Exemplifying the Inter-Disciplinary Nature of Visualization Research

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Abstract—*This paper proposes an interdisciplinary design process for the development of novel visualization techniques and discusses requirements for ensuring that such a process results in effective techniques which meet the demands of a the target user base. In essence, we are attempting to make explicit the process by which many researchers implicitly design visualizations and urge for greater explicit collaborations between fields to improve the effectiveness of visualization design. This process is dependent on the application of cognitive psychology, art and architecture, domain experts, and target users. We discuss how such a wide and disparate group must work together in an integrated fashion within the design process. We lay out the process itself as well as typical design goals. Given the importance of perception, we highlight the impact of perception, and thus cognitive psychology, on the visual interpretation process.*

Index Terms—Visualization, Inter-Disciplinary Design, Design Processes

1. Introduction

Data Visualization is the creation of graphical images for the representation of data through either abstract or physical relationships [19]. Such data visualization has garnered enormous interest in recent years due to the need for exploration and analysis of enormous volumes of data and the inability of automated techniques to provide the needed analysis. Visualization also maintains the user in the loop, allowing for intuition and expertise to take part in the analysis process. For example, bioinformatics-based data sets can be huge, in the GB range, with hundreds or thousands of parameters. The problem with such data sets is that it is not known what the analyst should be looking for in such a data set. Thus, automated techniques are limited in their effectiveness. The human analyst must direct the exploration and analysis process. Relying on solely textual responses from the analysis tools is a slow process as the human analysts must interpret and correlate the huge amounts of raw data with large amounts of computed data.

Thus, visualization attempts to represent both data in its raw form as well as the computed values, i.e., often statistical or mathematical results. In addition, when dealing with such large data sets the environment must provide for sampling, selection, or filtering of the data to ensure the most relevant information is presented on the screen. It is unfeasible to assume that even future display capabilities will be able to visually display the volume of data being discussed; especially considering the rate of growth of data collection processes in comparison with the growth rate of display technology.

The success of visualization derives from its reliance on human perception. Humans are able to visually interpret enormous amount of information that through other forms would be extremely slow and tedious. More specifically, reading textual information is considered a perceptually serial process as the reader must perceptually interpret each character in sequence to interpret a word and subsequently each sentence. A graphical image on the other hand can be interpreted in parallel, allowing a conceptualization of the image to be interpreted essentially instantaneously. There are particular visual characteristics that humans are particularly noteworthy at identifying and interpreting. These are traditionally termed pre-attentive components [8]. Such components include: texture, color, size, orientation, etc. These components allow the identification of anomalies, trends, and similarities essentially instantaneously. Thus, perception is a critical component of visualization research.

The development of novel and effective visualization techniques additionally requires more of an artistic component to ensure that the developed capabilities meet aesthetic requirements in addition to technical requirements. Incorporation of this discipline also provides more effective avenues for the generation of original visualization techniques; as computer scientists, the traditional designers of visualization techniques do not receive the level of training in design that artists or architects do.

As can be seen from the brief overview outlined above, data visualization research requires the integration of many disparate domains, including:

Computer Science – Computer Science provides for the identification of feasibility and appropriateness of proposed techniques, applications and integration of actual data, as well as for the implementation and deployment of the visualization techniques.

Mathematics and Statistics – Visualization essentially derives from statistics. This domain provides for much of the transformation and modeling metaphors as well as the sampling, filtering, and computational algorithms.

Art and Architecture – Experts in art and architecture are essentially trained to think outside the box and develop novel and interesting visual formats. Such individuals are critical for the development of really unique and fascinating visualization displays. Many of the best visualization research groups work hand in hand with such experts.

Cognitive Psychology – Perception, a specific field of cognitive psychology, identifies the rules intrinsic to designing a good visualization from a human vision point of view. Such rules are essentially used to refine the models developed by artists and architects.

Domain Experts – Visualization experts often design visualization techniques for specific domains based on their own comprehension of that domains needs. Alternatively, visualization techniques designed with the assistance of and in collaboration with domain experts are generally more effective and usable by the domain experts. This becomes of great importance when it is the domain expert that must use the resultant capability, and not the visualization expert.

Only through the integration of these domains can the most effective and usable visualization capabilities be developed. The rest of this paper examines the processes by which these disciplines are integrated and how they impact the resulting capabilities. Thus, the paper proceeds as follows: Section 2 outlines types of visualization techniques and their roles. Section 3 identifies the process of developing novel visualization techniques effectively. Section 4 discusses how perception can be integral to a visualization model. The remaining sections conclude the paper and discuss future work.

2. Visualization Techniques

Visualization techniques have been applied to a wide range of tasks and activities. In order to categorize the goals of a developed visualization technique MacEachren et al. describe visualization techniques based on their role or task (i.e., user goals) as follows [13]:

Presentation: Presentation based visualizations are designed to provide already discovered information in a meaningful way. For example, providing the results of an analysis to management or decision makers would be provided using presentation visualizations.

Analysis: Analysis based visualizations are designed to aid in determining meaning of a particular data set. Characteristics of the data set are already known and the analysis processes in conjunction with analysis visualizations are applied to derive greater understanding of the data.

Exploration: Exploratory visualizations are designed to support users when basic details of the data set are not known and the users ultimately do not know what they are looking for. Often this takes place as a first step with analysis being applied as a second step. Exploration aids the user in discovering the fundamental characteristics as well as anomalies, trends, etc. within the data set.

Synthesis: Synthesis provides for the integration of multiple data streams. In essence, it provides a form of visual data fusion. Such fusion is critical for correlating datasets and identifying meaning based on interrelationships, or a lack thereof.

The distinct differences in these different visualization techniques create a need for very different visualization techniques and interestingly enough additional participants in the design and development process. It becomes critical to include the users for whom the visualizations are being designed into the design process; i.e., the domain experts. For instance, presentation visualizations must incorporate management personnel and the decision makes who will be provided the resultant visualizations to ensure the visualizations meet their needs and whether or not they truly understand what the visualization is telling them. Similarly, with the other visualization types the appropriate users must be included in the process and their feedback taken seriously in the refinement and implementation of the techniques.

Of critical importance in the consideration of users is determining the capabilities that would be deemed appropriate for the target audience [3][7]. What capabilities would our target analysts be willing and capable of using? For example, Erbacher et al. [3] have described the need to design intrusion detection tools to work *with* an administrator's other tasks. This was done by limiting the work to two-dimensional visualizations that would not require an administrator's sole attention and with which they can easily associate. For work targeting security analysts, in contrast with system administrators, the visualizations would incorporate a wider variety of representations, due to their greater acceptance and ability to accommodate such techniques. As this is their primary responsibility they will be more willing to put in the time to learn a greater variety of techniques. However, the analysts will likely be working *with* system administrators and thus representations that not only provide exploratory capabilities but also present the identified data through a more familiar metaphor to system administrators will be a necessity.

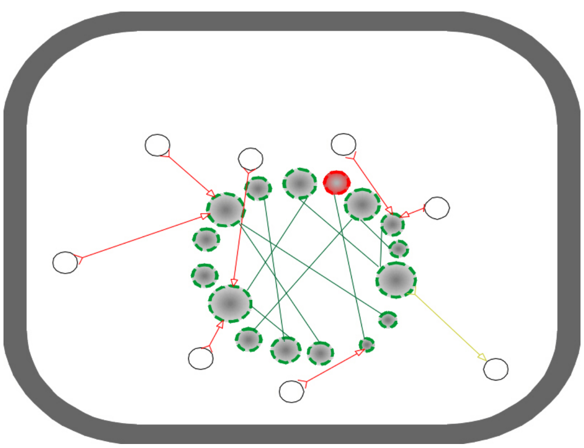

Figure 1: Original concept drawing for the network monitoring visualization environment and associated techniques. Concept drawings are critical for developing good visualizations and lay the ground work for the ideas to be implemented. At this stage the identified visual concepts may not be feasible, realistic, or perceptually refined.

Similar considerations must be applied to any domain to which visualization is being applied. The first step of such a process is determining the needs and requirements of the target user base. This is most effectively done through a cognitive task analysis (CTA) [8].

3. Developing Visualization Techniques

The development of visualization techniques requires that the involved researchers consider all relevant information in a cyclic process of refinement to ensure the creation of a complete and effective capability. In essence, the development of visualization techniques has a methodology as follows:

1. Identification of parameters and data characteristics to be incorporated.
3. Identification of relationships critical to the analyst to be incorporated.
4. Generation of concept drawings. It is unlikely

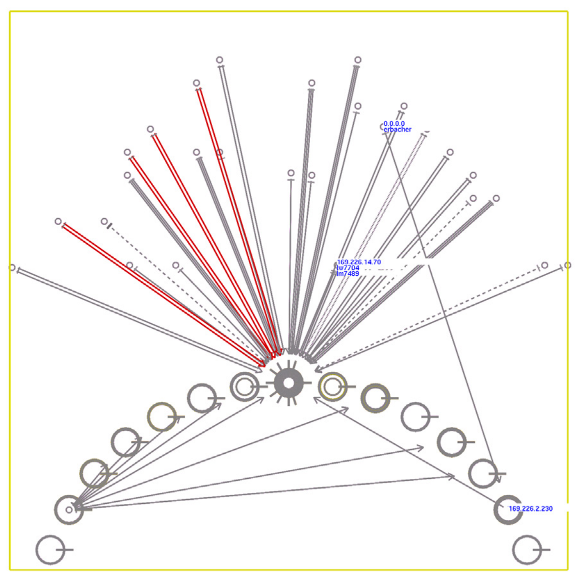

Figure 3: Final implementation of the network monitoring environment, derived from the concept drawing exhibited in figure 1. Clearly, much iteration was required to achieve this final result. Of particular note is the final node layout algorithm which was designed to minimize and make meaningful line intersections.

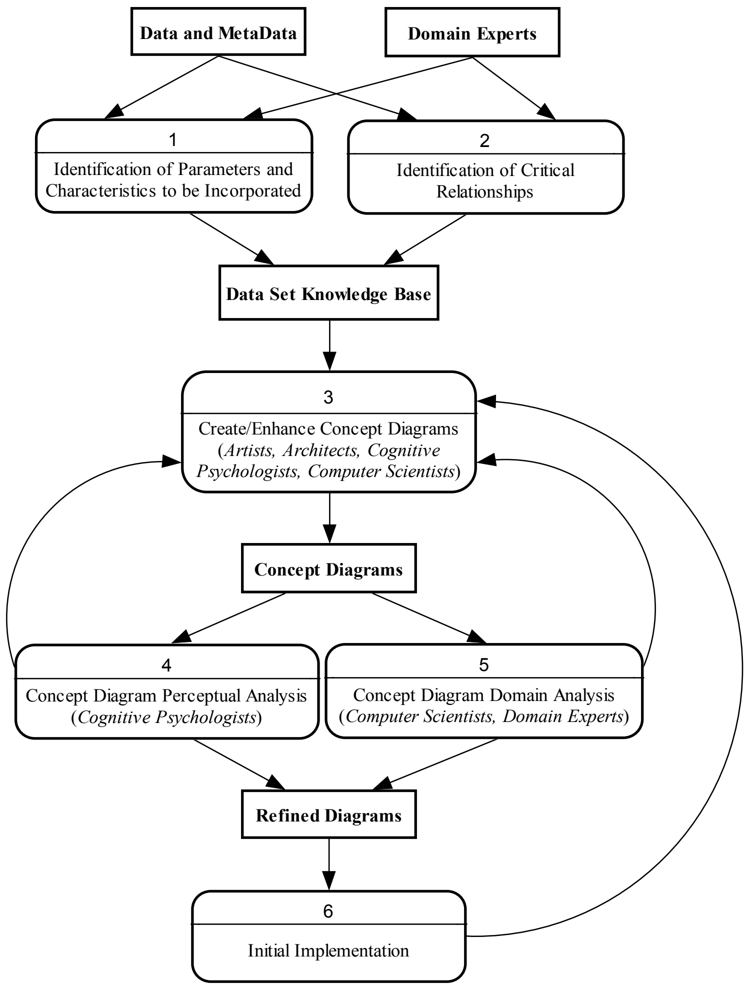

Figure 2: Process flow diagram for the development and implementation of effective visualization techniques. Many disciplines must take part in the process to ensure scientific and user needs are met.

jumping right into development will be effective. Multiple iterations of concept drawings will aid the development of techniques most likely to be effective. For example, figure 1 shows one of the original concept drawings for the design of network monitoring visualizations [5], [6]. Clearly much iteration resulted before the final implementation came to light.

5. Analysis of perceptual implications of design and concept drawing.

6. Garner feedback on concept drawings; i.e., are we missing anything? Do the techniques fulfill usability, effectiveness, and representational needs?

7. Initial implementation.

8. Repeat as needed.

This process is further exemplified in figure 2. This diagram is designed to show the integration of the multiple domains of expertise critical to the development of an effective visualization technique. Required or needed domains of expertise are exhibited in italic for each of the process steps. Steps not listing domains are within the domain of the computer scientists.

Applying this paradigm and consideration of the impacts of human perception led to the migration from the concept diagram in figure 1 to the implemented capability shown in figure 3 [4]. The philosophy behind this resultant visualization is that we are reducing line intersections, which act as perceptual foci, and making them meaningful when they do occur. Such effectiveness is critical for an effective visualization and highlights the scientific foundations underlying such research.

Without such solid underpinnings it becomes difficult to refine, improve, or validate the effectiveness of visualization techniques. Previously, this paper discussed the need to incorporate artists and architects in the design stage. This provides for the aesthetics but not the science. Comprehension of cognitive psychology and perception must further be applied to refine the purely aesthetic representations to provide a scientifically well-founded capability for the representation of data.

4. Mathematics and Statistics

Many of the fundamental visualization techniques and associated algorithms are derived directly, explicitly or implicitly, from mathematics and statistics. For instance, sub-sampling, dimension reduction, formal models, analysis of user study results, etc., are all fundamentally mathematical and statistical capabilities. While computer scientists often derive their own mathematical techniques there are additional avenues for research through collaborative research with mathematics; i.e. by relying on the expertise of mathematicians there is enormous potential to more substantially improve the underlying algorithms critical for visualization effectiveness.

Additionally, there is growing interest in creating formal models, i.e. algebras [10], for the representation or description of visualization techniques. Future work will require refinement of the algebras as well as the development of formal proofs.

5. Cognitive Psychology

We've indicated that perception is a critical component of data visualization. In this section we look at the impacts that perception has on the visualization techniques and some of the characteristics of perception that must be considered not only when designing visualization techniques but when they are being applied and used. In the use of visualization techniques, we are primarily concerned with the impact of the data parameter to visual attribute mappings, the selection of available and used visual attributes, and the choice of value ranges for the different visual attributes; e.g., the range of acceptable intensities, the range of acceptable line thicknesses, etc.

5.1. Perceptual Foci

In terms of perception of visual displays we are relying on two processes. First, is the process by which users will view the display in its entirety at a global scale before drilling down their focus to examine individual features or elements [11], i.e., the typical concepts of focus and context as well as drill down? Second, is the concept of perception of scale [19]. With perception of scale, larger elements within the display will perceptually draw the user's attention before smaller details do. This can be used in conjunction with the fact that crossed lines, and other visual characteristics, are perceived preattentively. Thus, a user interpreting the image in figure 4 will first perceive the larger crossed lines (center of the display) and their associated intersection before drilling down their focus to perceive the smaller line intersections shown in the upper left corner of the display. This becomes a contrast between global or large-scale artifacts and local, detail specific artifacts.

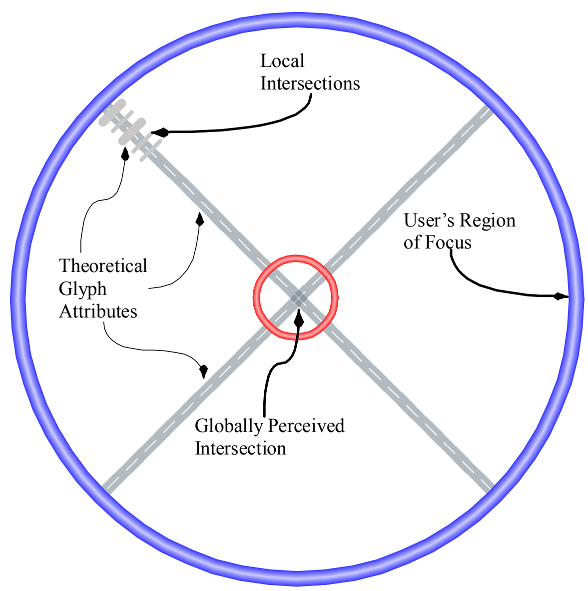

Figure 4: This image shows a combination of intersections at various scales, i.e., various perceptual levels. At the global focus, highlighted by the blue ring, the users attention will be dominated by, drawn to, the intersection within the red circle.

5.2. Preattentively Viewed Attributes

The described perceptual examples are not meant to be complete by any means. Many visual attributes could be included through the incorporation of different perceptual artifacts in which one group of characteristics are more quickly or readily perceived than a second group, e.g., preattentive versus nonpreattentive attributes or first order versus second order statistically linked visual attributes [8].

For example, typical glyph based (i.e., multi-parametric) visualizations create visual objects with multiple visual characteristics. Each of these visual characteristics is used to represent a different parameter in the database. Visual attributes such as size, color, and orientation are first order statistics and are perceived preattentively, not requiring analysis to identify trends and anomalies. Other characteristics such as position are second order statistics and require more analysis to interpret the meaning of.

In this paradigm, users will acquire first order statistical (preattentive) information first, followed by second order statistical information and so on. Thus, second order statistical information requires more attention (e.g., a visual search) in order to identify and extract meaning from.

5.3. Inter-Affects Between Visual Attributes

An additional characteristic of the impact of a user's focal scale is the inter-affects between visual attributes. This becomes particularly relevant with the ability to dynamically change the data parameters mapped to a visual attribute and the ability to enable or disable visual attributes. Our intention here is to exemplify the impact of changing visual attributes, either through changing the data parameters mapped to them, disabling or enabling them, or changing their range of exerted values.

For example, simply changing one visual attribute may impact the perception of many others. Making one visual attribute more dominant will have the effect of ensuring others require more analysis in order to interpret, and vice versa. This inter-dependency between visual attributes is one of the most challenging aspects of visualization research as it makes not only designing effective visualizations difficult but makes selection of parameters and ranges for the most effective representation of a specific dataset challenging. In this application of perception each visual attribute presents one view of the data and the fused set of parameters provide interdependent fused views of the data.

5.4. User Studies

Finally, cognitive science is critical in the performance of user studies. Again, while computer science has begun performing user studies in their own rights, this expertise derives from the cognitive science discipline and they are ultimately the experts.

As visualization becomes more refined, evaluations will become not only more common but also their deviations will narrow. This will require more refined, extensive, and carefully constructed user studies. Collaborations with cognitive science will guarantee more useful results.

Currently, the majority of user studies rely on qualitative assessments; often relying solely on Likert-style questionnaires. As user studies are refined there must be a more extensive reliance on quantitative assessments. These quantitative assessments will provide more accurately comparisons of the perceptual impact of various techniques. This will rely on accurately designing the experiments to avoid bias and include measures such as: critical performance parameters (CPPs) [14], heuristic evaluation [15], cognitive walkthrough [18], receiver operating characteristic (ROC) graphs [16][17], etc.

6. Art and Architecture

Artists and architects are trained fundamentally in design and aesthetics. Such individuals are trained to consider all aspects of visual design and how such design is interpreted by the viewer. Often they receive some understanding of perception as well. While computer scientists can design functional and usable visualization techniques incorporating an amount of aesthetic value, artists and architects can incorporate additional design characteristics that will significantly improve the effectiveness and aesthetics of the technique. Similarly, the artists and architects do not have enough understanding of the implementability, the algorithms, the data needing analysis, etc. to be able to independently design visualization techniques. This is becoming particularly important as visualization techniques become more main stream.

Recent work by Lang [12] has looked more extensively at the issues of design. More specifically, this work examines the design processes not just from art and architecture but from other fields such as engineering, management, and nature. Similarly, there are potential design ideas from theatre, dance, film, animation, choreography, etc [2]. These last domains can potentially provide new ideas for transitions, motion, and interaction. Thus, while we have focused on art and architecture there are many other domains which incorporate design that can provide new ideas for visualization design. The goal is to bring together complete interdisciplinary teams to provide for the most effective and yet aesthetic capabilities.

7. Domain Experts

It is the domain experts that will identify the type of visualizations that are needed; presentation, exploration, analysis, or synthesis. Domain experts will also aid identification of what data parameters are most relevant and in what combinations. Finally, domain experts will aid in interpreting results of the visualization techniques and identification of what needs improvement.

As an example, consider a bioinformatics dataset. With thousands of parameters and gigabytes of data it is much more efficient and effective to have a biologist identify a specific task, identify the relevant data parameters, and interpret the results, than having a computer scientist attempt the same task. Even a computer scientist that has become an expert in bioinformatics likely will not have the same level of expertise as a biologist who has trained in the field.

8. Computer and information Science

Computer and information sciences, in which visualization has traditionally been performed in isolation, must continue to be the catalyst for visualization research. It is these fields that must identify the implementability of the designed techniques, the representability of data parameters, integrate feedback from all other domains, interpret needs exerted by domain experts, etc. An actual implementation will generally deviate substantially from the original design and it is the computer and information sciences that must determine how the implementation should be done.

Additionally, it is the computer and information scientist that will design the added capability (the software architecture, the efficiency issues, etc.) which will make the actual design useful and effective.

9. Discussion

Each of the identified domains can contribute substantially to visualization research. Few fields receive as much benefit from as wide an interdisciplinary research team as visualization.

The importance of perception can not be under represented. As identified in this paper, the impact of perception on individual elements and the display as a whole can be extensive. It must therefore be considered throughout the design process in a series of refinement stages to ensure the most effective application of the human visual system. Ensuring the most effective integration of human perception requires collaboration with cognitive science.

The need to ensure that the resultant capabilities meet the needs of the target users brings in a wide variety of user domains. Additionally, the need for novel, yet aesthetic, visual displays requires collaboration with artists, architectures, and other visual design specialists.

Similarly, extensions can be sought which will require participation by even more domains. For example, sonification is the auditorial representation of data and is often used to enhance the visual representation. This requires collaborations with musicians and other audiophiles to ensure effective and meaningful sound reproduction.

10. Conclusion

This paper identified the interdisciplinary nature of computer visualization based research. Even more, we have identified the criticality of the interdisciplinary nature of this field of research. In particular, effective interdisciplinary collaborations within the visualization research process will ensure the development of more effective, usable, and deployable techniques. By working together the two domains can provide far better results than either working individually. A single researcher can not have the same level of expertise in multiple domains as multiple researchers focusing on their individual domains; this becomes particularly important when considering the number of domains impacting the visualization field.

Developing novel, effective displays requires a carefully tuned framework, incorporating expertise from the afore-mentioned disciplines. It is this inter-disciplinary knowledge base that validates the correctness of the visualization techniques under development within each domain, whether it is the user or target domain, the perception domain, aesthetics, etc.

While visualization experts have traditionally done many of the steps in isolation from other fields, they can not possible achieve the same level of expertise in all of the fields involved in the visualization design process and thus would benefit from collaborations with experts in these domains. With increasing interest in formalizing visualization as a scientific discipline [1], strengthening the identified collaborative ties will improve the acceptance of visualization as a scientific discipline. This is particularly true as cognitive science and mathematics are more tightly integrated.

11. Future Work

This paper provides a look at the interdisciplinary nature of visualization and our design process for incorporating experts from each domain into the design process. Lacking, however, are representative examples from successful design processes by other research groups. Additionally, a more extensive paper is required to examine the appearance of perceptual artifacts and impacts within developed visualization techniques.

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