ARTICLE IN PRESS

Visual Informatics ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Visual Informatics

journal homepage: www.elsevier.com/locate/visinf

Exploring the design space of immersive urban analytics

Zhutian Chen [a,b], Yifang Wang [b], Tianchen Sun [b], Xiang Gao [c], Wei Chen [b], Zhigeng Pan [c], Huamin Qu [a], Yingcai Wu [b,1,*]

[a] Hong Kong University of Science and Technology, Hong Kong
[b] The State Key Lab of CAD & CG, Zhejiang University, China
[c] Hangzhou Normal University, China

ARTICLE INFO

Article history:
Received 20 September 2017
Received in revised form 10 November 2017
Accepted 10 November 2017
Available online xxxx

Keywords:
Immersive urban analytics
Virtual/Augmented/Mixed reality
Urban visualizations
Information visualizations
Visualization theory

ABSTRACT

Recent years have witnessed the rapid development and wide adoption of immersive head-mounted devices, such as HTC VIVE, Oculus Rift, and Microsoft HoloLens. These immersive devices have the potential to significantly extend the methodology of urban visual analytics by providing critical 3D context information and creating a sense of presence. In this paper, we propose a theoretical model to characterize the visualizations in immersive urban analytics. Furthermore, based on our comprehensive and concise model, we contribute a typology of combination methods of 2D and 3D visualizations that distinguishes between *linked views*, *embedded views*, and *mixed views*. We also propose a supporting guideline to assist users in selecting a proper view under certain circumstances by considering *visual geometry* and *spatial distribution* of the 2D and 3D visualizations. Finally, based on existing work, possible future research opportunities are explored and discussed.

1. Introduction

1.1. Motivation

Urban visual analytics has been proven useful in solving various problems of urban cities, such as location selection (Liu et al., 2017), urban planning (Huang et al., 2016), and traffic analysis (Guo et al., 2011), by integrating the computational power of machines and the domain knowledge of experts. In urban visual analytics, visual representations of urban data provide a crucial context for exploration and analysis (Andrienko et al., 2007).

Most existing studies of urban visual analytics utilize 2D maps (Zheng et al., 2016) on which every point is viewed overhead. As 2D maps create an abstraction of the real world, the maps lose significant context information on the urban environment, consequently leading to the severe limitations in solving space-related problems in the urban context. First, the lack of depth information of vertical cities poses a significant challenge for making informed decisions in many scenarios. For example, selecting befitting locations to place billboards exclusively based on traffic flow on 2D maps would be difficult for advertising managers (Liu et al., 2017), because candidate locations in vertical cities may be near or under buildings, overpasses, utility wires, and so on. Second, a 2D map that lacks the appearance of the real world cannot provide users with a sense of presence. For example, in a 2D map, both magnificent skyscrapers and tiny bungalows are displayed as polygons. In such a lack of a sense of presence, users cannot fully apply their expertise and domain knowledge to making a confident spatial decision. Expensive field studies are frequently employed. Therefore, growing interest has been observed in applying 3D maps for urban visual analytics (Ferreira et al., 2015; Ortner et al., 2017).

In recent years, various of immersive head-mounted devices, such as HTC VIVE, Oculus Rift, and Microsoft HoloLens, have been invented and adopted in a wide range of settings. The immersive devices use stereoscopic techniques to create a natural support for 3D display, thereby creating an engaging and immersive visual environment (Bach et al., 2016). The significant development and broad adoption of the immersive devices shed new light on visualizing heterogeneous geospatial urban data in such an immersive environment; this field can be referred to as *immersive urban analytics*.

Recently, researchers from urban visual analytics (Andrienko et al., 2010) and immersive analytics (Bach et al., 2016) have raised questions on how to visualize the abstract data together with 3D models. Abstract data is commonly visualized in a 2D manner,

* Corresponding author.
E-mail addresses: zhutian.chen@outlook.com (Z. Chen), ycwu@zju.edu.cn (Y. Wu).

[1] This work was done when Zhutian Chen was a visiting student supervised by Yingcai Wu at Zhejiang University.

Peer review under responsibility of Zhejiang University and Zhejiang University Press.

https://doi.org/10.1016/j.visinf.2017.11.002

since the 3D display of the data remains controversial and may cause ambiguity (Munzner, 2014, Chapter 6). By contrast, as a type of physical data, city models can be naturally displayed in 3D. It remains unclear that how to seamlessly display 2D abstract data together with 3D physical city models in an effective way.

To address this issue, we first summarize an abstract model to characterize the visualization in immersive analytics. Based on our model and the fundamental theorem of Euclidean geometry, we propose an innovative typology classifying the ways to visually integrate physical and abstract data into three categories, namely, *Linked view, Embedded view*, and *Mixed view*. Furthermore, we conduct preliminary explorations and summarize two plain and comprehensive design considerations, namely, *Visual geometry* and *Spatial distribution*, to assist designers in effortlessly choosing the best view under certain circumstances. We demonstrate the effectiveness of our design considerations with several examples.

1.2. Related works

In recent years, with the popularization of low-cost immersive devices such as Leap Motion, Kinect, Oculus Rift and Microsoft HoloLens, an increasing number of researchers are developing an interest in Immersive Analytics, which aims to allow users to immerse themselves in data in a way that supports real-world analytical tasks (Bach et al., 2016; Sadana et al., 2016).

Research on immersive analytics can be classified into categories per computing modalities creating immersive environments, namely, CAVE style system (Bennett et al., 2014; Helbig et al., 2014), mobile augmented reality system (Engelke et al., 2016; ElSayed et al., 2016), data physicalizations system (Taher et al., 2017), and head-mounted display (HMD) (Cordeil et al., 2016, 2017; Kwon et al., 2016; Moran et al., 2015). In this study, we mainly focus on the works about emerging immersive technologies.

Many researchers have conducted studies on HMD-based immersive analytics. Kwon et al. presented a study on layout, rendering, and interaction methods for graph visualization in an HMD virtual reality (VR) environment (Kwon et al., 2016). The result showed that using their techniques is more highly efficient than traditional 2D graph visualization in HMD VR environments. Cordeil et al. developed a visually immersive prototype for collaborative aircraft trajectory visualization based on HMD VR devices (Cordeil et al., 2016). Moran et al. attempted to study the geographic distributions of Twitter data by developing a 3D application utilizing an HMD VR setting (Moran et al., 2015). However, they only displayed tweets with geo-tags on a 3D map. Users can explore those tweets through simple interactions. Baumeister et al. presented two users studies which compare the cognitive load of users using three augmented reality display technologies: spatial augmented reality, the optical see-through Microsoft HoloLens, and the video see-through Samsung Gear VR. Their results suggest that some of the restrictions of HMD increase user cognitive load. However, most of the existing studies focus on abstract data, especially the graph data.

Besides evaluations and techniques, some researchers propose theoretical models to characterize the design space of immersive analytics. Willett et al. introduced *embedded visualization* (Willett et al., 2017), a theory concept of using visual and physical representations of information that are deeply integrated with the real world. They differentiate situated visualization and embedded visualization based on physical data referents. Bach et al. presented the notion AR-CANVAS (Bach et al., 2017) of the augmented reality canvas for information visualization. Their theory model describes the content from the perspective of users where information visualization is displayed in-situ with respect to visible and invisible real-world objects. However, these works aim at embedding information visualization in the physical real world.

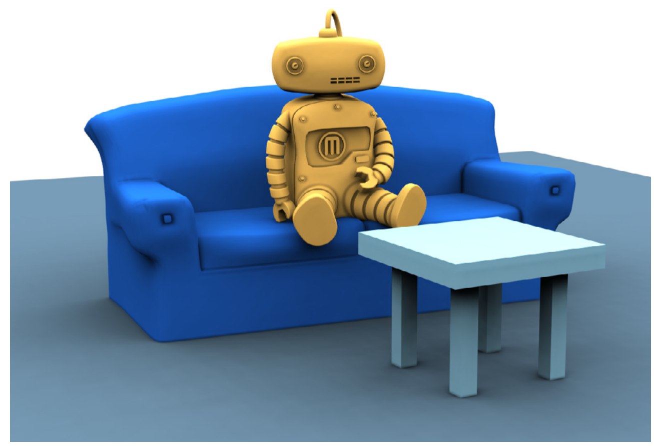

Fig. 1. The virtual reality environments entirely immerse the users in a virtual space, blocking the real world surroundings.

Few researchers in the field of data visualization have conducted explorations on urban data in immersive environments. To the best of our knowledge, our work is the first step in the direction of utilizing immersive technologies in urban visual analytics.

2. Terminology

Immersive technologies have been researched for several decades. We only focus on the emerging immersive technologies. These technologies can create various immersive environments which are different from each other. In this section, we first introduce the characteristics of different immersive environments, then we summarize the types of urban data which will be visualized in immersive environments.

2.1. Immersive environments

Immersive environments are the environments created by immersive technologies (Bach et al., 2016). Immersive environments can be roughly classified into three categories, namely, Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). Several existing works argued and gave formal definitions of VR, AR, and MR. However, since the immersive industry grows rapidly in recent years, most of these works are obsolete. Rather than redefine the concept of these environments, we prefer to identify their distinguishable characteristics, which can help us better understand the environments for visualization.

Virtual reality. We specify the virtual reality (VR) environments as environments created by VR head-mounted display devices, such as HTC Vive, Oculus Rift, Samsung Gear, and Google Cardboard. The cave automatic virtual environments (CAVE) system, which can also create VR environments, is exclusive from our discussion because it is not an emerging technology. The key characteristic of the VR environments is that they fully immerse the users in a digital world and entirely occlude the natural surroundings. Fig. 1 is an example of VR environments. Users can only see the virtual robot sits on a virtual sofa behind a virtual table.

Augmented reality. Azuma et al. defined AR (Azuma, 1997) as systems that have the following three characteristics: (1) combine the real and the virtual, (2) interactive in real time, and (3) (virtual content is) registered in 3D. This definition is well-accepted. However, in recent year, many famous products (e.g. Pokeman Go, Google Glass), which directly overlay the virtual content on top of the real world rather than register them in 3D, claim themselves

Please cite this article in press as: Chen Z., et al., Exploring the design space of immersive urban analytics. Visual Informatics (2017), https://doi.org/10.1016/j.visinf.2017.11.002.