Visualization in the VR-Canvas: How much Reality is Good for Immersive Analytics in Virtual Reality?

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ABSTRACT

Building user interfaces in virtual reality (VR) provides many incentives for the desire to replicate the real world within the "VR-Canvas"; three-dimensional spaces and objects, movement, direct interaction, realistic lighting, etc. While many of these design decisions might, in fact, support learning and provide a strong sense of familiarity, their benefit for effective analytic tasks remains controversial. Similar to how desktop interfaces adapt and *extend* metaphors from the real world, there is a widespread assumption that virtual reality environments will benefit from *not* replicating every part of the real world and instead focus on transcending reality and improving human experience, perception, and, eventually, cognition. In this paper, we collect evidence from studies, opinions, and examples to foster the current discussion on how replicating the real world can improve or impede tasks in immersive analytics. To clarify what we mean by "real world", we look at a range of aspects including *spatiality*, *physics*, *multimodality*, and *visual appearance*.

Index Terms: Human-centered computing [Human computer interaction (HCI)]: Interaction paradigms—Virtual reality;

1 INTRODUCTION

Visualization strives to find methods, visual metaphors, and interactive media to optimize the communication of information, the performance of analytic tasks, problem solving, and decision making [41]. Novel technologies for virtual reality (VR) have opened up a new space to support perception and interaction with data visualizations beyond the limits of the desktop [12]. Currently, more visualization interfaces for VR are explored and designed, using technology such as HTC Vive head-mounted displays, mature development environments such as Unity and RealEngine, and novel toolkits for immersive visualization design [34]. There are many reasons for considering visualization in VR: stereoscopic perception, direct interaction in 3D space, free body movement [13], a 360-degree immersive view as well as a potentially infinite space to place visual elements. As shown in previous research, these introduced properties can improve visual analytics tasks in certain aspects (e.g., immersion: improvements in task efficiency and effectiveness for spatial well-path planning [19]). Due to the beneficial effects of these characteristics, there is a natural desire to replicate the real world in VR. In most cases, these decisions can be a measure to increase familiarity and to support adaption and learning [20].

However, much has been discussed about replicating the real world in virtual worlds (Section 2). For example, Shneiderman argues "*why not making interfaces better than 3D reality?*" [32], while Elmqvist focuses the discussion on visualization and provides explicit guidelines for the use of 3D visualization on screens and in immersive environments [7]. To effectively use VR in immersive analytics, it is crucial to understand the specific affordances and the potential of VR concerning the level of immersion needed to provide users with successful user experience and an effective analytical workflow [2]. These affordances can include both: to adopt the real world and to transcend it by searching for novel solutions that improve perception, cognition, and the performance of analytic tasks in a virtual reality environment (VRE). For instance, stereoscopic view could ease the recognition of depth in volume visualizations. Depending on the analytic tasks to solve, user interfaces may use natural, supernatural, or abstract scene objects, resembling reality as far as technology allows.

In this paper we collect evidence from studies, opinions as well as examples to enrich the current discussion on how replicating the real world can improve or impede VA tasks in the context of immersive analytics. To structure our discussion about 'reality in virtual reality', we introduce the concept of the VR-Canvas as a conceptual model to think about designing immersive interfaces in virtual reality (Section 3). We further look at different aspects of the real physical world and their possible mappings to virtual reality (Section 4). The considered dimensions of the real world that can be replicated in a VRE may influence VA-relevant aspects in various ways (e.g., an increase in immersion may lead to higher levels of concentration). We discuss them in the light of possible beneficial effects, such as memorability or presence, that may lead to potential uses and applications for visualization tasks. Based on this analysis of the real world attributes mapping, we close this paper in Section 5 with a discussion of advantages and drawbacks of real world resemblance in VR.

2 CURRENT DISCUSSION IN INTERFACE DESIGN

Replicating reality in user interface is a strong mechanism and has been practiced since the beginning of interface design; buttons, sliders, the entire desktop metaphor including documents, paper bins and work spaces with the ability for direct manipulation, e.g., via drag-and-drop [33]. On the other side, Stuerzlinger and Wingrave [37] discuss how perfect simulation and realistic environments can lead to undesired, increased user expectations of a system. Moreover, metaphors and realistic replications of the real world may eventually, in the long run, be less efficient than proper techniques such as shortcuts [32].

For virtual reality, some guidelines mention to "establish familiarity" [5]. Others, discussed in various blogs [1, 3], include "Make it beautiful" and state that for an increase in immersion breathtaking scenes are advantageous. In fact, much effort has been put into understanding the psychological, perceptual, and cognitive effects of reality, including concepts such as immersion, social presence [6], and direct interaction [31]. In general, a sense of presence involves a sensation on the user's side of being present (spatial presence), and the interactions with other individuals (social presence) [6]. Immersion, in the context of VR, can also be defined as the sense of being present in a virtual environment, e.g., by removing as many real-world sensations as possible and replacing them with VRE sensations [28]. A study by Seiber and Shafer [31], which involved over 200 students, found that controller naturalness and natural mapping already lead to increases in spatial presence in VR, regardless of the display condition (head-mounted displays, standard monitor). Being used to a specific controller further increases the naturalness of an environment. In VREs, one could use one's finger as a pointer in the three-dimensional space, which would be perceived as more natural and therefore increase the presence of a user.

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Niklas Elmqvist discusses guidelines and challenges for the 3D visualization of non-spatial data in a blogpost [7]. One of this guidelines reads *"Don't Replicate the Real World"*. He states that the only advantage of increasing familiarity for a user interface by transferring known elements from the real world to 3D controls is insufficient as *"the whole purpose of a computer is to augment [human] abilities and eliminate [their] limitations, many of them imposed by the physical world"*. For instance, in a task that requires high levels of spatial memorability, the user could be forced to walk around if he wants to change his position. This would probably improve his spatial memory. In another scenario, in which spatial memory is not crucial, a teleport function could be introduced that allows the user to change position without walking and minimizing his physical efforts.

3 The VR-Canvas

Our definition of the VR-Canvas is loosely inspired by the *AR-Canvas*, a canvas-concept for augmented reality (AR) describing data visualization in AR compared to the *traditional canvas* for visualizations, such as 2D screens and paper [10]. The traditional canvas constitutes an empty, two-dimensional, monochrome display space. The type of canvas has a strong influence on the type and design of possible visualizations and their respective task efficiency.

In the same spirit, the VR-Canvas is purely conceptual, meant to support thinking about visualization design and the degree of reality in virtual reality; *What is possible?; What is desirable?; How can we make the best use of the characteristics of the VR-Canvas for visualization and analytic tasks by replicating reality?*

We describe the characteristics of the VR-Canvas with respect to reality as follows: **i) Spatiality**: The VR environment defines a three-dimensional space with stereoscopic perception. Using suitable controllers or gesture tracking methods, movements and positions from the real world can be mapped to interactions in the VR-Canvas [13]. An **ii) immersive 360-degree display** provides display space in each possible viewing direction while users' head-movements define their viewing direction. **iii) Multimodality** includes additional senses beyond visual perception and proprioception; haptics and tangibility, sonic information, speech-input, taste, smell, etc. [25].

Each of these characteristics can be used to create a sense of reality in a VRE. At the same time, they constitute the main motivation for the desire to replicate the real world through three-dimensional spaces and objects, realistic scenes, direct interaction, etc. As it is a thought model, the VR-Canvas is independent of any technical aspects, such as specific hardware (e.g., HTC Vive, Oculus Rift, mobile phone), data structures and algorithms (e.g., scenegraph, rendering method) or implementation details (e.g., programming language, rendering engine).

4 Aspects of Reality

To better deal with the complex concept of "reality", we look at a set of aspects of the physical reality and how they relate to an adaption into the VR-Canvas for visual analytics tasks. Our list is non-exhaustive at the moment, but can be used in future work as a basis to continue the discussion. This list of aspects of physical reality refer to VR properties which may influence characteristics like immersion and presence, which can have an impact on visual analytics tasks (e.g., [19]).

Three-Dimensionality and Stereoscopy—Three-dimensional objects and visualizations have largely been condemned for the use on 2D screens since they cause occlusion and perspective distortion, and are hard to interact with [7, 8]. Most of these problems persist within the VR-Canvas. While some studies have shown increased performance in perception for steroscopic virtual displays [16, 26, 42] and physical visualizations [21], others attribute the effect rather to motion parallax [9, 39]. Depending on the data (e.g., sparse, inherently spatial, such as fluids and anatomy) and task—e.g., general overview, convey a metaphor [8], identify purely 3D structures, such as a correlation in three dimensions, or perform complicated interactions that require a high number of degrees of freedom [9]—stereoscopy might be of limited use. The VR-Canvas [43] can provide alternatives to proper 2D representations.

Laws of Physics—Based on physics, humans can infer about objects in the real world, even if they have never seen the object before: gravity and direction of movement, occlusion and positioning, rigidness and elasticity of objects, etc. However, in the VR-Canvas, we have full control over the design space, which allows us to turn off physics for some or all objects. At first glance, disabling the laws of physics in the VR-Canvas may seem preferable as they often limit possible actions (e.g., floating points in a scatterplot visualization). Though, there are problems originating from removing the laws of physics. For instance, in the real world two objects never occupy the same position at the same time. Ignoring this assumption in the VR-Canvas (as well as on 2D media) can cause a person to miss information, such as overlapping points in scatterplots or lines in PCPs. On the other hand, the ability to ignore the rigidness of objects allows higher precision (in scatterplots) and comparing 3D objects through "superposition". The designer should take these effects into account and can offer additional complementary views. It is also possible to enable physics for some objects, but disable it for others, keeping in mind consistency and ways that prevent possible confusion. Depending on how many other aspects of the real world are included in the VR-Canvas, a user may even expect objects to be influenced by physics. If the VR scene only consists of abstract visualizations, it might be easier to accept that they float in mid-air than if the scene emulates an entire office with many objects known from the real world.

Visual Appearance—Visual appearance includes everything that influences the appearance of objects in the VR scene: texture, lighting, shading, reflection, etc. Light sources in the scene that create shading on the 3D objects can help the user to identify 3D shapes [38]. This effect can be increased by placing the light source in specific positions, ideally above a user's height [18]. For some tasks it can be advantageous to include light sources that cannot exist in the real world, for example by using some global illumination that makes the whole scene brighter. Lighting can also be used to emulate the day and night cycle in a VR environment. If the user is working at night, it can be confusing if he needs to switch between a dark real world environment and a bright virtual reality environment since the eyes need to adapt to the level of brightness, as is the case with most navigation systems in cars.

If objects from the real world were used in the VR-Canvas, it would be possible to use exact copies of real-world *textures*, which reduces the time it takes to recognize objects [30]. Textures can be used to convey information [24], yet they can make scenes visually complex. To the best of our knowledge, there are no studies to inform decisions about the extent to which texture and shading support or impede analytic tasks in virtual reality.

Environments and Objects—The replication of generally physically present objects (e.g., a desk, a room, a tool) inside the VR-Canvas has proven to be beneficial if the physical properties of the objects are maintained (e.g., location, mobility, shape) [35, 40]. Such replication leads to an increased suspension of disbelief in the virtual environment and was used for tangible user interfaces (TUIs) in VR [13]. Slater [36] identifies place illusion and plausibility illusion as two basic factors leading to realistic behavior of users in virtual reality environments (i.e., how real the place and its reaction to user actions is). The sensation of presence (i.e., feeling of "being there") is directly influenced by the two aspects. This is further supported by a study which concludes that "maximal presence in a mediated experience arises from an optimal combination of form and content" [29], i.e., a system has to reflect intended user purposes and mimic expected reactions to convey a high level of perceived presence.

However, there is also research contradicting this suggestion. Mental load could be reduced by minimizing the perceivable environment and helping to focus on the analytic tasks.

Navigation in VR space is a common problem as users often need to cover longer distances than they can or want to walk in the real world. While physical solutions exist [15], entirely virtual solutions include teleportation and fast movement. In case these methods are unavoidable, specific care must be taken to prevent motion sickness. Alternatively, spaces could be scaled down or virtual elements could be brought closer to the user, e.g., through pointing, without changing the user's actual position.

DIRECT MANIPULATION—The well-established device pair of mouse and keyboard is most commonly used for traditional screen-based user interaction. In contrast, there is no golden standard for virtual reality environments. Various techniques have been developed, using tangible controls, such as the Vive controllers, or implicit controls, such as movement or gestures. Wagner Filho et al. [40] purposefully used in their VA prototype a seated setting in combination with tangible controls to reduce the physical effort of the user for spatial navigation in their visualization. This may lead to a decreased feeling of presence due to a less real-world-like navigation, but increases the overall efficiency of the VA procedure.

COLLABORATION—In collaborative scenarios, it may be useful to realistically replicate physically remote collaborators in the VR-Canvas to facilitate more effective collaborations [11, 27]; users can point at objects and convey information through mimic and gesture [14, 17]. In collaborative scenarios, replicating the real world, i.e., at least the collaborators' position, hands, and facial expressions, is highly desirable. This enables the collaborator to use natural communication, such as gestures or facial expressions. Other than in reality, the collaborator does not have to be present in the same physical space as oneself. The use of embodiment as a tool to solve specific tasks was discussed by Mennecke et al. [27] and deployed in many areas, for example, to understand behavior [22] and to raise awareness of social matters [23].

SONIC INFORMATION—Sonic stimuli convey information in many cases: telephones, alarm bells, Geiger counters, or heart rate monitors. Some sound cues convey information even though they are not designed for this purpose, such as printers and cars. Using the same sound cues that people are already familiar with can avoid additional time for familiarization and provides an intuitive way to convey information to users. Sound can be especially useful to transmit ambient information within a VR-Canvas that supports body and head movement. This allows to divert the user's full attention towards specific elements at a time and the user effectively neglects the rest of the scene which might be behind him or far away. To decide whether a specific sound cue should be included in a VRE, it should be checked whether the sound carries important information and whether this information cannot be transferred more efficiently using visualizations. However, it should be taken into account that a sound can get the attention of users, regardless of the direction in which its source is located. In contrast, visual cues can only be noticed if they are in the user's field of view and may otherwise be overlooked. A comprehensive discussion on multimodality in immersive analytics is provided elsewhere [25].

METAPHORS A metaphor is a figure of speech in which a word or phrase literally denotes one kind of object or idea, but is used in place of another to indicate a similarity or analogy between them [4]. Interface metaphors have long been used to embody functionality and familiarity. Transferred to immersive analytics, visualization-, control-, or interaction-elements can be treated as metaphors to control interaction. For instance, one could draw a visualization on a 3D resemblance of a flip chart on a screen instead of depicting it on a modest plane. The visualization could then be hung on a virtual wall, printed on virtual paper, or be organized in shelves.

Even though the use of interaction metaphors, such as walking, grabbing, and gazing, may reduce the learning curve, it can also increase physical and mental effort, resulting in lower efficiency and fatigue. However, in some cases–especially in the context of VR—it may be reasonable to exploit advantages of such metaphors. For instance, by deploying the metaphor of walking (which could be replaced with teleporting in VR), spatial memory could be fostered. By forcing physical rotation for navigation, the sense of orientation could be improved, for instance, by placing items in cardinal directions around the user (who would learn that specific items are always north of him).

5 DISCUSSION

Our paper showcases some of the advantages and drawbacks of real-world resemblance in VR to foster discussion about its benefits and limitations. We only focused on replication, although other guidelines could have as well been considered in more detail. Even though our investigations were motivated by finding a guideline for replicating the real world in visualization tasks, our approach is also applicable to other domains (e.g., gaming, non-VA tasks). We identified eight main attributes to systematically analyze real-world resemblance. Our main concern is when and to what degree the real world should be replicated in a virtual environment for visual analytics purposes. We arrived at a selection of design considerations and recommendations from state-of-the-art related works. The selected papers address advantages and disadvantages caused by the replication of the real world, either explicitly or implicitly. We also analyzed other sources, such as online sources, that discuss design guidelines for VR, 3D and visualizations in general.

Firstly, we suggest that several rules regarding visualization and interface design for conventional media can be transferred to VR. In particular, we refer to the guideline "Don't replicate the real world" by Niklas Elmqvist [7]. When this rule is associated with user interface elements, it leads to a reduction in mental and physical effort to trigger certain actions. It is closely related to a rule established by Shneiderman: "Enable frequent users to use shortcuts" [32]. Thereby, inconvenient realistic actions are replaced by "unrealistic", effortless supernatural equivalents (e.g., allowing to teleport in VR to certain points through a click on the controller instead of forcing the user to walk through the virtual room).

Secondly, we argue that taking advantage of some derived effects of VR, such as immersion, presence, and spatial memory, could be beneficial for immersive analytic tasks, as shown by several prior works (e.g., [16,19,26]). Depending on the task at hand, the designer has to balance which aspects have to be replicated more realistically in order to achieve a specific goal and at what price this is done. It is important that the cost-benefit ratio is optimal—i.e., if a realistic replication of the real world is installed and comes along with some disadvantage (rendering effort, distraction), it has to be outweighed by its introduced benefits (e.g., increased level of immersion leading to better performance in a specific task).

Our discussion exposes that it is not generalizable how much reality should be striven for in VREs. Depending on the purpose and impact of possible real-world resemblance, an optimal trade-off between simplicity and realism has to be chosen individually for each application. Moreover, the discussion reveals many points for future research, e.g., to investigate a better understanding of visualization design spaces and to examine how to construct optimal working environments for visual analytics workflows, how to deploy shortcuts in VR, or if the VR-Canvas is suitable for the display of pure 2D contents (which are typical for state-of-the-art VA procedures).

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