

Article

3D-Geo-Vis: A Web-Based Environment for Interactive 3D Thematic Geovisualisation and Its Usability Evaluation

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Abstract

3D geovisualisation is increasingly used to represent spatial phenomena in engaging and interactive ways. However, 3D thematic methods and their user-centred evaluation remain challenging due to issues such as view distortion, variable scale, and complex interactions. Previous research emphasises that effective 3D thematic design requires careful treatment of visual variables and interactive camera control to mitigate overlap and occlusion. Building on this foundation, we present 3D-Geo-Vis, a web-based application with open-source code. The application visualises air temperature using seven methods of 3D geovisualisation and supports real-time adjustment of method-specific visual variables through a dedicated side panel. We report a usability study with 54 participants that combines (i) eye-tracking (Tobii Pro Spark, 60 Hz), (ii) interaction logging using our MapLogger tool, and (iii) a post-test questionnaire including the User Experience Questionnaire (UEQ) and open-ended feedback. Participants completed a structured scenario comprising free exploration and targeted analytical tasks. Across all sessions, MapLogger captured 15,457 interactions. The success rate of fully completed tasks was generally high for tasks involving the search for a specific value or modification of interface parameters (Task 2: 87.0%; Task 3: 85.2%), while the voxel-based analytical task showed slightly lower completion (Task 4: 77.8%), reflecting higher cognitive and interaction demands. UEQ results indicate a slightly positive overall user experience, with speed-related items rated most negatively. Triangulating gaze behaviour, interaction logs, and subjective feedback reveals key usability issues (e.g., insufficient salience of method switching, attention concentration on the side panel, and performance limitations of voxel rendering) and yields concrete recommendations for improving onboarding, feedback, and control discoverability in interactive 3D visualisation environments. These findings and resulting recommendations informed the development of the revised 3D-Geo-Vis 2.0 application.

Keywords: 3D geovisualisation; thematic mapping; web cartography; usability evaluation; eye-tracking; interaction logging; UEQ; visual variables



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1. Introduction

Three-dimensional applications have formed part of GIS research since the early development of the field, when 3D representations were discussed as a means of extending spatial analysis beyond conventional two-dimensional map displays [1]. Three-dimensional (3D) geovisualisation is increasingly used for exploring spatial phenomena in urban and

environmental contexts, largely because it can provide a stronger sense of spatial structure and support the simultaneous display of thematic information together with an explicit representation of the 3D scene (e.g., terrain, buildings, and other contextual objects) [2]. However, the benefits of 3D thematic representations are not unconditional [3,4]. Prior work emphasises that, alongside potential advantages such as additional display space and an improved “impression of reality” [5], 3D geovisualisations also introduce well-known cartographic and perceptual challenges, including occlusion and overlap, perspective-related distortions, variable scale, transparency-related ambiguities, and cast shadows that may interfere with thematic interpretation [6,7]. These trade-offs make the design of 3D thematic visualisations (and their user interfaces) inherently complex and strongly dependent on the context of use, tasks, and users.

A substantial part of this complexity stems from the fact that 3D geovisualisation is not a single “technique”, but rather a family of approaches that differ in how they encode thematic values into 3D symbols and other means of expression [8]. A recent conceptual contribution in this area [9] formalised seven cartographic methods of thematic 3D geovisualisation (Figure 1):

- **Horizontal Planes**—a method of displaying spatial data in which the entire dataset is placed at a constant elevation. Visualisation of 2D planes in the form of static outputs is quite limiting, as they overlap when displaying multiple planes at different height levels. For this reason, it is desirable to use this type of visualisation in an interactive environment [10];
- **Point Cloud**—a discrete visualisation in which three spatial coordinates represent each point. It can be a 2D point cloud, where all points have a constant Z coordinate, or a 3D point cloud, where the Z coordinate is variable. Point clouds can be distributed randomly or in a regular grid [9]. In thematic cartography, this method is suitable for dense spatial sampling where additional variables (e.g., colour or transparency) are mapped to individual points to reveal clustering, density, or internal structures of a dataset;
- **3D Surface**—a continuous visualisation usually created by interpolating points from a point cloud, where surface elevation varies according to the value of the represented phenomenon. The pixel height (Z coordinate) is variable depending on the value of the phenomenon. 3D surfaces are most often used to represent elevation (digital elevation models), but they can also be used, for example, to represent socio-economic phenomena (so-called social or digital surfaces) [9]. It is ideal for representing continuous spatial fields, as it leverages human perception of terrain to quickly identify gradients, peaks, and depressions;
- **Vertical Planes**—a vertical extrusion of a linear geometry [9]. This method is typically applied to represent flows, boundaries, or cross-sections, where the height or colour of the plane depicts the magnitude or intensity of an attribute along a specific trajectory;
- **3D Graduated Symbols**—a discrete visualisation in which attribute values are represented by the size (e.g., diameter or height) of 3D symbols of various shapes (e.g., spheres, columns, diagrams) [9]. While effective for communicating absolute quantities at specific point locations (e.g., monitoring stations), this method is highly susceptible to inter-symbol occlusion in dense spatial arrangements;
- **Prism Map**—a 3D choropleth map with extruded height used to encode a numerical attribute [9]. By extending traditional 2D choropleth maps into the third dimension, it provides an additional visual channel (extrusion) to convey magnitude, which can help overcome the limitations of relying solely on colour perception;
- **Voxels**—a representation of attribute values using volumetric blocks arranged in a regular 3D grid. It has common elements with 3D graduated symbols and a prism map.

Unlike 3D graduated symbols, in the case of voxels, adjacent blocks are connected to each other, and unlike a prism map, all polygons have the same size [9]. Voxels are highly effective for true 3D volumetric analysis, though they frequently introduce severe occlusion challenges and demand significant computational performance during interactive rendering.

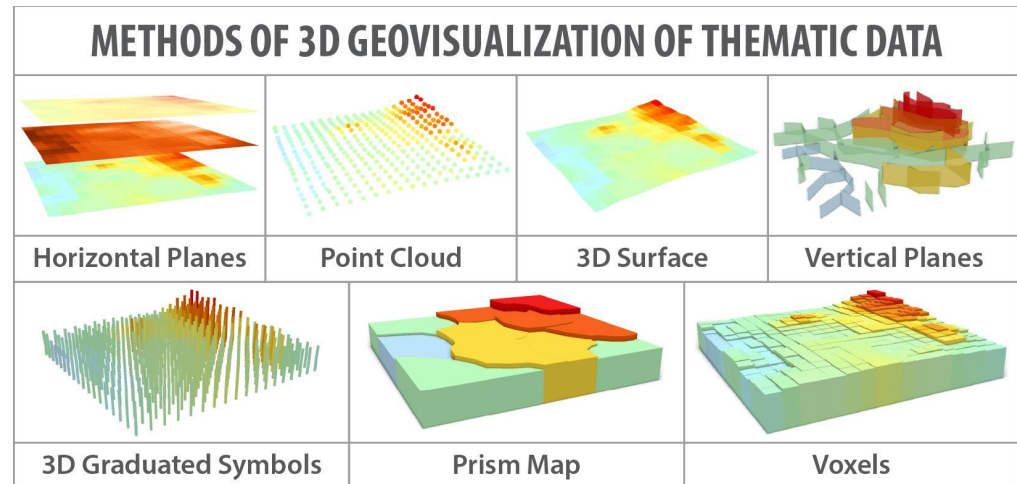


Figure 1. Graphical representation of seven cartographic methods of thematic 3D geovisualization [9].

Each method is characterised by specific strengths and limitations, implying that no universal solution can be expected across all analytical situations. At the same time, the design of 3D geovisualisation methods cannot be reduced to classical two-dimensional graphic variables alone; instead, it also involves 3D-specific variables that substantially influence the legibility and interpretability of the thematic message [5].

Graphic (visual) variables were first defined in 1967 [11] and have since been gradually expanded. The current list of graphic variables varies slightly among authors [12–14], but the core variables generally include position, size, shape, colour (hue, saturation, value), orientation, texture or pattern, arrangement, crispness or fuzziness, resolution, and transparency. In 3D cartography, it is additionally necessary to consider variables related to the third dimension, such as height, extrusion, camera position (point of view), and perspective [9].

From a cartographic design perspective, 3D geovisualisation therefore requires systematic reasoning about visual variables and their perceptual consequences [6]. In 3D environments, this reasoning extends from established principles of cartographic symbolisation (e.g., variable selection and visual hierarchy) to the management of scene-related parameters such as illumination and transparency. Furthermore, when thematic values are mapped to the vertical dimension (i.e., height or extrusion), the resulting scene becomes inherently view-dependent. Users may therefore need to actively manipulate viewpoint and scale in order to reach correct interpretations [7]. These characteristics lead to an important practical implication: 3D thematic maps should be understood and evaluated not as static graphics but as interactive systems in which perception is continuously coupled with interaction (e.g., navigation, filtering, and parameter adjustment) [15,16].

Because 3D thematic geovisualisations operate as interactive software systems rather than static graphics, their quality cannot be judged solely by cartographic correctness or visual appeal. Instead, they must also be assessed in terms of usability, defined as the extent to which specified users can achieve specified goals effectively, efficiently, and with satisfaction in a defined context of use [17]. In map-related research, these dimensions are typically operationalised through task accuracy or completeness (effectiveness), time and

effort required to learn and complete tasks (efficiency), and user preferences and comfort (satisfaction) [18].

Importantly, for interactive map interfaces, these criteria extend beyond symbol comprehension to include discoverability of controls, clarity of system state, error tolerance, and readability of system feedback [19]. This is particularly critical in 3D environments, where users often focus on the map scene itself, increasing the risk that less salient interface elements go unnoticed. Consequently, interface discoverability becomes a core usability requirement rather than merely an aesthetic concern [19].

In web cartography and related interactive geovisualisation domains, usability evaluation is therefore considered a necessary component of a broader validation cycle linking theory, implementation, and empirical testing [20]. In line with this perspective, the International Cartographic Association (ICA) has explicitly emphasised the importance of systematic qualitative and quantitative usability testing across different map and visualisation types [21]. Recent evidence syntheses in human–computer interaction and cartography further highlight that interactive geovisualisations—especially when content is dynamic and view-dependent—pose recurring methodological and analytical challenges, including limited standardisation of usability measures and difficulties in comparing results across studies [22]. For 3D thematic geovisualisation systems, these arguments imply that user-centred evaluation is not optional. Rather, it is essential to identify where interaction complexity, control discoverability, and performance constraints (e.g., the computational demands of advanced 3D methods) translate into measurable inefficiencies or errors during realistic analytical tasks, and to derive concrete redesign recommendations.

2. Main Goal and Research Questions

The main goal of this paper is to identify problematic features of a prototype 3D geovisualisation application through a user study and, based on the triangulation of collected data (eye-tracking, interaction logging, and UEQ), to propose specific recommendations for developing an improved version of the application.

To address this objective, the study focuses on the development and usability evaluation of 3D-Geo-Vis, a web-based application for visualising quantitative spatial data in a 3D map environment. The application was intentionally conceived as a comparative platform: it implements seven methods of 3D geovisualisation, allowing users to switch between methods and adjust key visual parameters using a dedicated side panel, with changes immediately reflected in the map view. This design follows the broader argument that interactive environments are essential for meaningful 3D thematic geovisualisation, as they allow users to adapt symbolisation and viewpoint to the current analytical task [23,24].

Initially, a proof-of-concept prototype of the application (3D-Geo-Vis) was developed. The subsequent user study was designed as a large-scale formative evaluation intended to capture a comprehensive spectrum of usability issues—ranging from fundamental interface discoverability to the complex cognitive barriers of specific 3D methods—before committing to the architecture of the final integrated application. For the development of this prototype, meteorological data from the ALADIN weather forecast model were used. These data were provided by the Czech Hydrometeorological Institute—<https://en.chmi.cz/> (accessed on 2 March 2026)—within the PERUN project [25]. Based on the evaluation results, the application was subsequently revised, and key feedback was incorporated into the final version (3D-Geo-Vis 2.0).

Eye-tracking has previously been used in cartographic research to specify user requirements for spatio-temporal data representations, including space-time-cube visualisations [26]. Because 3D-Geo-Vis is designed as a user-facing analytical tool rather than a purely technical demonstration, its value depends on usability in realistic task settings.

The present study therefore evaluates the application using a multi-method approach combining (i) eye-tracking-based observations of visual behaviour [27], (ii) interaction logging to capture behavioural strategies and efficiency patterns, and (iii) the User Experience Questionnaire (UEQ) [28] to capture subjective impressions. This triangulation enables analysis not only of whether users can successfully complete tasks, but also of how they explore the interface, where uncertainty or errors occur, and how preferences for different 3D thematic methods relate to observed behaviour.

More broadly, the study responds to a research gap identified in prior work on 3D thematic cartography [3]. Despite the growing repertoire of 3D visualisation methods and the recognition that interactive parameter manipulation can improve interpretability, there remains a need for empirical user testing that compares these methods in task-based settings and links performance and user strategies to specific interface and design decisions. By evaluating a system that integrates multiple methods within a common interaction paradigm, this study aims to provide empirically grounded guidance for both system redesign and the practical deployment of 3D thematic visualisations in web environments.

Therefore, the primary novel contribution of this study lies in the operationalisation of seven previously defined theoretical 3D geovisualisation methods into a functional, interactive web environment, coupled with their systematic empirical evaluation. By bridging the gap between theoretical cartographic concepts and practical software implementation, this work distinguishes itself from purely conceptual studies and purely technical demonstrations, providing an evidence-based foundation for interactive 3D web cartography.

The paper is guided by the following research question framework, with the main research question being: How can a 3D geovisualisation environment be improved through a usability evaluation to become more effective and user-friendly for visual analysis?

- RQ1: How do users orient themselves within the application interface during their initial interaction with the system?
- RQ2: What strategies do users apply when solving task-specific interaction and analytical tasks within selected 3D visualisation methods?
- RQ3: Which interface elements lead to manifestations of uncertainty, hesitation, or errors during task execution?
- RQ4: Which visualisations are subjectively preferred, and how are these preferences related to observed visual and interaction behaviour?
- RQ5: How do task completion time, number of interactions (including interactions per minute), and task success relate to the efficiency of users' strategies?
- RQ6: What key usability issues can be identified through the triangulation of eye-tracking records, interaction logs, and questionnaire data, and what implications do these findings have for improving the design of the 3D geovisualisation environment?

3. Materials and Methods

3.1. Description of the Application Prototype (3D-Geo-Vis)

The evaluated system was the web-based 3D-Geo-Vis application (Figure 2), designed as a platform for comparing multiple 3D thematic geovisualisation methods using data from the ALADIN weather forecast model. The application is available online at https://jakubzejdlk.github.io/3d_geo_vis/horizontal.html (accessed on 1 June 2026). Specifically, the application visualises air temperature on 1 January 2014 at 00:00. The application is implemented using a standard HTML/CSS/JavaScript architecture, and its source code has been made publicly available on GitHub (version 3.21.4).

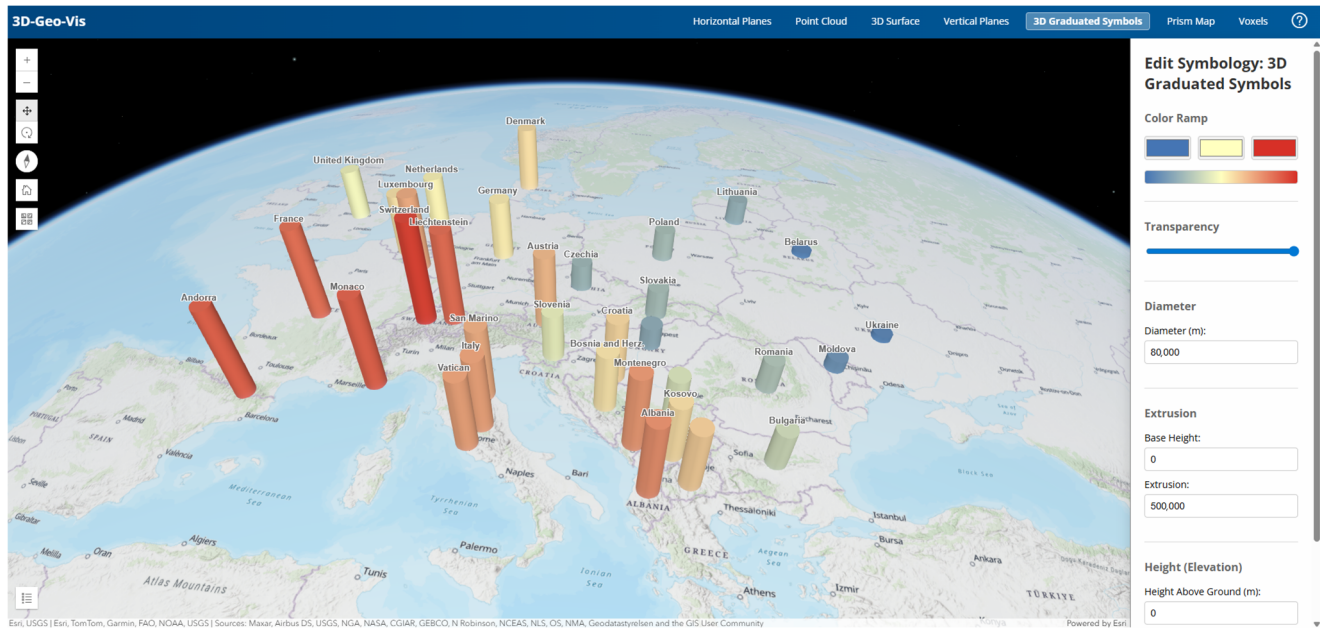


Figure 2. Prototype of the 3D geovisualisation environment (example of 3D graduated symbols).

Each 3D geovisualisation method is implemented as a separate page, and users can switch between methods using controls located in the upper-right part of the interface. A help section (accessible via a question-mark icon) provides information about application controls, the underlying data, and the authors.

The largest portion of the interface is occupied by the map window, where thematic data and basemaps are visualised. The application provides several navigation and control tools, including buttons for zooming in and out, panning and rotating the scene, returning to the initial view, changing the basemap, and displaying the legend. The most important interface component is the right-hand side panel, which allows users to interactively modify visual parameters of the displayed method in real time.

The set of editable graphic variables varies depending on the selected method. Only those variables that are relevant for a given method and technically feasible are provided. For example, interactive modification of vertical elevation is not available for the 3D surface method. All parameter adjustments are applied immediately and do not require explicit confirmation.

One limitation of the prototype is that it only visualises pre-prepared data and does not allow users to upload or edit their own datasets. In addition, different visualisation methods cannot be combined within a single view, because their rendering logic is implemented on separate pages. Other limitations include the inability to select attributes for visualisation or labelling, the absence of a layer list, and the lack of functionality for sharing the current state of the visualisation environment. These aspects will be considered in developing an improved version of the application. In addition, insights from the user study—aimed at evaluating how effectively users interact with the prototype—will inform the redesign process.

3.2. Study Design and Participants

The usability evaluation was conducted as a laboratory study combining three complementary data streams: (i) eye-tracking to capture participants' visual behaviour during interaction, (ii) interaction logging using the authors' MapLogger tool to record behavioural traces (e.g., mouse and keyboard input), and (iii) post-test questionnaires comprising the

standardised User Experience Questionnaire (UEQ) together with additional items on demographics, prior experience, and open-ended feedback.

The sample consisted of 54 participants (32 women, 59.3%; 22 men, 40.7%). The age structure was strongly skewed towards younger categories: 20 participants were aged 20 years or younger (37.0%), 29 participants were aged 21–30 years (53.7%), three participants were aged 31–40 years (5.6%), and two participants were aged 51 years or older (3.7%). Participants were recruited through an online sign-up sheet offering one-hour time slots, and participation required only basic computer literacy for everyday use. No prior experience with the evaluated 3D-Geo-Vis application was required.

To provide additional context for interpreting user behaviour, the post-test questionnaire also collected information about participants' prior experience with map-based and 3D environments. All participants reported using web maps regularly ($n = 54$, 100%). Their previous experience with 3D map applications varied: 11 participants reported no prior experience (20.4%), 24 reported basic experience (44.4%), 13 reported intermediate experience (24.1%), and six reported advanced experience (11.1%). Thus, although the sample was generally familiar with web maps, most participants had no or only basic previous exposure to 3D map applications ($n = 35$, 64.8%). Formal educational background was not collected as a structured questionnaire item; therefore, it is not reported to avoid unsupported post hoc inference.

It is important to note that the sample was a university-based convenience sample rather than a demographically representative sample of potential users of 3D geovisualisation tools. Recruitment was conducted within a single university environment in the Czech Republic, and the sample was strongly concentrated in the two youngest age categories, with 49 participants aged 30 years or younger. Consequently, the sample had a relatively homogeneous institutional and cultural background. Although this sampling strategy was appropriate for a controlled formative usability evaluation of an early prototype, it limits the generalisability of the findings to broader user populations, particularly older adults or users with lower digital literacy.

Data collection took place in a computer laboratory at the Faculty of Arts, Palacký University Olomouc, equipped with five identical stationary Tobii Pro Spark eye-trackers (60 Hz), enabling up to five participants to be tested simultaneously under standardised technical conditions. The 3D-Geo-Vis study was embedded in a broader one-hour laboratory session that comprised four separate experiments. The present study was administered as the second experiment, with optional individual breaks between consecutive experiments. Figure 3 focuses on the workflow of the 3D-Geo-Vis usability study. Participants received financial compensation of CZK 250 for completing the full experimental session, and all participants signed informed consent allowing the recording and research use of their data.

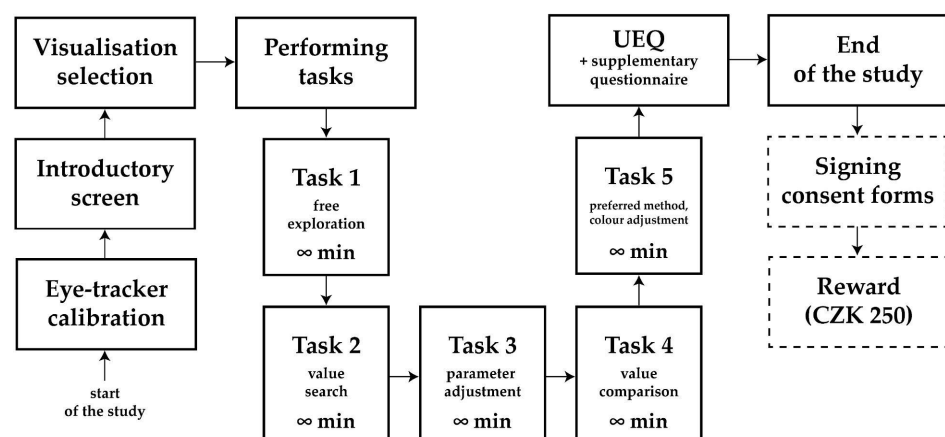


Figure 3. Workflow of the 3D-Geo-Vis usability study.

Before the experiment, each participant underwent eye-tracker calibration. When necessary, calibration was repeated until acceptable precision was achieved. The application was hosted on GitHub Pages and launched by the moderator from a pre-opened folder to avoid disruptions during the session.

After the application launched, participants first read an introductory instruction screen that asked them to work naturally, as they would in a real situation, and to proceed through the tasks by clicking the “Next” button after each task. Participants could initially choose which visualisation method page to load first, though most retained the default selection.

Participants subsequently completed five tasks (Table 1) presented in a fixed (non-randomised) order to ensure a consistent testing procedure across participants. Task instructions remained visible in a top screen bar throughout task execution, allowing participants to revisit the wording if needed.

Table 1. Five tasks for evaluating the usability of the 3D-Geo-Vis prototype application.

Task ID	Task Assignment
Task 1	Feel free to browse and explore the application. Try to find out what options it offers and how to navigate it. The goal is to familiarise yourself with the interface and controls.
Task 2	Find the “Point Cloud” visualisation and determine the highest temperature displayed by it.
Task 3	Go to the “3D Graduated Symbols” visualisation. Change the shape of the symbols and then adjust their diameter (size).
Task 4	Select the “Voxels” visualisation and find the difference between the minimum and maximum temperature values.
Task 5	Select the visualisation you like best. Adjust the colour scheme to make the result even more visually appealing to you.

The task set was designed primarily for controlled formative usability evaluation rather than for a comprehensive assessment of analytical reasoning in 3D thematic geovisualisation. The tasks intentionally combined free exploration (Task 1), value lookup (Task 2), parameter manipulation (Task 3), a simple analytical comparison within one method (Task 4), and preference-based visual adjustment (Task 5). This structure allowed the study to capture different interaction situations while keeping task demands comparable across participants. However, the task set also has an important limitation. Tasks 2 and 4 are relatively constrained operations: Task 2 focuses on locating a maximum value in the Point Cloud visualisation, whereas Task 4 requires identifying minimum and maximum values in the Voxels visualisation and computing their difference. These tasks are useful for evaluating discoverability, navigation, value reading, legend use, and interaction difficulties, but they do not fully represent the broader analytical value of 3D thematic geovisualisation, such as comparing multiple visualisation methods, recognising spatial clusters or gradients, identifying anomalies, or synthesising evidence across alternative representations. Task 5 involved a comparison between methods, but this comparison was preference-based and aesthetic rather than analytical. Therefore, the present task design should be understood as suitable for diagnosing usability barriers in the prototype rather than as a complete test of higher-level spatial reasoning with 3D thematic methods.

3.3. Measures and Data Processing

3.3.1. User Experience Questionnaire (UEQ)

To complement behavioural data (MapLogger) and perceptual observations from eye-tracking with a structured subjective evaluation, the User Experience Questionnaire (UEQ) was administered immediately after participants completed all experimental tasks. The inclusion of UEQ enabled a systematic assessment of participants' overall user experience and provided an important attitudinal component for triangulating behavioural findings.

The UEQ is a standardised and widely used instrument designed to capture both pragmatic and hedonic aspects of user experience [28]. It consists of 26 bipolar items rated on a seven-point semantic differential scale (−3 to +3), where each item represents a pair of opposite attributes (e.g., “complicated—easy”, “boring—exciting”). The items are aggregated into six established scales:

- Attractiveness—overall impression of the product;
- Perspicuity—ease of understanding and learning;
- Efficiency—support for efficient task completion;
- Dependability—feeling of control and predictability;
- Stimulation—motivation and engagement;
- Novelty—perceived creativity and innovation.

From a conceptual perspective, the first four scales primarily reflect pragmatic quality, whereas Stimulation and Novelty reflect hedonic quality. This distinction was particularly relevant to the present study because the evaluated application (3D-Geo-Vis) is an exploratory 3D thematic environment in which both analytical efficiency and experiential engagement are important.

All 54 participants completed the questionnaire after finishing the final task, ensuring that their responses reflected experience with all seven visualisation methods implemented in the application. The UEQ was administered under the same controlled laboratory conditions as the behavioural data collection.

Because the participant sample was strongly skewed towards younger age groups and was recruited from a single university environment, the UEQ results should be interpreted as reflecting the experience of a relatively young, digitally literate, and culturally homogeneous convenience sample rather than that of the broader population of potential users. This is particularly relevant because older adults, domain professionals, and users with different levels of spatial, technical, or cartographic expertise may evaluate the efficiency, clarity, and learnability of a 3D geovisualisation environment differently.

Additional demographic and open-ended questions followed the questionnaire; however, only the standardised UEQ scales were included in the quantitative analysis reported in this study.

Administering the UEQ after the full interaction sequence ensured that participants' evaluations were based on the overall system experience rather than on isolated interactions with individual visualisation methods. The original questionnaire structure was preserved, and no item randomisation was applied.

In addition to descriptive UEQ scale scores and benchmark comparison, we conducted an exploratory participant-level correlation analysis to strengthen the triangulation between subjective experience and behavioural data. For each participant, the six UEQ scale scores were correlated with three MapLogger-derived behavioural metrics: total task completion time, total number of interactions, and interactions per minute. Because the behavioural metrics were not normally distributed and because UEQ scale scores are derived from ordinal questionnaire items, Spearman's rank correlation coefficient (ρ) was used. The perceived speed item (“fast–slow”) was also analysed separately because it represented the strongest negative item-level UEQ result and was directly related to the performance-

related usability issues identified in the qualitative data. Higher UEQ values indicate a more positive evaluation; therefore, higher values for the speed item indicate a perception of greater speed.

3.3.2. MapLogger—Interaction Logging Tool

To complement eye-tracking and questionnaire data with objective behavioural traces, we employed MapLogger (MapLogger Suite v1.0.1, <https://vanicektomas.github.io/maplogger/>, accessed on 1 June 2026), an author-developed, MIT-licensed toolkit designed for rapid instrumentation and analysis of web-based interactive map applications. MapLogger was developed specifically for usability studies of interactive geovisualisations, where understanding user behaviour requires knowledge not only of where users look but also of the actions they perform and the task context in which these actions occur. A preview of the MapLogger Builder interface is shown in Figure 4.

MapLogger Builder

Turn your interactive map into a ready-to-run usability study. Everything happens in your browser.

Builder **Analyser** **CartoLogger**

1) Add your map files

Upload one ZIP that contains your map (HTML, JavaScript, CSS, images, data, fonts). We keep the folder structure and prepare every HTML page for logging. Anything that already loads from the web (e.g., map tiles) can stay as it is.

Drop your ZIP here, or

Choose ZIP

Files (0) · 0 B Remove ZIP

Add a ZIP file with your map.

2) Write participant tasks

Add short tasks in the order you want people to do them (e.g., "Find the nearest pharmacy in Olomouc"). Participants will see them in a fixed bar at the top of the study, and they will be saved to the log.

Take a moment to explore the map and familiarise yourself with the interface. ×

Tasks: 1 + Add task

Welcome message (shown once at the start):

Thanks for taking part. Please read the instructions, then click Start to begin.

This is your short intro. After the participant clicks Start, Task 1 begins.

Preview

Task 1 — Take a moment to explore the map and familiarise yourself with the interface. Next → END

1 Task 1

This shows the basic flow. The final look depends on the MapLogger client CSS.

☒ Create an entry page (index.html) if it's missing

The entry page shows the task bar and opens your pages inside an iframe. The internal session key is derived from the Output name.

3) Download the study ZIP

Output name:

MapLogger-instrumented

We'll generate a ZIP with your pages plus a ready-to-run entry page and CSV logging.

Create ZIP

This can take a moment — please click once and wait for the download.

Figure 4. Preview of the MapLogger Builder environment.

MapLogger is implemented as a fully client-side solution. All stages—study preparation, runtime logging, and subsequent analysis—are executed locally within a standard web browser. No backend server is required, and no interaction data is transmitted externally. This architecture reduces technical deployment barriers and minimises data-protection concerns, particularly when logs contain interface texts, URLs, timestamps, or device descriptors.

The toolkit consists of three logically separated components. First, the MapLogger Builder prepares an existing web map project for usability testing. Second, the MapLogger Client functions as an injected logging layer that runs during the experiment and records interaction events. Finally, the MapLogger Analyser loads the exported CSV logs and produces descriptive statistics and visualisations.

For the present study, the 3D-Geo-Vis prototype was first packaged as a single ZIP archive containing all HTML, JavaScript, CSS, and asset files. This archive was uploaded into MapLogger Builder, which preserved the original folder structure and automatically instrumented each HTML page by injecting a lightweight logging script and corresponding CSS.

In addition to technical instrumentation, the Builder allows the researcher to define the sequence of tasks presented to participants. For this experiment, all five tasks (free exploration and four analytical/manipulation tasks; see Table 1) were entered into the Builder interface in the intended fixed order. These task instructions were automatically embedded into the generated study package and displayed in a persistent top bar throughout testing. This ensured that task wording remained visible at all times, thereby reducing memory load and standardising experimental conditions across participants.

After defining the tasks and confirming the configuration, the Builder generated a new ZIP archive containing:

- Instrumented versions of all original application pages;
- A newly created host (entry) page managing study flow;
- The injected MapLogger client responsible for event capture and data export.

The resulting study package follows a “host + pages” architecture. The host page displays the task bar and study controls while loading the original map pages inside an iframe. This separation ensures that logging and task control remain consistent regardless of how the original application was structured.

The generated ZIP archive was subsequently deployed locally for laboratory testing. During all experimental sessions, the instrumented 3D-Geo-Vis prototype functioned without technical interruptions, and no logging-related runtime errors were observed.

During task execution, MapLogger records each captured event as a separate row in a per-participant CSV file. The logging mechanism operates at the browser event level. It listens to selected native DOM events generated within the instrumented pages and stores them together with the current task context supplied by the host page. The recorded events therefore describe observable interaction input at the web-interface level rather than fully reconstructed semantic operations of the 3D engine.

In the present study, the following main event types were logged: *click*, *dblclick*, *wheel*, *keydown*, and *contextmenu*. In addition, MapLogger stored meta-events related to the experimental session and task flow, including *session_start*, *session_page*, *task_start*, *task_next*, *task_end*, *end_clicked*, *session_end*, *resize*, *visibility*, *focus*, and *blur*. These meta-events were used to reconstruct the temporal structure of the session but were excluded from the main counts of user interactions unless explicitly stated.

Single-clicks and double-clicks were treated as separate browser event types. A single mouse click was recorded as *click*, while a browser-recognised double-click was recorded as *dblclick*. Importantly, MapLogger does not reinterpret the browser event stream

by suppressing or merging constituent click events. Therefore, depending on browser behaviour and the target element, a double-click may appear as a *dblclick* event and may also be accompanied by preceding *click* events. For this reason, *dblclick* was retained as a distinct event category in the event-type breakdown, whereas interpretations involving ordinary clicking behaviour were based primarily on the distribution of *click* events and on qualitative inspection of the corresponding screen recordings.

Mouse-wheel interaction was recorded as *wheel*. For each wheel event, MapLogger stored the wheel delta and direction where available (*deltaY*, *deltaMode*, *wheel_direction*, and *zoom_hint*). In the 3D-Geo-Vis prototype, wheel events were interpreted mainly as zoom-related interaction because the evaluated 3D scene used the mouse wheel primarily for scale or view-distance changes. Keyboard interactions were recorded as *keydown*, including the pressed key, physical key code, and modifier keys (*ctrl*, *alt*, *shift*). Context-menu calls were stored as *contextmenu*.

Each event row contained a fixed contextual schema: *session_id*, *timestamp_ms_since_start*, *local_time*, *iso_time*, *task_index*, *task_label*, *event_type*, *element_tag*, *element_id*, *element_classes*, *element_text*, *css_path*, *x*, *y*, *viewport_w*, *viewport_h*, *button*, *button_label*, *deltaY*, *deltaMode*, *wheel_direction*, *zoom_hint*, *key*, *code*, *ctrl*, *alt*, *shift*, and *extra_json*. The *extra_json* field was used for event-specific additional information, such as page URL, user-agent information, or task duration. The combination of relative timestamps and absolute UTC timestamps was included to support synchronisation with the simultaneously recorded eye-tracking data.

A methodological limitation of this event-capture model is that complex interactions inside the 3D scene are not automatically decomposed into semantic camera operations. In particular, dragging within the WebGL/canvas-based map view may correspond to panning, rotation, tilting, or other navigation operations handled internally by the 3D viewer. Because these operations occur inside the rendering component, MapLogger records the corresponding low-level browser-level event context and target element, but it does not by itself classify the action as “pan” or “rotate”. Therefore, the present analysis did not use MapLogger to separately quantify panning and rotation. Such operations were interpreted conservatively through the combination of event timing, target element information, wheel activity, task context, and qualitative inspection of gaze/screen recordings.

To verify the reliability of the collected logs, all participant CSV files were checked for the required schema, participant/session identifiers, task indices, timestamps, and expected session/task boundary events. The instrumented study package ran without logging-related runtime errors during laboratory testing, and all 54 participants generated valid per-participant CSV logs. This validation confirmed that MapLogger reliably captured the intended browser-level events and task context in this study. However, it should not be interpreted as validation of semantic reconstruction of all 3D navigation operations.

During task execution, MapLogger records interaction events and contextual data as detailed in Table 2.

Table 2. Overview of MapLogger data capture.

Category	Captured Elements
Interaction Events	Mouse clicks, double-clicks, mouse wheel events (including delta and direction), keyboard input (key and modifier keys), context menu calls, and session or task boundary events.
Contextual Schema	Session identifier, task index and label, relative timestamp (milliseconds since session start), absolute timestamps (UTC and local time), UI element descriptors (HTML tag, id, classes, visible text, CSS path), pointer coordinates (x, y), and viewport dimensions.

The inclusion of both relative and absolute timestamps is methodologically important, as it enables precise synchronisation with external data streams—specifically the eye-tracking recordings collected in parallel. This temporal alignment supports triangulation of gaze behaviour and interaction events, which were central to addressing RQ2, RQ3, and RQ6.

At the end of each session, participants entered their participant ID before pressing “Finish”. The system propagated this ID to the session identifier and automatically downloaded a corresponding CSV file. Consequently, each participant generated one standalone CSV file, facilitating subsequent aggregation and traceability.

Across all 54 participants, the instrumented system captured 15,457 interaction events (see Section 4), demonstrating the robustness of the logging layer under realistic experimental load.

All exported CSV logs were subsequently loaded into MapLogger Analyser. The Analyser operates entirely in-browser and allows the researcher to:

- Aggregate logs from multiple participants;
- Compute total and per-participant interaction counts;
- Visualise event-type distributions;
- Generate time-binned interaction timelines;
- Inspect task-level interaction profiles;
- Produce heatmaps based on recorded x/y coordinates and viewport dimensions.

In the present study, the Analyser was primarily used for descriptive statistics and for exploratory visual inspection of behavioural patterns (e.g., early-session interaction peaks and task-level intensity differences). These outputs were cross-referenced with qualitative eye-tracking video inspection and UEQ results in order to identify usability breakdowns and efficiency patterns.

Although the Analyser provides automated summary text and graphical exports (PNG and print-ready), all interpretations reported in this paper were manually verified and contextualised with respect to the experimental design and research questions.

Within the multi-method design of this study, MapLogger served as the objective behavioural layer complementing the qualitative inspection of eye-tracking recordings and subjective UEQ data. While the gaze recordings provided contextual evidence about where participants appeared to direct their visual attention, MapLogger clarified which actions were actually performed and how interaction sequences unfolded over time.

This integration proved particularly valuable in situations where gaze data alone were ambiguous. For example, when participants visually inspected a parameter without activating it, they hesitated before switching visualisation methods, or repeatedly adjusted controls during voxel-based analysis. Interaction logs enabled differentiation between visual consideration and actual manipulation, thereby strengthening the interpretive validity of the triangulation framework.

In sum, MapLogger provided:

- Standardised and reproducible interaction logging across all method pages;
- Precise temporal markers for synchronisation with gaze data;
- Task-aware contextualisation of events;
- Rapid descriptive analytics for behavioural profiling.

Its deployment ensured that behavioural data collection was systematic, comparable across participants, and independent of manual coding of screen recordings. In the context of evaluating interactive 3D thematic environments, this capability was essential for moving beyond purely perceptual analysis toward an integrated understanding of user strategies and usability constraints.

3.3.3. Eye-Tracking Data

As outlined in Section 3.2, eye-tracking data were recorded continuously while participants completed a fixed sequence of five tasks. In the present study, eye-tracking was used as a diagnostic component of a formative usability evaluation rather than as a basis for inferential comparison of visual attention between predefined Areas of Interest (AOIs). The analysis therefore relied primarily on retrospective inspection of gaze recordings with gaze overlays, focusing on visually observable manifestations of hesitation, uncertainty, overlooked interface elements, repeated checking of task instructions, switching between the map scene and control elements, and episodes of spatial disorientation in the 3D environment.

We acknowledge that standard quantitative eye-tracking metrics, such as fixation counts, fixation duration, or dwell time within predefined AOIs, are commonly used in eye-tracking research and would allow stronger statistical claims about the distribution of visual attention. However, these metrics were not systematically computed in the present study. This decision was made because the evaluated application was not a static stimulus but a highly interactive 3D environment in which the map scene, viewpoint, scale, occlusion relationships, active visualisation method, and side-panel parameters changed during task execution. Under such conditions, fixed screen-based AOIs would not necessarily refer to the same cartographic or interface meaning across participants or even within a single participant's session.

Nevertheless, we agree that dynamic AOI approaches represent a feasible and important direction for this type of research. Two possible alternatives can be distinguished. First, broad interface-level AOIs could be defined for relatively stable screen components, such as the map viewport, the method-selection menu, the task bar, the side panel, the legend, and navigation controls. Such AOIs could support coarse descriptive comparisons of attention allocation between the map and the interface. However, they would still provide limited insight into which specific 3D object, thematic symbol, visualisation method, or parameter state was being inspected. Second, a more robust solution would involve dynamic or semantic AOIs generated from the actual application state. In a web-based 3D environment, this would require synchronising gaze data with DOM element positions, interaction logs, active visualisation states, side-panel parameter values, camera parameters, and, where possible, hit-testing or ray-casting information from the 3D scene. This would allow gaze samples or fixations to be assigned not only to screen-based AOIs but also to semantically meaningful interface components or map objects.

The current prototype was not instrumented to store all information required for such post hoc dynamic AOI reconstruction, particularly time-synchronised camera states, object identifiers, bounding boxes, and visibility states of 3D scene elements. For this reason, retrospective quantitative AOI analysis would risk producing precise-looking but semantically ambiguous metrics. We therefore treated gaze recordings as an interpretive layer and triangulated them with interaction logs from MapLogger, task performance, UEQ scores, and open-ended feedback. Consequently, the eye-tracking results reported in this paper should not be interpreted as statistically supported claims about visual attention distribution. Instead, they provide qualitative evidence helping to explain observed interaction patterns and to identify usability breakdowns in the 3D-Geo-Vis prototype.

To improve analytical consistency, the visual inspection focused on a stable set of observable markers across tasks: initial orientation patterns during first contact with the interface; search strategies used to locate functions or target values; visual switching between interface controls and the map during parameter adjustment and verification; moments of behavioural uncertainty, such as pauses or repeated scanning without action; and episodes of spatial disorientation in the 3D scene. This coding logic supported the

interpretation of behavioural traces and subjective impressions, but it did not replace quantitative AOI-based eye-tracking analysis.

4. Results

The results combine three complementary sources of evidence: (i) interaction logs recorded by MapLogger, (ii) subjective evaluation using the UEQ supplemented with an open-ended feedback question, and (iii) qualitative inspection of eye-tracking recordings.

Across all participants ($N = 54$), MapLogger captured 15,457 interaction events. Per participant, this corresponded to an average of $M = 286$ interactions (min = 75; max = 745). The mean total task completion time was 11.9 min (Median = 11.5; range 5.2–23.8 min). Task duration and interaction count were strongly positively associated (Pearson's $r = 0.775$). Temporal aggregation further revealed that interaction activity was concentrated early in the session: within 30 s windows, peak activity reached approximately 1000–1300 interactions, whereas typical windows ranged from 200 to 350 interactions; only a small subset of participants exceeded 600 interactions overall.

Task performance was generally high, though it varied with task demands. Task 3 was fully solved by 46 participants (85.2%), partially solved by 6 (11.1%), and unsolved by 2 (3.7%). Task 4 showed the lowest performance: 42 participants solved it (77.8%), 6 partially solved it (11.1%), and 6 did not solve it (11.1%). In Task 5, 46 participants succeeded (85.2%), 7 were partially successful (13.0%), and one participant did not provide interpretable data due to an extreme or invalid response (1.9%). Across tasks, the highest full-completion rate was observed in Task 2 (87.0%), whereas Task 4 was comparatively weaker (77.8%) but still demonstrated a relatively high completion rate.

In Task 5, preferences for the “best” visualisation were not dominated by a single method. The three most frequently selected methods were Point Cloud, Voxels, and Horizontal Planes, each chosen by 10 participants (18.5%).

Qualitative evidence from task execution and gaze-video inspection revealed several recurring interaction and comprehension patterns. During initial exploration, attention was disproportionately drawn to the right control panel and the map frame, while controls for switching visualisation methods in the top-right corner were frequently overlooked; only about two-fifths of participants switched the visualisation method during free exploration.

In Task 2, some participants mistakenly searched for the “Point Cloud” visualisation among basemap options, while others spent extended time scanning the basemap list before identifying the correct dataset.

In Task 3, a notable source of hesitation and errors was the interpretation of parameter semantics, particularly confusion surrounding the “diameter” parameter, which some participants associated with the time-series curve rather than the mapped glyphs. Language factors appeared to contribute to this misunderstanding in some cases.

In Task 4, delays in loading and rendering the Voxels visualisation caused visible waiting behaviour and gaze shifts away from the display. Two dominant strategies emerged: (i) reading the legend followed by targeted searching, and (ii) systematic visual scanning of the scene. Some errors resulted from mismatches between legend interpretation and the perceived spatial distribution of voxels (e.g., clicking locations where no voxel was actually present).

In Task 5, two usability issues appeared repeatedly: (i) the colour selection dialogue required explicit confirmation via an “OK” button, which some participants did not notice, and (ii) performance limitations impeded smooth interaction, occasionally provoking excessive zooming and spatial disorientation when participants attempted to apply familiar 2D navigation strategies within the 3D environment.

Subjective evaluation using UEQ produced an overall neutral to slightly positive profile. All six scales remained within the conventional neutral interval $(-0.8, +0.8)$. The highest mean values were observed for Perspicuity ($M = 0.514$), Dependability ($M = 0.472$), and Attractiveness ($M = 0.392$), while the lowest values were reported for Efficiency ($M = 0.046$) and Stimulation ($M = 0.005$); Novelty remained mildly positive ($M = 0.301$).

At the meta-dimension level, Pragmatic Quality was slightly higher than Hedonic Quality ($M = 0.34$ vs. $M = 0.15$), although both remained within the neutral range. A key driver of the weak Efficiency profile was a strongly negative rating for perceived speed ("fast–slow"), reported as approximately $M = -1.5$ (item-level estimate $M = -1.481$).

To further examine the relationship between subjective evaluation and observed behaviour, we correlated selected UEQ dimensions with MapLogger-derived behavioural metrics. The analysis focused particularly on Efficiency, Stimulation, and the perceived speed item, because these variables were most relevant to the performance-related issues identified in the UEQ results and open-ended comments.

The correlations were generally weak. Efficiency was not significantly associated with total task completion time ($\rho = -0.061$, $p = 0.662$), total number of interactions ($\rho = -0.209$, $p = 0.130$), or interactions per minute ($\rho = -0.200$, $p = 0.147$). Similarly, Stimulation showed no statistically significant association with completion time ($\rho = -0.020$, $p = 0.884$), total interactions ($\rho = -0.136$, $p = 0.326$), or interactions per minute ($\rho = -0.218$, $p = 0.113$).

The perceived speed item showed weak negative associations with total number of interactions ($\rho = -0.271$, $p = 0.048$) and interactions per minute ($\rho = -0.287$, $p = 0.035$), whereas its association with total task completion time was negligible ($\rho = -0.055$, $p = 0.692$). Since higher values of this item indicate a more positive perception of speed, these results suggest that participants who interacted more intensively tended to perceive the system as slower. However, the effect sizes were small, and the results should be interpreted as exploratory rather than confirmatory.

These findings refine the interpretation of the UEQ results. The negative perception of speed was not simply a function of longer overall task duration. Instead, it appears to be more closely related to interaction intensity and to qualitative episodes of waiting, repeated manipulation, and uncertainty during rendering or parameter changes. This supports the triangulated interpretation that perceived performance limitations affected the interaction process even when participants were ultimately able to complete the tasks.

In the UEQ benchmark comparison, five scales were classified as "Bad" (Attractiveness, Perspicuity, Efficiency, Dependability, and Stimulation). In contrast, Novelty was classified as "Below Average", indicating that even slightly positive mean values were relatively low compared with the UEQ reference database (Figure 5). However, it should be noted that the UEQ benchmark database aggregates results from a broad range of digital products and interactive systems, not specifically from map-based or geovisualisation applications. Consequently, the benchmark comparison should be interpreted cautiously and primarily as a general reference point rather than as a strict indicator of usability quality in the specific domain of interactive cartographic environments.

Consistent with the questionnaire results, performance concerns dominated responses to the open-ended improvement question: 35 participants provided comments, and 25 (71.4%) explicitly mentioned speed, responsiveness, or graphical performance as the main areas for improvement.

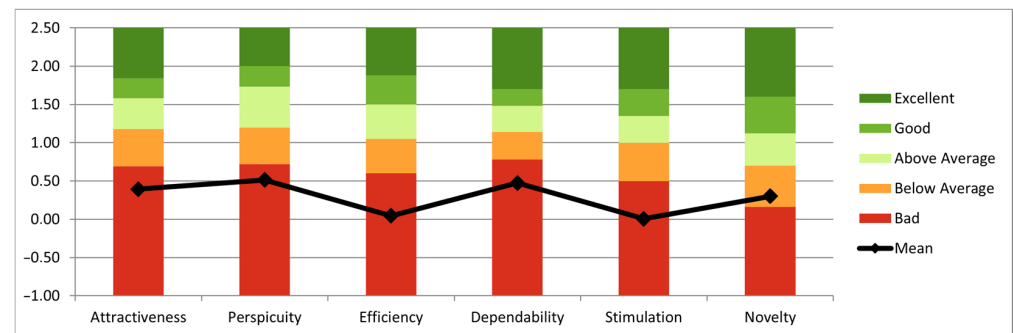


Figure 5. Average values for all six scales against the UEQ reference database.

4.1. Evaluation of Research Questions

4.1.1. How Do Users Orient Themselves Within the Application Interface During Their First Initial Interaction with the System? (RQ1)

During initial contact (Task 1), users typically entered a pronounced “warm-up” phase characterised by intensive exploration and frequent mouse-based navigation and view adjustment, reflected in high interaction intensity and repeated wheel events, and further contextualised through gaze-video inspection. This pattern is visible in the temporal interaction profile, where the first minutes exhibit markedly higher interaction intensity than later parts of the session.

Qualitative inspection of gaze recordings showed that early visual attention was disproportionately drawn to the dominant map view and the right-hand parameter/control panel, which functioned as the primary “anchor” for understanding how the visualisations could be manipulated. In contrast, the menu for switching between visualisation methods (located in the top-right corner) was often overlooked during the first-contact phase; only a minority of participants actively switched methods during free exploration.

A recurring orientation issue (in Task 2) was that some participants initially searched for the “Point Cloud” visualisation among basemap options, indicating that the conceptual grouping of options (basemap vs. thematic method) was not immediately clear for all users during their first interaction.

Answer to RQ1: Users orient themselves through an initial high-intensity exploratory phase focused primarily on the map frame and the right-side parameter panel. Controls for switching visualisation methods in the top-right corner are comparatively less discoverable during first contact, which can lead to misdirected search and delayed understanding of how to change visualisation methods.

4.1.2. What Strategies Do Users Apply When Solving Task-Specific Interaction and Analytical Tasks Within Selected 3D Visualisation Methods? (RQ2)

Across tasks, interaction logs and gaze inspection indicate that users’ strategies were primarily shaped by (a) the procedural versus analytical nature of the task and (b) the cognitive demands imposed by a particular visualisation method (most notably the Voxels representation).

Task 2 (locating the maximum value in the Point Cloud) typically elicited a procedural strategy. Once participants identified the correct visualisation method, they tended to follow a relatively consistent sequence of actions characterised by frequent clicking and limited diversification of interaction inputs.

Task 3 (switching to 3D Graduated Symbols and adjusting symbol shape and diameter) elicited a manipulation-oriented strategy centred on parameter adjustment. Compared with other tasks, some participants also made greater use of keyboard inputs when interacting with parameter fields.

Task 4 (Voxels; computing the difference between minimum and maximum temperature values) elicited two dominant analytical strategies: (i) participants who first examined the legend carefully and then targeted the scene to identify extreme values, and (ii) participants who engaged in systematic visual scanning of the voxel field while repeatedly consulting pop-up windows to reveal exact values.

Task 5 (selecting a preferred visualisation and adjusting the colour scheme) was characterised by exploratory experimentation combined with reflective visual assessment. Participants often alternated between brief parameter modifications and longer periods of visual inspection to evaluate the aesthetic outcome of the changes.

It should be emphasised that these strategies were observed in task-specific interactions with individual visualisation methods rather than in a scenario requiring systematic comparison of all methods. The present data therefore describe how participants approached constrained lookup, manipulation, and simple comparison tasks, but they do not provide sufficient evidence to infer how users would synthesise information across multiple 3D thematic representations in a more realistic analytical workflow.

Answer to RQ2: Users applied procedural, goal-oriented strategies for well-defined lookup and manipulation tasks, whereas the voxel-based task elicited more inspection-intensive strategies involving either legend-first interpretation or systematic scanning of the scene. However, these findings apply to constrained task-specific interactions with selected methods. The study does not allow strong conclusions about users' cognitive strategies when comparing multiple 3D visualisation methods or synthesising spatial patterns across alternative representations.

4.1.3. Which Interface Elements Lead to Manifestations of Uncertainty, Hesitation, or Errors During Task Execution? (RQ3)

Several recurring sources of hesitation and errors were identified across tasks.

First, method-switching controls exhibited relatively low visual salience compared with the dominant map view and the right-hand parameter panel. As a result, some participants continued manipulating parameters within an incorrect conceptual context because they did not immediately realise—or did not remember—how to switch to a different visualisation method.

Second, the distinction between basemap options and thematic visualisation methods was not always clear. In Task 2, several participants initially searched for the “Point Cloud” visualisation among basemap options or spent extended time scanning the basemap list before identifying the correct dataset.

Third, Task 3 revealed comprehension issues related to parameter semantics. Some participants adjusted incorrect parameters or did not immediately understand the intended meaning of the “diameter” parameter in relation to the current symbol design, leading to short trial-and-error interaction sequences.

Fourth, the Voxels visualisation introduced both interpretive and technical barriers. Participants occasionally struggled to reliably identify the minimum and maximum values within the voxel field, and the rendering process's performance limitations sometimes led to repeated corrective actions or pauses in interaction.

Finally, in Task 5, the workflow for adjusting the colour scheme occasionally induced hesitation—for example, when participants were uncertain whether their selection needed to be confirmed. This was particularly evident when system feedback was not sufficiently explicit.

Answer to RQ3: Uncertainty and errors are most consistently associated with (i) the low discoverability of method-switching controls, (ii) the ambiguous conceptual grouping of interface options (basemap vs. thematic visualisation methods), (iii) unclear parameter

semantics (notably in Task 3), and (iv) the combined cognitive and performance burden of voxel-based analysis.

4.1.4. Which Visualisations Are Subjectively Preferred, and How Are These Preferences Related to Observed Visual and Interaction Behaviour? (RQ4)

Preferences were not dominated by a single visualisation method: Point Cloud, Voxels, and Horizontal Planes were the most frequently selected options (each 18.5% of participants). This distribution suggests that users may value different visual properties (e.g., perceived three-dimensional expressiveness, clarity of spatial structure, or aesthetic appearance) rather than converging on a single universally preferred representation.

Importantly, preferences did not align straightforwardly with analytical task performance. Although the voxel-based task exhibited comparatively lower success rates, Voxels remained among the most frequently selected “best” visualisations. Qualitative inspection of gaze recordings and interaction patterns indicates that this preference may be associated with the visually expressive character of the representation, which encouraged longer episodes of visual inspection and comparison of alternative views. In several cases, participants prioritise the overall visual impression of the 3D scene rather than analytical simplicity.

Behaviourally, the preference task was characterised by repeated alternation between parameter manipulation (typically within the right-side control panel) and extended visual inspection of the map scene. This pattern suggests that aesthetic judgement relied on sustained visual evaluation rather than on rapid operational confirmation.

Answer to RQ4: Users’ preferences are diverse and cannot be reduced to a single universally preferred visualisation method. Observed behaviour suggests that preference formation may involve iterative parameter adjustments followed by reflective visual inspection of the scene. Some participants may favour visually expressive representations (such as Voxels), although the precise reasons for these preferences cannot be conclusively determined from the available behavioural data alone.

4.1.5. How Do Task Completion Time, Number of Interactions (Including Interactions per Minute), and Task Success Relate to the Efficiency of Users’ Strategies? (RQ5)

At the participant level, longer sessions tended to involve more interactions ($r = 0.775$), indicating that prolonged task completion was frequently accompanied by increased operational activity. However, interpreting these indicators requires caution, because interaction frequency and task duration reflect different aspects of the problem-solving process.

From a behavioural perspective, sessions characterised by both long duration and high interaction counts typically corresponded to trial-and-error exploration or orientation difficulties within the interface. In contrast, longer durations combined with relatively fewer interactions often reflected extended visual inspection of the map scene before action was taken, suggesting that participants were engaged in interpreting the visualised data rather than manipulating the interface.

This distinction aligns with the principles of cognitive load theory [29], which differentiates between intrinsic and extraneous cognitive load. Intrinsic load arises from the inherent complexity of the information being processed, while extraneous load is introduced by the way information or tasks are presented. In the context of the present experiment, interaction-intensive behaviour may indicate additional extraneous load associated with interface exploration or unclear control semantics. In contrast, longer inspection periods with fewer interactions may reflect intrinsic cognitive load related to interpreting complex 3D spatial patterns.

Task-level results illustrate this difference. Task 4 (Voxels) combined the lowest completion rate with the highest analytical demands. Participants often spent extended periods

inspecting the scene before interacting, indicating that efficiency was constrained not only by interface operations but also by the interpretive complexity of voxel-based representations. In contrast, Tasks 2–3 involved more procedural interaction sequences (e.g., locating values or adjusting parameters), which enabled participants to follow clearer operational steps and achieve higher completion rates.

Answer to RQ5: Efficiency emerges from the combined pattern of task duration, interaction intensity, and task success. Prolonged time together with high interaction counts tends to indicate orientation problems or trial-and-error interaction strategies. In contrast, prolonged time with fewer interactions may reflect higher cognitive demands related to interpreting complex visual representations. In the present study, the voxel-based analytical task is the most efficiency-challenging, while procedural lookup and parameter-manipulation tasks show comparatively higher efficiency.

4.1.6. What Key Usability Issues Can Be Identified Through Triangulation of Eye-Tracking Records, Interaction Logs, and Questionnaire Data, and What Implications Do These Findings Have for Improving the Design of the 3D Geovisualisation Environment? (RQ6)

The triangulation of gaze behaviour, interaction logs, and subjective evaluations reveals several systematic usability patterns that extend beyond individual tasks or interface elements. Rather than representing isolated issues, these patterns point to three broader categories of design constraints in the tested prototype: interface discoverability, the analytical interpretability of 3D representations, and the system's technical responsiveness.

First, multiple data sources consistently indicate limitations in interface discoverability and structural orientation. Eye-tracking recordings show that users' attention was strongly concentrated on the map scene and the right-hand parameter panel, while the method-switching controls located in the upper-right interface area were comparatively less visible during initial exploration. Interaction logs and task errors further confirm that participants sometimes searched for visualisation methods in inappropriate interface areas (e.g., among the basemap options), suggesting that the interface's conceptual structure was not always immediately understandable. These observations indicate that the prototype lacks a clear enough visual hierarchy to guide users to key navigation functions.

Second, the results highlight challenges in interpreting complex 3D thematic representations, particularly in voxel-based visualisations. The voxel task exhibited the lowest completion rate and frequently required prolonged inspection before users attempted interaction. Qualitative inspection of gaze recordings also revealed that the legend was used only sporadically; when participants consulted it, they often relied on it to read numerical values directly rather than systematically analysing the spatial structure of the voxel field. This behaviour suggests that, rather than supporting analytical exploration of the 3D scene, the legend served as a shortcut to obtain the required answer. Such behaviour indicates that the voxel representation may not always convey extreme values clearly through spatial perception alone and may therefore benefit from stronger visual cues or analytical aids that facilitate the direct identification of relevant values in the 3D scene.

Third, the triangulation identifies technical responsiveness and perceived system speed as a cross-cutting usability constraint. UEQ responses consistently rated perceived speed negatively, and open-ended comments frequently mentioned delays in rendering or in interaction feedback. Eye-tracking recordings provide additional insight into how participants reacted to these delays. During loading or rendering of certain visualisations—most notably the voxel representation—many participants fixated on the central area of the map scene while waiting for the visualisation to appear and progressively render. In other cases, participants scanned different parts of the interface with their gaze, apparently attempting to determine whether the system was responding or whether additional actions

were required. These behavioural patterns suggest that performance limitations not only affected subjective satisfaction but also introduced uncertainty into the interaction process.

The exploratory correlations further suggest that perceived speed was more closely related to interaction intensity than to overall task duration, indicating that responsiveness problems affected the perceived fluency of interaction rather than merely extending completion time.

Taken together, these findings indicate that usability limitations in the prototype arise from the interaction between interface structure, visualisation complexity, and technical performance, rather than from a single isolated design flaw. Addressing these issues, therefore, requires coordinated design improvements across several levels of the system.

Based on the triangulated evidence, several concrete design implications can be formulated for improving the 3D geovisualisation environment:

- Increase discoverability of global controls, particularly the menu with visualisations, for example by strengthening visual hierarchy, grouping related controls, or relocating the menu to a more central interface position.
- Improve the semantic clarity of parameter controls by adopting clearer naming conventions, providing contextual hints, and providing more explicit feedback after parameter changes.
- Support interpretation of complex 3D representations, for example, by enhancing legend–scene linkage, providing clearer visual cues for extreme values, or introducing guided analytical aids.
- Reduce perceived interaction latency, particularly in computationally intensive visualisations such as voxel-based rendering, by optimising rendering processes or enabling progressive visual updates.
- Provide stronger system feedback during parameter manipulation, ensuring that users can clearly recognise when changes have been applied.

Answer to RQ6: The triangulated analysis identifies three primary usability constraints in the tested prototype: limited discoverability of key navigation controls, interpretive complexity associated with certain 3D visualisation methods, and perceived performance limitations during interaction. These findings highlight the need for improved visual hierarchy, clearer parameter semantics, stronger analytical guidance for complex 3D representations, and enhanced system responsiveness. Together, these design implications form the basis for the redesign implemented in the improved version of the application.

4.2. Illustrative Redesign Proposal: 3D-Geo-Vis 2.0

Based on the usability evaluation, the design of an improved 3D geovisualisation environment should directly address the identified usability issues to enhance both effectiveness and user-friendliness in visual analysis. Such an environment can be conceptualised as an interactive system that integrates multiple visualisation methods within a cohesive interaction paradigm, thereby overcoming the limitations of the original prototype. Geovisualisation techniques have also been shown to support visual decision-making in applied domains, for example, in retail analysis, where spatial patterns are interpreted to inform strategic decisions [30].

A primary design requirement is to prioritise performance and efficiency. The evaluation consistently identified perceived speed, fluency, and rendering latency (particularly for voxel-based visualisation) as the most critical weaknesses. The application was therefore optimised to ensure smoother interaction during navigation and parameter manipulation, to reduce cognitive load, limit spatial disorientation, and support more efficient analytical strategies.

In addition, the interface was redesigned to improve discoverability and user control. The previously low salience of method switching was addressed by integrating all visualisation methods into a single environment, enabling users to combine methods, data layers, and graphical variables within a single interface. This approach eliminates the conceptual fragmentation of the page-separated prototype. The application also supports more realistic analytical workflows by enabling users to add custom data, select attributes for visualisation, and manage layers through a dedicated layer list. Micro-level interaction issues were addressed by providing clearer parameter descriptions and more explicit feedback mechanisms (e.g., during colour scheme adjustments), thereby reducing ambiguity and trial-and-error behaviour observed in the prototype.

Based on these design implications, a revised version of the application (3D-Geo-Vis 2.0, Figure 6) was developed (https://jakubzejdlk.github.io/3d_geo_vis_2, accessed on 1 June 2026). It is important to note that at this stage, 3D-Geo-Vis 2.0 serves as an illustrative redesign proposal—a direct technical implementation of the empirically derived recommendations—rather than a fully empirically validated final solution. Its primary purpose in the context of this study is to demonstrate how the identified usability barriers (e.g., discoverability, integration of controls, and parameter semantics) can be practically resolved within a unified web architecture. Compared to the prototype, the application introduces the following additional functionality:

- Add custom data from ArcGIS Online (version 2026.2) via a URL (including thematic data, elevation data, and 3D buildings),
- Visualisation using seven 3D methods (Horizontal Planes, Point Cloud, 3D Surface, Vertical Planes, 3D Graduated Symbols, Prism Map, Voxels),
- Real-time adjustment of graphical variables depending on the selected method,
- Attribute selection for thematic visualisation and labelling,
- Layer management (visibility toggling, symbology editing, deletion),
- Combination of multiple data sources, methods, and graphical parameters within a single environment,
- Automatic zoom to the spatial extent of uploaded data,
- Sharing of the current application state via a unique URL.



Figure 6. 3D-Geo-Vis 2.0—example of 3D graduated symbols.

The core of the application is a 3D map window displaying a virtual globe. Unlike the prototype, all visualisation logic is now implemented within a single page. Basic interface elements (zoom, pan, home, basemap selection, legend) remain on the left. A layer list is located in the lower-right corner, allowing users to manage active layers (visibility, editing, deletion). The symbology panel is hidden by default and becomes available only after data are added and a visualisation method is selected.

The main functionality is accessed via three buttons in the upper-right corner. The “Add Thematic Layer” button enables users to load ArcGIS Online Feature Layers via URL. The application automatically detects the data type and offers compatible 3D visualisation methods. After selecting a method, graphical variables can be adjusted in real time. An internal algorithm evaluates the data’s spatial extent (bounding box) and automatically determines suitable initial visualisation parameters (e.g., extrusion height, symbol size), ensuring immediate readability across different spatial scales.

The “Add 3D Buildings” function allows users to incorporate building models with adjustable visual properties (colour, transparency, edges). The “Change Elevation Layer” function allows modifying the terrain model. All layers can be renamed and are listed together with their associated visualisation method, improving clarity when working with multiple layers.

Another key feature is the “Copy Share Link” function, which allows the current state of the visualisation environment to be shared via a URL. This includes all uploaded layers, graphical parameters, and the current view (zoom and rotation). The “Help” section provides documentation of the application methodology (Figure 7), usage instructions, sample data, and author information.

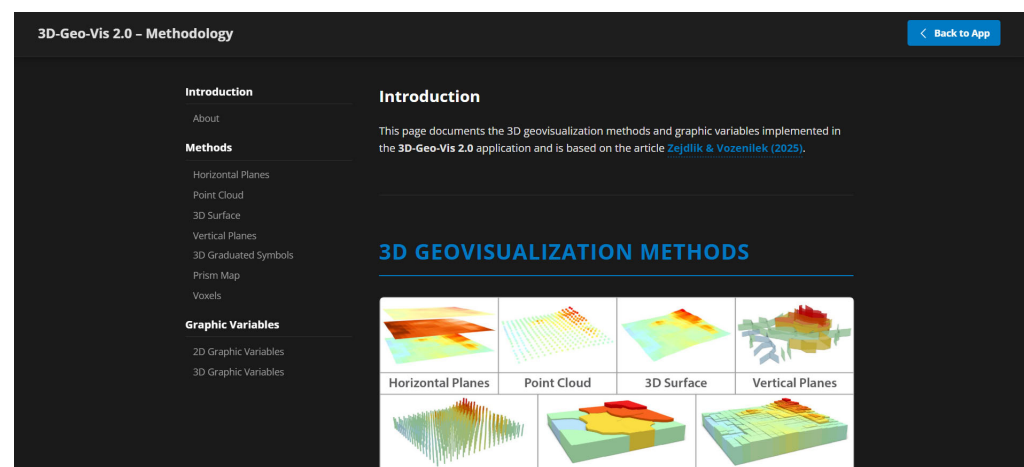


Figure 7. Application methodology describing 3D geovisualisation methods and graphic variables (captured in the application’s native dark mode interface).

5. Discussion

The present study provides a multi-method evaluation of a web-based 3D geovisualisation environment, combining behavioural logging, qualitative inspection of gaze recordings, and subjective user experience assessment. The findings highlight that usability issues in such environments emerge from an interplay of interface design, system performance, cognitive demands, and user expectations, rather than from a single dominant factor.

The exploratory correlation analysis between UEQ scores and behavioural metrics provides a more nuanced view of the triangulation between subjective and behavioural data. The low Efficiency score was not strongly associated with longer total task completion time, suggesting that participants’ perception of efficiency was not determined solely by how long the session lasted. Likewise, the weak associations between Stimulation and

behavioural metrics indicate that engagement was not directly reducible to interaction frequency or duration. The perceived speed item showed weak negative correlations with total interactions and interactions per minute, indicating that participants who interacted more intensively tended to evaluate the system as slower. This finding is consistent with qualitative evidence from gaze-video inspection and open-ended responses, where rendering delays, repeated adjustments, and uncertainty during visualisation loading were frequently observed. At the same time, the weak correlation with total completion time suggests that perceived speed is not simply a time-on-task measure. Rather, it appears to reflect the experienced smoothness, responsiveness, and predictability of interaction. This distinction is important for interactive 3D geovisualisation, where short but repeated episodes of latency may negatively affect user experience even when overall task completion time remains acceptable.

The interpretation of efficiency patterns (RQ5) should also be informed by both empirical observations and theoretical grounding. The combination of longer task duration and a high number of interactions was associated with trial-and-error behaviour and orientation difficulties. In contrast, longer duration with comparatively fewer interactions was interpreted as reflecting increased cognitive or interpretive load. This interpretation is supported not only by the observed gaze behaviour (e.g., prolonged inspection without interaction) but also by cognitive load theory, which distinguishes between different types of cognitive load [29]. In this context, the observed patterns may be linked particularly to intrinsic and extraneous cognitive load, where increased visualisation complexity or suboptimal interface design can elevate processing demands without necessarily increasing task-related actions.

At the same time, several methodological limitations must be acknowledged. First, eye-tracking data were analysed primarily qualitatively, without using standard quantitative gaze metrics such as fixation counts or dwell times within predefined Areas of Interest (AOIs). While such metrics would enable more direct statistical comparisons between visualisation methods, their application is problematic in highly interactive, dynamically changing environments, where both the map content and interface layout vary across participants and tasks. For this reason, the study prioritised a diagnostic, interpretation-oriented approach based on gaze-video inspection combined with behavioural logs and questionnaire data. Future research could complement this approach with more controlled experimental designs that allow stable AOI definitions and quantitative gaze analysis.

A core limitation of the study concerns the composition of the participant sample. The evaluation was based on a university-based convenience sample recruited within a single institutional and cultural context. The sample was strongly skewed towards younger participants, with 49 of 54 participants falling into the two youngest age categories (≤ 20 and 21–30 years). As a result, the findings primarily reflect the behaviour and subjective impressions of young users who are likely to be relatively digitally literate and familiar with web-based interfaces. This sampling bias limits the generalisability of the results. Potential users of 3D geovisualisation environments may include older adults, specialists from different professional domains, public-sector users, educators, students outside geoinformatics-related contexts, or users with substantially different levels of digital, spatial, and cartographic literacy. These groups may differ in their ability to navigate 3D scenes, interpret depth and occlusion, understand thematic visual variables, tolerate rendering latency, and discover interface controls. For example, older users or users with less experience in interactive 3D environments may experience greater difficulty with camera manipulation, spatial orientation, and the interpretation of perspective-dependent visual encodings. Conversely, domain professionals may employ more systematic analytical strategies and may evaluate the same interface more critically from the perspective of task efficiency and

data flexibility. Therefore, the results should not be interpreted as representative of the broader population of potential users. Rather, they provide evidence from a controlled formative usability evaluation with a relatively young and homogeneous participant group. Future studies should deliberately recruit more heterogeneous samples, including older adults, users from different cultural contexts, and professionals from relevant application domains such as urban planning, environmental analysis, meteorology, crisis management, public administration, and education. Such follow-up research would make it possible to assess whether the usability issues identified in this study—particularly method-switch discoverability, parameter interpretation, 3D navigation, and perceived performance—persist across user groups or vary according to age, expertise, and professional context.

Also, there was a significant linguistic mismatch between the application interface, which was presented in English, and the experimental task instructions, which were provided in Czech. This inconsistency introduced unnecessary cognitive friction. For instance, in Task 3, several participants struggled to interpret the exact meaning of the parameter ‘diameter’, not necessarily due to interface design but due to language translation efforts. This raises the valid concern that not all participants interpreted the tasks identically, thereby introducing an extraneous cognitive load that may have skewed task completion times and interaction counts. Future usability evaluations of such environments must ensure strict linguistic consistency to isolate actual UI discoverability issues from mere language comprehension barriers.

Another limitation concerns the interpretation of user preferences (RQ4). Although certain visualisations (e.g., Voxels) were frequently selected despite their greater analytical difficulty, the present data do not allow the underlying motivations for these preferences to be determined with certainty. The study relied on behavioural observation and post-task questionnaires, without employing concurrent verbalisation methods. Future studies could therefore benefit from integrating approaches such as think-aloud protocols, which would provide deeper insight into users’ reasoning processes and help explain why visually expressive but cognitively demanding methods may be preferred.

Another limitation concerns the granularity of interaction logging. MapLogger captured browser-level events together with task context, timestamps, pointer coordinates, viewport dimensions, and UI element descriptors. This was sufficient for reconstructing interaction intensity, event-type distributions, task-level behavioural profiles, and temporal sequences of user actions. However, the tool did not semantically decompose complex WebGL/canvas-based interactions inside the 3D scene. In particular, dragging operations could correspond to panning, rotation, tilting, or other camera manipulations handled internally by the 3D viewer, but these operations were not stored as separate semantic categories. Consequently, the present study does not report separate quantitative metrics for panning versus rotation. Future versions of MapLogger should be extended with application-level hooks to record camera state changes, including camera position, heading, pitch, roll, zoom or view distance, and active scene object identifiers. Such instrumentation would allow more precise reconstruction of 3D navigation strategies and would improve the reproducibility of behavioural analyses in interactive 3D geovisualisation environments.

A further limitation concerns the analytical scope of the task set. Although the five tasks covered several relevant interaction situations—initial exploration, value lookup, parameter adjustment, simple analytical comparison, and preference-based visual refinement—they did not fully capture the core analytical potential of 3D thematic geovisualisation. In particular, Tasks 2 and 4 were deliberately constrained: Task 2 required participants to locate a maximum value in the Point Cloud visualisation, while Task 4 required them to identify the minimum and maximum values in the Voxels visualisation and compute their difference. These tasks were appropriate for experimental control and

for diagnosing usability issues related to method switching, value identification, legend interpretation, and voxel rendering. However, they did not require participants to compare multiple visualisation methods analytically or to synthesise spatial patterns across alternative representations. Consequently, the study provides stronger evidence about interface usability and task-specific interaction behaviour than about higher-level analytical reasoning in 3D thematic geovisualisation. The preference task partly addressed the comparison between methods, but this comparison was subjective and aesthetic rather than analytical. Future evaluations should therefore include scenario-based tasks that require users to compare the same phenomenon across several 3D visualisation methods, identify spatial clusters, gradients, outliers, or regional contrasts, and justify which method best supports a given analytical question. Such tasks would make it possible to study not only whether users can operate the interface, but also how they use different 3D representations to construct, verify, and revise spatial interpretations.

The implementation of the improved 3D-Geo-Vis 2.0 environment also revealed several technological and conceptual constraints that are inherent to web-based 3D geovisualisation systems. The application currently relies on data from ArcGIS Online web layers, which limits data input flexibility, as users cannot directly upload local datasets. While ArcGIS Online provides a convenient infrastructure, its free tier is restricted to personal use, which limits the platform's broader deployment. Future iterations should therefore identify and integrate alternative, open-source solutions for handling custom data in web environments. Potential approaches include deploying an independent backend server (e.g., GeoServer or QGIS Server) to publish standardised OGC web services, or implementing robust client-side parsing that allows users to directly upload and render open spatial formats, such as GeoJSON, entirely within the browser. This design choice also affects system performance, particularly when working with large or complex 3D datasets, where increased loading times and rendering delays may occur. Furthermore, the capabilities of the underlying programming interface restrict the implementation of certain visual variables (e.g., orientation or texture), and the system currently supports visualisation of only a single attribute per layer, limiting more advanced multi-attribute representations.

From a perceptual and cognitive perspective, the study also confirms known challenges associated with 3D visualisation. Issues such as occlusion, perspective distortion, and difficulties in comparing values across depth complicate the interpretation of spatial patterns, especially in dense or complex datasets. The design of 3D-Geo-Vis 2.0 attempts to mitigate these limitations through interactive features such as rotation, zooming, and transparency control, which allow users to adapt the viewpoint dynamically. Nevertheless, the cognitive demands of working in 3D environments remain inherently higher than those of traditional 2D representations.

As the results indicate, several participants struggled with fundamental interface issues, such as the low discoverability of global controls. In retrospect, the large-scale study functioned largely as a formative evaluation of a preliminary prototype. Conducting a small-scale pilot study or a heuristic evaluation prior to the main experiment would have allowed us to identify and resolve these basic navigational flaws earlier in the process. Consequently, the main experiment with 54 participants could have focused more exclusively on the advanced cognitive and analytical challenges inherent to 3D thematic geovisualisations, rather than on general UI discoverability.

Finally, it is important to note that the improved version of the application (3D-Geo-Vis 2.0) was not subjected to a full-scale usability evaluation within the scope of this study. Because of this logical gap, we explicitly frame 3D-Geo-Vis 2.0 as an illustrative proof-of-concept for the proposed design changes rather than an empirically validated system. The true validation of this redesign will require a follow-up comparative study that

carefully isolates the new interaction paradigm from the added complexities of custom data management. Both practical and methodological constraints influenced this decision. The development process itself required substantial time investment, leaving limited resources for additional testing. More importantly, designing an appropriate testing scenario for the revised system proved methodologically complex. A controlled setup with predefined datasets would simplify testing but omit a critical interaction phase—namely, the process of searching for and adding data layers. Conversely, requiring participants to locate and upload data themselves would significantly increase task complexity and duration, potentially introducing frustration and biasing the evaluation. Addressing this trade-off represents an important direction for future research. A carefully designed evaluation framework that isolates these factors while preserving ecological validity would provide a more comprehensive assessment of advanced 3D geovisualisation systems.

In summary, the study demonstrates that usability evaluation of interactive 3D geovisualisation environments requires a holistic perspective that integrates behavioural, perceptual, and subjective dimensions. The findings not only inform the redesign of the evaluated application but also contribute to a broader understanding of how users interact with complex 3D mapping systems and where key challenges remain for future research and development.

6. Conclusions

The answer to the main research question—How can a 3D geovisualisation environment be improved based on a usability evaluation so that it becomes more effective and user-friendly for visual analysis?—can be synthesised into three key design priorities derived from the usability evaluation:

1. **Performance and efficiency optimisation:** The study consistently identified perceived speed and rendering latency—particularly for computationally demanding methods such as Voxels—as the most critical weakness affecting user experience. Improving usability, therefore, requires substantial optimisation of system performance to ensure smooth and responsive interaction. This is essential for reducing cognitive load, preventing user frustration, and supporting stable spatial orientation during analysis.
2. **Integrated and intuitive interface design:** The evaluation highlighted limitations of the page-separated prototype, particularly the low discoverability of method-switching controls and an imbalanced distribution of attention across interface elements. An improved environment should therefore adopt a unified interaction paradigm in which visualisation methods, data layers (via a layer list), and graphical variables are managed within a single coherent interface. Such integration enhances transparency, reduces unnecessary search behaviour, and supports more efficient interaction workflows.
3. **Data flexibility and clarity of interaction.** To function as a genuine analytical tool rather than a fixed demonstration, the system must allow users to incorporate their own data and dynamically select attributes for visualisation. At the same time, micro-level usability issues—such as unclear parameter semantics or insufficient feedback—must be addressed through explicit, immediate system responses and unambiguous interface terminology, thereby reducing trial-and-error behaviour.

In summary, an effective 3D geovisualisation environment should combine high performance, functional flexibility, and a clearly structured interaction paradigm.

These principles were implemented in the revised 3D-Geo-Vis 2.0 application. The insufficient salience of method switching was addressed by replacing the page-based structure with an integrated interface that enables simultaneous management of visualisation methods, data layers, and graphical variables. This redesign also mitigates the previously

observed concentration of user attention on the side panel by introducing a more balanced and cohesive layout.

Performance limitations, particularly for voxel-based visualisation, remain only partially resolved, as they are influenced by external factors such as the underlying Esri technology, data volume and spatial extent, and network conditions. Consequently, practical optimisation strategies—such as reducing voxel density (e.g., by increasing cell size)—are necessary when preparing data for web-based visualisation.

Ultimately, the primary novel contribution of this study is the successful operationalisation of seven theoretical 3D mapping methods into a functional web-based environment, and the subsequent systematic empirical assessment of their usability. By moving beyond purely theoretical formalisations and isolated technical demonstrations, this research provides an evidence-based framework that demonstrates how conceptual cartographic design translates into actual interactive user experiences. A key methodological contribution is the implementation and evaluation of these seven methods, combined with a broad set of graphical variables, which provided users with substantial flexibility for exploring spatial patterns and relationships.

However, these conclusions should be interpreted in light of the university-based and age-skewed participant sample; further validation with older users and domain professionals is required before the findings can be generalised to the broader population of potential users of 3D geovisualisation systems.

The findings should also be interpreted in relation to the constrained task design: the study diagnosed usability barriers in task-specific interactions with the prototype, but further scenario-based evaluations are needed to assess how users compare methods and synthesise spatial patterns across multiple 3D thematic representations.

The web-based architecture further enhances accessibility by leveraging cloud technologies and eliminating the need for specialised desktop GIS software. In this sense, the application represents not only a technological solution but also a validated framework for the design and evaluation of interactive 3D thematic geovisualisations.

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Abbreviations

The following abbreviations are used in this manuscript:

AOI	Area of Interest
UEQ	User Experience Questionnaire
UI	User Interface
RQ	Research Question

References

1. Raper, J. (Ed.) *Three Dimensional Applications In GIS*; CRC Press: London, UK, 2020; ISBN 978-1-003-06945-4.
2. Christophe, S.; Gautier, J.; Chapron, P.; Riley, L.; Masson, V. 3D Geovisualization for Visual Analysis of Urban Climate. *Cybergeog* **2022**. [CrossRef]
3. Bittner, O.; Zejdlik, J.; Burian, J.; Vozenilek, V. Exploring Unconventional 3D Geovisualization Methods for Land Suitability Assessment: A Case Study of Jihlava City. *ISPRS Int. J. Geo-Inf.* **2025**, *14*, 269. [CrossRef]
4. Fitzpatrick, M.; Hedley, N. Review of the State of Practice in Geovisualization in the Geosciences. *Front. Earth Sci.* **2024**, *11*, 1230973. [CrossRef]
5. Häberling, C.; Bär, H.; Hurni, L. Proposed Cartographic Design Principles for 3D Maps: A Contribution to an Extended Cartographic Theory. *Cartogr. Int. J. Geogr. Inf. Geovisualization* **2008**, *43*, 175–188. [CrossRef]
6. Shepherd, I.D.H. *Travails in the Third Dimension: A Critical Evaluation of Three-Dimensional Geographical Visualization*. In *Geographic Visualization*; John Wiley & Sons: Hoboken, NJ, USA, 2008; pp. 199–222. ISBN 978-0-470-98764-3.
7. Bleisch, S. 3D geovisualization—Definition and structures for the assessment of usefulness. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2012**, *I-2*, 129–134. [CrossRef]
8. Neuville, R.; Poux, F.; Hallot, P.; Billen, R. Towards a normalised 3D Geovisualisation: The viewpoint management. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2016**, *IV-2-W1*, 179–186. [CrossRef]
9. Zejdlik, J.; Vozenilek, V. Methods of 3D Geovisualization of Thematic Data in the Context of Graphic Variables. *Int. J. Cartogr.* **2025**, *12*, 195–210. [CrossRef]
10. Zejdlik, J.; Vozenilek, V. Evaluation of 3D Geovisualization of Volumetric Geospatial Data in the Form of Horizontal Planes Using Selected Software. *Geogr. Cassoviensis* **2024**, *18*, 5–25. [CrossRef]
11. Bertin, J. *Sémiologie Graphique: Les Diagrammes, Les Réseaux, Les Cartes*; Gauthier-Villars: Paris, France, 1967.
12. MacEachren, A.M. *How Maps Work: Representation, Visualization, and Design*, 1st ed.; Guilford Press: New York, NY, USA, 2004; ISBN 978-1-57230-040-8.
13. Morrison, J.L. A Theoretical Framework for Cartographic Generalization with the Emphasis on the Process of Symbolization. *Int. Yearb. Cartogr.* **1974**, *14*, 115–127.
14. Roth, R.E. Visual Variables. In *International Encyclopedia of Geography*; John Wiley & Sons: Hoboken, NJ, USA, 2017; pp. 1–11. ISBN 978-1-118-78635-2.
15. Roth, R. Cartographic Interaction Primitives: Framework and Synthesis. *Cartogr. J.* **2012**, *49*, 376–395. [CrossRef]
16. Herman, L.; Stachoň, Z. Comparison of user performance with interactive and static 3D visualization—Pilot study. *ISPRS Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2016**, *XLI-B2*, 655–661. [CrossRef]
17. ISO 9241-11:2018; Ergonomics of Human-System Interaction—Part 11: Usability: Definitions and Concepts. International Organization for Standardization: Geneva, Switzerland, 2018.
18. Çöltekin, A.; Heil, B.; Garlandini, S.; Fabrikant, S.I. Evaluating the Effectiveness of Interactive Map Interface Designs: A Case Study Integrating Usability Metrics with Eye-Movement Analysis. *Cartogr. Geogr. Inf. Sci.* **2009**, *36*, 5–17. [CrossRef]
19. Roth, R.E.; Ross, K.S.; MacEachren, A.M. User-Centered Design for Interactive Maps: A Case Study in Crime Analysis. *ISPRS Int. J. Geo-Inf.* **2015**, *4*, 262–301. [CrossRef]
20. Roth, R.E.; Harrower, M. Addressing Map Interface Usability: Learning from the Lakeshore Nature Preserve Interactive Map. *Cartogr. Perspect.* **2008**, *60*, 46–66. [CrossRef]
21. UX: Designing the User Experience—A Commission of the International Cartographic Association. Available online: <https://use.icaci.org/> (accessed on 5 June 2026).

22. Vanicek, T.; Vojtechovska, M.; Popelka, S. A Scoping Review of Eye-Tracking Studies on the Usability Evaluation of Interactive Geovisualisations. *Int. J. Human–Computer Interact.* **2026**, 1–26. [[CrossRef](#)]
23. MacEachren, A.; Kraak, J.A. Research Challenges in Geovisualization. *Cartogr. Geogr. Inf. Sci.* **2001**, 28, 3–12. [[CrossRef](#)]
24. Kraak, M.-J. Geovisualization Illustrated. *ISPRS J. Photogramm. Remote Sens.* **2003**, 57, 390–399. [[CrossRef](#)]
25. PERUN—Prediction, Evaluation and Research for Understanding National Sensitivity and Impacts of Drought and Climate Change for Czechia. Available online: <http://www.perun-klima.cz> (accessed on 2 March 2026).
26. Popelka, S.; Voženílek, V. Specifying of Requirements for Spatio-Temporal Data in Map by Eye-Tracking and Space-Time-Cube. In *Proceedings of the International Conference on Graphic and Image Processing (ICGIP 2012), Singapore, 5–7 October 2012*; SPIE: Bellingham, WA, USA, 2013; Volume 8768, p. 974.
27. Kiefer, P.; Giannopoulos, I.; Raubal, M.; Duchowski, A. Eye Tracking for Spatial Research: Cognition, Computation, Challenges. *Spat. Cogn. Comput.* **2017**, 17, 1–19. [[CrossRef](#)]
28. Laugwitz, B.; Held, T.; Schrepp, M. Construction and Evaluation of a User Experience Questionnaire. In *Proceedings of the HCI and Usability for Education and Work*; Holzinger, A., Ed.; Springer: Berlin/Heidelberg, Germany, 2008; pp. 63–76.
29. Sweller, J. Cognitive Load Theory. In *Psychology of Learning and Motivation*; Academic Press: Cambridge, MA, USA, 2011; Volume 55, pp. 37–76.
30. Hernandez, T. Visual Decisions: Geovisualisation Techniques within Retail Decision Support. *J. Target. Meas. Anal. Mark.* **2005**, 13, 209–219. [[CrossRef](#)]

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