Contextualization of Design Qualities in Interactive Story-Based Visualization Applied to Engineering

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Abstract. Visualization is widely employed in the engineering industry to fulfill the increasing demand for robust data exploration and insight enhancement tools. It is valued for its ability to improve the performance and efficiency of various engineering tasks. Narrative visualization is a growing interdisciplinary field with a great potential for mission-critical, pressure-filled, and time-sensitive operations. Because of the novelty of the discipline, there is a lack of research focused on design strategies of story-based data representation in the engineering domain. Based on the existing visualization research, we identified four prominent design qualities: aesthetics, usability, novelty, and complexity; and examined them in the context of interactive story-focused engineering visualization. We concluded that: 1) Terminology needs to be re-evaluated in the new context; 2) All four design dimensions we analyzed are subjective and prone to personal interpretation; 3) All four design qualities can be both positive and negative, depending on the context; 4) Trade-off between design qualities has to be made; 5) There is a lack of completed case studies in the field. We hope this research will be beneficial for bridging the gap between storytellers, visualization designers, and engineers, as well as establishing design strategies for this emerging visualization form.

Keywords: Interactive digital narrative · Visualization · Engineering

1 Introduction

Growing data complexity and abundance, coupled with extreme performance requirements of pressure-filled, mission-critical, or other engineering-specific applications, increase the demand for robust data exploration tools. Visualization is the most widely employed technique for rapid knowledge extraction, insight enhancement, and information retention. It takes advantage of the human perceptual system to mitigate cognitive overload and ameliorate comprehension. It has been extensively used to aid engineers and scientists in a variety of tasks, such as design, simulation, monitoring and maintenance, remote collaboration, training, evaluation and optimization, risk modeling and assessment, decision-making, and presentation. Visualization techniques are constantly evolving to fulfill the requirements of their applied field and keep up with technological

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development. Narrative visualization is a growing discipline that amplifies visualization capabilities by framing data as a story [1]. Storytelling always had an important role in knowledge transfer [2]. Story-structured data communication improves memorability [3], comprehensibility, credibility, and involvement [4]. Narrative visualization is a communication tool that goes beyond conveying facts [5]. Wojtkowski and Wojtkowski argue that visual storytelling might be crucial for real-time and intuitive exploration of large, complex, and diverse data resources [6]. This narrative visualization capability is central to time-sensitive and analytics-based engineering applications. Examples of such use cases include extended reality (XR) immersive experiences, cyber-physical systems, and Internet of things (IoT) solutions.

Visualization in engineering and sciences is determined by its practical value and improvements in the performance of a system or a task [7, 8]. A significant body of work has been devoted to showing how different visualization aspects affect its overall efficiency. They include, for instance, aesthetics [9–13], complexity [14], and memorability [15]. The correlation between different design dimensions has been studied as well, for example, appearance and usability [16–19], complexity and aesthetics [20], and complexity and usability [21]. This collection of works provides strong empirical evidence and a theoretical foundation to support adequate visualization practices. However, there is a lack of research contributions focused on different design qualities of story-based data representation in engineering and sciences.

In this paper, the term visualization will be used broadly and as an umbrella term encompassing various subdisciplines (such as information and data visualization, and visual analytics). We provide an overview of prominent design qualities of narrative visualization. We discuss their effect on the visualization performance, i.e., the potential to improve the speed, accuracy, or efficiency of engineering operations. We focused on interactive applications because the human operator needs to be able to interactively and promptly exchange information with the physical or digital equipment, system, or environment. In the first part of this paper, we examined the relationship between digital narratives and engineering visualization. In the second part, we present concepts that received attention in the visualization research and examine them in the context of interactive story-focused engineering visualization. Based on the existing literature, we identified four prominent visualization qualities: aesthetics, usability, novelty, and complexity. Even though this is not a comprehensive list, we believe this research will benefit the visualization design process and help establish good visualization practices for interactive narratives in engineering.

2 Interactive Storytelling Concepts in the Context of Visualization for Industrial Purposes

Interactive narrative (IN) principles for serious applications significantly differ from those for the media or entertainment industries. Despite the promising potential that INs hold for scientific storytelling, the discipline has received little attention in the literature. Visualization is a non-traditional medium in which the understanding of narrative structure components is reshaped. Vosmeer and Schouten examined how narrativity, interactivity, and engagement are mutually reshaped when the same immersive technologies are applied to different domains [22]. They compared different disciplines in media entertainment (video games and cinematography). For industrial visualization, which is a disparate experience form, this means a further re-evaluation of established concepts. Ma et al. [4] emphasized the differences in key narrative elements (setting, character, and plot) of traditional and scientific storytelling. According to them, in traditional media, such as theatre, film, or gaming, the setting is treated as the physical or virtual environment in which the story is set, while in visualization it is the background information that provides context. Characters, which would normally be people or protagonists, are visual elements or data in visualization. Visualization's plot is the comparison, interaction, and evolution of visual elements.

In IN theory, the narrative progression is controlled by the author, observer, or both. Interactivity is determined by varying degrees of autonomy provided to the user. Wohlfart and Hauser proposed a model for different kinds of story consumption based on multiple levels of control between the author and the observer [23]. The example of full author-driven control is passive, non-interactive visualization; while the extreme opposite is liberal data exploration, dictated by the end-user. Segel and Heer explored the balance between author and reader-driven experiences through the identification of different genres of narrative visualization [24]. In evolving systems that employ robust analytics and learning techniques, visualization can also progress algorithmically. This type of storyline development takes data iterations as input. Algorithmic changes in visualization's narrative progression can be treated as an author-driven approach, as AI-generated work can be extrapolated to be human-generated [25].

3 Design Qualities of Narrative Visualization in Engineering

In the previous paragraph, we examined how basic concepts of IN theory, which are established in "old" storytelling media, should be reconsidered for engineering visualization applications. In this section, we will discuss different design dimensions of narrative visualization and how they impact the overall performance of visualization, which is particularly important for the engineering sector. Most of the visualization qualities have been already discussed in the literature. While Ghidini et al. focused on the analysis of design strategies of narrative visualization, taking narrative design space proposals as a starting point [1], we decided to take a different approach. We took publications in the field of visualization as the base premise for our research. The reason for this is that the IN theory focuses on the user and user experience, while the visualization theory's goals are targeted at improvements in system or task performance too. The latter is of great importance for engineering applications, which are the primary focus of this paper. We have identified four key qualities that are relevant for narrative visualization for engineering applications: aesthetics, usability, complexity, and novelty. Aesthetics and usability were included in the selection because their roles in visualization have been extensively discussed in the literature through theoretical and empirical research. Complexity and novelty were chosen because the engineering industries are facing rapid technological revolution and data expansion, which require adaptation from the users and visualization designers. The reader should note that this paper doesn't provide an extensive list of visualization qualities and it should be treated as a starting point for further research.

3.1 Aesthetics

Beauty can be used as a guiding principle in the practice of sciences and systems engineering [26]. The concept of aesthetics, its usage, and effect on storytelling and visualization has been extensively discussed in the literature. It has caused polarized opinions among visualization researchers. Iliinsky outlined this dichotomy, noting that beauty in visualization can be achieved through compelling graphical construction of visual elements, or as another opportunity to increase the utility of the visualization [27]. While merely decorative elements might not be in the interest of practitioners from engineering and sciences, they might appreciate aesthetics for its potential to add to the visualization's efficacy. For Krzywinski, form with function is beautiful [28]. Kyndrup argued that beauty is an independent quality and should, therefore, be assessed separately from the primary goals of the visualization [29]. He did, however, express the concern that too beautiful visualizations can disturb the viewer's attention and perception. Beauty is a subjective judgment that is difficult to quantify, so the appropriate level of beauty for visualizing data remains abstract. Benefits of aesthetics for data representation have been mostly addressed through its relationship with usability, which is the principal prerequisite for implementation of interactive experiences. Studies have shown a positive correlation between aesthetics and usability, a strong relationship between the perceived appearance and the usability of the interface [18, 30], and that users handle aesthetic visualizations more patiently and profoundly [17]. However, a recent study by Flangas et al. has failed to prove that aesthetic elements of the visual interface affect user performance or decision fatigue [31].

In interactive digital narrative (IDN) theory, aesthetics is understood through Murray's seminal model [32]. She proposed three aesthetic categories for interactive storytelling analysis: immersion, agency, and transformation, which will be briefly discussed in the context of narrative visualization.

Immersion is the sense of physical or mental absorption in content or medium, which is experienced by an interactor. It is a sensation and experiential pleasure of taking part in a synthetic reality in which the user's actions impact the immersive environment and follow its logic. Raja et al. showed that immersion in visualization results in better user performance, especially when viewing large datasets [33]. Aesthetic visualizations can facilitate a greater mental immersion into the data [9].

Agency denotes the user's ability to take meaningful action, which will happen in a dynamically responsive world. The changes should not be a result of arbitrary exploration of utilities, they rather have to reflect the user's intentions. While in IDN theory agency originally refers to user's responses within the domain of the digital environment, in narrative visualization the concept can be extended to the physical world, too. In some engineering applications (e.g., cyber-physical systems), the user can act as a bond within the real and the virtual world and send input to both ends of the system.

The beauty of narrative also comes from the transformational experience that can happen on multiple levels. Transformation can manifest through variations on the theme or role play. For narrative visualization, this can help the viewer gain a better understanding of data by providing insight in various forms (e.g., layering the data, providing different viewing angles, or using diverse graphic formats). Personal transformation is the ability of storytelling to change the viewer. It is crucial for the success of serious applications [34], such as engineering or scientific applications. In story-based visualization, personal transformation can be achieved through learning, knowledge discovery, and gaining a novel outlook on the subject matter.

3.2 Usability

Usability is tremendously important for interactive narrative visualizations, as it is a prerequisite for data exploration and message extraction. Lack of usability in engineering applications poses health, safety, malfunction, and error risks, which can have serious financial or fatal consequences. Usability has been widely evaluated as a dimension of user experience for IDNs [35]. From a human-computer interaction perspective, usability can be understood as the user's experience with both hardware and software. For an interactive experience, system usability is essential for its potential to influence efficacy, autonomy, and meet user expectations [34]. Roth and Koenitz identified usability as a subcategory of agency using Murray's model. Thus, it can be interpreted as an aesthetic experiential category of IDNs. We decided to treat the terms aesthetics and usability separately, as they bear different meanings in visualization research.

Usability can be interpreted as readability or visual literacy in visualization systems. It manifests as the user's ability to receive and disentangle content. As a visual exploration technique, visualization is prone to misinterpretation and mismatching between the creator's intent and the viewer's understanding.

Some limitations of hardware interaction arise from the user's unfamiliarity with the technology or adverse effects on the user (such as cyber or motion sickness). Failure to adequately interface with the software comes from the user's inability to navigate, operate, and manipulate the system and results in misapprehension, confusion, frustration, and task abandonment.

3.3 Novelty

In the context of story-based interactive visualization, novelty refers to perceived innovation and originality in different elements of the experience [35]. Novelty is powerful for narrative visualization because it triggers interest, facilitates learning, and elicits cognitive pleasure [36]. Unfamiliar or unexpected visualizations and interactions are more memorable to the user [37, 38]. A user study by Kolhoff and Nack [39] showed that novelty initiated the engagement of users with interactive narrative content. Cawthon and Moere compared various visualization methods and disproved the notion that familiar examples, which people are more exposed to, accustomed to, and trained to comprehend, result in high effectiveness [17].

Original visualization techniques can, however, be repelling if they aggravate the readability of the visual narrative. Novelty can negatively affect usability, which is a trade-off that has to be carefully considered for serious applications. According to the theory of preference-for-prototypes, people are biased towards the most familiar choices because they minimize the risk of the unknown [10, 40]. In time-sensitive and mission-critical engineering applications, decision-makers will want to avoid unpredicted scenarios and they might perform better in a well-known environment. It is easier to perform tasks in computer interfaces that take advantage of previously learned techniques [41]. This is particularly relevant to non-tech-savvy users, who will need to be trained to maneuver novel hardware or software solutions. Higgins and Howell explained that a stimulus that is excessively novel triggers a displeasure response and results in disengagement with the stimuli [42]. They also noted that the threshold for unpleasurable arousal is subjective and it differs between individuals. In the engineering environment, it will be important to determine how comfortable the users are with novelty and in which domains. It will be crucial to mitigating the possibility of an adverse reaction that can lead to negative feelings, errors, and task abandonment.

3.4 Complexity

The complexity of IN for the visual articulation of data is expressed as the degree of cognitive effort needed to extract and receive information, the quantity of content, or the number of options the narrative provides. We approached the complexity problem from two viewpoints: data complexity (e.g., types of data, layers of data, tasks to be performed), and narrative complexity (e.g., the number of decision points or autonomy levels).

First, we will consider the concept of data complexity. Presentation of complex and massive amounts of real-time information is extremely difficult, even when using visual media [43]. Data has to be organized and structured efficiently, so it doesn't overload the receiver. The complexity and scale of data are increasing, as insight gained from analytics is at the core of the Industry 4.0 revolution. For real-time engineering applications, this means that optimization techniques need to be employed to increase the visualization's efficiency and prevent bottlenecks. Some data complexity issues can be resolved using custom optimization techniques (e.g., limiting the polygon count and introducing different levels of detail in a virtual environment for immersive applications), while others are dependent on new generations of robust technology (e.g., using 5G network to instantaneously send and process data from the physical to the virtual world, and vice versa). Excessive intricacy can be also solved by carefully designing and organizing information. The rule of the thumb is to manage it by layering and displaying only the necessary information at a time [44]. Even though additional visual information can increase the system performance and mental effort requirements, it can aid the knowledge-grasping process [41]. Preference for complexity or simplicity varies between individuals. Some people tend to enjoy cognitive effort [42] and they will enjoy performing complex tasks more than those in a lower need for cognition, who opt for simple tasks [45]. Personal preferences and mental capabilities of users need to be taken into account when designing narratives for interactive engineering visualization.

In this paragraph, we will discuss the complexity of the narrative. Using IDNs to comprehend complex phenomena has received more attention in recent years, and it is best seen through initiatives such as INDCOR[1]. Complexity provokes interest [20], so it

[1] https://indcor.eu/.

initiates involvement with the narrative and motivates users to spend more time engaging in it. In the context of IDNs, complexity is best correlated with interactivity. Creators have to balance the interactive complexity and the quality of the IDN artifact [35]. Giving the users too much freedom can result in unexpected behavior in which users can, for instance, navigate away from the area of interest. Complexity can also be related to autonomy, the independence to choose from a series of options without the feeling of being pulled in a single direction [34]. The number and the quality of available options to influence the narrative has to satisfy the user's expectations and meet the author's intent. Too much content or available options result in increased anxiety [46]. Limitations are also necessary for designing a usable system, as complex systems and interfaces are harder to use [47].

4 Discussion and Conclusion

The goal of this paper was to examine design qualities relevant for visualization research and evaluate them in the context of interactive narrative visualization for engineering applications. Our motivation was to aid practitioners in the design process by setting up a theoretical foundation based on existing literature. We identified four design qualities (aesthetics, usability, novelty, and complexity) that are relevant for visualization research and which have a great potential for interactive story-based visualization in engineering. We discussed their interrelationships and influence on visualization efficiency (see Fig. 1). Our aim was not to create a comprehensive list, but rather to provoke critical thinking and provide a starting point for further development of this nascent field.

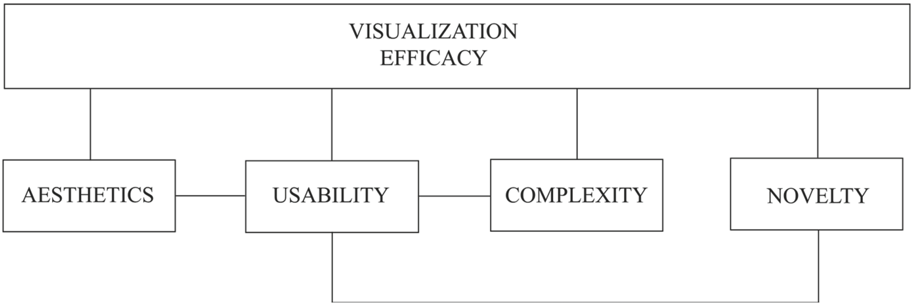

Fig. 1. Diagram presenting the four design qualities of interactive narrative visualization for engineering applications and their interrelationships.

As a result of our research, we concluded that:

1. Terminology needs to be re-evaluated in the new context. In the first part of this paper, we discussed the idea of narrative visualization and identified the need to re-evaluate IN concepts in the new context. We further compared the shared concepts of aesthetics, usability, novelty, and complexity in visualization and IN research, and showed similarities and differences in their usage and understanding.

2. All four design dimensions we analyzed are subjective and prone to personal interpretation. Different reactions, comfort levels, and preferences among users are associated with factors such as demographics, previous experiences, intellectuality, personal taste, etc. Designing a good visualization is a complex process and while some guidelines exist, there is no guarantee that they will be successful in a particular context. More user studies will need to be conducted as the field develops.
3. All four design qualities can be both positive and negative, depending on the context. Closely related to the first statement, presented concepts can be beneficial or disadvantageous as a result of a subjective judgment. There is a point beyond which subjects start experiencing negative effects and finding that threshold for every individual might be crucial. Also, different applications will require different design principles. Our research focused on the needs of the engineering industry, which can differ from those of other industries. Differences can be also made between different engineering subdisciplines and specific applications.
4. Trade-off between design qualities has to be made. Design qualities can also positively or negatively affect each other. Visualization designers will need to determine the end goal of visualization and give priority to features that best reflect the desired intent. This network of mutual relationships of visualization or story components will also vary with the application.
5. There is a lack of completed case studies in the field. Despite the great potential of interactive storytelling for visualizing engineering data, the lack of completed case studies is evident. While work in the field of narrative visualization has been addressed in the literature, it only touches upon engineering applications. More practical visualization solutions are needed to expand our list and set up a theoretical foundation of the field.

The greatest limitations of our work come from a lack of available case studies and a small number of qualities compared. Different conclusions might be drawn from analyzing practical visualization examples and expanding the list of design qualities. Also, some of the research conducted in the visualization field is specific for 2D, static information visualization, and might not be directly applicable to more complex visualization formats, and vice versa. We interpreted the term visualization broadly because interactive narrative visualization for engineering applications combines various visualization methods. We believe our research is the first step to establish this emerging visualization field, identify its requirements, and conceptualize adequate design practices. We hope these results will help to bridge the gap between storytellers, visualization designers, and engineers and expedite collaborative efforts to employ interactive narratives for visualizing engineering data.

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