Change your Perspective: Exploration of a 3D Network created from Open Data in an Immersive Virtual Reality Environment

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***Abstract*—This paper investigates an approach of how to naturally interact and explore information (based on open data) within an immersive virtual reality environment (VRE) using a head-mounted display and vision-based motion controls. We present the results of a user interaction study that investigated the acceptance of the developed prototype, estimated the workload as well as examined the participants' behavior. Additional discussions with experts provided further feedback towards the prototype's overall design and concept. The results indicate that the participants were enthusiastic regarding the novelty and intuitiveness of exploring information in a VRE, as well as were challenged (in a positive manner) with the applied interface and interaction design. The presented concept and design were well received by the experts, who valued the idea and implementation and encouraged to be even bolder, making more use of the available 3D environment.**

***Keywords*–human-computer interaction; virtual reality; immersive interaction; information visualization.**

I. Introduction

Virtual reality (VR) is not a particularly new research area [1], however having a fully immersive VR experience required expensive equipment and elaborate maintenance in the past [2]. Touch input has introduced a natural way of interacting with digital content, because it is the most intuitive way for humans to interact with their environment [3]. Through head tracking technologies and systems like head-mounted displays (HMD), VR has the potential to achieve a similar effect regarding naturally handling digital content for human vision [2]. Putting yourself into a virtual reality environment (VRE) and thus directly inside things, dramatically changes how you feel, completely shifting your perspective in a break of tradition [3][4]. Therefore, there is a lot of potential regarding the visualization of digital content within a 3D environment suited for immersive VR [5].

Information visualizations are used by humans to gain insights and acquire an understanding of data in a more comfortable and easier way compared to, e.g., reading information in text format [6][7]. This is attributable to the human cognitive capabilities to perceive information visually, interpret the graphical representation of data, and infer meaning [7]. However, humans usually perceive digital information in a very limited way, through the small and fixed window of a computer screen while using counter-intuitive 2D tools, such as keyboard and mouse, to interact [3][8]. A combination of VR as natural user interface (NUI) for human vision, and motion controls (particularly hand tracking [2]), as NUI for the interaction with digital information, could deliver an immersive and natural user experience. This is a not a trivial task and deserves deeper investigation in terms of the interplay of these technologies, as well as the challenges of crafting interaction and interface design for presenting digital data in a VRE.

In order to address these challenges and to examine the suitability of the use of immersive VR technologies in the context of interactive information visualization (InfoVis), we have identified a number of relevant research questions:

RQ1 Is immersive virtual reality suited for exploration of open data and content retrieved from the web?

RQ2 Is the usage of head-mounted display technologies and (vision-based) motion controls suited to work together, and can they benefit from each other in order to create a natural user experience?

In this paper, we present our approach to explore open data in an immersive VRE. We designed and implemented a VR prototype using a HMD and vision-based motion controls, to visualize and enable the user to explore a network of European capital cities, based on open data obtained from DBpedia. The remaining of this paper is organized as follows: Section II describes the foundations (including the concept and design approach) and a brief overview of the technical implementation. Related work is described in Section III. Details about our applied research methodology are provided in Section IV. In Section V, we provide the results of our conducted studies. Section VII presents our conclusions and proposes possible lines of future work.

II. Foundations

Immersive VR enables its users to visually perceive computer-generated content as if it was real [2]. For VR systems, HMDs have usually a closed view in a non-see-through mode; consequently, the user is visually isolated from the real world, completely surrounded by computer-generated content. Using head- and even body-tracking, the user is able to naturally look around and explore the three-dimensional virtual scene according to the real world paradigms [9][10].

Vision-based motion controls, sometimes also referred to as vision-based gesture recognition, have the potential to be a powerful tool in order to support the user with interaction and manipulation in the 3D space without the need to hold physical sensor devices [11]. As the prefix "vision-based" indicates, technologies following this approach usually use one or

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multiple cameras or infrared sensors to visually recognize the user's hand or body movements, and translate these movements accordingly into the digital space [11][12][13]. As the most expressive form of human communication, gestures have the potential to be useful in HCI as their application goes directly in line with the concept of NUI [14].

The interaction between humans and computers represents the heart of modern InfoVis [7]. Especially through the growing amount of collected data, tools of different nature (from artistic to analytical to mixtures of both) have been developed in order to provide a novel perspective to our surroundings, and InfoVis is considered essential in making data more accessible to a broader audience [15]. Within the area of HCI, particularly visual analytics deal with questions regarding how to combine and integrate strengths of both humans and computers into creative and interactive mechanisms to interpret and extract knowledge [16]. In the community, the use of 3D in InfoVis is regarded with skepticism, but in certain cases, such as for spatial layouts, 3D visualizations can provide advantages over traditional 2D. However, since moving from 2D to 3D can be expensive in various ways, it needs careful justification and the benefits must outweigh the costs. If a meaningful 3D representation implicitly exists within the dataset (e.g. airflow, skeleton, location), a 3D visualization approach is easily justifiable. If the spatial model and layout is rather chosen than given, it is the visualization designer's task to carefully map values and relations of the dataset's items to appropriate variables within the 3D space [17].

A. Concept and interaction design

While VR using HMDs has possibilities to provide a visual NUI, approaches to create a NUI for user input in combination with VR had to be considered to create a natural user experience. Vision-based motion controls enable manipulations of virtual objects to a realistic degree [11]. This is particularly important since the user will be visually isolated of the real world surroundings when wearing a HMD [14]. The applied prototype scenario was conceptualized around these technologies.

The identification of a concrete user scenario and consequently designing towards exactly that scenario is one of the most important considerations in the process of crafting an interactive InfoVis [15]. Keeping the conducted foundational research about VR in mind, the idea to build a network of different nodes within the 3D space came up, and a user scenario with the purpose of exploring available open data about European capital cities within an immersive VRE was identified. Since VR has the potential to drastically change the user's perspective [3], the thought of putting the user "inside" the InfoVis came to mind early in the design process. In more traditional InfoVis approaches, the user is put "outside" the visualization quite often, providing an overview about the data in a role of an observer. With the HMD VR technology and the available 3D virtual space at hand, the change of the user's perspective to the inside rather than to the outside of the InfoVis seemed attractive and novel to pursue. Features to enable the user to explore the network of nodes itself as well as each individual node in more detail had to be implemented. Two options to implement the exploration of the network were considered: enabling the user to move completely free without any restrictions within the VRE, or restricting the user movement to traversing between the nodes. Since there are known cases of intensified motion-sickness when letting the user move freely around in the VR space (without physically moving in the real world) [18], the decision was made to restrict the user movement to only traverse between nodes. Wikipedia was identified to serve as the data source. A practical look at Wikipedia articles about European capital cities provided the idea to request data items within an article's "infobox" (e.g. country, geolocation, area, population, images) using DBpedia's available API and its semantic layer [19]. The concept of filtering is a common interaction technique in InfoVis [6]. Therefore options to filter all European capital cities towards their area and population were introduced to support users in their exploration of the network.

Ultimately, the conceptual interaction and interface design of our VR prototype can be summarized to contain the following key features:

- Present open data about European capital cities received from Wikipedia (through DBpedia).
- Each capital is represented by an individual node in the 3D space.
- Put the user perspective inside the network visualization rather than looking at it from the outside.
- Automatic traversal for node-to-node movement, no "free" movement in the 3D space outside the node network.
- Two view modes: *exploration* and *content* view.
    - Exploration view: present minimal information about each node, explore the entire network.
    - Content view: present detailed information about one node, explore the current node.
- Filter options to display connections to cities with higher/lower area or population.
- Scale the sizes of the nodes' 3D models to proportionally represent the cities' individual area and population in respect to all others in the network (making them visually comparable).
- Swipe gesture interaction to initiate movement to other nodes and to trigger/dismiss exploration or content view mode.
- Interactive 3D GUI to operate filter and scaling options.
- Visualization of the user's hands, and providing visual feedback for gesture interactions.

B. Implementation of the prototype

The developed prototype can be divided into two parts: a) a server and database and b) the VR application. Figure 1 illustrates the overall system architecture.

Server and database (see Figure 2) are based on *Node.js* and *MongoDB*, completing the following tasks:

1) Queries data items of a given European capital city from an open data source (DBpedia).
2) Persistently stores the queried data items in a structured and uniformed way.
3) Provides access to the stored data items, prepared for visualization.

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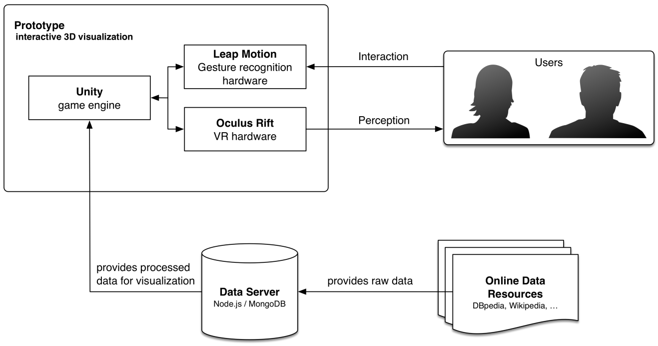

Figure 1. System architecture

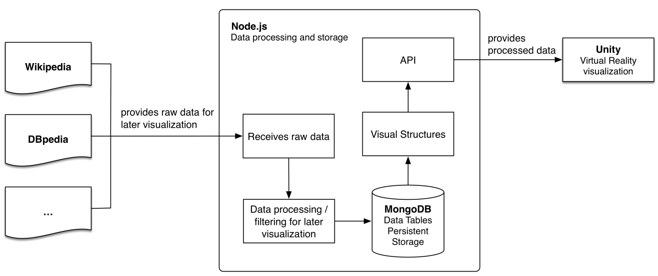

Figure 2. Server and database overview

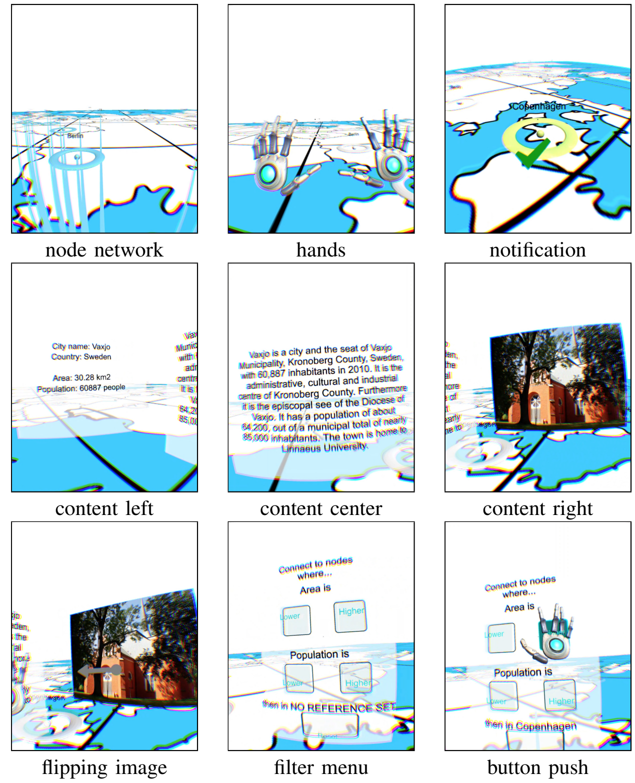

Figure 3. Multiple screenshots of the VR application

The visualization engine and thus the complete software development of the VR application is based on the cross-platform development system *Unity*. The *Oculus Rift DK2* was used as HMD, while a *Leap Motion* controller (attached in front of the HMD) served as the vision-based motion controller.

The implemented VR application can be divided into seven main GameObjects. The `NetworkVisPlayerController` GameObject handles all tasks related to the application's user, such as providing instances of the VR camera and the Leap Motion controller as well as handling the user interaction and visual feedback upon successfully recognized gesture interaction. The `NetworkCreator` GameObject is responsible for keeping track of the network's current status and is able to dynamically manipulate the nodes of the network according to the user's input. Furthermore it is able to receive information about the European capital cities from the complementary server and database and to instantiate a `VR-NetworkNode` GameObject for each city. The `NetworkVisualization` GameObject is a wrapper for holding all VR-NetworkNode GameObjects together, ultimately taking care of rendering and representing all nodes within the network. The `EuropeMapLayer` GameObject presents an underlying outline of all European countries to the user. Responsible for rendering detailed information about a network node is the `VR-NetworkNode-ContentView` GameObject, displaying description, numerical data as well as images about the city on three 2D content planes located in front of the user as well as to the left and right. The interactive 3D GUI presenting the different filter options is handled by the `VR-FilterExplorationView` GameObject. Furthermore, the VR application features a `LoggingSystem` GameObject, keeping track of every user interaction by writing detailed information in a .csv file, which can later be analyzed.

Figure 3 illustrates multiple screenshots, giving a visual impression of the created VR application. The video at [20] demonstrates the features of the developed prototype.

III. Related Work

Donalek et al. [21] recently described their initial explorations of finding optimal use practices for the application of immersive VR as a platform for interactive and collaborative data visualization and exploration. They focused on the visualization of highly dimensional data based on large digital sky surveys that can be represented as abstract feature vectors and experimented with different approaches of multidimensional data representation in VR [21]. Design challenges for a 2D gesture interface in a 3D VR environment have been explored by Lee et al. [22], who developed and evaluated an immersive VR game, concluding that cross-dimensional interfaces may significantly reduce simulator sickness. Ren and O'Neill [13] investigated 3D selection with freehand gestures and propose overall design guidelines. According to their results, designers should consider mapping 3D hand movements to 2D interaction for simpler user interfaces with few elements [13]. Abrash [4] argues that immersion can make VR interesting, but great VR requires custom software. Bayyari and Tudoreanu [5] investigated perceptual and interaction characteristics of immersive displays and conclude that they support better understanding of data and are thus superior to traditional desktop visualization.

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IV. Methodology

The purpose of our investigation is to answer the questions of whether and how appropriate the application of immersive VR is in order to visualize and naturally explore content from the web. Our research approach has rather deductive characteristics [23].

We carried out a user interaction study to gain insights and real experiences about the design and operation of the developed prototype in practice. It was of particular interest to gather the user's thoughts about their ability to naturally interact with the visualized content and explore the data network. We conducted eleven one hour sessions between the researcher and each participant. The six female and five male participants, aged between 16 and 32 years, were introduced to the prototype by watching a pre-recorded video [20] that demonstrated the features of the developed prototype.

The eleven participants were given two tasks: to find a city with a population (or area) of a certain number of inhabitants (or square kilometers), using all the features of the prototype such as the filter options, the movement functionalities as well as receiving more detailed information about a visited city in network node. They were encouraged to explore the visualized network and let the researcher know once they found a city that they considered to satisfy the request of each task. Before their sessions, each participant had the chance to become familiar operating the developed prototype in order to understand the basic functionalities as well as getting used to wearing a HMD and using the vision-based motion controls. Based on the participant's prior experience with the immersive technologies, this warm-up phase took no longer than five to ten minutes. There were no time constraints regarding the completion of the tasks and the participants were asked to operate the prototype at their own speed. However, the completion of a single task should not exceed ten minutes.

A mixture of both quantitative and qualitative data collection methods were used. Self-constructed pre- and post-session questionnaires, featuring a mixture of Likert-scale and open questions, were used to examine the participants prior experiences with the presented technologies as well as examining the developed prototype in more detail. To gain focused feedback, the post-session questionnaire was structured into the following evaluation categories: *Perception of the content generated with data from the web*, *Spatial perception of my location within the 3D network*, *Interaction using the vision-based motion control interface* and *Human factors and ergonomics*. The implementation of a log-file system enabled us to evaluate all interactions of the user with the prototype, e.g., metrics such as the time needed to complete a task, the time spent on individual nodes (cities) and the amount of user interactions applied to complete a task. Each study was closely observed by the researcher, who kept written notes. After completing the tasks, each participant was asked to estimate the felt workload, based on the Task Load Index (TLX) workload estimation developed by NASA [24][25]. Receiving insights about a participant's workload helps to analyze and estimate the interaction and interface design, providing indications if the participants felt, e.g., bored, neutral or overburdened within the VRE.

Additionally, experts within the field of HCI and (interactive) InfoVis were selected from within the staff at the Faculty of Technology at Linnaeus University and invited to participate in approximately one hour long discussions between the researcher and the experts. Within these discussions, the researcher presented the concept, idea and motivation of the conducted work to the experts as well as information about the identified problem domain, scenario and research questions. The researcher conducted also a live walkthrough presenting the developed prototype to the experts, during which they were encouraged to communicate their feedback, comments and thoughts towards the project. They were furthermore encouraged to not only think about the presented scenario, but to think further, more abstract towards similar interactions or activities in similar cases.

Figure 4. Participants interacting within the developed VRE

V. Results and Analysis

This section presents the results of the conducted user interaction study and expert discussions as described in Section IV. Figure 4 presents some impressions of the participants during the user interaction study.

A. User interaction study

The participants were asked to find a European capital city close to 1.5 million inhabitants during the first task, and one featuring an area of close to 750 km^2 during the second task. Valid result sets for both tasks were identified beforehand and are illustrated in Table I. All participants had to start from the node representing Växjö (where Linnaeus University is based).

As shown in Table II, two participants did not name a solution within the set of valid results for task 1 (they chose Copenhagen and Sofia instead), but all eleven participants correctly identified a city close to the asked parameter in task 2. Additionally, it can be observed that the majority of participants were able to name a solution rather close to the asked parameter within both tasks.

Utilizing the implemented log file system, a detailed analysis of the participants' interactions was undertaken. Figure 5 gives a summary for all participants, including both average values and standard deviation for tasks 1 and 2. Comparing the two tasks, it is interesting to note that the averages of the time spent in a traveled city, as well as the amount of visited and uniquely visited cities, do not show significant differences, while it is noticeable that the overall amount of interactions increased and the overall amount of time needed for the task completion decreased within task 2. It also appears that the participants interacted more heavily with the filter related features during task 2. The task order was the same for all participants, therefore this expected outcome would indicate increasing confidence and familiarity with the interface.

TABLE I. SET OF CITIES IDENTIFYING SUCCESSFUL TASK SOLUTION

Task 1

City name	*Inhabitants (in million)*
Vienna	1.724
Budapest	1.722
Warsaw	1.717
Belgrade	1.339
Prague	1.249

Task 2

City name	*Area (in km^2)*
Berlin	892
Kiev	839
Zagreb	641
Madrid	605.8

TABLE II. PARTICIPANT TASK SOLUTIONS (CITIES ESPECIALLY CLOSE TO THE ASKED PARAMETER ARE MARKED IN BOLD)

Task 1

City name	*Count*
Vienna	1
Budapest	1
Warsaw	**1**
Belgrade	**5**
Prague	1
correct answer	9 / 11
other / incorrect	2

Task 2

City name	*Count*
Berlin	2
Kiev	**3**
Zagreb	**6**
Madrid	0
correct answer	11 / 11
other / incorrect	0

Analysis				**Task 1**		**Task 2**	
				AVERAGE	**STDEVA**	**AVERAGE**	**STDEVA**
Average time spent in traveled City (in sec)				32.94	12.94	31.82	10.93
Amount of unique visited cities (max. 45)				11	4	11	4
Amount of visited cities				14	5	13	5
Amount of interactions				42	15	48	19
	Movement/Travels	**SUM**		15	8	15	8
		Successful		13	5	12	5
		Unsuccessful		2	3	1	2
		Forbidden		1	3	2	2
	Content Exploration	**SUM**		14	5	13	5
		Trigger		12	4	12	5
		Dismiss		11	4	12	5
		Rotation		2	3	0	1
	Filter Menu	**SUM**		13	8	20	11
		Trigger		4	2	5	2
		Dismiss		4	2	5	2
		Connection		8	6	13	10
			Area	0	1	8	6
			Population	6	4	1	2
			Reset	2	2	4	3
		Size		1	0	2	1
			Area	0	0	1	1
			Population	1	0	0	0
			Normal	0	0	1	1
Amount of time for completion (in sec)				421.84	160.61	391.74	142.33
in minutes				7.03	2.68	6.53	2.37

Figure 5. Results - Summary of log files for both tasks

B. NASA Task Load Index

The estimated workload of all participants averages at 47.5 percent with a standard deviation of 17.6. Excluding the two outliers (that estimated their workload significantly lower and higher than everyone else, respectively) the workload average does not differ significantly at 48.54 percent but with a lower standard deviation of 11.2.

Looking at the participant's determined weights and ratings of the individual TLX factors *mental* and *physical demand* as well as *performance* and *effort* were rather important to the participants' experience of workload, while the factors *temporal demand* and *frustration* were of less importance during the task completion. The participants experienced comparatively higher mental and physical demands as well as the need to make efforts in order to complete the given tasks within the VRE. The average ratings also showed that the participants felt a comparatively low level of both temporal demand and frustration. Furthermore, the low performance value corresponds to a good level of performance, indicating that the participants felt rather successful and satisfied with their accomplishment by completing the tasks. It is particularly noteworthy that the participants were not given any indication about the success or failure of the task completion and their given answer.

C. Post-session questionnaire (PTQ)

Perception of the content generated with data from the web: The participants felt throughout rather positively about the perception of the presented content, which was ultimately generated with data received from the web. The participants valued the amount of presented information about the cities within the VRE. The textual description of a city was rated not too long nor too short. Together with providing important facts (area, population, country) in bullet point format, the designed interface enabled the participants to get a quick and pleasant rated city overview. Additionally, the participants liked that not only textual data were presented to them, but also photos about the cities, asking even to provide more images in the future. Overall, with displaying content on 2D planes in front as well as to the user's left and right (see Figure 3 middle row), the layout and the animation of the city data (`VR-NetworkNode-ContentView`) was perceived positive. Some participants commented that they felt "closer to the information (and its value)".

Spatial perception of my location within the 3D network: The participants considered to have had a solid understanding about their own location within the network at all times. Observations and answers of the open questions further indicate that the participants are in line with the prior mentioned design decision to offer node-to-node movement and no free movement within the 3D space from an interaction point of view. Furthermore, they expressed the supportive value of the underlying map, indicating the importance of such an essential cornerstone towards the visual guidance in the presented VR prototype. The visual node to node connections helped identifying potential targets to travel to, as a result of applying a filter. Most negatively mentioned within this category was the ability to change the nodes' size according to their area or population value and in relation to all other nodes within the network. Through the change of perspective and thus putting the user's perspective inside the visualization, the participants expressed their inability to properly compare the nodes' sizes, e.g., actually larger nodes in the further distance would effectively appear smaller compared to nodes closer to the users location due to the perspective.

Interaction using the vision-based motion control interface: The participants enjoyed operating the VR prototype by using gestures made through hand movements, although they had rather neutral feelings towards a precise interaction due to the inaccuracy of the gesture recognition. Some participants had to try multiple times to perform a successful gesture. The overall interaction using gestures, and thus the user's body, was received as fun, even fast and fluent, experience. The applied gesture set was easy to learn and remember. The interaction with the 3D GUI was particularly enjoyable. The implemented visual feedback, indicating the successful performance and recognition of a gesture interaction, was considered valuable, ultimately representing a crucial response from the VR prototype to the user.

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Human factors and ergonomics: Providing users with a swivel chair proved to be a good idea, since the participants strongly agreed that it supported them in the 360 degree exploration of the network. Some participants expressed concern that operating the VR prototype might get physically too tiring or stressful after longer usage. This would need to be further investigated in future studies. The actual visualization of the user's hands within the 3D space and thus the visual translation of their physical hands to the virtual space was mentioned positively. Since the users are not able to see their physical hands anymore while wearing the HMD, translating these accordingly into the virtual space seemed to be an essential bridge between physical and virtual world.

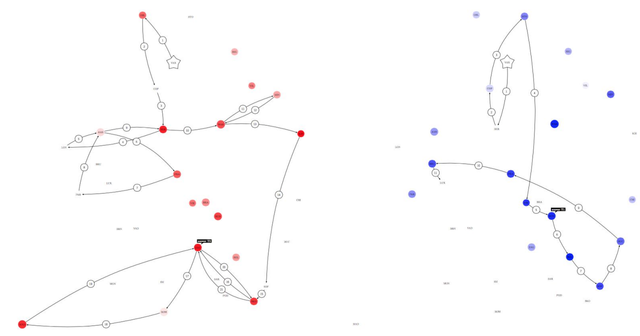

Figure 6. Explorative behavior: revisiting (left) vs. straight (right)

D. Expert discussion

As mention in Section II, the use of 3D within the InfoVis community is met with skepticism. But in case of the implemented VR prototype and considering its intention and purpose, the experts agreed that the presented scenario is one of the few where 3D interactive InfoVis works fine. Due to its focus on the exploration of data, the interactive visualization in the 3D space provides a unique perspective and thus fresh approach towards data exploration and browsing. The experts also stated that the developed VR prototype and its scenario is probably quite valuable as a learning tool, arguing that children learn from their 3D environment. Therefore being surrounded by the content instead of looking at it from above is potentially beneficial in this context. Although the implemented filter options work fine within the presented scenario, encouraging the user to play around, explore and move around as much as possible, the experts state that for "real" data exploration these are not enough and need to be assisted by the ability of putting numbers into the filters, e.g. using range sliders.

To avoid getting lost in larger networks, the experts suggested to implement features to support additional guidance or navigation, such as an isometric or aerial perspective. For future work the experts also suggested to support and implement features to select, highlight (e.g. glowing effects) and compare multiple nodes within the network. The implementation of concepts such as a radar, a minimap, or a "quest marker" (as known from computer games), could provide additional guidance and navigation depending on the given task.

Although the prototype made usage of the 3D space, the network node arrangement used 2D geometry. The experts suggested to think about the potential of the 3D environment to come up with effects and solutions to overcome some real world problems. An example they provided in the particular case of overcoming occlusion within a 2D arrangement was to investigate the implementation of a "world bending" effect, similar to the ones shown in the movie *Inception* or the *Halo* computer game series. The experts positively acknowledged the visual feedback as result of recognized gestures, reasoning it being crucial to the user. The 3D interactive GUI was received positively as well, noting that it feels very easy to operate the interface elements.

VI. Discussion

Although the participants had only minor experience with VR technologies, if any, in the past, it was particularly interesting to see their adaption to the presented setup and thus the interaction with the developed VR prototype. The participants' answers show that they were successfully able to solve the given tasks by exploring the 3D virtual network and consuming the displayed data. This furthermore confirms the proper functioning of the VR prototype, both in terms of design and implementation. Examining the log file data it appears that the participants learned and adapted quickly to the overall interaction, which is interesting given the comparatively short amount of time they spent with the prototype (approx. 20 minutes, including warm-up phase and the completion of task 1 and 2).

The implementation of a log file system for this kind of application turned out to be an essential asset for analyses as every recognized interaction between user and the prototype could be tracked (see Figure 5). Particularly interesting was the tracking of the participant's routes, visualizing their exploration while solving the given tasks. This provided some insights in their behavior and even search strategy. Two types of explorative behavior were identified, as seen in Figure 6: either featuring an increased degree of revisiting already explored network nodes, or going straight from one city to another until a suitable solution was found. At this point, it is not possible to derive concrete conclusions why sometimes each strategy was chosen. To further investigate this matter, more studies need to be conducted in the future, e.g., including the presentation of the visualized pathways to the participants after task completion and interviewing them about it.

The NASA TLX analysis revealed that the participants' estimated workload averaged at 47.5 percent. Given the participants' prior experiences with VR technologies and the novel approach of the presented VR prototype, a workload of around 50 percent can be considered ideal, indicating that the participants were neither bored nor overburdened with operating the prototype, especially considering that the majority of participants were confronted with such a setup and scenario for the first time.

The results of the post-session questionnaire, asking the participants concretely about their experience with the VR prototype, are encouraging as well. The presentation of the content was accepted positively, pointing out the overall intuitiveness, novelty and pleasantness of the designed interface. Textual content within a 3D environment can arguably be tricky, but within a VRE with no high resolution display devices, users could become faster exhausted by exclusively visually perceiving content, due to potential blurriness. Therefore, the amount and way of how to display textual content using today's broadly available HMD devices can be considered crucial to the overall user satisfaction (which was ranked satisfactory in our prototype). In general, the three element layout of putting visual content to the user's left, right and front, in combination with a HMD setup found practical acceptance. The chosen movement transition, enabling users to move exclusively from one node to another, was perceived positively as well, especially in regard to the overall physical stationary setup. While the users move in the virtual space, they do not actively translate their location in the physical space. Therefore transitional movement effects can be considered well chosen (see also "Swivel chair" experience [26]). The users were able to quickly learn and remember the functionalities of the VR prototype and make use of the complete feature set. Both the gesture and the 3D GUI interaction were perceived enjoyable and intuitive. Both interaction mechanisms have their value regarding the application within an immersive VRE. Whether to use one or the other seems highly related to the functionality or feature the interaction will embody.

Receiving the comments that the developed VR prototype and its presented scenario can be assigned to the few cases successfully demonstrating 3D interactive InfoVis was very encouraging for our proof of concept. However, at the same time the experts also argued for the importance of including more traditional features, e.g., maps or isometric perspectives, aerial respectively. Although the presented change of perspective for in this scenario feels fresh and novel, one should not forget or ignore potential limitations that it might come with it. Therefore, features to support the guidance and navigation of the user are more important than in other scenarios and should be considered when designing an application of that kind. After all, humans use even in the real world maps or other applications to assist them in their path-finding and exploration.

VII. Conclusions and Future Work

The aim of this paper was to investigate how an immersive VRE using a HMD and vision-based motion controls could be used to let the user naturally explore and interact with content and data received from open online accessible resources. We presented the design and implementation of an immersive VR prototype, ultimately enabling the user to explore a network of European capital cities based on data from Wikipedia. In order to gather insights, thoughts and recommendations of the user experience while operating the implemented VR prototype, a user interaction study and discussions with experts were conducted to explore the relevant research questions:

RQ1: Is immersive virtual reality suited for exploration of open data and content received from the web? The designed and developed VR prototype, and the gathered results, indicate that immersive VR is indeed suited for the exploration of traditional data and content from the web. Using a HMD device the users were able to perceive visually the content within the 3D space, while interacting using their hands. The results show that the participants valued the enjoyment, intuitiveness and novelty provided through the presented approach, while they learned quickly to make full use of the prototype's feature set, even solving the given tasks satisfyingly. Some participants tried to solve the given tasks very systematically, while others seemed a bit more open in their course of action. Both approaches of exploration ended in successful task completion. The fact that almost all participants were encouraged out of own will to find a particularly good solution towards the given tasks speaks for the acceptance and enjoyment of operating in the presented immersive VRE and its scenario. This is in line to the results of the NASA TLX estimation, indicating that the participants were positively challenged with the newly experienced environment and its technological components to a reasonable extent. Consequently, the developed VR prototype presents a practical approach for the overall successful design and implementation of a) translating traditional content from the web to a 3D environment and b) crafting an interaction interface enabling users to explore a 3D environment and its visualized content.

RQ2: Is the usage of head-mounted display technologies and vision-based motion controls suited to work together and can they benefit from each other in order to create a natural user experience? Although both technologies presented some minor issues (experienced blurriness, low comfortability of the HMD, inaccuracy of gesture detection), the presented VR prototype showed that HMD and vision-based motion controls can successfully work and, even more importantly, complement each other. While users are wearing a HMD, they are visually isolated from their physical environment. Designing more immersive input mechanisms is a crucial part towards supporting the user with more natural interaction possibilities. The study participants used the combination of both technologies to explore the 3D virtual environment (VE) and successfully complete their given tasks. Design approaches of the interaction through gestures and a visible 3D GUI were explored. Both found acceptance, indicating that interaction possibilities following these approaches can work in a meaningful way within a VRE. Interactive 3D GUI elements have the benefit of being visible to the user at all times, thus indicating and reminding the user on their functionalities. At the same time, interaction through gesture recognition seem to enable the user to operate fast and fluent interactions. However, these gestures need to be easy to learn and simple to remember. Overburdening the user with too complex gestures on the one hand and a set featuring too many gestures on the other, should be avoided. Furthermore, through our observations it is recognizable that the combination of both technologies requires the user to apply a higher degree of physical movements than compared to traditional HCI setups. Consequently, the intended duration of how long an application should be experienced needs to be considered within the application's design. While the combination of HMD and vision-based motion controls worked well in case of the presented prototype, the user interaction study and the dialog with the experts also revealed their curiosity towards additional (input) technologies, such as voice recognition, 3D audio and haptic interfaces, which seem promising to investigate in the future.

The presented prototype can be considered a first step and proof of concept into the direction of creating immersive VREs that feature traditional web content. Although the basic functionalities and visualization approaches throughout worked satisfactory, the experts made some valid arguments for future considerations, such as more features supporting the guidance of the user or making more use of the unique possibilities only a 3D VE can offer in order to overcome real world limitations. In conclusion, it is noticeable that which design approaches and decisions will work and which will not is highly dependent on the applied scenario and use-case and should thus be considered individually. Through its focus on exploration, the presented prototype demonstrates one of the few use cases, where immersive 3D VR InfoVis can be useful.

Still, some changes on the existing feature set of the implemented prototype can be applied. The overall color scheme could be reworked, also investigating the application of heat map filter options in order to support the ability to better compare network nodes using the newly presented perspective. Additional features to support the user's navigation and path-finding can include a minimap, the implementation of a temporary isometric or aerial perspective, or even the implementation of world-bending effects. Also, the addition of other emerging technologies such as voice-input, 3D audio or haptic interfaces needs to be in investigated in the context of immersive VREs.

Furthermore, the VR prototype should be presented to a larger audience in additional user studies in order to gain further insights. The presented results showed that participants rated the developed prototype as "enjoyable" and "intuitive". Long term studies should be performed to prove the effectiveness of VR or reveal if the participants' opinions are just an instant reaction to a new experience. Within this study, the duration of the participant interacting with the VR prototype lasted approximately 20 minutes. Longer interaction sessions and their implications could thus be investigated in the future as some participants expressed their worries particularly towards the physical exhaustion in prolonged interaction sessions.

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