Visualizing Movement Trajectories in an Immersive Space-Time Cube

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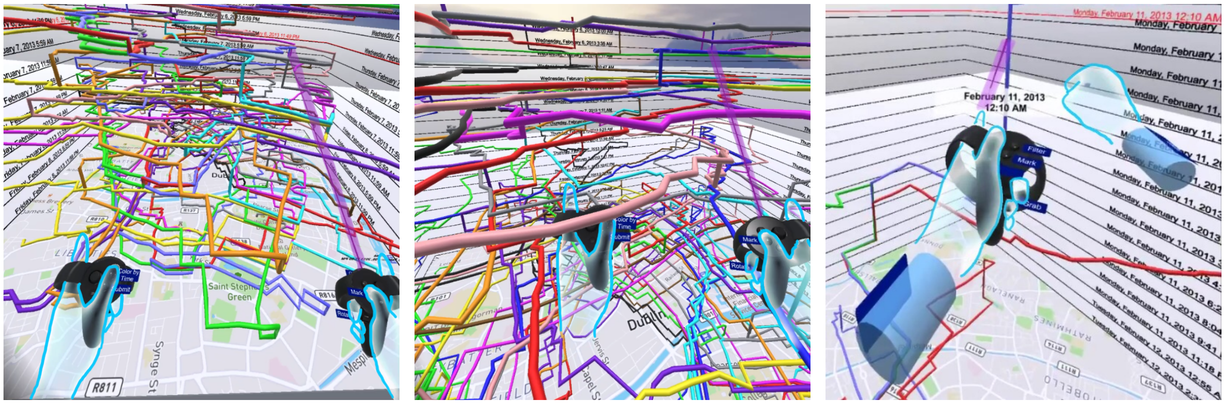

Figure 1: Our research investigates how different visualization and interaction design choices affect the exploration of an immersive space-time cube. Preliminary results indicate different advantages for exocentric (left) and egocentric (center) environments, as well as benefits in combining virtual hand and virtual pointer interaction (right). Hand contours and ray highlights added for clarity.

Abstract

The ever-growing amount of human movement data challenges us to develop new visualization techniques and to revisit existing ones with different perspectives. Traditional 2D movement visualizations focus either on the spatial or temporal aspects of the data, potentially hindering the observation of relevant features. Emerging Immersive Analytics approaches offer the opportunity to revisit a three-dimensional visualization that allows the integrated analysis of both. With the aid of stereoscopic virtual reality and 3D user interfaces, an immersive Space-Time Cube might overcome challenges that limited its adoption in the past. In this paper, we provide an overview of the results obtained in our ongoing research on this immersive representation. We also discuss insights obtained with different navigation and interaction approaches, and our next planned steps.

Index Terms: Human-centered computing—Visualization—Visualization design and evaluation methods; Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality

1 Introduction

Our research focuses on the design and assessment of immersive visualization techniques for analysis of spatio-temporal datasets. We hypothesize that immersion into virtual environments (VEs) will aid in the exploration of human mobility data through a combination of 2D and 3D interactive visual representations. By employing latest-generation stereoscopic Virtual Reality (VR) head-mounted displays (HMDs) and natural interaction techniques, we can provide a multi-sensory analytical environment that takes full advantage of human cognitive capabilities, leveraging abilities developed for the interaction with the real world. Immersive VEs also offer unlimited display space and the opportunity for embodied local and remote collaboration between analysts. Recently, such approaches have demonstrated benefits in some data domains [8], serving as an example of a developing research field called Immersive Analytics [4].

In the context of spatio-temporal data, 3D representations have the ability to more adequately visualize some critical features and patterns, e.g., by employing the perpendicular axis of a map to represent the time component, resulting in a Space-Time Cube (STC) [14]. Even with the aid of animation, common 2D visualizations make it challenging to observe features such as varying movement duration and speed, stop lengths and locations, and meetings between different individuals (when they share the same position in time and space). While the STC is typically challenging to interpret in conventional setups, such as desktops [15], we expect it to be a good fit for an immersive approach, due to the support for stereoscopic 3D and for more intuitive ways of interacting with the 3D trajectories.

Our research goal is to identify the most efficient design choices to support the visual analysis of complex trajectory datasets, through iterative user evaluations employing simulated and real-world datasets. To this end, we are proposing and evaluating Immersive Analytics environments centered around the STC. In this paper, our goal is to provide the reader with an overview of our initial findings and planned steps.

2 Related Work

Originally proposed by Hägerstrand [10], the STC has been revisited by Kraak [14] in the context of an extended interactive geovisualization environment, and later applied to diverse domains, such as event data [9], ship trajectories [2], air-traffic analysis [3], and mobile phone positioning data [15]. Similarly to other 3D representations, however, the STC suffers from well-known limitations in terms of perception and interaction when used in conventional desktop setups. These are a result of the difficulties in estimating distances and visual depths from monocular depth cues alone [32] and the mismatch in terms of control with 2D interaction devices, as well as of the challenges introduced by occlusion and visual clutter. This is even worse when taking into account that domain experts are typically not — and should not be required to be — trained in

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3D manipulation. Previous work identified that experts specifically complained about a steep learning curve for the STC [15].

In this context, we hypothesize that the usability of visualization environments centered around the STC could greatly benefit from an immersive approach. Immersive Analytics applications combine stereoscopic, immersive display, and intuitive 3D interaction techniques to facilitate exploring 3D data representations [4, 18], with promising results found in multiple domains [5, 7, 16, 30]. However, grounded visualization and interaction design guidelines are still much-needed [23].

Some initial efforts to implement immersive representations of movement data have been reported by Theuns [25], using a VR HMD-based prototype, and Saenz et al. [21], using an Augmented Reality (AR) HMD. Moran et al. [19] explored a VR approach for the visualization of geotagged Twitter posts that originated from the MIT campus. They distributed the tweets with their different visual representations in a virtual recreation of the university. In *HoloMaps*, real-time geotagged tweets and traffic information were displayed in a 3D city model, using the Hololens AR HMD [11]. In the *GeoGate* AR system, Ssin et al. [24] combined a 2D tabletop display with a 3D AR "hologram" to visualize trajectories in the maritime domain. *GeoGate* reduced errors in tasks where users had to correlate different data sources. Yang et al. [33] investigated how design choices affect 2D and 3D representations for origin-destination flow maps in immersive environments. They identified that 3D globes are preferred for global flows, while flat maps are more adequate for regional ones — in both cases, flow heights should be proportional to distances. Finally, the *FiberClay* [13] and *ReViVD* [12] immersive systems were recently proposed to enable the visualization and efficient filtering of large volumes of 3D trajectories up to 20 million individual positions, for example, in the air-traffic domain. Our goal is to contribute to these efforts by providing a more precise understanding of the effect of different visualization and interaction design choices in such VEs.

3 Concept Validation

We have already confirmed the potential of immersive approaches in comparison to an equivalent Desktop baseline. We based our first proposed data exploration metaphor on the improvement and extension of the *VirtualDesk* framework [28]. Trajectory data was rendered on a small scale above a virtual reproduction of the analyst's real desk, enabling embodied and tangible interaction and providing strong stereopsis and proprioception cues. In a user study with 20 novice participants, seven tasks of varying difficulty, and two different levels of visual clutter (3 or 24 simultaneous trajectories), this approach improved the users' qualitative experience, with much higher usability and preference, very low simulator sickness incidence, and a significantly lower mental workload [31]. Immersion also changed interactivity patterns, increasing exploration through data translation and scaling, and allowing the users to move their heads to change points of view.

We also conducted free exploration sessions and unstructured interviews with fifteen spatio-temporal data analysts experienced in geovisualization [29]. Most of them were able to quickly familiarize themselves with the environment regardless of previous experience with VR devices. They spent considerable time — often more than 20 minutes — exploring different possibilities and comparing them to their earlier experience with GIS software. The provided suggestions for improvements included incorporating coordinated views for easier identification of patterns, cutting planes for comparisons, and advanced interactive filtering mechanisms.

4 Investigating Navigation and Interaction

More recently, we started to investigate the effects of different exploration modes and frames of reference for the STC and Immersive Analytics in general. Through a controlled user study with 36 participants, we compared nine different conditions. We found that egocentric room-scale exploration (see Fig. 1, *center*) significantly reduced mental workload, while exocentric room-scale (Fig. 1, *left*) improved performance in some tasks. Combining navigation and data manipulation always made tasks easier by reducing workload, perceived temporal demand, and physical effort [27]. We were also able to confirm findings from prior work [17, 22], such as the effect of individual characteristics, e.g., spatial ability, previous VR experience, and gaming frequency, on user performance and preferences.

Another relevant design variable is the interaction metaphor used. To investigate this, we compared a virtual hand, virtual ray pointer, and a combined implementation seamlessly integrating both without explicit mode switches (see Fig. 1, *right*). In a controlled user study with 15 participants, we did not find significant differences between hands and ray in terms of task performance, workload, or interactivity patterns [26]. Yet, the majority of participants preferred the mixed-mode and benefited from it by naturally choosing the best alternative for each low-level task. This mode significantly reduced completion times by 23% for the most demanding task, at the cost of a 5% decrease in overall success rates — something that we are now investigating how to avoid.

5 Ongoing Work

The next steps in our research will focus on different visualization designs and evaluations with real-world data. They will include performing more detailed assessments with domain experts and extending our approach to support larger datasets in different domains, such as urban mobility and public health. Different categories of data, such as event data, origin-destination data, and GPS trajectories, will likely also require different visualization designs.

So far, our evaluations were limited to, at most, twenty-four simultaneous trajectories. To represent larger volumes of data we are investigating the most suitable visualization approaches for large datasets. We are assessing how to efficiently represent the data in such scenarios, e.g., by employing lines or three-dimensional meshes, aggregation techniques, or color encodings. In terms of the interaction design, we will evaluate how to efficiently filter and query the data, e.g., through regional or semantic filters, and brushing mechanisms. Taking into account the typical workflow of data analysts, we will also investigate the best ways to afford collaboration (for either collocated or remote people) and their effects on analytic performance.

6 Conclusion

Immersive Analytics benefits from stereoscopic 3D display and more natural forms of navigation and interaction, which offer an unprecedented opportunity to efficiently explore classical three-dimensional spatio-temporal representations such as the Space-Time Cube. We believe this new resource can contribute to analysts' workflows, especially when exploration tasks require the integration of the spatial and temporal components of the data. Since we base our approach entirely on the use of consumer-grade low-cost HMDs, our results can benefit both data experts and also regular users — *"everyone is a spatio-temporal analyst"* [1]. Regular users could also use it as a means of casual data exploration [20] and citizen participation [6].

The preliminary findings summarized here partially validate our research hypotheses, indicating that an immersive Space-Time Cube environment increases usability and reduces workload, making it easier to adopt this helpful but complex data representation. Our ongoing work aims to uncover the benefits and disadvantages associated with multiple possible design choices in the vast design space of Immersive Analytics.

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