

Science and Smart Graphics

Wissenschaft und intelligente Grafiken

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Summary As the field of informatics matures, the range of disciplines that contribute to our understanding of information systems and their use must increase. The International Symposium on Smart Graphics is one of the pioneers of this interdisciplinary scholarship of computation. The highly interactive workshop format includes participants from cognitive and perceptual sciences, art and design, and the humanities as well as the more familiar disciplines of human-computer interaction, artificial intelligence and computer graphics. This paper describes how the new science of visual analytics has built upon the interdisciplinary conversations that events such as Smart Graphics began. This new field of research holds a great deal of promise for a variety of application areas, and serves as an example of how the Smart Graphics approach can support other emerging fields of study. ▶▶▶ **Zusammenfassung** Je weiter sich

die Informatik als Forschungsgebiet entwickelt, desto wichtiger wird es, andere Disziplinen heranzuziehen, um Informationssysteme und ihre Anwendung insgesamt zu verstehen. Das Smart Graphics Symposium ist einer der Wegbereiter dieses interdisziplinären Ansatzes. An den sehr interaktiven Veranstaltungen nehmen Wissenschaftler verschiedenster Richtungen, wie Kognitions- und Wahrnehmungs-Wissenschaft, Kunst und Design, aber auch konventionellere Ausrichtungen innerhalb der Informatik, wie Künstliche Intelligenz und Computergraphik teil. Dieser Artikel beschreibt, wie das neue Forschungsgebiet Visual Analytics auf dem interdisziplinären Diskurs aufbaut, der bei Gelegenheiten wie dem Smart Graphics Symposium begonnen wurde. Dieses neue und viel versprechende Forschungsgebiet dient als Beispiel, wie die Methodik von Smart Graphics entstehende Forschungsgebiete mit formen kann.

Keywords 1.3 [Computing Methodologies: Computer Graphics]; visual analytics, cognitive science, interdisciplinarity, interaction design, graphics ▶▶▶ **Schlagwörter** Computergraphik, Kognitionswissenschaft

1 Introduction

At the closing session of the 2005 International Symposium on Smart Graphics at Frauenwoerth Cloister, participants identified a variety of ways in which interactive graphics can be “smart”. These include:

- “Smart” AI techniques for computer graphics, e.g., intelligent camera control,
- “Smarter” design of computer graphics, i. e., better informed by graphic design knowledge and by theories of human perception and cognition, and
- Overall “smartness” of the human-computer system in the performance of cognitive tasks, such as situation assessment and decision-making.

This paper will briefly overview each of these topics with the goal of integrating them into a coherent whole. We will then describe how the “smart graphics approach” has helped to guide a new field known as *Visual Analytics*. Defined as “the science of analytical reasoning supported by interactive visual interfaces” [1], visual analytics is

characterized by human interaction with graphical depictions of data, information and knowledge with the goal of solving complex “wicked problems” in diverse application domains. I will suggest that visual analytics provides one example of how Smart Graphics’ unique interdisciplinary approach can bear fruit. Other examples exist in other application areas, such as games and simulations, which are also characterized by an emphasis on human cognitive, social, or experiential outcomes as a metric of the success of the technology that delivers those experiences. Among the shared characteristics of these areas are the need for a new science of interaction that combines aspects of cognitive science and systems science. I will give a few examples of this emerging field.

2 Smart Humans and Smart Computers

Technological enhancement of human cognitive abilities such as learning, analysis, creativity, and communication was a goal of early information and communication

technology (ICT) pioneers such as Vannevar Bush, J. C. R. Licklider, and Douglas Engelbart. Bootstrapping [2] by Therry Bardini documents the conflict between two approaches to using information and communication technologies to address complex problems. The AI approach, as attributed to Licklider, sought to build truly intelligent systems that could partner with humans, bringing two independent and qualitatively different forms of understanding to bear on problems. In contrast the much smaller human augmentation approach, attributed to Engelbart, sought to better integrate computing into human cognitive operations (e.g., Engelbart's 1962 paper "Augmenting Human Intellect: A Conceptual Framework" [3]).

While much has changed technologically over intervening years, it is still the case that the mass of work presented in AAAI journals and conferences does not draw from current theories and models of human information processing. Studies in attention, perceptual processing and other characteristics of human information processing operations are not considered necessary as a guide to AI development, which focuses on computational methods of proven effect. This continues the Licklider model of AI as a "stand-alone" method of solving problems.

Interest in human information processing has a greater impact on scientific and information visualization research presented at IEEE Information Visualization and Visualization workshops in various journals. Since the goal of this field is to utilize the human operator's innate "visual intelligence" to solve problems presented to them on interactive graphical displays, a good deal of attention is paid to studies of human perception.

One of the origins of Smart Graphics (Smart Graphics #1 above) was the perceived need for a greater level of integration of AI and computational methods into graphical applications such as visualization. If our goal is overall "Smartness" of the human/computer system (Smart Graphics #3) we should also consider ways to incorporate both the skill and creativity of graphical and interaction designers and a science of human cognition for interactive visualization, which is to say, Smart Graphics #2.

3 Origins of Visual Analytics

Visual analytics combines cognitive science and interaction design with mathematics and information technology to support the design of information systems that enable human operators to perform difficult cognitive tasks. These include working under time pressure, with data that may change over time, and on problems that are ill-defined. This challenge for Visual Analytics, how to more effectively design graphical interfaces to provide support for difficult cognitive tasks, we know as Smart Graphics #3.

A second major driver for visual analytics is volume of information that must be taken into account in many

cognitive tasks. The pace of innovation in information and communication technologies that has enabled the generation of large, dynamic data sets that could potentially support decision-making in areas as diverse as medicine, scientific research, design and manufacturing, land-use planning (e.g., mining exploration), and law enforcement. Additional complications lie in the messiness of these data, which vary in their level of certainty, task relevance to the problem at hand, and localizability in space and time.

This combination of cognitive complexity, time pressure, high volume and varying certainty of data poses a difficult challenge for computational methods. Accordingly, visual analytics places an emphasis on the use of interactive visualization in support of human processing of information, building complex visual interfaces that represent data in visual forms that are designed to be easily understood by human decision-makers.

However, as the amount and complexity of information increases, the need to optimize graphical displays for human visual capabilities becomes increasingly important. Attempts to increase the bandwidth of information available to users has led to the use of multiple, large screen, and projected displays. A variety of approaches to the presentation of binocular stereo images have been utilized, as well as for the display of extremely high (200 000 : 1) ranges of luminance [4] in comparison to conventional LCD and CRT display monitors.

The combination of cognitive tasks, broad range of applications, large data sets, and new display and interaction technologies has driven a re-evaluation of development methods for interactive visualization systems. This re-evaluation gave rise to the new field of visual analytics. While methods for creating interactive visualizations are reasonably well understood, visual analytics takes a novel, interdisciplinary approach to directly address the process of human reasoning with the aid of interactive visualization tools. Visual analytics combines scientific investigation of human perception, cognition and interaction with computational, mathematical and statistical approaches to processing massive data sets that may contain uncertain or erroneous data. It integrates statistical and modeling analyses with human decision-making through the use of interactive visualization.

Situation analysis takes place in the context of organizations, comprising many individuals with specific (and sometimes informal) roles and small groups of decision makers at multiple levels of the hierarchy. In order to be effectively used, visual analytics must adapt to the roles and processes of a given organization and provide technological support for integration of visual analytic processes in ways that are appropriate to that organization. Thus, input from specialists in organizational behaviour and business process analysis is needed.

A comprehensive understanding of all aspects of visual analytics clearly exceeds the capabilities of any individual student or single-discipline team. Effective visual analytics

research and implementation will require the combined efforts of a range of scholars and practitioners, each of whom carries a deep understanding of their discipline, and in addition brings the ability to participate in focused cross-disciplinary collaboration.

The approach taken by visual analytics researchers [1] places substantial emphasis on the development of AI, mathematics and statistical approaches in visualization. If we are to take the definition of visual analytics as a science to heart, it should be a science in the strong sense of employing the scientific method, including empirical falsification of hypotheses. It must be both a cognitive science (since it deals with analytical reasoning) and a complex systems science (since it addresses reasoning in mixed-initiative human/AI systems). This deviates from existing disciplines in cognitive science such as experimental and cognitive psychology, neither of which address cognitive systems, and from human-computer interaction, which does not have at its core the goal of building a theory of cognition in these environments, but rather works towards facilitating interaction itself.

4 Science and Application

The science of visual analytics is also unusual in that it was created in dialog with a ready-made application domain, the principled creation of interactive mixed-initiative visualization environments. The technology of visual analytics serves to validate the findings of the science when the systems it creates demonstrate that they increase the quality of cognitive processing that can be brought to bear on real-world problems. Interaction with the user populations, situations of use, and technical hurdles encountered by the technology stream also serves to generate new scientific questions that can be addressed in the laboratory. This is similar to the relationship between clinical medicine and biomedical research, which support a rich bidirectional flow of research questions, theories, and predictions between research labs and clinical settings. This dialog between science and application creates constraints as well as opportunities for both. For the underlying science of visualization systems they might be:

- *Graphical validity*: Researchers must address complex perceptual environments and tasks. This requirement eliminates the vast majority of current laboratory studies in perception and cognition.
- *Systems thinking*: Research teams must extend the social science model of description of human abilities in natural situations to understanding how human/technology systems will perform their tasks.
- *Situational constraints*: Researchers must extend their understanding of human performance in novel situations, under time pressure etc. to enable “satisficing” [5] performance of the human operator under those conditions.
- *Individual differences*: Research must address performance differences within a population of users, e.g., cultural differences, levels and types of expertise (es-

pecially the unique characteristics of highly skilled individuals, “thinking styles”, etc.).

- *Strong prediction*: A science of interaction must move beyond interface design guidelines to provide specific predictions of performance. While inferential hypothesis testing has its place, mathematical and computational models whose free parameters can be fitted and evaluated for a given user and context of use provide more explanatory power and should be emphasized.

Based on this conceptual analysis I will propose some possible avenues for scientific study, and give examples of early attempts to address them.

5 Research Topics and Methods

5.1 Cognitive Architecture of Visual Analytics Task Performance

Cognitive architecture refers to the large-scale structure of human information processing. The most “architectural” aspects of information processing have been determined by eons of human evolution, while others are learned early in life or mastered after much practice. The majority of studies in human perceptual psychology deal with a single sensory modality (e.g., vision, hearing or haptics). The goal is frequently to disassociate the complexities of cognitive performance from the relatively straightforward sensory processes, in the case of psychophysics by fitting mathematical functions to an individual’s performance data on low-bandwidth laboratory stimuli and tasks. These methods must be extended to more complex sensory situations. For example, rich perceptual environments such as those generated by computer graphics affect a number of basic perceptual channels, and human perception in these situations is itself an inferential process. Irvin Rock’s [6] “logic of perception” refers to the visual system’s ability to compensate for inadequate sensory information (the so-called “poverty of the stimulus”) and to reconcile conflicting sensory information through processes of unconscious inference. Perceptual inference is largely data-driven, and does not take into account the perceiver’s conscious thoughts, beliefs, intentions, etc.

Pylyshyn’s “cognitive impenetrability” [7] test distinguishes these two levels: while learning does train perception’s inferential processes (and so individuals will differ one from another in their abilities, and experts will differ from novices) the perceiver’s conscious thoughts, beliefs, intentions, etc. do not actively participate in perception. Thus input from end-users can give only limited insight into their perceptual logic. The term “metacognitive gap” [8] describes this counterintuitive break between the ways in which these two logics must be understood, and hence the need for a new cognitive science of human interaction with visualization systems.

When we understand a situation or a data set we do so by attending to the conceptual implications of in-

formation that is itself constructed by the pre-conscious logic of perception. Visually enabled reasoning will be most successful when we fully understand how to design images and dialogs that enable the logic of perception to support the logic of conscious reasoning.

5.2 Understanding Individual Differences and Expert Cognition

Preliminary studies [9] from my lab demonstrate how novel perceptuomotor situations interact with (and perhaps elicit) individual differences in the integration of information between sensory cues in interactive tasks. These studies demonstrated shifts in performance over time and between users that are thought to be the result of the user's perceptuomotor recalibrations (e.g., Epstein's "recalibration by pairing" [10]) to accommodate discrepancies in their perceptual experiences in the environments. Our approach to this theory-practice gap has been to incorporate empirical methods and theories from cognitive science at the level of cognitive architecture. These include the two-visual system theory, the FINST theory of Pylyshyn [11], and psycholinguistic pragmatics "Joint Activity" theories of Herbert Clark [12]. These theories differ from the more familiar perception work (e.g., colour and form discrimination, visual search) usually utilized in visualization and related fields in that these theories relate more directly to rich perceptual environments such as ubiquitous, immersive, and multimodal displays. At the other extreme, they also differ from the higher-level theories of Gibson [13], Varela [14] etc. in more directly addressing the nature of information processing that occurs in those situations. As such they fall into Marr's "middle ground" [15] of processing algorithm analysis that can more precisely inform the specifics of interaction design. They do so by constraining the large design space of highly interactive multimodal display and control technologies, particularly for unstructured design goals (e.g., visual analytics for creative problem solving across a wide range of aircraft parts failure scenarios) and when acceptable error rates are extremely low (e.g., for air traffic control).

The research has four aspects:

- *Task decomposition based on human cognitive architecture*: Using research on the structure of perceptual cognition (e.g., attentional tokens and visual routines) with particular emphasis on perceptual and enactive cognition and how they underlie cognitive processing. A task decomposition based on cognitive architecture provides a way of "carving interaction at its joints", deriving key aspects of interaction that will generalize across situations.
- *"Toy world" studies focused on key aspects*: Devising small focused studies that examine the impact of specific aspects of the interaction on key perceptual and cognitive processes. For example, my work with air traffic control applications applied spatial indexing models to generate a test of the robustness of tracking

multiple display targets over global transformations typical of fishtank VR approaches. Our findings [16] supported an allocentric model of attentional tracking, which would indicate that the deployment of attention in air traffic control would be robust against a wide range of display changes.

- *Sophisticated analysis techniques, including use of indicator variables that correlated with subject of interest*: Sensitivity of the dependent measure in any empirical study is critical. In an applied study with many variables of interest, a sensitive DV enables us to study interactions and attribute effect to cause. As a result, studies conducted in the context of an iterative design cycle preferentially utilize real-time measures that can be tracked and mapped onto display events rather than more ecologically valid but less sensitive measures such as overall performance, which are relegated to summative studies at the conclusion of the design cycle.
- *Focus on individual and subgroup patterns of results*: The goal of the natural sciences is to uncover general laws of nature. Social and cognitive sciences have adopted these goals, and seek to uncover general principles of mental life. In contrast as interaction designers, we seek to support individual users from a specific user community. This requires us to determine not only the general rules, but also the ways in which those rules can be parameterized so as to customize interaction for a particular individual.

6 Research Example: Individual Differences and the Personal Equation of Interaction

Work on space constancy in my laboratory serves as an example of this process. While the basic phenomena were known to psychology for some time [17; 18], the elicitation of individual differences in performance combined psychological approaches with HCI manipulations such as level of visual feedback and temporal lag. These variables are not at all central to the development of general models of perceptual processing and so have received little study within psychology. Similarly individual differences themselves are of limited importance in deriving global information processing models, and so have not received sufficient attention from researchers. From the perspective of interaction design however, the former grounds the research in practical issues while the latter supports interface customization to support a given user's perceptual abilities and characteristics.

In the course of our studies [19], doctoral candidate Barry Po and I found evidence of clear individual differences in the impact of these theories on performance on gesture versus verbal responses in large-screen display environments. While nearly all subjects showed the general pattern of increased context-induced localization errors in verbal report versus pointing (a prediction of the two-visual-system hypothesis), changes in interaction characteristics such as visual feedback and performance lag affected different subjects in strikingly different ways.

Follow-on studies on reaching tasks for targets in upper versus lower visual fields found a similar pattern, as did preliminary findings from research conducted in collaboration with Doctoral student Reynald Hoskinson and Masters student Caitlin Akai [9] on depth judgments using active stereo (shutterglasses) technology.

The common thread in these findings is that the creation of large screen and ubiquitous computing environments, coupled with the use of more direct interaction techniques such as pointing and reaching place a greater burden on users' ability to recalibrate their perceptuomotor systems to deal with geometry errors and temporal lags. Different individuals will respond differently to these errors, based on their basic level of recalibration ability, perceptual experience, fatigue, age etc. Findings from our studies confirmed that there was no global optimal setting for the population of subjects. Rather, each individual's low-level perceptuomotor systems appeared to place different emphasis on different aspects of the interaction. Given the range of situations that present similar conflicts, it seems likely that these findings will generalize to other visual, auditory, and haptic cross-modal feedback discrepancies.

I predict that optimal interaction design for a population of users will require customization for a given user's characteristic ability to adapt to the conditions of the interface, something that I am calling the user's "personal equation of interaction" [20]. This would consist of obvious static factors such as stereo sensitivity and colour discrimination together with adaptation factors such as the ability to recalibrate auditory space based on visual evidence (the ventriloquism after-effect), the tendency to utilize more robust but less accurate (dorsal system) visuomotor representations rather than more accurate but more context-sensitive (ventral system) representations [13] in a given task. Both research and anecdotal evidence from skilled GM automotive CAD designers suggest that the ability to recalibrate perception to reduce conflicts is high among skilled CAD users.

7 Research Example: Technology-Enhanced Human Perceptual Capabilities

While some studies expose threats to human understanding posed by the use of interactive graphics, others demonstrate unexpected human abilities in these environments. Among these is our study [16] on the possible impact of the use of changes in point of view in a fishtank VR air traffic control environment. Rather than test air traffic control tasks, we examined a perceptual-cognitive subtask that is necessary for ATC performance. In so doing we were able to isolate variables that apply to a broad class of interfaces and vary them to determine the sensitivity of that subtask to changes in the display environment.

We examined the ability of users to individuate a subset of identical display items in a field of distractors and maintain their identity as they move through the display

space. In an ATC situation these would represent a set of aircraft in a controller's fishtank VR display. We then tested the ability of users to maintain individuation over a set of display transformations that are being considered by designers of ATC environments. In order to increase the number of errors to measurable levels we gave the aircraft erratic flight paths. Initially we varied the level of realism of the display and compared performance on a multiple display object tracking task. Since performance was not affected by a shift from a realistic to a more abstract mock-up, the abstract view was used in subsequent experiments.

In one study, observers viewed 16 display items corresponding to aircraft in an ATC display. On each trial, 2, 4, or 6 items were briefly tagged as the "target" class. All objects then underwent 10 s of random motion at uniform speeds. A single object was then tagged, which the observer was then asked to identify as a target (i.e., "one of my aircraft") or a non-target.

In experimental trials, an additional global motion of the display space took place. Thus, in addition to varying the speed of objects relative to the center of the box (object motion), the motion of the whole box was varied (scene motion). In different trials the scene underwent translation, zoom, rotation, or even a combination of all three motions ("combined motion").

A simple retinal tracking model (i.e., "egocentric tracking" in a viewer-centered coordinate system) would predict that when the overall retinal motion produced by object motion and display motion combined reached the measured "breakdown point", performance would fail. Conversely, if users were able to utilize the spatial regularities of the fishtank environment to track "allocentrically", i.e., in virtual display space, they might maintain their ability to track targets at greater aggregate (display + item) speeds than would be predicted by egocentric tracking.

Viewpoint transformations did not significantly affect tracking performance, even when they increased the object speed to levels that were found to impact performance in the static frame condition. Variations in scene motion had no measurable influence on attentional tracking performance. This was true for translation, zoom, rotation, or even a combination of all three motions.

There is no obvious survival advantage of the ability to track allocentrically, as such situations are rare in the environments in which humans evolved. It may be that early exposure to novel camera movements in television and cinema has helped us to develop a novel perceptual ability that is of use in those situations, or it may be that we are uncovering an innate mechanisms of unknown function.

8 Research Example: Pacing of Display Events and Cognitive Processing

As the studies referenced above suggest, temporal aspects (e.g., the rotation of viewpoint in the air traffic

control study) of human interaction with graphical displays are intricately linked to cognitive operations. Alan Newell [21] posited “bands” of mental activity ranging from biological-level neural firings over 10 ms. and below, cognitive operations that take place on the order of seconds, rational activities that take place on the order of minutes and so on.

What Newell did not explicitly consider were that many temporal constraints on cognitive processing are due to the cost of acquiring information from the environment through motor activity. At lowest level eye and head movements strategically (albeit unconsciously) sample the visual world so as to support processes of perceptual inference discussed above. According to Ballard et al., the time required to execute an eye movement to acquire needed information constrains the speed of cognitive processing [22; 23]. In reading, for example, the processing time of a fixated word is slowed so as to enable the eye to have the time to make a saccade to the next word in the sentence. Given the hard constraint of the time required to make an eye movement, this “just-in-time” cognitive processing reduces the load on short-term memory in reading.

The correspondence of eye movement and processing times is characteristic of many perceptuomotor “interactive routines”. These routines comprise epistemic actions that reveal information, externalizing actions that modify the perceptual world to reflect conceptual understanding, and coordinating actions that bind concepts to content. In the case of expert performers (e. g., skilled musicians or very experienced computer users) these interactive routines are effectively “compiled”, taking place automatically under supervisory control of conscious problem solving processes.

This line of investigation has significant implications for visualization applications that support human reasoning. Wayne Grey’s “soft constraints” [24] cognitive cost accounting hypothesis posits that small changes in the time required for the user to acquire information from a visual display can impact information comprehension and discourse and cause significant shifts in task performance and strategy. Work by Po et al. [25] demonstrated that factors as simple as the orientation of a graphical cursor can have an impact on task completion times. While the size of this effect was small, it is possible that small changes in the temporal aspects of human-information dialog can interact with the intrinsic time course of cognitive processes to support or impede cognitive processing. This suggests that temporal rhythms in solo and collaborative use of technology can both detect and support Csikszentmihalyi’s “flow” [26] of effective cognitive processing and fluency of interaction. Addressing the sequential nature of human-information dialog will require new empirical methods that integrate mathematical modeling of sequences of interaction and human-mediated qualitative research methods.

9 Conclusion

This paper has briefly described visual analytics, a new field of study in which the integration of cognitive science methods and the design visualization applications have been a priority. It focuses not only on current perceptual and cognitive sciences, but describes how a cognitive science of visual analytics might evolve in dialog with the development of visualization technologies. Parallel examples exist in other application areas, such as games and simulations, which are also characterized by an emphasis on human cognitive, social, or experiential outcomes as a metric of the success of the technology that delivers those experiences. This approach depends on the development of effective information exchange between designers of visual analytics technology and cognitive scientists who focus on those systems. The goal is an interdisciplinary field of visual analytics, which contains within it scientists, engineers and, as described elsewhere in this journal, mathematicians, artists, and designers. The methods of collaboration, the language that they will use to communicate, and the constraints they will exert on each other’s work are as yet unknown. Workshops such as the Smart Graphics series are providing the venues through which those methods will evolve.

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Received: December 1, 2008



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