The experience of using virtual reality for interactive spatial visualisation of environmental data

Isak de Villiers Bosman [1,2], Annique Smith [1,2], Kwan Sui Dave Ka [1], Koos de Beer [3] and Jan A. Maritz [4]

[1] *Virtual Reality and Interaction Lab, Department of Information Science, University of Pretoria, Cnr Lynnwood and Roper Street, Pretoria, South Africa*
[2] *Gamification Group, Faculty of Information Technology and Communication Sciences, Tampere University, Finland*
[3] *XRi Research and Development, Pretoria, South Africa*
[4] *Department of Mining Engineering, University of Pretoria, Cnr Lynnwood and Roper Street, Pretoria, South Africa*

Abstract

Virtual reality possesses various properties that have the potential to be beneficial for the visualisation of spatial data, including intuitive gestural affordances for looking around and interacting with data and the illusion of being physically located within a virtual space. However, some properties of the medium might also be detrimental to this purpose, such as limitations of the display technology and the possibility of motion sickness. While the medium is already being used for a variety of 3D visualisation purposes, there is no formulation of clear use-cases for virtual reality as a visualisation tool based on medium-specific considerations. Our work provides a preliminary overview towards this purpose by comparing two versions of an application for visualising environmental data in a mine: a virtual reality version and a standard desktop version. Using an exploratory approach with 26 participants and both qualitative and quantitative methods, the results highlight the ability of virtual reality to engage with spatial cognition but also some pitfalls in the design of user interfaces for interacting with large datasets.

Keywords

Virtual reality, data visualisation, user interface design, user experience

1. Introduction

Data visualisation utilises the visual capabilities of technology to represent datasets in an intuitive manner, which facilitates pattern and trend recognition in individuals [1]. Visualising data can help individuals make intuitive sense of their properties, even if such individuals are unable to explain these properties in technical language [2]. Digital technologies also allow visualisation parameters to be controlled and the resulting data to be updated in real time [3].

While information visualisation generally makes predominant use of 2-dimensional (2D) visuals, i.e., where data is mapped only on the x- and y-axis, the use of 3D visualisation that creates the illusion of a z-axis for the mapping of properties for more complex/multi-dimensional datasets has been utilised in previous research [2]. There are several arguments to consider for or against the choice of using 3D to represent data. Firstly, some data are inherently 3D, such as spatial data derived from representations of the physical world [4], which makes representing them in 3D a logical choice in such cases. Beyond

7th International GamiFIN Conference 2023 (GamiFIN 2023), April 18-21, 2023, Lapland, Finland.
EMAIL: isak.bosman@up.ac.za (A. 1); annique.smith@up.ac.za (A. 2)
ORCID: 0000-0002-6840-9043 (A. 1); 0000-0002-7887-9655 (A. 2); 0000-0003-2516-8232 (A. 3); 0000-0003-0871-1782 (A. 4); 0000-0002-4176-8919 (A. 5);

this, however, 3D visualisation affords the ability to view data from various perspectives [3] which in turn provides a larger visual area on which to map data points [4] and allows for larger and more complex datasets to be visualised than when relying only on 2D. Conversely, criticism against the use of 3D visualisation includes the fact that it is often used without adding value through the potential to generate new insights and has the ability to bias interpretation of data, e.g., by occluding data points behind other data or distorting the relative size of data points based on viewing perspective [2]. Appropriate use of 3D visualisation of data therefore requires consideration of the perceived benefits against the limitations and how these may be addressed.

Virtual reality (VR) technology offers many benefits that could improve 3D visualisation. A VR user wearing a head-mounted display (HMD) controls their viewpoint by moving their head around, which is a much more intuitive way to explore 3D space than traditional approaches such as mouse and keyboard [5], [6]. The display itself provides stereoscopic 3D by delivering different images to either eye, which creates a more accurate representation of depth [7]. VR also facilitates the illusion of finding oneself located within the virtual environment created by the software, which is sometimes referred to as immersion [5], embodiment [1], [8], or the place illusion as part of the experience of presence [6]. By creating spatially embodied experiences, VR has been anecdotally linked to ease of understanding information visualisation [5], [8]. In comparison with desktop-based visualisation, the use of VR has been linked to performance advantages, such as increased accuracy and depth of insights gleaned from data, as well as experiential advantages, such as feeling more successful and satisfied in terms of task performance for dataset exploration [1]. More broadly, the use of VR compared with desktop has also been linked with desirable experience outcomes, such as an increase in intense positive emotions, immersion, and flow [9] as well as a reduced sense of boredom and mental workload [10].

The use of VR, however, is not without its limitations. Firstly, the field of view (FOV) of the visual display technology for most commercial HMDs is less than half of the average human FOV [11]. Compared to desktop screens, the resolution of HMDs also requires text to be relatively large to be easily readable [11], which makes these devices less useful for text-heavy applications. Lastly, while research on extended VR use is scarce, some research indicates substantially worse performance and experience measures compared to desktop setups due to factors such as motion sickness and discomfort [12]; this currently limits the use of VR to short periods of time.

While there have been explorations in the use of VR as a visualisation tool in various ways, there is still frequent occurrence of converting 2D techniques, such as bar graphs and scatter plots, to 3D [7] and such explorations are often limited to providing specific demonstrations or proof-of-concept applications for using VR technology. As such, there are a lack of broader perspectives on the use of VR for visualisation that consider the benefits and limitations of the medium itself toward the formulation of sensible use-cases [8], [13]. Similar to the gratuitous use of 3D for data visualisation, there are many examples of unmotivated use of VR within visualisation contexts [13], which is especially pertinent given the considerable resources required to create such applications due to the lack of dedicated tools and standardised approaches. To inform the sensible use of VR, our study provides a starting point for the development of use-cases for VR visualisation by focusing on the differences in user experience as a result of the technological differences between two versions of an application for visualising 3D environmental data: one using a VR headset and one using a standard desktop PC. By comparing these two versions using an exploratory approach, we provide insight into the platform-specific differences that have the potential to impact the experiential differences of the application as a visualisation tool. These differences provide preliminary guidance on the design of VR visualisation applications and point to future research areas that have the potential to yield fruitful results.

The study was driven by the following research questions:

1. How is the experience of using VR beneficial over a desktop application for the visualisation of environmental data?
2. How is the experience of using VR detrimental or ineffective over a desktop application for the visualisation of environmental data?

2. Method

A small-scale within-subjects exploratory study was conducted to compare the desktop (PC) version of the system to the VR version in order to determine the effectiveness of VR in this context. The participants in the study were students with a background in engineering or technology at the University of Pretoria. A total of 26 participants were recruited through a message posted on the institutional learning management system and chosen using convenience sampling. No incentives were offered for participation.

2.1. Materials

The study involved an application which is aimed at visualising environmental data in the form of land formations in the context of mining engineering. The 3D layouts of these formations indicate future mining face positions as per the mine plan. Users interact with the application by moving their input device to control a "laser pointer" and pressing buttons to click and/or drag interface elements (Figure 1). Users can alter the appearance of the mine over time by controlling separate sliders for future days, months, and years (**Figure 2**). Movement is performed by navigating to a minimap and selecting a position to instantaneously "teleport" there. Users can also click on blocks of land to view information about them, such as the weight of mining material.

The application's intended goal is for mine-planning purposes and it is meant to be used by employees of a mining company to make decisions about resource-use over time. Traditionally, systems of this kind take the form of complicated desktop applications. Presenting this data in VR is therefore a novel way of visualising the changes to the mine over time. Furthermore, VR was chosen for its ability to make it easier for users to explore the large mine space and make informed decisions whilst being far removed from the physical location. It was assumed that the improved visualisation of the terrain afforded by VR over PC would allow stakeholders to interact with the data more intuitively.

Two versions of the application were developed: a VR version and a desktop version. The versions differ only in terms of the interaction techniques, where the PC version uses a mouse and keyboard, and the VR version runs on an Oculus Quest 2 device and uses the standard device controllers. In all other ways, the versions are the same.

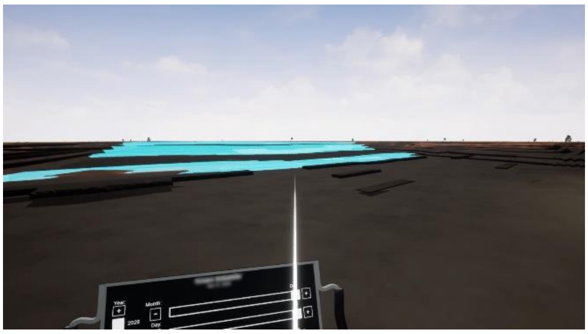

Figure 1: the mine environment with some land blocks selected in blue (some details have been obscured for non-disclosure purposes).

Figure 2: the control panel that shows the date sliders and the "laser pointer" for interaction (some details have been obscured for non-disclosure purposes).

2.2. Procedure

The study consisted of two parts, the first of which involved a usability test to compare the two versions of the application. The participants were randomly allocated to one of two groups, with one group starting with the VR version and the other group starting with the PC version. This was done to counteract order effects from learning to use the application [14]. Each test was carried out in a private room, with a facilitator present to assist the participants, deliver the tasks, and conduct the post-test interview. The test lasted about 40 minutes. During the test, participants executed a series of predefined tasks, which were defined with the assistance of a mining engineer who was familiar with the purpose of the application, and which could be considered typical tasks which might be carried out using such a system. The tasks included navigating around the virtual space, selecting blocks and viewing their information, and modifying the time sliders to view the changes to the mine over time.

After using each version, participants completed a validated user experience questionnaire (UEQ) [15]. The UEQ is a commonly-used instrument for measuring a range of experiential aspects through six subscales. Attractiveness is an overarching dimension which describes the user's overall subjective impression of the product. The pragmatic dimensions are perspicuity (how easy it is to become familiar with the product), efficiency (how much effort is required to perform a task), and dependability (whether the user feels in control of the interaction). The hedonic dimensions are stimulation (whether the product is exciting and motivating to use) and novelty (whether the product is innovative).

Due to the intuitive gestural affordances of the VR technology it was expected that the VR version would be easier to learn and perform tasks with. We also expected the relative novelty of the technology to significantly influence participants' affective experiences. The null hypothesis was formulated as follows:

H_0: There is no statistically significant difference between the VR and PC versions regarding i, where i ε (attractiveness, perspicuity, efficiency, dependability, stimulation, novelty).

In the second part of the study, a semi-structured interview with open-ended questions was used to explore participants' feelings about the two systems (see appendix for interview questions). These interviews were recorded and later transcribed.

All participants provided their informed consent before the commencement of the study and the study was approved by the institutional ethics review committee (protocol number: EBIT/206/2022). Clearance was not granted to collect demographic information such as gender and age.

3. Results

This section presents the qualitative results from the interviews followed by the quantitative results of the UEQ survey.

3.1. Qualitative data

For the qualitative analysis, the interview transcriptions were imported into ATLAS.ti 22. The first two authors worked together and performed a thematic analysis on the data according to the procedure described by Braun and Clarke [16]. First, both researchers familiarised themselves with the data by reading through it and taking notes and then collaboratively coded the data. Using the initial candidate set of codes, the first two authors separately reviewed this list and made a list of suggested changes, which were then resolved together. Following this, the codes were analysed and grouped into themes and then sub-themes. The themes were then reviewed by reading the collated extracts relating to each one and determining whether they formed a coherent whole or whether they needed to be re-coded or the theme renamed. An initial candidate thematic map was created to gain a better understanding of the themes and this was used to further refine the themes. Lastly, the theme names were refined and the data read through again by each researcher to check for inconsistencies.

As a result of the analysis, three primary themes were identified and a fourth "miscellaneous" theme was used to group the codes that did not fit elsewhere. The themes describe (1) outcomes directly related to the VR display technology, (2) outcomes directly related to the design of the interface, and (3) experiential outcomes of using VR. The themes are discussed below.

3.1.1. Outcomes of VR display technology

This theme describes outcomes of participants' experiences that are specifically related to attributes of the VR display technology, specifically the stereoscopic 3D display, proximity of the display to one's eyes, and the visual resolution.

Sub-theme A - Spatial cognition: This sub-theme is arguably one of the most important in this study as it relates to the preference for VR with reference to the specific aspects that contributed to its visualisation capabilities. The VR version allowed participants to understand the layout of the mine more effectively by providing a clearer indication of the distances between objects and giving them a broader perspective of the mine as a whole. This clearer indication is aided by the inherent ability of VR displays to provide stereoscopic 3D imagery by providing slightly different perspectives for the left and right eye respectively. "*You can see the depth, whereas on the desktop version you don't have stereo 3D, it's less pronounced.*" (P8).

Closely related to this was the concept of scale. Participants found the VR version more effective at showing the relative sizes of objects, thus making effective use of scale to visually represent information. Some also felt that on the desktop version, the objects were smaller than they would be in real life or, conversely, that in the VR version things felt closer: "*When you're working on the [desktop] screen you can't really look or see the scale of things…you can't get the depth or the width of the real value or size or scale of it, so VR definitely brings out the scale of the actual pit in relation to the benches and the height and all of that.*" (P1)

In addition to improved depth and scale, the VR version also allowed the participants to view the data more easily. This was coded as "taking in more" and it describes instances where participants explained that the VR version allowed them to see the minute changes in the life of the mine more clearly: "*The desktop, I think the difference was more visible on a larger scale, like 2022 and 2026 for example, that's when I could see an actual difference. Whereas with the VR it was more visible what happens within months...The data made sense on a larger span, so on what was happening monthly or daily, it was not very apparent to see that this has been mined out [on PC]…whereas the VR provided all of that....*" (P9)

While some participants did note a similar level of understanding from both platforms, this sub-theme underscores the benefit of the VR version for applications where spatial data are being visualised. The ability of VR to provide users with a more realistic representation of what they are seeing affords them the ability to grasp what is being shown more easily.

Sub-theme B - Visual quality: A common problem in VR is the quality of display due to the proximity of the displays to the viewer's eyes, causing lower perceived resolution and resulting in problems with reading text. The lower resolution of the VR version led to some participants expressing a preference for the desktop version in that regard, causing blurry text and eye strain for some users: "*I think I would have to say the desktop one was a bit more visually clear. So like, it's just a monitor, so you can just see it, and in the VR one you still have to look around a lot and the text is very hazy, so I think the font size is too small, so maybe if that's bigger then you'll probably see it a lot better.*" (P20)

In summary, current VR technology possesses varying attributes that are especially relevant for 3D data visualisation. The stereoscopic and surrounding display aid spatial cognition while the low perceived resolution creates a negative sense of display quality and harms the readability of text. The potential for some users to experience eye strain also limits the amount of time VR can be used.

3.1.2. Outcomes of interface design

This theme describes outcomes directly related to the way that the technology allows participants to interface with the application. This relates mostly to the design aspects of the VR hardware and software on its own, but also compares this with participants' previous experience with desktop hardware and software.

Sub-theme C - Learnability: Participants expressed varying stances on the learnability of the VR application. Firstly, some participants expressed a preference for the manner in which they could interact with the application, both in terms of navigating through the virtual environment and the use of the controls. The concept of intuitive/natural interaction was raised by some participants as the reason why they preferred the VR version. The interaction with the system was described as "easier" and "more natural" compared to a desktop and mouse, although the latter was considered by some to be faster: "*...even though you can do it faster with the keyboard, but I would prefer the controls [of the VR version] because it's effortless, you just click, you don't have to think about stuff.*" (P11)

On the other hand, some participants explained that they were "more comfortable" or "more familiar" with using a desktop and this made it easier for them to interact with the PC version initially: "*…it took me some time to get used to the VR controls, whereas with the PC and the mouse it was quite easier [sic] for me to get used to it because with VR, I'm adding the fact that it was the first time that I was using it, so the learning curve was a bit steeper than with the PC version.*" (P25)

Lastly, some participants did not prefer one particular system over the other when it came to visualising the data. The VR and PC versions were designed to be as similar as possible, with only the method of interaction differing between the two, as this allowed the users to compare the systems more easily. It is therefore not surprising that some users would find little to no difference between the systems when it came to using them to interact with the data.

Sub-theme D - Selection accuracy: While participants noted that the natural interactions of the VR version made the system easier to use, the lack of precision afforded by the VR version somewhat harmed the experience. Participants described having difficulty selecting specific sliders on the dashboard or specific benches to view information. One participant attributed this to having shaky hands and a lack of familiarity with VR, while others spoke more generally of having less control and accuracy with the VR controls. The problem of reduced accuracy by way of utilising larger arm movements rather than smaller actions (hand or finger movements) has been discussed in previous research and alternative approaches have been suggested to improve interaction accuracy, such as using a “pen grip” instead [17].

Sub-theme E - Navigation: This theme generally describes the navigability of the virtual space. The intuitive controls discussed in sub-theme C extended to navigating around the virtual mine. Some participants attributed this to controls, while others explained that being able to look around in the space made it easier to identify where to go and how to get there. However, some participants described navigation within the virtual space as a challenge, partially because the VR headset needed to be tethered to a computer via a cable, which hampered head movement. This is also related to a suggestion given by some participants to show position on the minimap in a way that also indicates orientation, e.g., in the form of a cone. This is an important consideration to make for 3D visualisation applications, where the navigable space may be too large for users to easily keep track of their position within the space.

3.1.3. Experiential outcomes of VR

While the previous two themes are related to specific aspects of the VR technology, this theme describes participants’ descriptions of their experiences while using the VR application. These outcomes relate to the holistic experience created by the VR technology, rather than specific aspects of the input/output mechanisms.

Sub-theme F - Affect: This sub-theme described general feelings of enjoyment relating to the use of the VR version. As an explanation for these feelings, some participants only used the word “fun” when describing the VR version in comparison to the desktop version: “*...it feels more fun to play with the VR versus the desktop version.*” (P7).

The concept of novelty is also included in this sub-theme because several participants mentioned that the VR experience was more interesting or exciting because it was their first time experiencing VR: “*I definitely prefer VR more than the PC version, probably because it was the first time I used VR, so it was quite exciting…*” (P25).

The benefits of novelty in terms of data visualisation, however, are complex. On the one hand, novelty has been associated with desirable outcomes such as increased learning and retention [18] and satisfaction [19]. On the other hand, it is unclear how persistent these benefits might be once the novelty effects start to wear off with prolonged use [20]. Nevertheless, considering that the design of the application did not include any direct attempts at improving its hedonic, i.e., non-goal-oriented qualities, the perceived positive affect experienced from the VR platform alone is worth mentioning. Novelty is also a double-edged sword in this instance, as the lack of experience with VR controllers was seen as a drawback of VR by some participants, as discussed in sub-theme C.

Sub-theme G - Immersion and presence: This sub-theme collectively refers to all instances where participants mentioned experiences that, in the VR literature, are generally referred to as either immersion or presence. A notable example is that of facilitating the place illusion [6] where participants felt like they were “in” the environment being visualised: “*I think the VR one [contributed to understanding the data being visualised], because I was actually in the space, so you could see everything around you and it made you feel like you were there, I think, a lot more than the PC which was more like you were just looking at a simulation or something like that.*” (P21)

The term “immersive” was used by participants to describe a wider range of experiences, but a central commonality was the surrounding nature of displays that replace sensory stimuli from the physical world and direct more of their attention toward the application: “*[Preference for] the VR version, because it's user friendly, you don't have the keyboard in front of you, you don't have too many screens, you're only focusing on one thing…compared to the screen* *where there's a laptop, there's people, so you're kind of focusing on one thing with the VR.*" (P11)

"*But other than [the resolution] the VR version felt natural to use, the clicking on the box, the pointer and the map, everything just felt like I was engrossed in the system.*" (P16)

As illustrated by the second quote, the immersive experience was also facilitated by the natural interaction metaphors provided by VR, as discussed in sub-theme C.

3.1.4. Miscellaneous

This theme contained one code which could not logically be grouped with any others, which relates to the "learning effects" where a participant described their experience of either the PC or VR version of the system being made easier because of their prior experience with the other version. While this is a limitation of the within-subjects design, it was also countered to some extent by randomly dividing the participants between the conditions and ensuring that half began with either condition. Furthermore, the other themes provide evidence that users did experience a difference between the two versions in terms of how the data was presented and interacted with and that this difference was attributable to the nature of VR as a medium.

3.2. Quantitative data

The quantitative analysis was performed in IBM SPSS 28.0.1.0. First a Shapiro-Wilk normality test was carried out on each of the six subscales of the UEQ. The results showed that normality was violated for the subscales relating to dependability ($p = .009$), stimulation ($p = .008$) and novelty ($p < .001$), while it was not violated for attractiveness ($p = .054$), perspicuity ($p = .132$) and efficiency ($p = .031$). However, the non-parametric Wilcoxon signed-rank test was still used to analyse all the scales due to the small sample size and to make it possible to compare the results.

Table 1 shows the descriptive statistics for the survey results, categorised according to each system type. Each question in the survey was rated on a Likert scale ranging from 1 to 7.

Table 1
Descriptive statistics for each subscale, categorised by system version (VR or PC). ATTR = attractiveness, PER = perspicuity, EFF = efficiency, DEP = dependability, STIM = stimulation, NOV = novelty

UEQ Subscale	System version	Mean	Median	Std. Dev.
ATTR	VR	5.859	6.083	1.053
	PC	5.244	5.500	1.152
PER	VR	5.990	6.125	1.023
	PC	5.904	5.875	0.778
EFF	VR	5.721	6.250	1.372
	PC	5.596	5.750	1.093
DEP	VR	5.481	5.500	1.098
	PC	5.625	5.750	0.988
STIM	VR	6.087	6.250	0.880
	PC	5.029	5.125	1.491
NOV	VR	5.990	6.000	0.838
	PC	4.923	5.375	1.505

A Wilcoxon signed-rank test was conducted to compare the ratings for each of the six UEQ subscales for the VR and PC versions of the system (Table 2). Data are medians unless otherwise stated.

For attractiveness, 17 out of the 26 participants rated the VR version higher than the PC version, 6 rated the PC higher than the VR and 3 rated no difference between the two systems. There was a statistically significant median difference (.333) between the VR (6.08) and the PC (5.5) version, $z = -2.684$, $p = .007$ with a moderate effect size ($r = .372$). Therefore, the alternative hypothesis is supported.

For perspicuity, 13 out of the 26 participants rated the VR version higher than the PC version, 9 rated the PC higher than the VR and 4 rated no difference between the two systems. There was no statistically significant median difference (.125) between the VR (6.13) and PC (5.88) version, z = -0.717, p = .473. Therefore, we fail to reject the null hypothesis.

For efficiency, 12 out of the 26 participants rated the VR version higher than the PC version, 10 rated the PC higher than the VR and 4 rated no difference between the two systems. There was no statistically significant median difference (.0) between the VR (6.25) and the PC (5.75) version, z = -.717, p = .473. Therefore, we fail to reject the null hypothesis.

For dependability, 13 out of the 26 participants rated the VR version higher than the PC, 11 rated the PC version higher than the VR and 2 participants rated no difference between the two systems. There was no statistically significant median difference (.125) between the VR (5.5) and the PC (5.75) version, z = -.433, p = .665. Therefore, we fail to reject the null hypothesis.

For stimulation, 20 out of the 26 participants rated the VR version higher than the PC, 3 rated the PC version higher than the VR and 3 participants rated no difference between the two systems. There was a statistically significant median difference (.75) between the VR (6.25) and the PC (5.13) version, z = -3.507, p < .001 with a moderate effect size (r = .486). Therefore, the alternative hypothesis is supported.

For novelty, 21 out of the 26 participants rated the VR version higher than the PC, 1 rated the PC version higher than the VR and 4 participants rated no difference between the two systems. There was a statistically significant median difference (.75) between the VR (6.0) and the PC (5.38) version, z = -4.034, p < .001 with a large effect size (r = .559). Therefore, the alternative hypothesis is supported. The summary of hypotheses is provided in Table 3.

Table 2
Wilcoxon signed-rank test for each of the six subscales

[Subscale] VR - PC	Z	Asymp. Sig (2-tailed)
Attractiveness	-2.684^b	.007
Perspicuity	$-.717^b$	.473
Efficiency	$-.737^b$	.461
Dependability	$-.433^a$	.665
Stimulation	-3.507^b	<.001
Novelty	-4.034^b	<.001

[a] Based on positive ranks, [b] based on negative ranks

In summary, the two hedonic aspects of the UEQ (stimulation and novelty) were rated significantly higher for the VR version, while the three pragmatic aspects (perspicuity, efficiency, and dependability) did not differ significantly between the two systems. Attractiveness as an overarching impression was also significantly higher for the VR version. Due to the small sample size, these statistical results are intended to support the qualitative results, rather than present a strong argument as to the differences between the two systems.

Table 3
Summary of hypotheses

Subscale	Result
Attractiveness	Alternative hypothesis supported *
Perspicuity	Fail to reject null hypothesis
Efficiency	Fail to reject null hypothesis
Dependability	Fail to reject null hypothesis
Stimulation	Alternative hypothesis supported **
Novelty	Alternative hypothesis supported **

*p < 0.05; ** p < 0.001

4. Discussion

In order to discuss the main outcomes of the study, this section discusses the results in terms of the research questions of the study. We also present suggestions for the design of user interfaces based on the perceived benefits, shortcomings, and suggestions gleaned from our data.

4.1. RQ1: How is the experience of using VR beneficial over a desktop application for the visualization of environmental data?

The two scales of novelty and stimulation were rated significantly higher for the VR than for the desktop version. The “affect” sub-theme with its codes of enjoyment and novelty is especially relevant here, since participants used terms such as “fun” and “interesting” when describing their preference for the VR version. However, other sub-themes also have to be considered as a contributing factor to feelings of novelty and stimulation, such as the immersive nature of the experience, interaction that is intuitive as opposed to traditional input devices, and the feeling of "being there", i.e., the place illusion. This provides evidence of the usefulness of VR as a tool to create new and interesting visualisation experiences that individuals might want to experience for the sake of the platform itself, which could be used to extend the reach and impact of such applications. As also mentioned above, the effects of novelty and stimulation in this case are expected to be beneficial for desirable outcomes such as satisfaction and retention of information, although the long-term carryover of such effects are not clear. Research into future applications of VR visualisations would thus benefit from deeper insight into how these hedonic affective components could be effectively harnessed toward accomplishing long-lasting goals.

Within the UEQ, attractiveness comprises an overall impression of a product based on both the pragmatic and hedonic aspects [15]. As such, it is worth noting that, even though the pragmatic components were not rated significantly higher in either platform, the overall attractiveness for the VR version was rated higher. In addition to the hedonic aspects already discussed under novelty and stimulation, it is expected that intuitive interaction and realism would have played a role here, since both were cited by participants as having a positive effect on their overall experience of the VR version. Furthermore, while seemingly goal-oriented aspects such as improved sense of depth perception and scale did not seem to have a significant impact on participants' impression of pragmatic aspects, these might also have contributed to general feelings of quality preference of the VR version. Our results also suggest that the distortion of 3D data could be addressed by the improved perception of scale and depth that is facilitated by VR display technologies. It must, however, be emphasised that our results are preliminary and that our study was not specifically aimed at testing the comprehension of data.

4.2. RQ2: How is the experience of using VR detrimental or ineffective over a desktop application for the visualisation of environmental data?

Based on UEQ scores, none of the pragmatic, i.e., goal-oriented aspects of the application were rated significantly higher for the VR version than the desktop version. There are several considerations to be made here.

Firstly, some participants expressed negative reactions to limitations in the display resolution. This led to difficulty reading text, poor resolution, and eye strain for some. Such discomfort could put a limit on periods for which VR technologies can be used in real-world settings and highlights the necessity to keep text size in mind when designing VR applications for visualisation.

Secondly, the fact that some participants experienced the interaction mechanisms and their level of understanding to be largely similar in the two versions supports the lack of a significant difference in the use of these mechanisms to interact with and retrieve data from the application. This is not surprising, considering that the two versions were intentionally designed to be similar in every way, except for those necessitated by the differences in platform. This does, however, emphasise that designers of VR visualisation applications need to consider optimal utilisation of the platform itself in order to improve pragmatic aspects as well, for which we provide suggestions based on our data.

These suggestions relate to the benefits of intuitive interaction through natural interaction metaphors as well as the drawback of reduced precision when using gesture-controlled controllers. The natural interaction metaphors contributed to the learnability of the application, which emphasises the value of this approach (sub-theme C), but this approach also tends to make use of larger muscle groups, such as the arms and shoulders, which is appropriate for larger movements but can make it harder to perform precise motor actions (sub-theme D). This problem is especially relevant for visualisation applications that might have many adjustable options for displaying and modifying sets of data.

There are several possible solutions to this problem, perhaps the most obvious being to make the menus and selectable elements themselves larger (i.e., larger hitboxes as mentioned in sub-theme D). However, this is not necessarily ideal, since a larger menu uses up more screen real estate and blocks out more of the observable environment. Furthermore, it is not always feasible to make interactable elements larger in visualisation solutions, since size itself is often used to denote information.

For general UI elements, a solution that affords more precise motor movements might be to approach the design of such elements in a way that utilises smaller muscle group movements. An example of such an implementation would be replacing sliders that afford up/down or left/right movement with dials/knobs that afford rotation and thus allow users to anchor their arm in space and perform precise movements primarily with their forearm and wrist.

5. Limitations

The sample size of the study was small but considering the research questions and the goal of the study to provide guidelines to improve the VR system, the quantitative was considered supplementary to the qualitative data in this study. Secondly, a small amount of discomfort was encountered by some participants during the study when the VR version was being used due to the short cable which was used to attach the headset to the computer. The cable was necessary since the large amount of data included in the application did not allow it to run on the headset alone. However, the short cable inhibited the participants' movement in the virtual world somewhat and this was commented on by 7 participants and coded under "difficult navigation". The participants filled in the UEQ twice before being interviewed, which could have primed their interview responses to be more in line with UEQ measures. Finally, the design of the application could not be fully described here due to non-disclosure agreements, thus making replicability of the study difficult.

6. Conclusions and future research

Our study has provided preliminary evidence that the VR platform outperforms a traditional desktop in terms of providing a more attractive, novel, and stimulating experience for visualising environmental data. These differences, however, were not found to be significant for dependability, perspicuity, and efficiency. We have also followed an inductive approach to provide factors that contribute to these differences, or lack thereof, of which the affordance of spatial perception might be considered to be the most relevant. The combined results suggest that sensible use cases should consider the tradeoffs between desired outcomes, such as enjoyment, spatial cognition, and presence, against undesired ones such as reduced text legibility, selection accuracy, and knowledge carryover from existing platforms. Design alternatives should also be considered, such as avoiding reliance on large blocks of text, using large/bold fonts, and utilising smaller muscle movements for selections where possible.

Our study has pointed toward fruitful avenues for future research. Firstly, we have provided preliminary evidence that VR enhances cognitive engagement with 3D data through its affordance of spatial perception, particularly through the perception of scale and depth. Future work might thus explore the effects that this has on desired outcomes of 3D data visualisation, such as comprehension and retention. Furthermore, while our study has not attempted to determine the exact causes of these cognitive benefits, such as stereoscopic 3D vs. intuitive navigation through movement, the similar capabilities offered by other XR technologies such as head-mounted augmented reality (AR) suggest that these might provide similar benefits.

7. Acknowledgements

This research was funded through the Exxaro Chair in XR Technology in the Department of Information Science at the University of Pretoria. The VR system used for this study was developed by Zander van Beest van Andel and Liam Botha. We would like to thank Nicole Lou who helped with some of the data collection and all the participants who took part in this study. Finally, we would like to thank members of the Gamification Group for their insightful comments.

8. Appendix

The interview questions used in this study are provided below: (1) Between the desktop and VR platform, which did you prefer and why? (2) Which platform facilitated your understanding of the visualisation more effectively and why? (3) How did the different platforms affect your ability to interact with the data? (4) Please provide some suggestions for improving the VR application.

9. References

[1] P. Millais, S. L. Jones, and R. Kelly, "Exploring Data in Virtual Reality: Comparisons with 2D Data Visualizations," in *Extended Abstracts of the 2018 CHI Conference on Human Factors in*

Computing Systems, New York, NY, USA, Apr. 2018, pp. 1–6. doi: 10.1145/3170427.3188537.

[2] D. A. Szafir, “The good, the bad, and the biased: five ways visualizations can mislead (and how to fix them),” *interactions*, vol. 25, no. 4, pp. 26–33, Jun. 2018, doi: 10.1145/3231772.

[3] J. L. Wesson and P. R. Warren, “Interactive visualisation of large multivariate datasets on the world-wide web,” in *Proceedings of the 2001 Asia-Pacific symposium on Information visualisation - Volume 9*, AUS, Dec. 2001, pp. 151–157.

[4] R. Brath, “3D InfoVis is here to stay: Deal with it,” in *2014 IEEE VIS International Workshop on 3DVis (3DVis)*, Nov. 2014, pp. 25–31. doi: 10.1109/3DVis.2014.7160096.

[5] D. Raja, D. A. Bowman, J. Lucas, and C. North, “Exploring the Benefits of Immersion in Abstract Information Visualization,” in *In Proceedings of 8th International Immersive Projection Technology Workshop*, 2004, pp. 61–69.

[6] M. Slater, “Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments,” *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 364, no. 1535, pp. 3549–3557, Dec. 2009, doi: 10.1098/rstb.2009.0138.

[7] E. H. Korkut and E. Surer, “Visualization in virtual reality: a systematic review,” *Virtual Reality*, Jan. 2023, doi: 10.1007/s10055-023-00753-8.

[8] J. Huang, M. S. Lucash, R. M. Scheller, and A. Klippel, “Walking through the forests of the future: using data-driven virtual reality to visualize forests under climate change,” *International Journal of Geographical Information Science*, vol. 35, no. 6, pp. 1155–1178, Jun. 2021, doi: 10.1080/13658816.2020.1830997.

[9] F. Pallavicini and A. Pepe, “Comparing Player Experience in Video Games Played in Virtual Reality or on Desktop Displays: Immersion, Flow, and Positive Emotions,” in *Extended Abstracts of the Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts*, New York, NY, USA, Oct. 2019, pp. 195–210. doi: 10.1145/3341215.3355736.

[10] H. C. Lum, R. Greatbatch, G. Waldfogle, and J. Benedict, “How Immersion, Presence, Emotion, & Workload Differ in Virtual Reality and Traditional Game Mediums,” *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 62, no. 1, pp. 1474–1478, Sep. 2018, doi: 10.1177/1541931218621334.

[11] M. H. Lynn, G. Luo, M. Tomasi, S. Pundlik, and K. E. Houston, “Measuring Virtual Reality Headset Resolution and Field of View: Implications for Vision Care Applications,” *Optometry and Vision Science*, vol. 97, no. 8, pp. 573–582, Aug. 2020, doi: 10.1097/OPX.0000000000001541.

[12] V. Biener *et al.*, “Quantifying the Effects of Working in VR for One Week,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 28, no. 11, pp. 3810–3820, Nov. 2022, doi: 10.1109/TVCG.2022.3203103.

[13] M. Kraus, “Assessing the Applicability of Virtual Reality for Data Visualization,” 2021, Accessed: Jun. 07, 2022. [Online]. Available: https://kops.uni-konstanz.de/handle/123456789/55791

[14] J. Lazar, J. H. Feng, and H. Hochheiser, *Research Methods in Human-Computer Interaction*. Morgan Kaufmann, 2017.

[15] M. Schrepp, J. Thomaschewski, and A. Hinderks, “Construction of a Benchmark for the User Experience Questionnaire (UEQ),” Jun. 2017, doi: 10.9781/ijimai.2017.445.

[16] V. Braun and V. Clarke, “Using thematic analysis in psychology,” *Qualitative Research in Psychology*, vol. 3, no. 2, pp. 77–101, Jan. 2006, doi: 10.1191/1478088706qp063oa.

[17] A. U. Batmaz, A. K. Mutasim, and W. Stuerzlinger, “Precision vs. Power Grip: A Comparison of Pen Grip Styles for Selection in Virtual Reality,” in *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, Mar. 2020, pp. 23–28. doi: 10.1109/VRW50115.2020.00012.

[18] J. Schomaker, “Unexplored territory: Beneficial effects of novelty on memory,” *Neurobiology of Learning and Memory*, vol. 161, pp. 46–50, May 2019, doi: 10.1016/j.nlm.2019.03.005.

[19] N. Talukdar and S. Yu, “Breaking the psychological distance: the effect of immersive virtual reality on perceived

novelty and user satisfaction," *Journal of Strategic Marketing*, vol. 0, no. 0, pp. 1–25, Aug. 2021, doi: 10.1080/0965254X.2021.1967428.

[20] W. Huang, "Investigating the Novelty Effect in Virtual Reality on STEM Learning," Ph.D., Arizona State University, United States -- Arizona, 2020. Accessed: Dec. 01, 2022. [Online]. Available: https://keep.lib.asu.edu/items/158443