

Enhancing Environmental Data Communication Through VR

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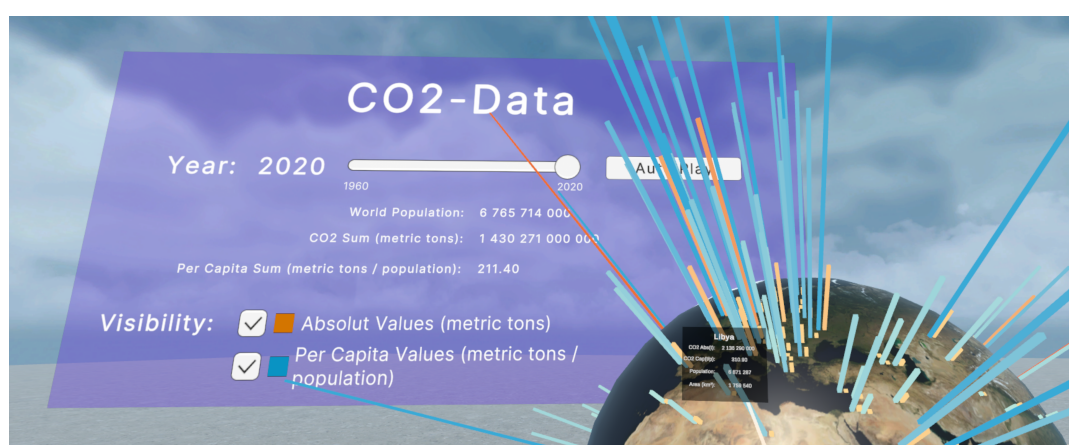


Figure 1: Screenshot of the VR application showing the user menu with 2020 data selected and displaying a virtual globe with country-specific CO₂ emissions in both absolute and per capita terms, as well as details on demand for Libya (including CO₂ emissions (absolute/per capita, in metric tons), population, and area in km²).

Abstract

This paper examines how environmental data can be effectively communicated to non-experts in interactive, immersive 3D spaces. Utilizing a use case centered on global spatio-temporal CO₂ emissions and population dynamics over the past six decades, we explore techniques for presenting both absolute (country-level) and per capita data within meaningful spatial and temporal contexts. We developed a VR prototype visualizing these data on an interactive 3D globe and conducted a qualitative user study to evaluate its clarity and interpretability for non-expert audiences. Our findings suggest that incorporating clear geographical context, intuitive representations, and user-centered interactions can enhance engagement and certain aspects of understanding. We thereby offer a practical contribution to tackling environmental data visualization and communication in immersive environments. This promotes transparency and mitigates the risk of misinterpretation or misinformation in data communication across emerging digital media platforms.

CCS Concepts

• **Human-centered computing** → **User studies; Virtual reality; Information visualization;**

1. Introduction

As data becomes increasingly central to everyday decision-making, public communication, and civic engagement, the need for a clear, balanced, and comprehensive data visualization has never been more critical. Hence, effectively presenting data within a meaningful context, whether spatial, temporal, or relative in scale, is essential for empowering individuals, communities, and policymakers

to make informed decisions based on reliable evidence rather than distorted or misleading representations. This involves creating visual representations of data that are equitable, inclusive, and transparent, making complex information understandable and accessible to a wide range of audiences. Given that interactive, immersive 3D environments are equally gaining prominence in data visualization, exploration, and communication, the principles of such responsible visualization [Mah24] must adapt to new dimensions of

design, perception, and interaction. In this setting, these considerations go beyond simply presenting data accurately. Rather, they are also about how users navigate, perceive, and interact with data in immersive and spatial ways. Generally speaking, immersive environments introduce new variables, such as depth, scale, motion, and embodied interaction, that can subtly influence user interpretation and experience [YJD*18, QJ20].

Generally speaking, to provide accurate, readable, and transparent visualizations, certain technical/design aspects have to be considered. Some key considerations for 2D visualizations are illustrated in the work of Romano et al. [RSDG20] who demonstrated that simple technical choices, such as using a logarithmic scale versus a linear one, can significantly influence how people interpret and respond to visualized information. Focusing on COVID-19 data, they showed how inappropriate or non-transparent scale choices can unintentionally contribute to misinformation and distort public understanding and risk perception. As further explored by Lisnic et al. [LPLK23], misleading visualizations that violate established visualization design principles (using truncated axes or inappropriate chart types) can significantly distort public information interpretation. Despite their inherent flaws, such visualizations often retain an illusion of credibility, giving the false impression of trustworthy data-driven insights. In contrast, the application of such principles within immersive 3D environments remains somewhat underexplored. This gap is stressed in the findings of Korkut and Surer [KS23], who identified both the absence of standardized VR guidelines and a prevailing tendency to simply translate traditional 2D visualization techniques into 3D forms. Yet, research by Marriott et al. [MSD*19] indicates that while neither 2D nor 3D visualizations are universally superior, immersive 3D approaches can offer distinct advantages, particularly when representing spatial data and relationships, e.g., using the Earth's curvature, thereby enhancing users' understanding of locations, distances, and regional interconnectedness. Furthermore, while the work of Kraus et al. [KKF*21] investigated the general value of immersive visualization and outlined scenarios where immersion can meaningfully enhance data analysis (e.g., tasks requiring spatial awareness and interaction), it primarily emphasizes functional benefits. Like much of the field, their work gives comparatively less attention to considerations such as information transparency and the potential for user misinterpretation, which are often overlooked, leaving a critical gap in understanding how immersive visualizations can be used responsibly to support diverse audiences. Initial efforts in this direction have been taken by Lee et al. [LBL*21], who introduced the concept of *data visceralization* - a novel approach aimed at providing users with an intuitive, immersive experience of data to enhance their understanding of physical measures and quantities. Their work explored how VR can foster a deeper, more embodied sense of data comprehension, enabling insights that might remain hidden or abstract in traditional, screen-based visualizations.

To address **misleading visualizations**, the **absence of guidelines** for immersive 3D, and the **limited spatial intuitiveness** of 2D visualizations we explore how responsible visualization can be achieved in immersive 3D environments, specifically in virtual reality (VR), by employing specific design techniques for data representation, aggregation, and user interaction that foster clarity, inclusivity, and transparency. To achieve this, we build on a use case

involving spatio-temporal data on global CO₂ emissions per country over the past six decades, combined with corresponding population dynamics. For this visualization, it is essential not only to present total country-specific CO₂ emission figures, but also to provide users with more pertinent information (i.e., per capita) and contextual insights about the size of individual countries and their populations, for a transparent representation of the circumstances surrounding emissions. The specific contributions of this work are:

- **Integration of Multi-Dimensional Data in VR:** We design and implement a VR prototype that combines macro-level (total country emissions) and micro-level (per capita emissions) CO₂ data with spatial and temporal context on an interactive globe, supporting exploration through user-controlled interaction.
- **User-Centered Analysis and Insights:** We present the results of an exploratory user study examining how non-expert users engage with and interpret multi-dimensional climate data in VR.

2. VR Prototype

Data sources: Our application integrates multi-dimensional spatio-temporal data from freely available sources: country-specific annual CO₂ emissions data [Bha22] throughout 1960 to 2020, and respective population figures [Ash22] were used to provide a context for the environmental and demographic aspects of each country. In addition, a dataset containing longitudes and latitudes of each country [Pei20] was required to accurately position the data on a virtual globe, enabling spatial analysis across different countries. If there were missing or inconclusive annual data for a country, we removed it from the visualization. For a country to be included, it had to be present with the same identifier in all three datasets.

Data representations: In this application, it is essential to present not only the CO₂ emission figures but also contextual information regarding the population of each country to make them comparable. To ensure the accuracy and clarity of this information, we have chosen to use an interactive 3D globe rather than relying on flat 2D projections, like Mercator maps, which often introduce distortions due to the challenges of representing a spherical surface on a flat plane. There are several approaches for visualizing spatio-temporal data on a 3D globe [KKS22, SEC*21]. Guided by the design principles of Satriadi et al. [SEC*21], we opted for a method that employs 3D bars aligned with the surface normals of the globe. In this method, the height of each bar corresponds to a data value (scaled based on the highest entry per category, absolute and per-capita), which can be color-coded for clarity. To enhance usability, the bars are positioned at the geographic center of each country, ensuring that users can easily associate each bar with its respective country. The underlying globe texture provides spatial context without country borders. This was done to not encode the size of a country, but to keep the focus on the population.

User interactions: To enhance data customization, users can toggle between total emissions, per capita emissions, or both, thereby allowing for flexible data visualization (Figure 1). A slider enables users to select a specific year or to activate autoplay, which sequentially cycles through the available years. The interactive 3D globe permits users to resize and rotate the visualization, providing an optimized spatial perspective. For a more in-depth exploration,

users can interact with individual 3D bars to retrieve detailed information on emissions, population, and country size (Figure 1).

Implementation: To enable immersive interactivity, the prototype was developed using Unity (version 2022.3.37f1) [Tec23] and the XR Interaction Toolkit (3.0.3) for the Meta Quest 2 platform using standard controllers.

3. Evaluation

To evaluate our approach, we (1) examined whether our prototype **improves users' understanding** of spatial multidimensional data and (2) assessed the **perceived value and effectiveness** of our virtual globe visualization. Our evaluation methodology followed a task-oriented approach, in which participants were also encouraged to verbalize their experiences and perceptions throughout the process. In total, 10 individuals (3 females, 7 males) with an age range from 26 to 38 ($M = 30.3$, $SD = 3.8$) participated in our user study. Most (8) of the participants had a background in data science and/or computer science. Two participants had no prior VR experience, three had used VR once, five had used it multiple times, and none were regular VR users. When asked “Where do you see yourself on a scale from *Layperson* to *Expert* on climate-related topics?” on a 5-point scale, two selected 1 (*Layperson*), six selected 2, two selected 3, and none selected 4 or 5 (*Expert*).

We developed a set of questions (Table 1) for both pre- and post-test phases to establish a baseline of participants' prior knowledge, which we subsequently used to measure changes in understanding. The testing phase began with a guided training session followed by the study tasks where participants retrieved the absolute and per capita data from certain countries in specific years and comparing two countries' CO₂ emissions in a certain year (e.g., Germany and India in 2018, USA and Qatar in 1975). After completing the tasks, participants were able to freely explore the application. Following the test, we conducted an open-ended interview to explore how participants' understanding evolved, and compared it with their initial responses. Additionally, we applied the ICE-T questionnaire framework [WAM*19] to systematically assess the perceived value and effectiveness of the visualization. The ICE-T survey form includes structured questions based on four key components *Insight*, *Confidence*, *Essence*, and *Time*, to derive the value of the visualization.

4. Results

All responses to Q1 (correct: increased) (Table 1) during both pre- and post-test phases, offered varying levels of detail on the cause, but consistently concluded that overall emissions had increased. In the pre-test phase, the majority of participants (8) suggested *China* in relation to Q2 (correct: USA), while the remaining two participants suggested it might be either the *USA* or *India*. For all participants, Q3 (since the correct answer could only be calculated, we accepted the following as correct: Estonia, Luxembourg, Trinidad and Tobago, USA, UK, Germany, Belgium) was more difficult to answer, and they changed their responses more frequently than for Q2. However, the majority (8) settled on the *USA*, one on *China*, and one chose *Germany* in the pre-test phase. Participants expressed varying ideas about how the CO₂ emissions changed regionally (Q4 - no definitive correct answer). Two participants spec-

ulated that emissions in Europe might have plateaued or even declined as a result of EU-wide emission reduction measures [Eur19]. Some mentioned that they expected countries in Africa and South America to have very low overall emissions, while others expected these to increase rapidly due to deforestation and industrialization. The same assumptions were made for Asia by four participants. All participants collectively agreed that the *USA* was unlikely to have implemented any meaningful measures to reduce CO₂ emissions. Lastly, all participants answered Q5 (no definitive correct answer) with “yes” in both the pre- and post-test phases, but offered different justifications. One participant grounded their response in *historical* CO₂ emissions, while others based theirs on the wealth and resources available to a country.

During the VR testing phase, all participants were able to fulfill the tasks and give correct answers, but some chose to round up the numbers to simplify their pronunciation (see Figure 1 for formatting details). During the testing phase, the participants spent 16.44 minutes on average ($SD = 6.27$ minutes) in the VR application. The fastest response was given in 26 seconds, while the longest response took 7.36 minutes before the participant was satisfied with their answer. Two participants voiced their struggle while comparing two countries that are far apart (Germany and India), as it was hard for them to first identify Germany, followed by rotating the globe to find India. It was observed that both of these participants stood closer to the globe than other participants, which could have impaired the rotation interaction.

After the participants had experienced the VR application and interacted with the data, they changed some of their answers and justifications in the post-test phase. One participant, who initially thought that *India* had the highest absolute emissions (Q2), changed their answer to *China*, while another participant chose to keep their original response of *China*. Eight participants correctly answered Q2, compared to one right answer given during the pre-test interview. Six participants answered Q3 with *USA*, one remained with *Germany*, one switched from *USA* to *Luxembourg*, one switched from *USA* to *UK*, and one person switched from previously answering *China* to *Qatar*. Therefore, nine out of ten participants gave a correct answer in both pre- and post-test interviews, with some switching from a correct answer to an equally correct answer, and one participant switching from a wrong answer to another wrong answer. Since Q4 had no definitive correct answer, we observed whether participants could improve their understanding of regional differences over the given time period. Multiple participants identified different increasing rates of absolute CO₂ emissions across different countries, while others also observed that per capita emissions not only increased but sometimes fluctuated between years. Lastly, for Q6, some participants expressed a desire to have additional graphs to compare multiple countries in more detail, along with the option to select countries so that the details on demand (as seen in Figure 1) would stay active without needing to hover over the bar. The participants' ratings obtained via the ICE-T survey are shown in Figure 2. According to the ICE-T evaluation criteria, an overall score of 5 or higher indicates a good visualization [WAM*19]. The overall average of all four components in our sample is 5.81. While average values for *Insight*, *Time*, and *Essence* are close to 6, the average *Confidence* score is lower ($M=5.23$, ± 0.92). This originates from lower ratings on the final two ques-

Q1	How do you think the overall CO ₂ emissions change over the decades?
Q2	In absolute numbers, which country do you think has the highest CO ₂ emissions over the last years?
Q3	In per capita data, which country do you think has the highest CO ₂ emissions over the last years?
Q4	In which ways do you think the CO ₂ emissions shifted regionally and compared to one another over the last 6 decades?
Q5	Should wealthier or more industrialized countries take on greater responsibility in terms of mitigating their emissions?
Q6	Do you have any other remarks that were not covered by the previous questions?

Table 1: Open questions (Q1 to Q6) that were asked before and after the testing phase of the VR application. In the post-test sessions, the phrase “Now that you have seen the data...” was added. Additionally, Q6 was only asked in the post-test session.

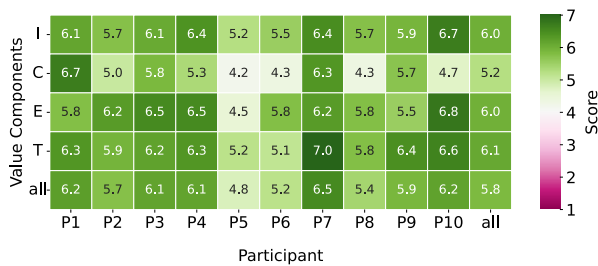


Figure 2: Heatmap of ICE-T scores for the components Insight, Time, Essence, and Confidence per participant.

tions of the Confidence component, where participants were asked whether the visualization helps users learn more broadly about the data domain and whether the visualization helps users understand data quality, both of which were not the main focus of the tested VR application, but are integral to the ICE-T survey. Only one user (P5) gave an overall average rating of less than 5.

5. Discussion

The collected qualitative data and the observations we made during the experiments indicate that our VR visualization effectively supports non-experts in understanding multi-dimensional CO₂ data within an immersive environment. During the testing phase, participants found it easier to differentiate between absolute emissions in comparison to per capita data when focusing solely on the bars. This is due to their scales, which worked on different magnitudes, and variations between millions and billions were more apparent than subtler shifts between hundreds and thousands. This was particularly evident when per capita bars with only slight height differences were spaced farther apart. While a logarithmic scale could potentially alleviate this problem, previous work showed that it may negatively influence the user’s interpretation of the data [RSDG20].

During the experiment, all participants explicitly mentioned making discoveries that they found surprising. This was often related to a case where a certain country had either lower or higher per capita emissions than they expected (e.g., South Africa, Trinidad and Tobago, Estonia, Qatar, India, Canada, Australia, New Zealand, and Iceland), prompting them to reflect on the possible reasons. After engaging with the data, participants were able to give more informed and elaborate suggestions on Q5. This indicates that

the responsible data visualization, especially through the addition of per-capita data, benefits the presentation and direct comparison.

All participants were able to intuitively interact with the VR application, independent of prior VR experience, and needed no further assistance. However, three participants needed encouragement to approach the globe more closely to make use of the spatial benefits of the immersive environment. One crucial aspect that has to be considered when working with spatio-temporal data that relies on countries’ locations and sizes relates to the shifting of borders and the creation of new countries over the years. For this visualization, we decided to use the data as present in the datasets without adjusting for historical accuracy. The results from the ICE-T evaluation also reflect this aspect, as the lowest average scores were present in the Confidence component. Specifically, participants gave lower scores regarding the visualization highlighting data issues. This could be resolved, for example, by introducing glyphs on the globe that indicate that there is no data available, and by treating each year individually to account for shifting country borders and names.

6. Conclusion & Future Work

We explored how VR can support the responsible communication and understanding of multi-dimensional data to non-experts. The immersive integration of the spatial context with absolute and per capita CO₂ emissions improved certain aspects of understanding and prompted users to reflect on their knowledge of environmental data. All participants were able to give informed answers to questions on global CO₂ emissions and showed a more profound understanding after they interacted with our VR visualization. These results highlight the potential of immersive visualization for communicating environmental data to laypeople. In future work, we would like to include participants’ suggested features to improve our VR application; these include additional information on countries (e.g., a breakdown of emission sources by sector or further information on the country’s economy), which would require the integration of additional data sets.

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