Collaborative immersive analytics: Building a virtual reality platform to support asymmetric data exploration

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ABSTRACT

The research presented in this document aims to explore user interaction design in immersive virtual reality (VR) environments using head-mounted displays, specifically within the context of Immersive Analytics, and, at this stage, corpus linguistics. Two main parts of the research are concerned with (1) investigating interaction design approaches to navigate time-oriented data using 3D user interfaces, and (2) collaborative aspects of interacting in the VR environment in an asymmetrical scenario, where one collaborator is immersed in VR, while another operates a non-immersive application for the purpose of synchronous collaboration for data analysis. An immersive data exploration system in VR has been developed, and multiple iterations have been empirically investigated in various experiments and software demonstrations. Research in the areas of VR, 3D User Interfaces, Immersive Analytics, and Computer-Supported Cooperative Work informed the conducted research in regards to methodological and evaluative aspects. The research aims to contribute in advancing analytical workflows that (1) facilitate engagement and motivation during the data analysis activity, (2) integrate in existing data analysis practices, and (3) encourage collaboration and co-located meaning- and decision-making through data analysts using both immersive and non-immersive tools. Additionally, the research aims to contribute to the emerging field of Immersive Analytics through the investigation of (4) novel interaction approaches to navigate time-oriented data within the immersive 3D space, and (5) features that support and facilitate collaboration using a mixture of (new) immersive and (existing) non-immersive tools. This document describes the current state of the conducted research by presenting the first three iterations of the developed immersive data analysis system.

KEYWORDS

3D user interfaces, computer-supported cooperative work, immersive analytics, virtual reality

1 INTRODUCTION

Immersive Analytics (IA) is an emerging field of research that is concerned with the application of immersive technologies, for instance Virtual Reality (VR) or Augmented Reality (AR), with the purpose to support data understanding and decision making [Dwyer et al. 2018]. Display and input devices that enable immersive interaction, such as modern head-mounted display (HMD) devices, e.g., the Oculus Rift or HTC Vive, and tracking controllers, e.g., Leap Motion, have become affordable and accessible to a broad audience. This is important not just for gaming and entertainment related purposes (which are arguably a driving force behind the recent development of these technologies), but also for non-entertainment ones such as education [Holappa et al. 2018], architecture [Wolf et al. 2017], productivity [Lanman et al. 2014], training [Olbrich et al. 2018], or data visualization [Streppel et al. 2018], to name just a view. In times where massive amounts of data within different scenarios and contexts are collected at almost all times (often referred to as the "Big Data challenge") it becomes more and more important for researchers to visualize, interpret, find patterns, and make meaning from those data [Chandler et al. 2018; Donalek et al. 2014; Mahyar and Tory 2014; Reda et al. 2013]. Even though techniques such as machine learning and data mining are rapidly improving and provide assistance with pattern and point-of-interest (POI) discovery within big datasets, there is still a need for human interpretation, contextualization, and further meaning and decision making based on these discoveries and insights [Hackathorn and Margolis 2016]. Consequently, tools and workflows to support human users with the latter are desirable. Immersive visualization and interaction technologies hold potential to provide such tools.

2 RESEARCH CHALLENGES

The application of immersive technologies for the purpose of data analysis poses various multi-disciplinary research challenges. First, emerging 3D display and input technologies allow researchers to explore novel, intuitive, natural,[1] and engaging applications to visualize and interact with data [Bach et al. 2016; Cordeil et al. 2017; Donalek et al. 2014; Reda et al. 2013]. Information Visualization (InfoVis) and Visual Analytics (VA) have established theories and practices for data visualization and interaction, most commonly in two dimensions (2D), displayed through normal computer monitors, and operated through key and pointer operations [Fikkert et al. 2007; Roberts et al. 2014]. However, investigations are needed towards the development of methods to support three-dimensional (3D) data exploration within the context of IA, either adapted from existing ones or built from the ground up. It is important to emphasize that IA research is not intended to substitute existing 2D practices, but instead add new 3D user interfaces (3D UIs) that synergize and complement the overall data exploration workflow. Particularly within the scope of exploring big datasets, there is not one application to satisfy all of a user's needs, but rather various ones, each for their own intend and purpose, framing an overall greater workflow. Consequently, there is potential for interplay of novel 3D UIs and established 2D practices, especially in regards to existing human-centered challenges within this context, collaborative visualization and effective interaction among others [Laramee and Kosara 2007].

[1] In our context, natural denotes no need for expertise in order to make use of a tool.

Second, allowing data immersion in VR using HMD devices reveals design and interaction challenges for active collaboration between multiple users. By wearing a HMD, the user is visually isolated from the real-world surroundings and confronted with computer-generated content, creating a rather user-centered, single-user experience [Cordeil et al. 2017; Hackathorn and Margolis 2016]. However, enabling multiple users to collaboratively explore and interpret data is often desired: (1) big datasets require a broad expertise, unfeasible to be covered by a single analyst [Isenberg et al. 2011; Zimmer and Kerren 2017]; (2) collaboration is more effective than working alone [Billinghurst et al. 2018], arguably because it is anchored within the human nature [Neumayr et al. 2017]; (3) besides perceptual and cognitive processes, visual analysis and decision making also involves social processes, such as analysts debating about the interpretation of data, providing individual and contextual knowledge [Billinghurst et al. 2018; Heer and Agrawala 2008]. As a result, more research towards collaborative IA experiences is necessary, bridging the gap between user-centered experiences and collaborative data analysis.

Third, there is a need for new techniques and metaphors for the interaction with nontraditional computing environments, as traditional input devices, for instance keyboard and mouse, are inappropriate and inadequate to be used within VR [LaViola, Jr. et al. 2017]. More specifically, within the context of IA, new approaches for the design of 3D UIs are required to support typical tasks in order to interact with multivariate data, for instance geospatial or time-oriented data [Aigner et al. 2011]. Such interactions range from data selection, filtering, sorting, and navigation, to reconfiguration as well as labeling and annotation [Büschel et al. 2018]. However, the design of user-friendly 3D UIs is considered a major challenge [LaViola, Jr. et al. 2017].

Finally, the human-computer interaction (HCI) community relies heavily on descriptive frameworks and taxonomies in order to describe and review complex real-world applications and scenarios [Lee and Paine 2015; Neumayr et al. 2018]. With the emergence of new technologies that are fundamentally different from traditional ones, it becomes important to critically analyze existing frameworks, review their applicability, and potentially propose meaningful extensions or propose new ones. Particularly within the case of Collaborative IA, which is still underexplored by the research community [Billinghurst et al. 2018], the formalization of a framework or task taxonomy may assist with the analysis of such heterogeneous multi-user data analysis scenarios.

The goal of my research within the context of my doctoral studies is to explore the interaction in immersive VR environments, particularly within the context of IA. I am interested in two subject matters: (1) the investigation of time interfaces, using 3D UIs to navigate time in VR; (2) the investigation of collaboration between users in an asymmetrical scenario, where one user is using immersive technologies ("*inside VR*"), while another user is using non-immersive technologies ("*outside VR*") in order to conduct together data analysis related activities.

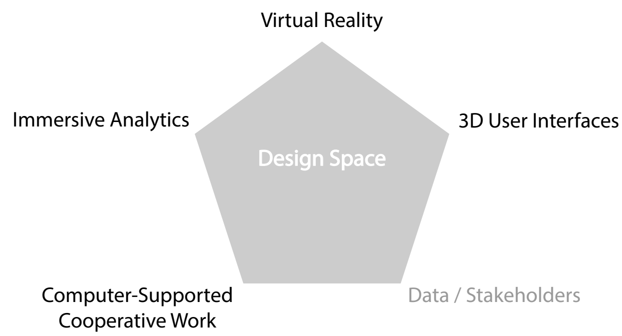


Figure 1: Design space of the research. 4 (VR, 3D UIs, IA, CSCW) + 1 (context / scenario of data and stakeholders).

3 RELATED WORK

The design space of my research, illustrated in Figure 1, requires a synthesis of related work according to four topics: (1) Virtual Reality; (2) 3D User Interfaces; (3) Immersive Analytics; (4) Computer-Supported Cooperative Work.

3.1 Virtual Reality

LaValle [2019] defines VR as follows: "*Inducing targeted behavior in an organism by using artificial sensory stimulation, while the organism has little or no awareness of the interference*". While the artificial stimulation of all senses (sight, hearing, touch, smell, taste) through various interfaces is possible today [LaValle 2019], using visual and auditory ones are arguably most commonly associated with VR. The ability to visually surround and immersive the user in computer-generated content, in a way that leaves the user unaware of the environment's artificiality, can lead to the sense of "presence", i.e., the subjective feeling of "being" in the virtual world [LaValle 2019]. Although the ability of inducing a feeling of presence is certainly one of the stronger selling points of VR, the goal can also be to facilitate engagement and increase motivation to complete tasks that can be rather "dull" using more traditional methods, or to provide visualizations that are purposefully abstract, for instance in order to facilitate the user's spatial understanding or to decrease information clutter [Bowman and McMahan 2007]. As VR presents a fundamental shift in how users can perceive digital information, various research challenges arise in order to create immersive virtual environments that, e.g., facilitate the user's visual perception, provide natural movement options, and assist the user with meaningful affordance and constraints [LaValle 2019; LaViola, Jr. et al. 2017]. On the one hand, the design of a VR environments is often influenced by real physical world concepts that we have learned all our lives, while on the other VR provides an opportunity to overcome real world limitations [LaValle 2019].

3.2 3D User Interfaces

Display technologies such as HMDs allow the user to "look around" and thus naturally perceive virtual information. 3D UIs enable the user to go beyond from being a passive observer to become an active part in the virtual 3D environment. Special input technologies, for instance physical controllers, hands-free 3D gestural input, or voice commands, provide information from the user to the computer system [LaViola, Jr. et al. 2017], allowing various ways of interaction. Such input hardware is equally important as display technologies (or output hardware) in order to provide an immersive experience by closing the human-virtual environment interaction loop [Bowman and McMahan 2007]. Foundational interaction techniques include selection and manipulation of digital artefacts, travel, and system control [LaViola, Jr. et al. 2017]. The concept of "feedback" is one of the most important design considerations for 3D UIs, as it is responsible to communicate the state of the computer system as well as user interactions back to the user [LaViola, Jr. et al. 2017]. Other important considerations involve the understanding of human factors, i.e., the human user's physiological and psychological capabilities in order to design effective, user-friendly 3D UIs [LaViola, Jr. et al. 2017].

3.3 Immersive Analytics

IA is a new interdisciplinary field that unites researchers with backgrounds in InfoVis, VA, HCI, and VR/AR, to name just a few [Dwyer et al. 2018]. Its research is concerned with the exploration of new tools and techniques that promote analytical processes and reasoning with the aid of immersive technologies [Chandler et al. 2018; Dwyer et al. 2018]. Due to the nature of such immersive technologies, IA researchers need to reconsider the value of 3D visualizations, since its application for data exploration is rather rare outside of Scientific Visualization (SciVis) [Marriott et al. 2018]. Using depth cues as an additional information dimension, presenting data with a spatial embedding, having (literally more) space for arranging multiple views, or to simply increase the engagement of the user in the analysis activity are only a few benefits that have been identified as potential benefits of immersion [Marriott et al. 2018]. Several studies investigating the application of VR for immersive data exploration have been conducted recently [Cordeil et al. 2017; Donalek et al. 2014; Ivanov et al. 2019; Streppel et al. 2018]. Besides the actual visualization of data in the 3D space, two other important subjects of interest in regards to the success of IA are concerned with the interactive [Büschel et al. 2018] and collaborative [Billinghurst et al. 2018] aspects an IA system should provide. Interaction and collaboration mechanisms in VR, for instance interacting with information and media, text entry and editing, or gestures and facial expressions, might sound trivial at first, but are particularly challenging when being visually isolated from the physical space, thus requiring more research in the future [LaValle 2019].

3.4 Computer-Supported Cooperative Work

Computer-Supported Cooperative Work (CSCW) is concerned with investigating how computer systems can support collaborative activities conducted by more than one user. Isenberg et al. [2011], Cerna [2015], and Billinghurst et al. [2018] provide more specific definitions for Collaborative Visualization, User-Centered Collaborative Visualization, and Collaborative IA, respectively. Various existing descriptive models and frameworks can assist with the measurement of collaborative aspects, such as Johansen's [1988] time-space matrix, Gutwin and Greenberg's [2002] workspace awareness, Tang et al.'s [2006] and Isenberg et al.'s [2012] coupling styles during collaboration, Neumayr et al.'s [2018] hybrid collaboration and coupling styles in partially distributed teams, or Lee and Paine's [2015] model of coordinated action. "Common Ground" is an important concept within the context of CSCW, describing that users constantly monitor and review their mutual understanding during their communicative efforts, for instance through facial expressions and body language [Heer and Agrawala 2008]. Furthermore, the ability to create (spatial) references in combination with using deictic expressions, for instance by pointing to a POI and stating "over there", is fundamental when collaborating around visual media [Heer and Agrawala 2008]. However, by using rather self-centered technologies such as a HMD for immersive VR, many of these collaborative information cues (facial expressions, body language, spatial references, and more) are no longer available. This is just one challenge, among many others, posed for the design of collaborative immersive environments.

4 RESEARCH FOCUS AND OBJECTIVES

The overall purpose of my research is to gain significant knowledge on the criteria that support and facilitate collaboration between multiple human users in a scenario that involves both immersive and non-immersive data analysis applications. The goal is to investigate collaborative aspects and the interplay between the users' interactions, each operating a fundamentally different data analysis tool. Notably, even with constant improvements in the quality of immersion (i.e., display resolution, tracking, response and refresh time), some tasks remain more suitable to be conducted using non-immersive technologies. For instance, reading large amounts of textual data "inside" an immersive environment is more strenuous compared to conducting this task "outside" using a normal computer monitor. Use cases that support synchronous collaboration inside and outside the immersive environment (instead of everyone being immersed inside) are considered a novel aspect [Billinghurst et al. 2018; Chandler et al. 2018].

Furthermore, my research focuses on the application of VR using HMDs and 3D UIs in order to conduct data analysis related interactions within the immersive environment. In particular, I am interested in investigating 3D UI design that supports the navigation of time-oriented data in VR.

In order to address these foci, as illustrated in Figure 2, three research objectives have been defined as follows:[2]

- RO1: Design and implementation of a system that allows data analysis using immersive technologies and interaction through 3D UIs.
- RO2: Investigation of 3D UI design approaches in order to navigate time within immersive data analysis.
- RO3: Extension of the immersive data analysis system to support collaboration using immersive and non-immersive technologies to facilitate the processes of data analysis and meaning making.

[2] A more detailed description of all research objectives including functional requirements is stated in Appendix A.1.

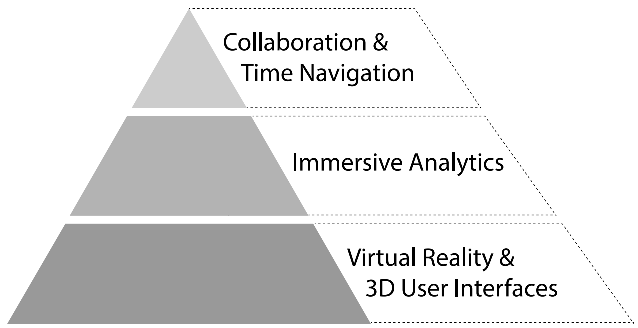


Figure 2: Focus of the research.

5 METHODOLOGY

The investigation of my research objectives is pursued in six, partially iterative steps: (1) a comprehensive literature review of related research, (2) the development of immersive and non-immersive applications that allow data exploration, (3) an empirical examination through the conduction of hands-on interaction studies with human participants, (4) the analysis of the collected qualitative and quantitative data, (5) various iterations of steps (2) to (4) under considerations of the results of previous iterations, (6) the definition of design guidelines reflecting the results of the various user interaction studies.

Development of immersive and non-immersive applications follow common practices, for instance starting with a rather informal evaluation, and then moving towards a more formal one [LaViola, Jr. et al. 2017]. Data collection and evaluation methodologies are addressed by closely following established practices in the various research areas (i.e., VR, 3D UI, IA, CSCW). The user interaction studies follow an experimental design approach, where participants are asked to perform concrete tasks using the provided technologies and applications. The involvement of human participants in the various user interaction studies require careful ethical considerations, which are more elaborately described in Appendix A.2.

6 PROGRESS AND INITIAL FINDINGS

Following the initially stated research objectives, my progress (so far) can be divided, in order, into three milestones as described in the following subsections.

6.1 Data Exploration in VR

In order to address (RO1), I developed a system that is able to visualize data from multiple online sources in a unified interface, enabling a user to browse and explore displayed information in an immersive VR setting[3] (see Figures 3a and 3b); the system is presented in the paper by [Reski and Alissandrakis 2019]. To investigate the 3D UI design of the system's interactive aspects, this initial VR system supported three different input technologies for its operation: gamepad, 3D gestural input, and room-scale. To gain insights of the developed system in practice, a user interaction study was conducted to compare the three implemented input technologies (n = 24, n = 8 per input technology, between-group design). In a scenario that encouraged the participants to explore the voting results of the 2016 US presidential election (using data from Wikipedia, Wolfram Alpha, and The New York Times) in the immersive environment, I investigated experienced workload, perceived flow of interaction, and VR sickness. The results indicate trends towards user preference of a visual (virtual) representation of the input technology (i.e., 3D gestural input and the hand-held controller of room-scale), but no clear trends regarding the application of physical controllers (over 3D gestural input). The scenario encouraged exploration with no time limitations. The concept and interaction design of the developed initial VR system as well as its resulting comparative study of input technologies were heavily informed through a comprehensive literature review [Reski and Alissandrakis 2019].

The successful task completion results in the conducted study (21 of 24 participants scored 2/2 answers correct, while the remaining 3 scored each 1/2 correct) and overall positive reception by its users[4] encouraged the continuation of developing, extending, and modifying this initial VR system, or immersive data analysis sandbox, in order to examine other research objectives going forth.

6.2 Nordic Tweet Stream in VR

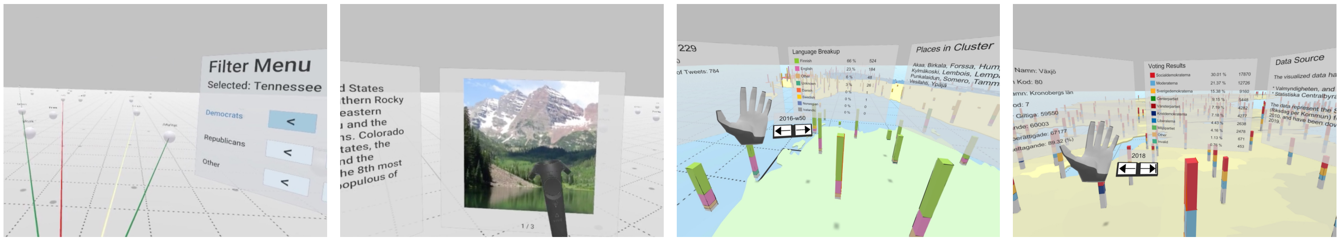
To investigate immersive data exploration in a real world setting within the context of the digital humanities, I started collaborating with corpus linguistics researchers from the Department of Languages at Linnæus University. In particular, the initially developed VR system was extended to visualize geospatial linguistic data of the Nordic Tweet Stream (NTS) corpus [Laitinen et al. 2017, 2018]. The NTS is a big and rich corpus of geolocated tweets and metadata sent from the Nordic region, and was initiated in 2016 with the objective to broaden the empirical basis of sociolinguistic research. Each captured tweet contains rich metadata, some of which is related to the the location, language, time, and message itself of the tweet. Currently, the NTS contains over 1.5 billion metadata points.

Data visualizations have developed into a major aspect of the digital humanities and corpus linguistics [Bradley et al. 2018; Siirtola et al. 2016], leading to advances in for instance the visualization of textual data [Kucher and Kerren 2015]. Enabling the exploration of corpus linguistics data in immersive VR is novel and can provide several advantages, such as enhancing user engagement, finding meaningful patterns in the data, and making large linguistic data more approachable.

Concretely, the extended VR system allows a user to explore the NTS data with a focus on language variability in tweets within the Nordic region from both a geographical and a time-oriented perspective[5] (see Figure 3c). Individual tweets are accumulated in clusters (a total of 309), which can be navigated to and explored in more detail using the hand-held controller input functionalities in the VR environment. On first sight, each cluster, represented as a stacked cuboid, provides insights about the amount of tweets as well as the most dominant languages of all its tweets, while displaying

[3]Data Exploration in VR: Video demo (via Vimeo).

[4]The developed VR system was positively received by the described study participants as well as by visitors attending the VR_SCI Fest 2017, where the system was publicly available for testing (see *Virtual Reality project presented at VR_Sci Fest 2017* via lnu.se).
[5]Nordic Tweet Stream in VR: Video demo (via Vimeo), 360° interactive, annotated VR scene.



(a) VT17 – HT17 **(b) VT17 – HT17** **(c) HT17 – HT18** **(d) VT19**

Figure 3: Impressions of the developed VR prototypes. Left to right: (3a) Filter menu, (3b) hand-held controller interaction (of room-scale VR), (3c) Nordic Tweet Stream in VR, and (3d) Swedish Election in VR.

a detailed language break-up of all detected languages and other information upon further investigation (i.e. user interaction).

To gain empirical feedback of the VR system within the context of the NTS, two experiments with first-year language students were conducted in May ($n = 7$) and September ($n = 5$) 2018. Both experiments featured tasks related to multilingualism in the Nordic region and aimed to investigate the system's overall ease of use and the users' ability to interpret data within the virtual environment [Alissandrakis et al. Forthcoming]. Furthermore, researchers of the corpus linguistics community tested the VR system within the scope of a software presentation in May 2018 ($n = 26$) [Alissandrakis et al. 2018]. Generally, all participants were able to make insightful inquiries and observe interesting phenomena in the explored data, some of which led to enthusiastic conversations and speculations with the experiment's instructors. The participants' response was very positive, with some participants stating that the immersion (subjectively) "allowed them to experience the data in a more real and memorable way" [Alissandrakis et al. Forthcoming]. Other feedback gathered from the experiments include, aspects of the usage (e.g., the participants' exploration approach), the UI design (e.g., the request for additional, or logically subsequent, information), and desired features (e.g., an export function for POIs discovered during the exploration session in VR to follow-up with additional investigations "outside" VR). Even though operating the VR system using the hand-held controller succeeded, it felt rather unintuitive to the users and could hinder the exploration in scenarios where the user had little to no prior VR experience.

Additionally, a noteworthy feature of the developed VR system is that it is *data agnostic*, enabling the visualization and exploration of other, different datasets with only minimal programming efforts. A demonstration of this feature is illustrated in a functional proof-of-concept prototype enabling the user to explore voting results of the Swedish parliament elections in 2018, 2014, and 2010[6] (see Figure 3d).

6.3 Hybrid Collaborative Immersive Analytics

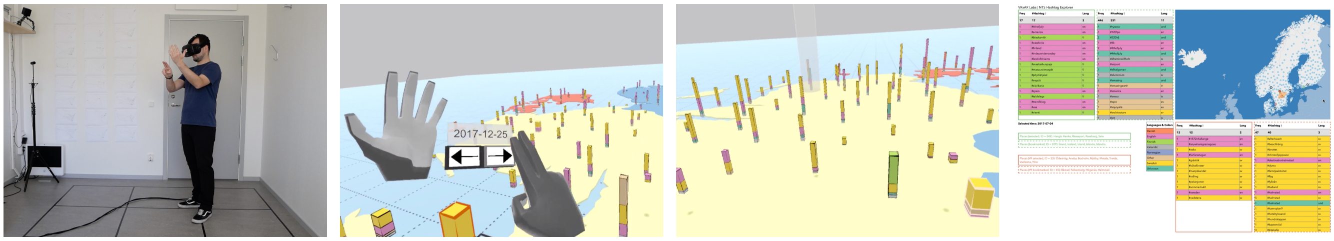
Based on the prior experiences and results of exploring the NTS data in VR, a couple of changes were made to the system. These changes include some more obvious ones, such as moving the input controls from (the as previously reported rather unintuitive) hand-held controller to 3D gestural input (see Figures 4a and 4b), and some less obvious ones, such as some modifications to the application's internal architecture and rendering capabilities.

With an overall look at the research challenges and literature (see Sections 2 and 3), two things become apparent: first, there is rarely a single tool or application used to investigate all aspects of a dataset, and second, data exploration activities are seldom done by a single analyst. Especially in regards to the latter, it was interesting to observe participants in the (public) software demonstrations of the developed VR system. Usually, such a demonstration involves a big screen or monitor that displays what the user in VR is currently looking at. This invited bystanders on countless occasions to attempt to verbally communicate (and collaborate) with the VR user, prompting the VR user to move to and investigate a certain location. However, these attempts turned out rather difficult to achieve, as the VR user was not able to successfully identify where the bystander's prompted POI was. There was a lack of visual reference, since the VR user was wearing a HMD, or a lack of features in the bystander's oral description, or both, preventing collaboration between VR user and "outsider".

This encouraged the further development of the VR system to be accompanied by a non-immersive (desktop) application that is running in the web browser and can be displayed using a normal computer monitor and operated with keyboard and mouse. Most importantly, both the immersive and non-immersive application feature functionalities that connect them in real-time, enabling synchronous asymmetrical collaboration between two users, one "inside VR" and one "outside", to explore the same dataset, creating a overall hybrid collaborative IA experience. For instance, on the one hand, the VR user's position, orientation,[7] and selection in the virtual environment are displayed in an interactive map view of the desktop user's interface (see Figure 4d). On the other hand, the desktop user's interface allows the selection of clusters, which in return are also highlighted for the VR user in the virtual environment (see Figure 4c). Features like these enable both analysts, for instance, to share important "Common Ground" [Heer and Agrawala 2008] during the data exploration activity. Furthermore, such a collaboration approach enables us to investigate different relevant matters, including the exploration of design choices of incorporating aspects of proxemic interaction to support collaborative data analysis

[6] Data taken from Valmyndigheten and Svenska Statistika Centralbyrån (SCB); Video demo (via Vimeo), 360° interactive, annotated VR scene.

[7] Spatial attributes of an object or user, such as for instance position, orientation, and movement, are referred to as "proxemics" [Hall 1966].



(a) (b) (c) (d)

Figure 4: Impressions of the developed immersive analytics platform (HT18 – VT19). Left to right: (4a) User with HMD and 3D gestural input, (4b) switching time in VR with 3D gestural input, (4c) desktop user's selection highlighted in VR, and (4d) non-immersive application to explore hashtags and language variability in the NTS dataset.

[Roberts et al. 2014], as well as the analysis of how exactly the collaborators approach their interplay in qualitative and quantitative ways by visualizing user interaction data from both applications.

At this point, two non-immersive applications have been developed within the context of the NTS: a first proof-of-concept prototype focusing on aspects of multilingualism in the data,[8] and a second prototype focusing on the usage of hashtags in tweets[9] (see Figures 4c and 4d). The first collaborative proof-of-concept scenario was tested by "Big Data" researchers within the format of a software demonstration ($n = 11$) in November 2018.[10] Following positive feedback and further investigations, the second collaborative scenario was presented as an invited software demonstration to corpus linguistics researchers in May 2019 [Reski et al. 2019]. Furthermore, a formal experiment with first-year linguistics students ($n = 15$) was conducted in May 2019 in order to investigate the collaborative system's usability as well as self-assessed aspects of the user's communication, coordination, and collaboration. The participants used both the VR and desktop application in alternating roles in order to solve tasks related to the use of hashtags and language variability on Twitter using the NTS corpus. The collected data (observations, interview, log files, system usability scale questionnaire) of this empirical investigation are in the process of being evaluated [Reski et al. In preparation].

7 FUTURE PLANS

In regards to the initial research objectives (see Section 4), (RO1) has been more or less completed with the development of the immersive analytics platform. Of course, certain extensions and adjustments are naturally to be expected as part of the work on (RO2) and (RO3). For the remainder of my studies, I want to focus on investigating (RO2) and (RO3). Following (RO2), investigations of the navigation (and annotation) of time-oriented data in VR, likely within the context of the corpus linguistics, is planned to be initiated during Spring 2020. These efforts will involve the design and formal evaluation of different 3D UI design approaches to navigate data along the time dimension. Furthermore, I intend to continue the ongoing investigations regarding the developed system's collaborative aspects "inside" and "outside" VR, in order to explore (RO3).

[8]Hybrid Collaborative Immersive Analytics: Video demo of prototype 1 (via Vimeo).
[9]Hybrid Collaborative Immersive Analytics: Video demo of prototype 2 (via lnu.se), 360° interactive, annotated VR scene.
[10]4th Annual Big Data Conference, Nov. 29-30, Växjö, Sweden

With the developed and functioning IA sandbox at hand, a practical overlap of examining (RO2) and (RO3) in parallel is naturally to be expected.

Finally, within the *VRxAR Labs* research group we believe in the concept of "open source". Throughout my doctoral studies, I have made several parts of my work publicly available (see Section A.3). Consequently, towards the end of my doctoral studies, I intend to release a well documented version of the developed immersive analytics platform under an appropriate open source license. This will enable other researchers and practitioners to: (1) use the developed system with their data; (2) extend its implementation based on their individual needs and requirements.

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A APPENDIX

A.1 Research objectives: detailed

Based on this overall research focus, three research objectives (ROs) are defined. The first objective is concerned with the development of an immersive data analysis system.

> **RO1**: *Design and implementation of a system that allows data analysis using immersive technologies and interaction through 3D user interfaces.*

More specifically, the system has to fulfill a set of functional requirements:

- RO1.A: The system should be data-agnostic in order to handle various data from potentially multiple, different sources with only minimal programming efforts.
- RO1.B: The system should support the exploration of multi-variate data along the three spatial dimensions as well as the time dimension.
- RO1.C: The system should allow a user to (passively) observe the visualized data in immersive virtual reality (VR) using a head-mounted display (HMD) device.
- RO1.D: The system should allow a user to (actively) interact with the data using 3D gestural input (hand postures and gestures).

The second objective is concerned with the investigation of using 3D gestural input to control time in the immersive data analysis system.

> **RO2**: *Investigation of 3D UI design approaches in order to navigate time within immersive data analysis.*

More specifically, the investigation is set to answer a couple of required key questions:

- RO2.A: How can 3D gestural input support the time navigation in an immersive VR environment?
- RO2.B: How can user interface (UI) design provide feedback to the user about the current time context and other available time-dependent events in the data?

The third objective is concerned with collaborative aspects of using immersive and non-immersive technologies for data analysis.

> **RO3**: *Extension of the immersive data analysis system to support collaboration using immersive and non-immersive technologies to facilitate the processes of data analysis and meaning-making.*

More specifically, the extension of the developed system is focused around a set of requirements and questions:

- RO3.A: Exploration of the design and implementation of non-immersive companion prototypes that communicate with the developed immersive data analysis system.
- RO3.B: Exploration of features to support synchronous collaboration between immersed and non-immersed data analyst.
- RO3.C: Exploration of features to support asynchronous collaboration.
- RO3.D: Development of a task taxonomy and design space to support immersive data analysis in collaborative scenarios as described in requirements *RO3.A*, *RO3.B*, and *RO3.C*.

A.2 Ethical considerations

As the conduction of the various user interaction studies within the scope of my research involve human participants, it is important to address ethical considerations. The participants, all of them adults, will be involved in the evaluation of the developed immersive and non-immersive applications as users and test subjects. The personal data collected from the participants will only concern their identity and information relevant to evaluating their ability to complete the tasks, for instance their previous experience in the subject field and interaction with various technologies. No information will be collected on ethnicity, religion, sexual orientation, or other personal and private topics. The subjects will be anonymized in any presentations and publications derived from the conducted research.

In terms of the interaction studies specifically, the participants will wear a HMD device [Lanman et al. 2014]. A HMD is a device that is worn on the head, similar to glasses or ski goggles, visually isolating the user from the physical real-world surroundings. Instead, the user is presented with computer-generated virtual content, which can be explored by moving the head and thus looking around. In particular, in our research lab we are using common consumer VR HMDs such as the Oculus Rift CV or the HTC Vive. Although these technologies and devices are widely available and established on the consumer market, it is possible that in rare cases the users may encounter what is referred to as “VR sickness” [LaValle 2019]. VR sickness can be described as any unintended and uncomfortable side effects that may occur when using a VR system, e.g., nausea, dizziness, or fatigue [LaValle 2019].

Generally, a strict protocol is followed when conducting user interaction studies that involve the usage of such VR technologies. First, participants are introduced to the overall context and scenario of the study and the tasks that are involved. As part of this introductory phase, the participants provide their consent to partake in the study, acknowledging that (1) the participation is voluntary, (2) they may terminate their participation at any point in time without explanation, and (3) no sensitive personal information is collected and any data collection by the researchers is confidential. Furthermore, before conducting the actual task as part of the study, each participant is given the time (a “warm-up” phase) to get familiar with the hardware, i.e., the HMD, and the software, i.e., the developed application. Realistically, a participant will wear the VR HMD for approximately 15 to (max.) 30 minutes. Once the actual task in VR has been completed, the participants are asked to fill in some questionnaires, and finally answer some questions as part of an interview, which concludes the user interaction study.

A.3 Open Source

As part of the work on my doctoral studies, I have made several work packages and modules publicly available via GitHub,[11] in particular:

- unity_polyextruder: Create custom meshes (2D polygons) in Unity3D, incl. functionality to extrude them (into 3D prisms). *This is still actively used to extrude custom polygons/meshes, for instance creating from geographic information system (GIS) data representing country borders, for visualization and interaction in the 3D space.*
- unity_log2csv: A simple logging system for a Unity application to write log entries into a .csv file. *This is still actively used to create application log files of the various developed prototypes, and has also been used by other students for similar purposes in the past.*
- unity_ios_of_osc: A project demonstrating bi-directional communication between a Unity application to a iOS application (built with openFrameworks) using the OSC (Open Sound Control) communication protocol. *This was used in some early hybrid collaborative immersive analytics prototypes, before switching to use WebSocket Secure (WSS) as communication prototol.*
- tlx-vis-r: A R script to analyze and visualize NASA Task Load Index (TLX) data. *This was used to visualize the collected data about the participants' perceived workload [Reski and Alissandrakis 2019].*

[11]The author's GitHub repository: github.com/nicoversity