such as information visualization output) based on their intuition, knowing little about the effectiveness of graphic displays and human perceptual capabilities. Designers' focus is typically rather on finding out which design works best than to understand how and why. Since information visualization is said to support decision-making we argue and propose that information design theory must include knowledge about the domain which enables decision-making, namely the brain.

KEYWORDS: Information design, visual attention, visual variables.

INDEX TERMS: H.1.1 [Systems and Information Theory]: General Systems Theory; H.1.2 [User/Machine Systems]: Human factors

1 INTRODUCTION

Since the computational advances in the 1980s information visualization research concentrates on the objective quality of systems. Cognitive research on the more subjective quality of decision-making lags far behind the ongoing data acquisition and the development of useful algorithms. As a result a large discrepancy between users and systems exists: whereas systems process large datasets faster and more accurate than users, users visually process information more rapidly and precisely than systems. To better link systems' computation capability to users' visual skills we suggest to intensify the use of knowledge about brain processes in information design theory.

In the 1980s psychologists could provide first evidence for an intrinsic visual information processing network [1]. Since then cognitive research has provided sophisticated knowledge about how and why humans process visual information. Surprisingly, this knowledge has rarely found its way into information design research. The brain is treated somewhat like a black box. Still, the focus is on finding out which information design works best. Fundamental basic research on why a design may be more effective than others and on how users extract knowledge from graphic information has received considerably less attention. As information visualization is said to support decision-making we propose to open this black box, i.e., to include in information design theory knowledge about what makes decision-making possible, namely brain processes between visual input and behavioural output.

2 RELATING BRAIN PROCESSES TO INFORMATION DESIGN

After having reviewed the amount of definitions for 'information visualization' one can identify two basic aspects; it abstracts complex information, and supports decision-making. We believe that, from an information designers' perspective, it is hence favourable to first borrow knowledge from psychology for understanding how people generate decision-making to then adapt the design of information to their cognitive skills.

Human behavioural performance depends on, and follows, the selectivity of neurons, the basic units of brain areas. Inspired by this phenomenon, we consider the function of a brain area as a promising starting point. It initiates our study on the relationship between intrinsic visual information processing and external information visualization.

2.1 Intrinsic Visual Information Processing

Information processing itself is a constructive process that does not only depend on the encoded information of a given stimulus. It is also controlled by intrinsic characteristics of visual information processing (Fig.1). After sensory signals on the eye's retina (RT) have been extracted by the visual system, the primary visual cortex (V1) distributes these single features to two main paths. Neurons in brain areas along the *where path* respond to spatial vision. Neurons in brain areas along the *what path* are selective in object vision. Both streams converge into the prefrontal cortex (PFC) involved in binding visual input into a unitary concept of information. Depending on working memory processes, PFC participates in decision-making. Finally, signals are send to areas which monitor eye-movements.

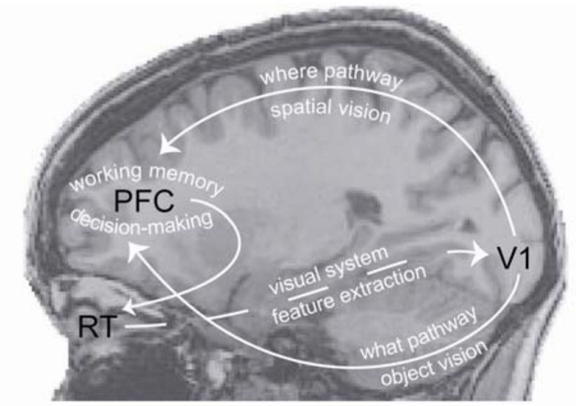

Figure 1. Basic visual information processing sequences. Retina (RT), primary visual cortex (V1), prefrontal cortex (PFC).

2.2 External Information Design

Information designers often formulate visualizations based on Bertin's visual variable theory [2]. His seminal work providing the basis for successful information visualization in general [3] reconciles data attributes with graphic symbol characteristics to encode information. New computational visualization methods

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have inspired researchers to develop extensions of this approach. Others have presented sets of sonic, tactile, and dynamic variables, all inspired by Bertin's concept of graphic semiology. Interestingly, the concept, often referred in cartographic literature to as 'cartographic language', is applied to information design intuitively. It has neither explicitly been based on cognitive theory nor empirically evaluated.

2.3 Cognitive Relationships

We have specified brain area functions along processing paths and visual variables in graphic displays as the two basic interacting components involved in generating knowledge from information visualization. In this section we elaborate on their cognitive relationship. We do so based on two hypotheses which are inspired by MacEachren's [4] perspective on communicating information through maps and knowledge in cognitive psychology. MacEachren suggested that maps do not contain nor transmit messages to map readers. We refine this view and hypothesize that information visualizations are complex visual stimuli which are then combined by intrinsic processes to form meaningful information. Furthermore, MacEachren suggests that maps stimulate inference-making and thus can generate new knowledge. We also refine this view and hypothesize that information visualizations stimulate functions of brain areas along the *where* and *what* processing paths, to then include knowledge for a specific task.

In the following, we use the above-described perspective on underlying cognitive processes to model the relationship between intrinsic processes and external information design. The model consists of four visual information processing domains (Fig.2).

Figure 2. Cognitive relationships between external (continuous line) and intrinsic (dashed line) processing domains.

(1) *Sensory signaling* specifies a design methodology which follows cognitive design principles. The relevant information within this methodology is displayed with a set of visual variables that must match with visual cues known to trigger neural response in brain areas along the *where* and *what* paths.

(2) *Detecting* includes the visual system and respective brain areas along the *where* and *what* paths responding to object and spatial properties more or less independently. This functional segregation reduces information complexity by separating the recognition of a stimulus from its location.

(3) *Converting* determines areas which neurons are selective to working memory processes like transforming sensory signals into information and decision-making.

(4) *Performing* includes brain areas involved in initiating and executing visuo-motor tasks like stimulating eye muscles to direct gazes to relevant information.

The cognitively inspired design methodology (*sensory signaling*) simplifies the extraction of visual input, and systematically stimulates visual brain area functions (*detecting*). This sequence reduces the cognitive workload and improves the efficiency of inference and decision-making (*converting*). The more effectively we can adapt the design of information to these components, the more markedly we might reduce the workload imposed on users, and optimise attentional capacities respectively. In turn, we expect to improve the decision-making performance (*performing*) which we judge amongst others by means of improved gaze shifts towards information of interest.

3 DISCUSSION

We proposed that information design theory should include knowledge about relevant brain processes as they monitor how and why people process information. This might help to understand how and why information visualization works.

During our work, we have noticed that modeling the relationship between brain processes and information design quickly results in too complex, not understandable diagrams. This occurred particularly when we related specific design issues to the interplay of sensory-guided (bottom-up) and memory-guided (top-down) information processing. We have therefore shifted our focus towards the functional relationships between basic intrinsic processing sequences that neuroscientists determined by means of neuroanatomical tract tracing methods. As neurons in visual brain areas tend to respond to sensory input 'chronologically' we aim to systematically design information that first triggers lower brain area functions (along the *where* and *what* paths) to cause the release of higher functions (e.g., decision-making).

One might argue that considering the behavioural performance as an intrinsic domain (Fig.2) is somewhat contradictory as we investigate amongst others externally observable eye-movements. In fact, we can record eye-movement parameters from outside the brain. However, previously activated brain areas initiate, monitor, and control these movements. Therefore studies on the design of mediating artifacts, like those conducted in the emerging area of neuroergonomics, also combine eye movement recordings with brain imaging techniques.

4 CONCLUSION

We have sketched a theoretical approach that brings brain processes to the fore of information design theory to better adapt the design of information to the visual skills of users. In collaboration with neuropsychologists, we followed an inductive research tradition by systematically decomposing the two basic interacting domains 'brain' and 'design' into their primitives (i.e., brain area functions and visual variables). So far, we have taken advantage of this atomistic approach. In a previous study we have cross validated the perceptual effects of individual components (e.g., a set of ordinal variables matched with visual cues) with a computational attention model. In turn, we then evaluated the overall graphic impact of these computer generated outcomes on a user with human test participants.

Based on the theoretical framework presented here, we currently decompose an information design space into sub-dimensions. This enables us to identify thresholds for information saliency and demotion as well as for information complexity in more detail. A basic challenge within this concept is to transfer knowledge and test-methods from psychology to information visualization in a meaningful way.

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