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Feasibility of the Space–Time Cube in Temporal Cultural Landscape Visualization

Edyta P. Bogucka * and Mathias Jahnke

Chair of Cartography, Department of Civil, Geo and Environmental Engineering, Technical University of Munich, Arcisstraße 21, 80333 München, Germany; mathias.jahnke@tum.de

* Correspondence: e.p.bogucka@tum.de; Tel.: +49-89-2892-2830

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Abstract: Change acts as an inherent characteristic of the landscape, and expresses dynamic interactions between its tangible and intangible elements. While the documentation and analysis of spatiotemporal patterns have been broadly discussed, major challenges concern the design of task-oriented, user-friendly landscape visualizations. Geographic information system (GIS) techniques and approaches from visual analytics may bring solutions to those questions. This paper considers the milestone documents for the representation of cultural heritage, and proposes a workflow for assessing the feasibility of the space–time cube concept in landscape representation. The usability of the visualization was examined during the interview with domain experts and potential interdisciplinary users. The evaluation session covered benchmark tasks, feedback, and eye-tracking. The performance of the space–time cube was compared with another spatiotemporal visualization technique and measured in terms of correctness, response time, and satisfaction. The Royal Castle in Warsaw, which was registered in 1980 as a part of Warsaw's World Heritage Site of United Nations Educational, Scientific and Cultural Organization (UNESCO), served as the case study. The user tests show that the designed space–time cube excels for the completion rate; however, more time is required to provide answers to question tasks focusing on comparisons. Together, the case study and feedback from domain experts and participants demonstrate the benefit of the space–time cube concept in designing landscape visualizations.

Keywords: space–time cube; historical GIS; spatiotemporal visualization; visual analytics; virtual exploration; geovisualization; eye-tracking

1. Introduction

The European Parliament announced 2018 as the European Year of Cultural Heritage, as this is increasingly becoming a vital factor in socioeconomic development. Resources inherited from the past include many forms, among them monuments, sites, and landscapes [1]. Reflection on the conservation of cultural heritage proves that digital resources such as texts, images, videos, and records can also serve as a method of promotion and preservation. Cartography, with its fundamental mission of mapping landscapes, greatly contributes to the visibility of the cultural heritage, integrating elements such as its spatial location and uniqueness into visual stories.

Inherent elements of the environment are especially interesting for cartographic visualizations. Landscape objects such as buildings, by nature, have a spatial location and a date of creation, reconstruction, and/or destruction. Most of the current data also possess a spatial component [2], and their creation date is stored within the database systems. Mapping the spatial location of the landscape elements together with their life span (creation–destruction) and data of different qualities can provide new insights into the development of a city or the landscape in general, if they are visualized in an appropriate way. To ensure common standards in heritage interpretation and presentation, heritage professionals prepared the general guidelines to be applied to historical sites. The Charter for the Interpretation and Presentation of Cultural Heritage Sites [3] issued by the International Council on Monuments and Sites (ICOMOS) describes representation as a part of the overall process of heritage conservation and management. The third cardinal principle of the charter—giving context information—is particularly important for developing spatiotemporal visualizations. The principle states that, "the surrounding landscape, natural environment, and geographical setting are integral parts of a site's historical and cultural significance, and, as such, should be considered in its interpretation". As for the temporal component, representations should clearly indicate and date the successive development phases and any conditions that had caused or influenced the site changes. Moreover, contributions of all of the historical time periods should be respected and incorporated into the visualization tool, without consciously avoiding or neglecting the particular epochs. The charter stresses the important role of collaboration between representation designers and different stakeholders such as heritage professionals, researchers, authorities, and any users interested in the heritage topic. This collaboration aim to share expertise, opinions, needs, and future perspectives for domain-specific use cases. The developed representation should have an educational potential for different groups of end users and use cases. The charter also mentions a few examples of educational usage, for instance in school curricula, lifelong learning programs, events, and information media.

To ensure that the visualization techniques are applied with great care and rigor, every computer-based visualization should follow the guidelines of the London Charter for the Computer-Based Visualization of Cultural Heritage [4]. This milestone document gives particular attention to user-centered design. Each representation at a heritage site should be easily understood and allow users to give feedback. It should be clear to them what the purpose and actual content of the visualization is—whether it presents the existing state, an evidence-based restoration, or a hypothetical reconstruction of the site. User-centered visualization should also communicate the extent and type of uncertainties regarding historical development, such as a lack of evidence or questionable evidence. Finally, it should be carefully designed based on the actual user needs to maximize possible benefits.

The London Charter gives an example of the study of change over time, which could be useful in interpreting and understanding the cultural heritage. To achieve these goals, approaches from visual analytics—spatiotemporal visualization techniques in particular—seem to be suitable. A common approach for depicting the trajectories (paths) of moving objects is the space–time cube (STC) representation [5]. This well-known visualization technique was developed by Hägerstraand [6] and originates from the humanities research investigating human movements in space and time [7]. The two-dimensional geographic space is represented by the base of the cube (x-, y-plane) [8], while the time is shown by the vertical dimension (z-axis). Spatial and temporal dimensions can be additionally adjusted to cover specific time spans or certain areas [9]. The space–time cube concept is nowadays integrated into different visual analytics frameworks, and serves as an interactive data-mining tool [8].

During a recent time period, researchers investigated further space–time cube applications for movement and event detection, as well as for methods to enhance the cube's usability in connected application domains. The behavior of car drivers following similar routes was analyzed by Andrienko et al. [5]. Gatalsky et al. [8] applied the STC visualization approach to detect spatiotemporal clusters within an earthquake series in Marmara, Turkey. The visualization of temporal characteristics of archeological sites was examined by Kraak and Koussoulakou [10], while Huisman et al. [11] extended the cube concept to investigate historical events in Puerto Rico between 600–1500 AD. Based on the storytelling concepts, Eccles et al. [12] built a tool for displaying geohistorical events in a space–time cube environment. Windhager et al. presented how to use the cube's concept to organize museum exhibitions [9]. The series of different STC applications impressively shows the diverse applicability of this approach.

Beside the visualization itself, its usability should be considered as one of the main issues when developing a thoughtful user interface. Design workflow should ensure that the intended user is satisfied and able to obtain adequate information. Therefore, usability describes the system's ability to aid the user in retrieving the desired information [13,14]. Blade and Padgett [15] specified the usability as "the effectiveness, intuitiveness and satisfaction with which specified users can achieve specified goals in particular environments, particularly interactive systems". The International Organization for Standardization [16] defines usability as the "extent to which a system, product, or service can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context". In conjunction with memorability and learnability [13], those five different quality components provide a framework through which the usability can be quantified. Different methods such as questionnaires, user observations, thinking aloud, and eye-tracking can be used to estimate a usability measure [17–21]. The influence of display design and user characteristics for geovisual application using eye-tracking were investigated by Maggi et al. [22]. Several studies compared the usability of the space–time cube and other visualization techniques, such as animations [23], single static maps [23,24], multiple static maps [23], two-dimensional (2D) and three-dimensional (3D) visualizations [25,26], dot animation, and density maps [27]. Common practices in usability assessment are benchmark tasks: actions that users want to perform to retrieve information. Those actions should be selected carefully to cover a variety of use cases for a designed system. The type-by-task taxonomy of Shneiderman [28] suggests the following benchmark tasks: overview, zoom, filter, details-on-demand, relate, history, and extract. Andrienko et al. [29] propose the operational task typology for interactive visualizations. In their approach, tasks are differentiated based on the cognitive operation involved, the search target, and the search level. Kveladze et al. [7,30] focused on the user-centered design of space–time cube applications following a problem–solution–evaluation approach to improve cartographic design and data exploration processes. In general, the visualization design, the provided interactivity, and the usability together form a suitable and useful visualization application from which the user can generate knowledge to support decision-making.

In one of its principles, the London Charter [4] addresses the strong need for researchers to perform a systematic, documented evaluation of "the suitability of visualization methods for particular use cases". One of the main gaps in our knowledge about the space–time cube is that it lacks insights from different end users. The information about end users' typical tasks and preferences is useful not only to create a visually appealing tool, but also to ensure that their exploration tasks will be performed efficiently and correctly. With these objectives in mind, our study investigates to what degree the space–time cube is a feasible tool for cultural heritage visualization. The proposed workflow presents how to identify specific problems and errors in the space–time cube design for landscape representation. Based on the insights from the eye-tracking tests and interviews, the usability of the visualization can be improved. Although the concept of the space–time cube is broadly used in geospatial domains [5,7,8,10–12], to the best of the authors' knowledge, this technique has not been used yet to depict historical landscapes, and is not common in cultural heritage representations. The proposed approach was tested on the space–time cube solely designed to present the history of the Royal Castle in Warsaw, Poland. However, this workflow can be further used to evaluate space–time cubes for other cultural heritage sites.

The remainder of the paper is organized into five sections. In the following section, we propose the workflow for testing the space–time cube's usability for cultural heritage visualizations. The evaluation approach covered benchmark tasks, feedback, and eye-tracking tests. We also introduce the case study of the Royal Castle in Warsaw, and provide a brief overview of designing a dedicated space–time cube. Section 3 summarizes the results of this work. It provides basic usability metrics, users' impressions, and users' insights into their virtual exploration strategies. The implementation and evaluation of the space–time cube technique from a usability perspective is further discussed in Section 4. We reserve the final Section 5 to reflect more broadly on landscape visualizations and discuss the potential directions of future developments.

2. Materials and Methods

2.1. Methodology

The workflow followed the principles of the London Charter [4] and the ICOMOS Charter for the Interpretation and Presentation of Cultural Heritage Sites [3]. The setup aimed to serve as a paradata: a record of human processes of understanding and interpreting historical data in the space–time cube. The methodology consisted of the interviews with the domain experts and the representative target users. In the first part of the workflow, we asked domain experts from the Royal Castle in Warsaw to identify typical spatiotemporal visualizations representing this heritage site. A common practice is to use the slider-based visualizations, in which users can move a time slider to see different historical maps changing over time. However, the idea of the space–time cube was new to the experts. After familiarizing themselves with this visualization concept, the experts advised the visual appearance of the cube, and its functionalities to be implemented. Based on their experience in promoting cultural heritage, experts formulated the most common types of questions asked by the tourists while visiting the site. Detailed benchmark tasks were designed to identify people's strategies about exploring spatiotemporal datasets—specifically, datasets on historical buildings and natural features such as rivers. Proposed tasks were further used to test the usability of the designed cube. The second part of the workflow consisted of a combination of individual interviews and eye-tracking tests with the target users. The historical geodata on the history of the Royal Castle in Warsaw were presented to the participants in two visualizations: the slider-based visualization and the space–time cube. The users performed the benchmark tasks suggested by the domain experts and evaluated the space–time cube and the slider-based visualization in terms of appearance, intuitiveness, and usage satisfaction. The gaze patterns recorded with the eye-tracking devices helped to identify the main problems in the interface design of the applications. This case study serves as an example on how to use the space–time cube concept for depicting historical landscapes, and how to improve this application with feedback from the users.

2.2. The Case Study Data

For the purposes of this research, we acquired access to various open data portals. We collected the appropriate imagery and descriptive materials from which the necessary datasets for exemplary spatiotemporal visualizations were created. The detailed workflow, from the paper maps to the 3D buildings, as well as methods applied to visualize the space–time relationships of the castle's buildings and surrounding objects, are described in more detail hereafter.

The Royal Castle in Warsaw—the former residence of the Polish monarchs, with its side buildings and surrounding gardens—served as a case study for our analysis (Figure 1). The castle's eventful history covers a time span of 600 years, from its initial construction in the 14th century until now, including a large-scale extension within the 16th and 17th centuries, complete destruction during World War II and reconstruction, which started in 1971. Only nine years later, the rebuilt castle became a part of Warsaw's UNESCO World Heritage Site. This history makes the castle an outstanding object for the investigation of long-lasting changes over time [31].

The input materials for this contribution were based on freely available resources, which include online repositories as well as open source mapping and visualization tools. To create a suitable reference dataset, historical maps and aerial images were used (Figure 2). The National Library in Poland, the Office of Surveying and Cadastre of Warsaw, and additionally the European Collections Project, served primarily as the main sources of those datasets.

Georeferencing the historical maps was the first step of the workflow to obtain 3D-modeled, digital footprints of the castle at different times throughout the centuries. As the root mean square error (RMSE) was dependent on the year in which the maps were manufactured and the maps' scales, it varied from 1.8 m to 10.2 m. This can imply an impact on the visualization and interpretation of different landscape states. Therefore, the datasets that were derived from maps dating between 1390–1590 could have an increased uncertainty, which can lead to the questionable existence and location of some uncertain medieval castle parts. From the georeferenced maps, the buildings' footprints were manually digitized, and enriched with the metadata by using QGIS 2.16 software. Information concerning the different historical objects included temporal frames such as construction and destruction times, as well as additional descriptive hints. Afterwards, the datasets were exported to exchange formats to be further used in a web-based slider application and a web-based space–time cube.

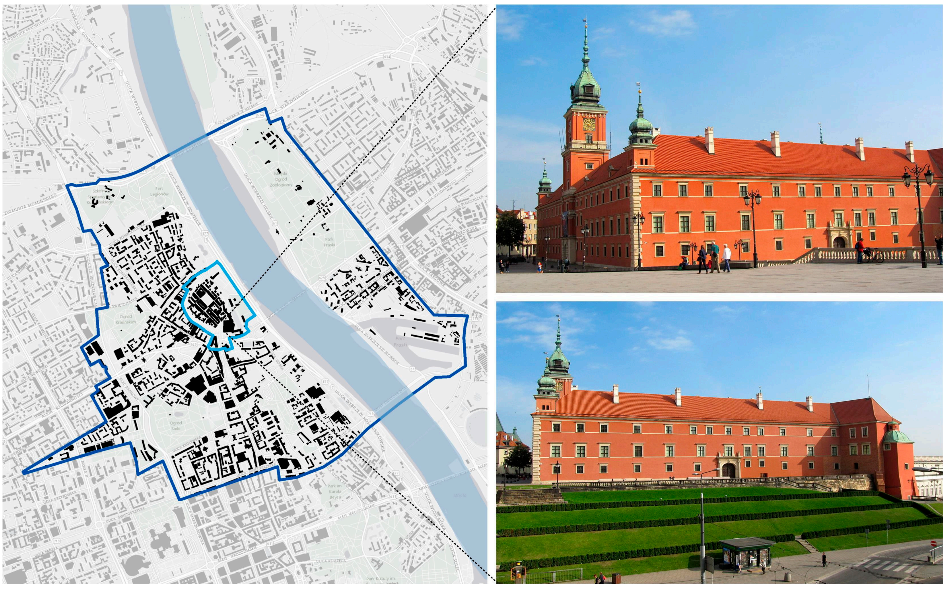


Figure 1. The map of Warsaw showing the location of the Royal Castle in the context of the UNESCO World Heritage Site (the inner ring) with its buffer zone (the outer ring). On the right, two photographs of the castle are shown (images by Geociekawostki, distributed in Wikimedia Commons under a CC-BY-SA-3.0-PL license).

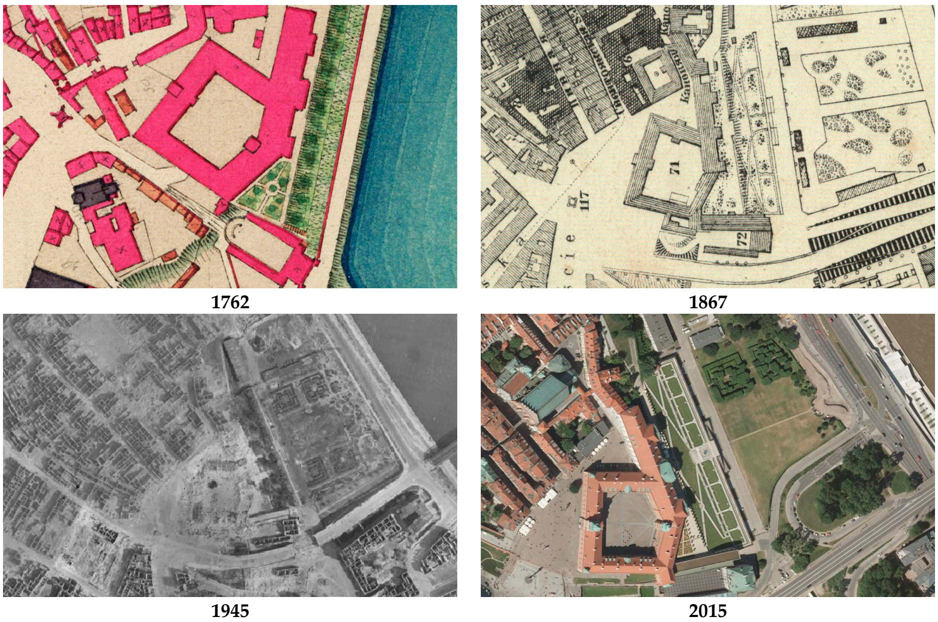


Figure 2. The Royal Castle in Warsaw presented on the historical maps from 1762, 1867, an aerial image from 1945, and an orthophotomap from 2015 (map images distributed by the National Library in Poland under a public domain license; an aerial image and an orthophotomap distributed by the Office of Surveying and Cadastre of Warsaw as public information).

For visualization purposes, Cesium 1.34 was used, which is a JavaScript library for interactive geospatial visualization in the web browser that relies on open standards such as HTML, CSS, and JavaScript. This allows users to integrate this visualization into any other webpage. Cesium enables multiple interactions such as navigation through the virtual globe with zooming, panning, and rotating. Cesium also provides a build-in time slider to show buildings existing only at a specific point in time or over a time span. This ensures the simultaneous view of space and time, which is an important feature for visualizing landscape continuity.

2.3. Design of the Case Study Visualization

The appearance and functionalities of the spatiotemporal applications were designed based on the needs assessment, which was conducted with two institutes from the Royal Castle (Centre for Castle Information—Press Office and Department of Archaeological Researches). In total, four domain experts from the fields of landscape history, marketing, and archaeology were interviewed. They identified the landscape features to be represented in the cube, suggested the functionalities to be implemented, and proposed research questions to be answered [31]. The most important suggestions summarized from the interviews were to use the simplification approach and limit the presented historical objects. For greater clarity, they recommended grouping the landscape elements into the following classes: buildings, defensive walls, gardens, and water bodies. Upon the findings from the interviews, two landscape visualizations were designed, which handle the representation of the time component in different ways:

- Slider-based visualization: spatial visualization of 3D objects with a temporal component provided by the built-in time slider.
- Space–time cube: four-dimensional spatiotemporal visualization, where the temporal component is represented both by the time slider and a vertical z-axis.

The slider-based visualization enables the exploration of the temporal dimension of the study area by using the built-in timeline. Clicking and dragging on the time slider shows different points (timestamps) and periods in time. The 3D historical objects are clamped to the terrain, which is textured with an orthophotomap of the region to offer a more realistic impression for the user (Figure 3a). The content of the visualization relies on the selected time period and is adjusted accordingly if the time period changes. The dataset can be explored by the aforementioned navigation functionalities of the application.

Within the space–time cube, the buildings are visualized differently (Figure 3b). Historical features are placed vertically along the z-axis on horizontal x and y-planes in the form of space–time prisms. The z-axis indicates two units of measurement simultaneously: (1) the space–time prisms are ordered chronologically, and (2) the building height follows a continuous scale.

Each prism represents the landscape in a predefined timespan, starting from 1300–1400 AD. The oldest historical features are placed further away from the terrain at the upper boundary of the space–time cube. The prism representing the most contemporary (1901–2000) landscape is clamped to the ground level. In this case, the prisms are equally spaced, and represent 100 years (one century). To provide the perception of the stability of the 3D landscape objects, each prism is visualized with the ground slice indicating the study area. Users can explore the information space in two ways. First, they can change their perspective, beginning with an overview, through zooming, panning, and rotating the cube. Secondly, they can point at a certain date on the time slider to adjust the content of the cube. Within the space–time cube, the time slider serves both as a spatial and temporal exploration tool. The map panel will present only those time prisms that existed in the study area until the selected timestamp. Choosing the date of 1650 will display four prisms (1330–1400, 1401–1500, 1501–1600, and 1601–1700). To see the overview of all of the historical objects that have ever existed in the study area, users need to move the time selection to the 20th century.

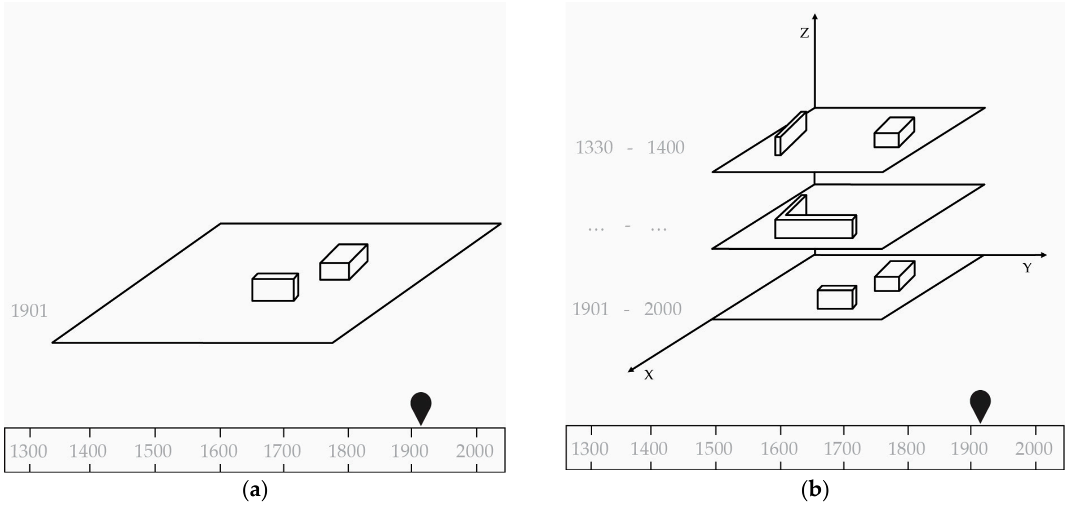


Figure 3. General design approach for spatiotemporal visualizations in (**a**) a slider-based visualization; and (**b**) a space–time cube.

Applications share the same interface controls, navigation, and symbology, but require different data exploration strategies for landscape change detection. Based on the components of spatiotemporal information and the test procedure, interface controls were organized into four interface panels (Figures 4 and 5):

1. **Map panel**—represents the spatial extent of exploration space and encompasses the area of the Old Town in Warsaw. The background map serves as a reference layer for displaying geohistorical data, and gives users a better feeling and understanding of the spatial context. The orthophotomap in the panel was acquired via web map services of Bing Aerial Maps. The map panel enables basic interactivity operations: panning, zooming, and view rotation. The user can also change the view angle and return to the base view of the old town. Operations are executed by clicking on and moving the mouse, and are additionally described in the navigation information button.
2. **Timeline panel**—provides controls for temporal (slider-based visualization) and spatiotemporal (space–time cube) exploration. Users can freely interact with the slider. First, users can select a timestamp of interest by clicking on the slider. Secondly, they can see landscape changes during the interval, and then simply drag the timestamp selection to another timestamp. In the applications tested, no opportunity was provided for the users to change the temporal units of analysis. The shortest perceptible time unit was set to two years by default.
3. **Attribute panel**—provides simple controls for attribute exploration—map legend and pop-up window with information on the object. Landscape features are visualized with a memorable, easily associative color scheme and category label. For each object, the info-box provides a short description, pointing out the name of the feature, its characteristics, or an interesting historical fact. Information is retrieved after users click on the object of interest. The only form of interaction with the attribute panel is the camera symbol, on which users can click to focus the camera on a particular object.
4. **Test panel**—serves as the organization panel for testing procedures. Contains operational functionalities such as: display visualization, "Start test", move to "Next question", and "Finish test". Clicking on the "Feedback" button enables user to view the second visualization.

Figure 4. Interface of the slider-based spatiotemporal visualization of the Royal Castle in Warsaw.

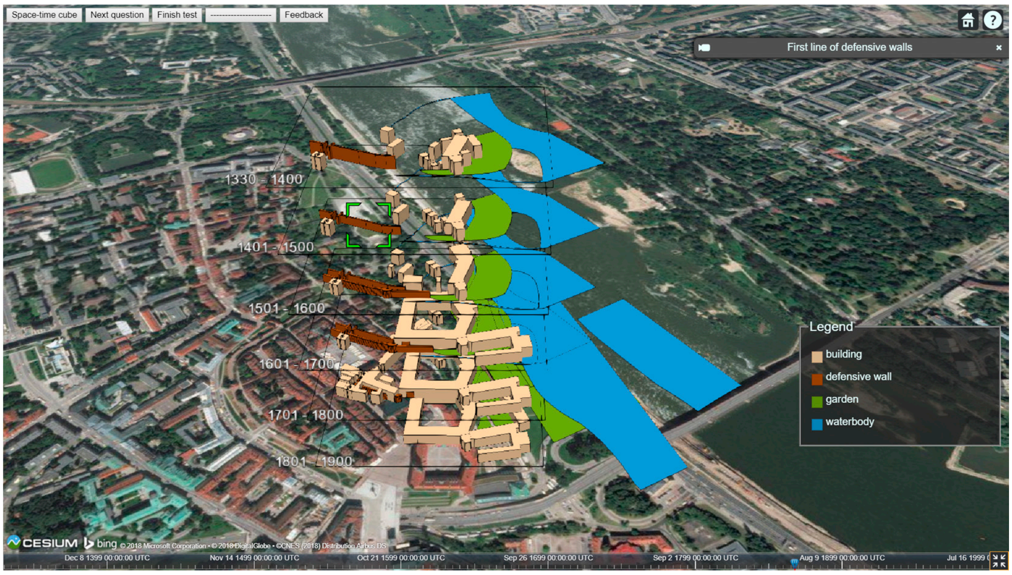


Figure 5. Interface of the space–time cube for the Royal Castle in Warsaw.

2.4. Benchmark Tasks and Usability Metrics for Spatiotemporal Visualizations

The domain experts from the Royal Castle suggested a possible range of tasks for landscape change detection. From their perspective, tasks of particular importance were: event-based temporal queries (“What happened during this period?”), quantity change detection (“How many objects were built?”, “What is the direction of changes?”), and free dataset exploration (“How did the landscape look in . . . ?”). Based on this insight, as well as an operational task taxonomy for spatiotemporal visualizations [29] and the characteristics of space–time models [32], the following benchmark tasks were developed:

1. Question 1: Indicate in which timespan the greatest number of buildings was destroyed? (Single choice, possible answers: (A) 1600–1650; (B) 1360–1450; (C) 1805–1820; (D) 1930–1950).
2. Question 2: Find the location of the Grodzka Tower, one of the oldest parts of the castle.
3. Question 3: Mark timespan(s) in which the Grodzka Tower existed in the study area.

(Multiple choice, possible answers: (A) 1980–1990; (B) 1950–1965; (C) 1480–1530; (D) 1610–1640)

4. Question 4: Give the name of the oldest building around the Royal Castle in 1795.

Each of the proposed tasks differed in terms of the query type, search output, cognitive operations involved, and knowledge discovery strategies. Q1 focuses on quantitative change perceptions. Users were asked to assess the magnitude of destructive events over multiple time periods. According to the task, they were expected to count destroyed buildings in given timespans and choose one time during which the greatest number of objects was devastated. Q2 is an exploratory task, in which users were not given a clear starting point from which to find the tower. Additional information on the tower's age added just a subtle hint to start either from the latest time point (the tower is a part of the present castle) or the earliest one (the tower is the oldest part of the castle). This leads to the development of particular search strategies, which differ based on the participants and the application that they use to retrieve the information. To cover another possibility—existence and non-existence—after finding the tower, users were supposed to track its presence in the study area. During the time investigated, the tower was incorporated from being a stand-alone building into the main castle's structure. Although Q1 and Q3 seem to be similar, different cognitive operations need to be performed by the users. Q1 focuses on change comparison, whereas Q3 focuses on the identification of a condition. The last task is a compilation of identification and comparison operations. First, participants needed to identify buildings surrounding the castle, then compare their age, and finally identify the oldest one. A summary of the benchmark tasks proposed in our usability study is presented in Table 1.

Table 1. Benchmark tasks to assess the usability of spatiotemporal visualizations: the slider-based visualization and the space–time cube.

Benchmark Task Characteristics	**Question 1:** Indicate in which timespan the greatest number of buildings was destroyed	**Question 2:** Find the location of the tower	**Question 3:** Mark timespan(s) in which the tower existed in the study area	**Question 4:** Give the name of the oldest building around the castle in 1795
Query type [1]	Change (quantity)	State (quality)	State (quality)	State (quality)
Search output [1]	Time—multiple choice	Location—single choice	Time—multiple choice	Attribute—single choice
Cognitive operation [2]	Comparison	Identification	Identification	Identification Comparison
Search task with respect to time [2]	General (search in time intervals)	General (search in time intervals)	General (search in time intervals)	Elementary (search in a timestamp)
Search level [2] with respect to time and object [2]	General (subset of objects)	Elementary (individual object)	Elementary (individual object)	General (subset of objects)

[1] classified based on Pequet [32]; [2] classified based on Andrienko et al. [29].

The aim of the experiment was to determine the following metrics encompassing three components of usability:

1. Effectiveness—expressed by the completion rate. This binary metric states whether users accomplish the task goal, where 0 = task failure and 1 = task success.
2. Efficiency—measured as the solving task time. It is the time that the participant needed to successfully complete or quit the task.
3. Satisfaction—searching strategies and scan patterns, feedback (lists of functionalities that users particularly liked about the visualization, and further improvements to be applied) and preference (choice of the preferred application).

The aforementioned metrics obtained during the evaluation cannot be generalized over the large set of user profiles, but they can be used to improve the product.

2.5. Interviews and Eye-Tracking Tests

The experiment was executed in a dedicated Eye-Tracking Lab of the Chair of Cartography, Technical University of Munich. The lab is fully equipped with a Gazepoint Eye-Tracking system for user experience testing. Gazepoint Control software enabled the calibration process, and Gazepoint Analysis (version 4.1.0) served as a recording and analysis environment. Users interacted with visualizations on a standard PC with a mouse and a 27-inch screen display.

Session duration was planned for 40 min; however, it was not limited in time. Participants were informed beforehand about the purpose of the study, the usability research methods to be applied (screen recording, eye-tracking, interview), and the experiment's safety and ethics. After this brief introduction, we calibrated the eye-tracker and collected key metrics about the participants. We asked users to provide information on their age, gender, current position, and domain background. Two additional questions concerned prior visits to the study area and familiarity with spatiotemporal visualizations. Therefore, users needed to describe themselves with one of the following statements: "I have never heard about spatiotemporal visualizations", "I have heard about spatiotemporal visualizations, but I have not used them yet", "I have heard about spatiotemporal visualizations and I have already used them". This helped us ensure that an unbiased perspective of the users was examined. Before the actual test session, users had the opportunity to familiarize themselves with the test environment. We demonstrated functionality, interface, and navigation possibilities, and let them explore the visualization for 5 min. During that time, they could ask for assistance or clarification.

The experiment consisted of two parts, and was conducted in two variations (Figure 6). Users were divided into two groups solving the same analytical tasks, with the use of either slider-based visualization or the space–time cube. The first part of the experiment was to find answers to the four aforementioned benchmark tasks. No auxiliary help was allowed. After finishing, users were asked to write down their opinion on the application: which functionalities they appreciated, and which needed further improvements. In the following part of the experiment, we presented the users with the second visualization, with the request only to explore the dataset, and provide once again the feedback on it. Finally, users were asked to point out the visualization that they found to be the most suitable for landscape change detection.

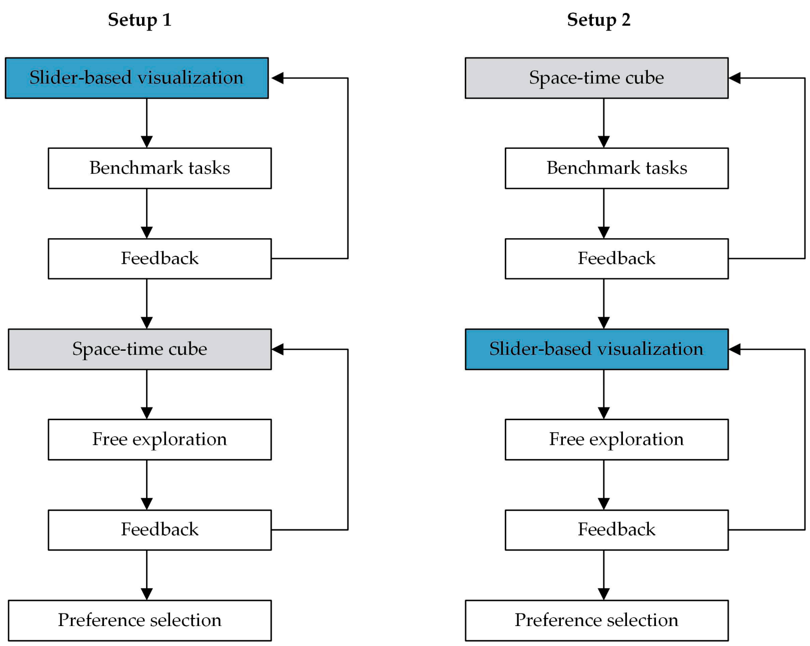


Figure 6. The overview of the experiment setups with two feedback loops on the presented spatiotemporal visualizations.

3. Results

The final study was executed on 21 participants aged between 21–40 years old. The first setup of the study was performed on 10 users (five women, five men), while the second setup had 11 users (five women, six men). Participants were purposefully sampled to ensure that they had previous knowledge of landscape concepts, geohistorical data, and mapping. Therefore, the following groups of users from related fields were recruited: undergraduate students of cartography and environmental engineering, graduate students doing research in economics, cartography, remote sensing, photogrammetry, and professional economics researchers.

To provide insight into the visualizations usability, the first component assessed was effectiveness, which was expressed as a task-completion rate. Figure 7 reports on this metric concerning the type of the application tested. Only two participants with an economics background answered all of the questions correctly. In our case study, users better perceived and assessed the extent of change using the more complex visualization environment. This difference was observed in Question 1, for which the failure rate for the slider-based visualization was significantly higher than for the space–time cube (82% versus 20%). All of the participants found the Grodzka Tower, so the completion rate for Question 2 was maximized (task success) for each application. Question 3, regarding the perception of conditions, was answered almost equally, resulting in a 45% success rate for the slider-based visualization and a 40% success rate for space–time cube. The identification of the oldest building around the castle (Q4) was easier with the cube (70% correct answers). In these benchmark tasks, the space–time cube proved to be a more effective tool. The overall success rate for the cube was 70%, while the slider-based visualization scored 50%. While solving the tasks, users encountered simple errors: object omissions and navigation slips.

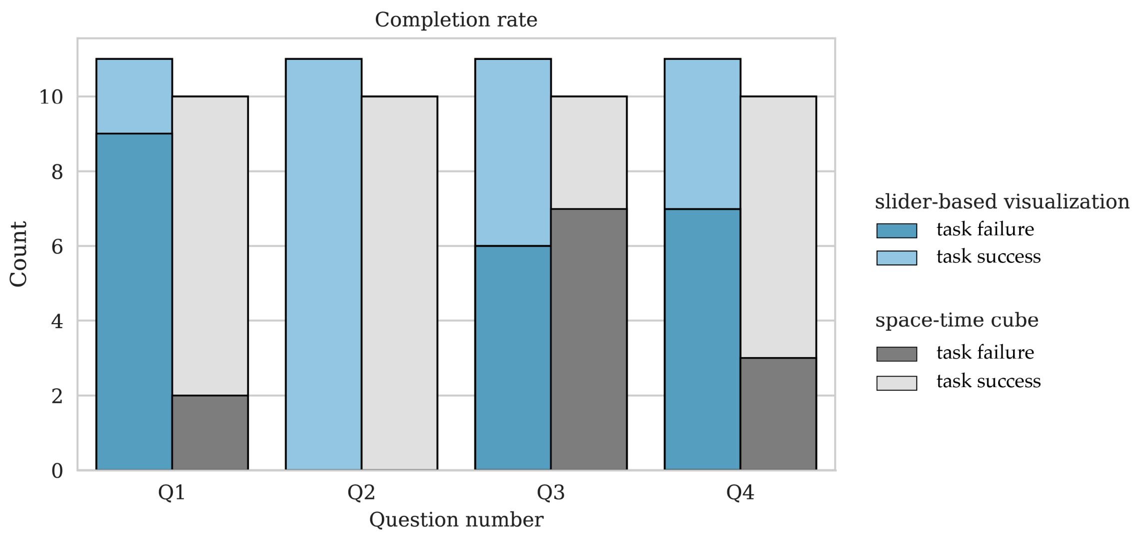


Figure 7. Completion rate for benchmark tasks for tested applications: the slider-based visualization and the space–time cube.

The time that users needed to successfully complete the benchmark tasks was recorded as an efficiency metric. The results were analyzed in relation to the application tested, the effectiveness, and the familiarity with spatiotemporal visualization techniques (Figures 8–10). The users performing tasks on the space–time cube needed more time to explore the dataset and finalize their answers. Removing the outliers, solving task times for the slider-based visualization were only slightly diversified: between 40–211 s for Q1, 50–168 s for Q3, and 48–199 s for Q4. The identification task Q2 was accomplished faster with the space–time cube (Figure 6). This form of visualization resulted also in more diverse task time patterns: from only 12–58 s for Q2, up to 62–398 s for Q1. Figures 9 and 10 give an overview of the effectiveness of the applications in correlation to time. For correct answers (Figure 9), the results are consistent with the findings from Figure 8. False answers on Q4 were obtained quicker with the space–time cube than with the slider-based visualization (Figure 10).

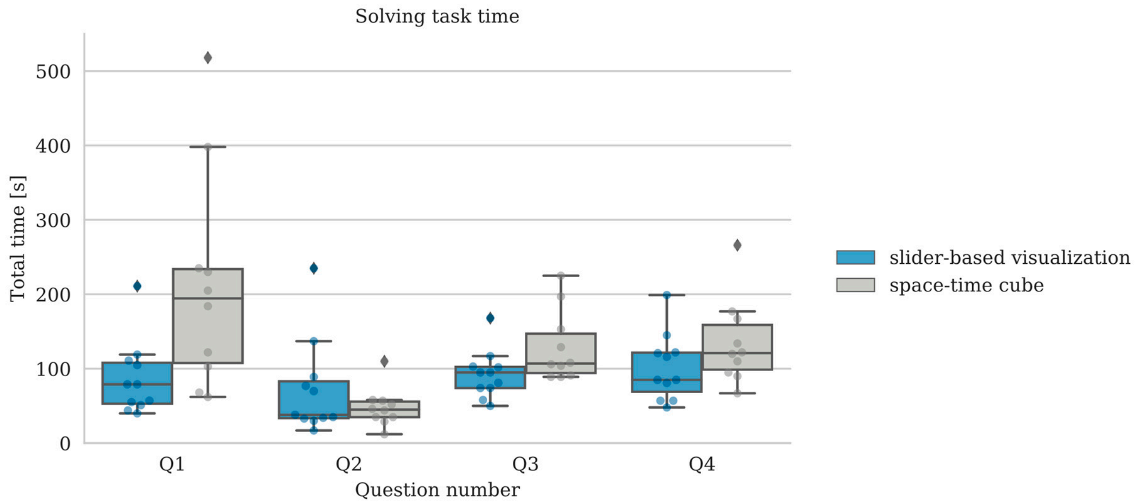


Figure 8. Solving task time for tested applications: the slider-based visualization and the space–time cube.

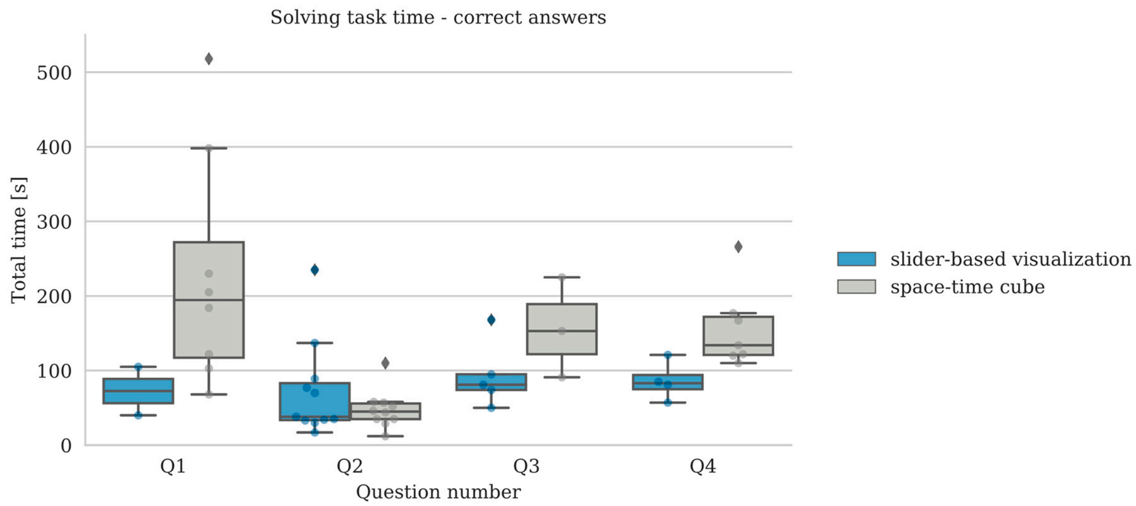


Figure 9. Solving task time to successfully complete the benchmark tasks. The users gave correct answers to the questions.

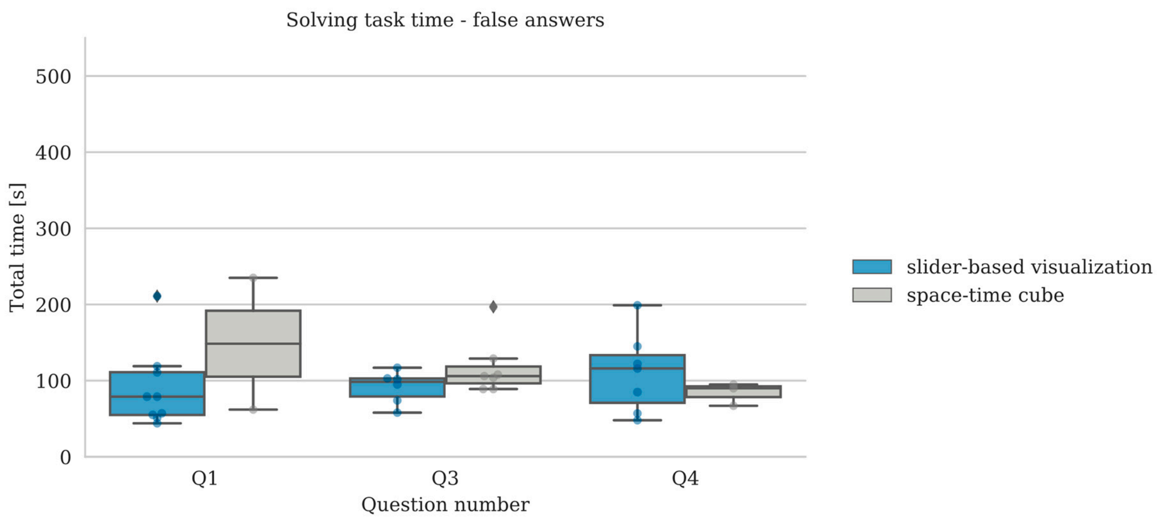


Figure 10. Solving task time to complete the benchmark tasks. The users gave false answers to the questions.

The previous knowledge of the interviewees could influence the solving task times. Therefore, the users assessed their familiarity with spatiotemporal visualizations by choosing one of the following categories: never heard about spatiotemporal visualizations (19%), heard about spatiotemporal visualizations, but had never used them (57%), and heard about spatiotemporal visualizations and used them (24%). The results of the query are presented in Figure 11. Some noticeable disagreement is evident: the users who were the most familiar with the concepts were not always faster in providing answers. Although they solved the identification task Q2 in a very short time, in completion rates, they performed significantly worse than users with no experience in spatiotemporal mapping (Figure 12). For all three groups, Q1 was reported as the most time-consuming task.

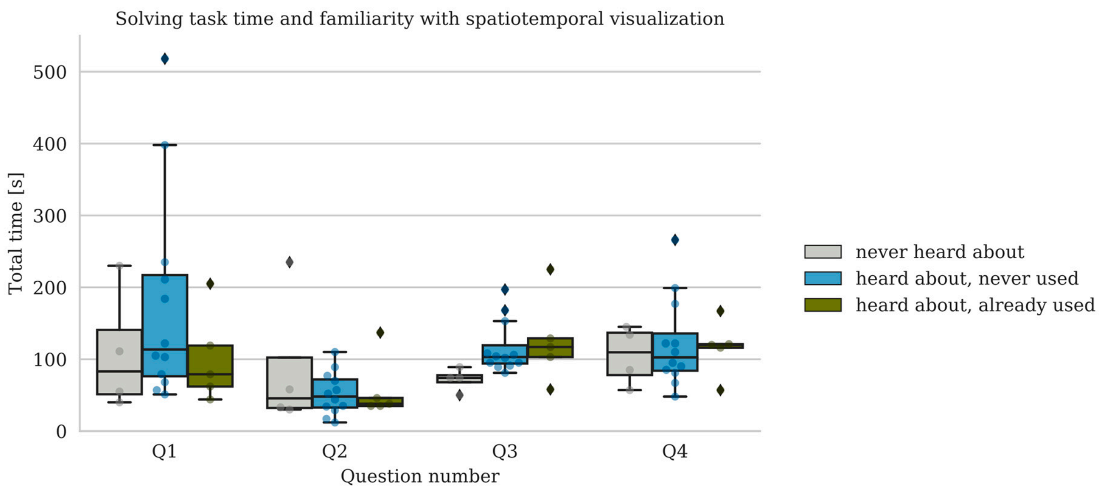


Figure 11. Solving task time grouped by questions and users' familiarity with spatiotemporal visualization techniques.

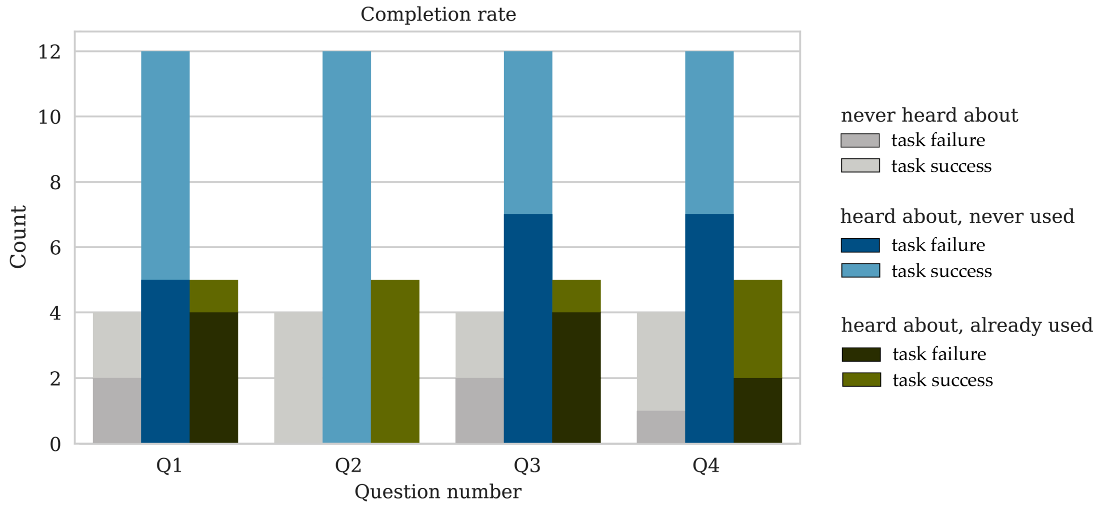
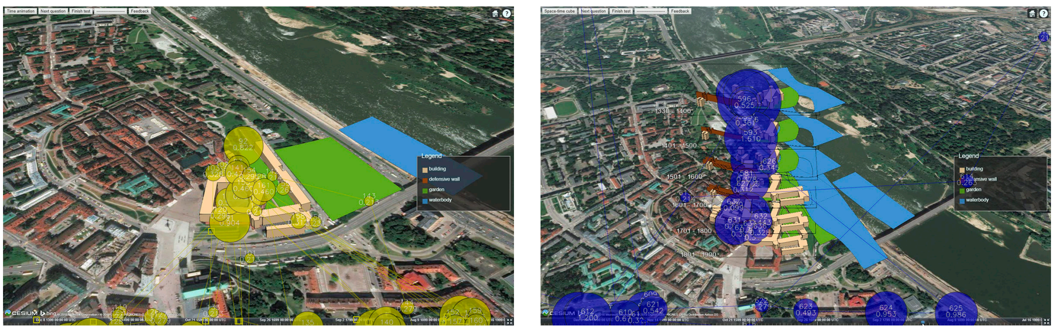


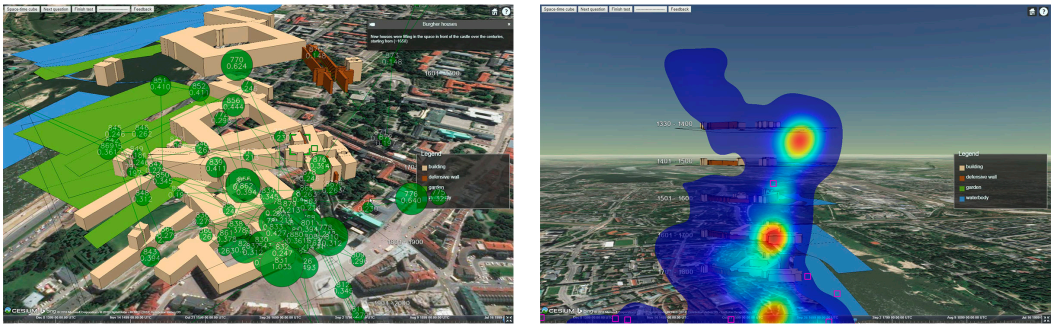
Figure 12. Completion rate for benchmark tasks grouped by questions and users' familiarity with spatiotemporal visualization techniques.

To investigate satisfaction as part of the usability, searching strategies for each user were recorded, analyzed, and grouped. The first strategy was to get the overview of the dataset and concentrate on the map panel. The temporal filtering happened when users clicked on the time slider to select a specific year. To get better insight into the datasets, users zoomed the view and clicked on the historical objects to see details-on-demand in the info-box. The last strategy was to observe the relationships between the historical objects and relate them to their location in space and time. The searching strategies for Q1 are compared in Figure 13. Triangle-shaped gaze patterns (Figure 13a,b) are an effect of overview and the temporal filter searching strategy. To assess the number of destroyed buildings in the timespan, users clicked on the time slider and focused on the study area. As this click-focus movement was performed several times, gazes and saccades shaped the triangular graph in the bottom part of the screen. This pattern was observed for both the slider-based visualization and the space–time cube. The following subfigures report other interesting search patterns, such as the zoom and relate operation (Figure 13c), and the overview and relate operation (Figure 13d), both of which were recorded only in the space–time cube.



(**a**) (**b**)

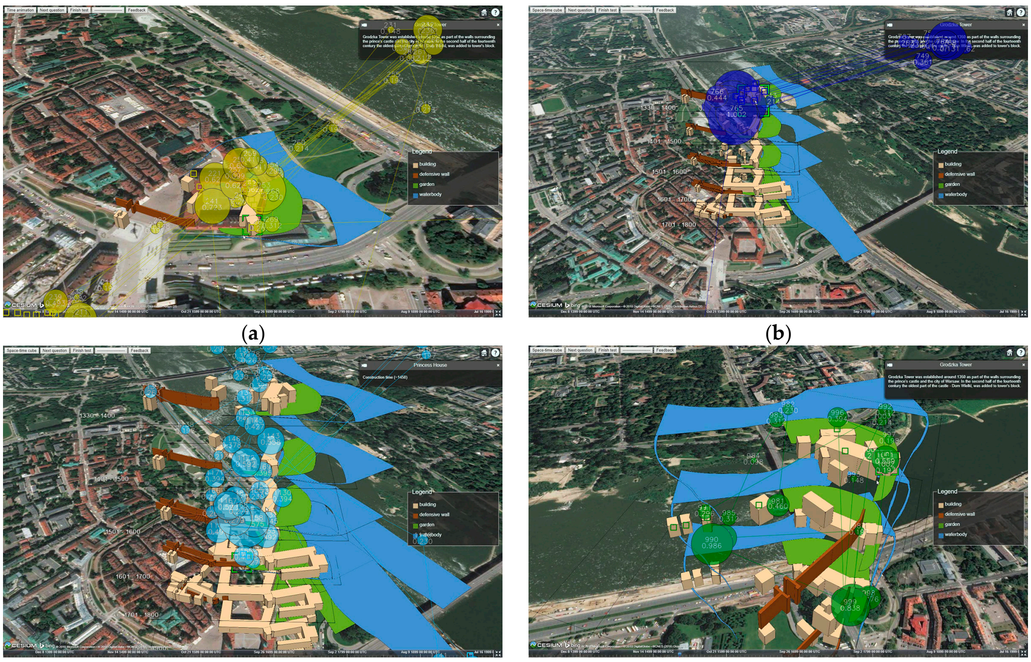
Figure 13. *Cont.*



(c) (d)

Figure 13. Searching strategies for Q1: (**a**) overview and temporal filter in the slider-based visualization; (**b**) overview and temporal filter in the space–time cube; (**c**) zoom and relate operations in the space–time cube; (**d**) overview and relate operations in the space–time cube.

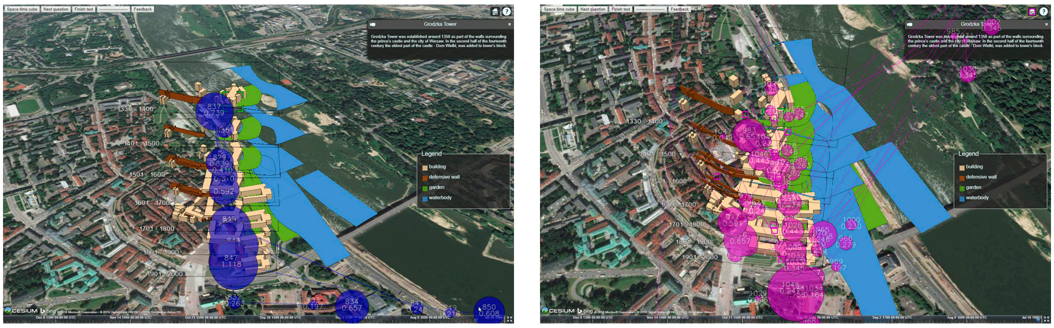
The second question focused on the identification of the Grodzka Tower. Users got the confirmation of success through the info-box, which displayed the name of the selected object. This enabled us to observe a specific gaze pattern in the upper right corner of the screen in both visualizations (Figure 14a,b). The gazes were located exactly between the info-box and the content of the cube. Participants using the time-slider visualization clicked on a selected timestamp, while participants using the space–time cube looked at the highest time slice. Both groups selected one historical object within a study area. To check whether their choice was correct, they looked at the info-box. This step was repeated several times until the tower was found. The following subfigures present other search patterns recorded in the space–time cube. Some users focused and selected objects not only in the highest time slice, but also in the slices beneath (Figure 14c). To make the study area more visible, some used the zoom option (Figure 14d).



(c) (d)

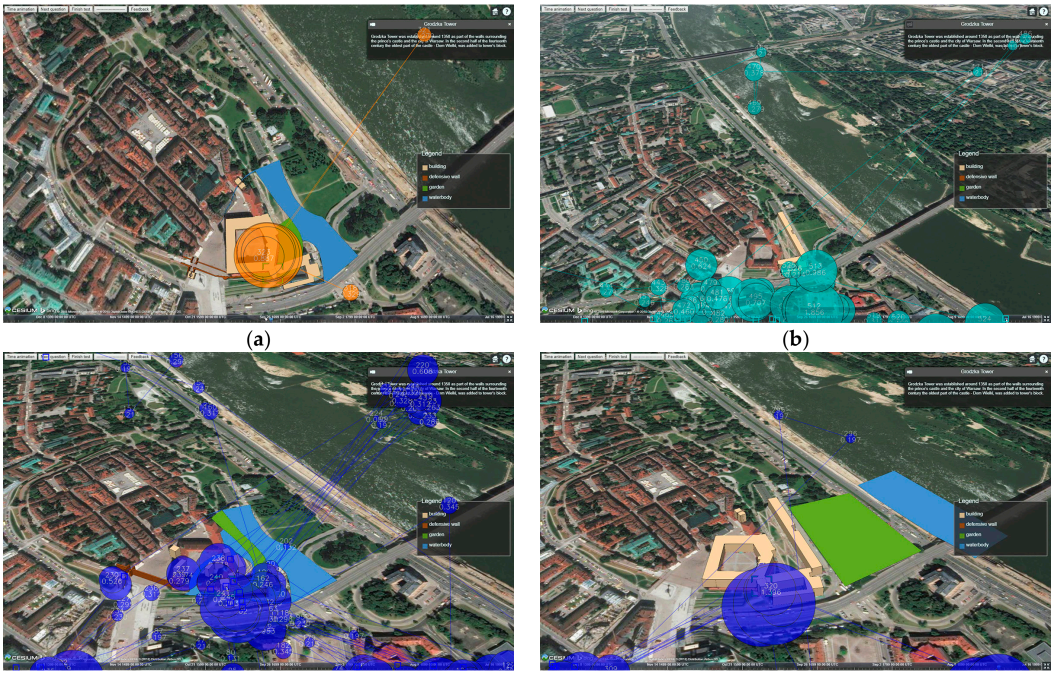
Figure 14. Searching strategies for Q2: (**a**) overview, temporal filter, and details-on-demand in the slider-based visualization; (**b**) overview and details-on-demand in the space–time cube; (**c**) overview, relate, and details-on-demand operations in the space–time cube; (**d**) zoom and relate operations in the space–time cube.

Within the third question, users were expected to check whether the Grodzka Tower existed in the study area in the given timespans. The users of the space–time cube generally focused their interest on the location of the tower in each time prism, which resulted in a characteristic, vertical gaze pattern (Figure 15a,b). The users of the slider-based visualization developed more different strategies for this task. Some participants kept concentrating on the tower location and quickly dragged the slider to get the animation over whole application timespan (Figure 16a). Another clicked on the timestamps (Figure 16b) and used the information provided in the info-box (Figure 16c). Of particular interest is the strategy presented in Figure 16d. After the test, this user mentioned that the most uncertain periods for building existence were the Middle Ages and the time of World War II. Therefore, in his searching strategy, he additionally looked at two opposite parts of the time slider: the earliest dates placed on the left side of the time slider, and the latest dates from the right side.



(**a**) (**b**)

Figure 15. Searching strategies for Q3 in the space–time cube: (**a**) overview and relate; (**b**) overview, relate, and details-on-demand.



(**a**) (**b**)

(**c**) (**d**)

Figure 16. Searching strategies for Q3 in the slider-based visualization: (**a**) overview, temporal filter, and details-on-demand; (**b**) overview and temporal filter; (**c**) overview, temporal filter, and details-on-demand; (**d**) overview and temporal filter with focus on edge time values.

The last benchmark task required finding the oldest building around the castle in 1795. To retrieve the information, both user groups selected historical buildings and obtained the information on their date of construction through the info-box (Figure 17a–c). Some of the users of the space–time cube answered this question without looking at the info-box (Figure 17d). Instead of checking all of the buildings in 1795, they first looked through the stacked prisms. Based on this insight, they could better predict which building to click on to find the right answer.

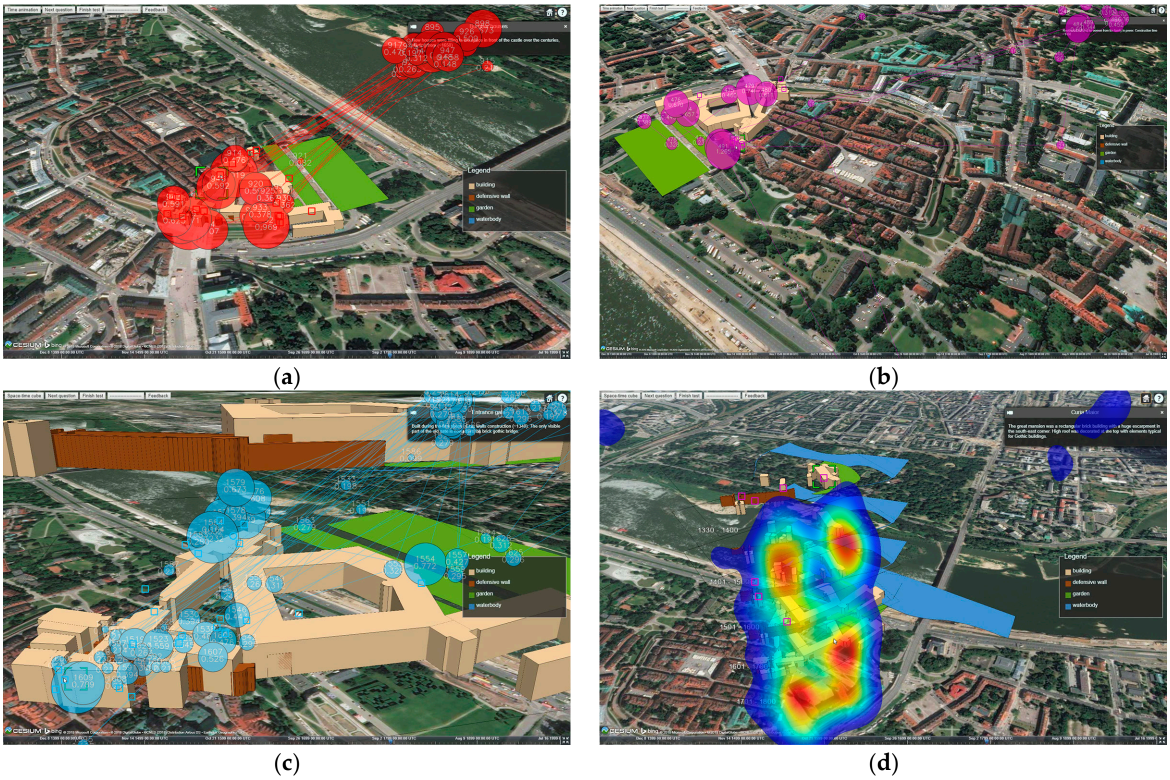


Figure 17. Searching strategies for Q4: (**a**) overview and details-on-demand in the slider-based visualization; (**b**) overview and details-on-demand in the slider-based visualization; (**c**) zoom and details-on-demand operations in the space–time cube; (**d**) overview and relate operations in the space–time cube.

Among the users performing benchmark tasks on the slider-based animation, 64% preferred the space–time cube. Similar patterns were observed among participants from setup 2: 60% of space–time cube users described slider-based visualization as more appealing and convincing. As mentioned before, the users were asked about their personal opinions concerning how to improve the functionality of both the slider-based visualization and the space–time cube. The participants were asked immediately after fulfilling the benchmark tasks and answering the questions. The participants were not given any predefined answer choices; instead, they were free to write whatever they wanted. The answers were grouped into 10 different categories, each of which were mentioned by at least four different test users. These categories were assigned into three different groups. The first group referred to the map panel design, the second group consisted of interactions aspects, while the third group referred to the issue related to the application programming interface (API) implementation (Table 2).

The three most-mentioned categories referenced the design issues and interaction issues. The first design issue involved the appearance of the time slider (14 mentions), while the second concerned the presentation of additional information within the map panel (13 mentions). The third most often mentioned category referred to the interaction of the user with the data, the possibility of comparing different centuries, and selecting a period in time for visualization (11 mentions). The two least-mentioned categories both belonged to map panel design issues, and were reported by four users tested. The first suggestion had to do with an unfortunate choice of icon symbols, and the second had to do with adding transparency to the buildings for a better overview. The latter case was only mentioned for the slider-based visualization. A third category is worth noticing, as it is more often mentioned for the space–time cube (six mentions) rather than for the slider-based visualization (only one answer). This category refers to the navigation within the space–time, because using the mouse to change the view of the cube was not as intuitive for the users as had been assumed.

Table 2. Categorized issues mentioned by the test participants divided into different groups.

Group	Category	Number of Times Mentioned		
		Space–Time Cube	**Slider-Based Visualization**	**Overall**
Design issues	The appearance and appropriate design of the time slider	6	8	14
	The opportunity of selecting a year and showing this year in the map panel	3	2	5
	Improving the affordance of the icons	2	2	4
	Modeling the buildings and/or facades in more details	3	4	7
	Making the buildings and layers more transparent	0	4	4
	More information about the objects in the info-box	3	2	5
	More contrast between the background map and the data, information closer to the selected feature	5	8	13
Interaction issues	The opportunity of comparing different centuries/years and/or highlighting a specific period	7	4	11
	Not intuitive navigation with the mouse	6	1	7
Implementation issues	Challenging selection of different objects	3	3	6

In the questionnaire, users were asked to write what they particularly liked in the design of the space–time cube. Ten users mentioned the good overview of the whole landscape continuum. For seven users, the ease of comparing different time layers was a significant plus over the slider-based visualization. Although navigation within the cube was reported as a problem, nine users appreciated the freedom of exploration given by zoom, rotation, and selection options.

4. Discussion

To test applications with the user-based methods, it is required to enroll the representative set of the target users. However, particular costs such as time, money, and participant access [33] need to be considered. When transitioning a well-established technique from one domain to the new application domain, benchmark tasks and interviews are considered to be good starting points. As the users themselves and their needs are poorly known, a discount approach of Nielsen [13] can be applied. It involves a small number of participants (three to five) per user group, and allows the detection of the majority of usability problems. Slocum et al. tested the application for spatiotemporal point data exploration on 17 participants from three groups [33,34]. The software was assessed through interviews and focus groups of six novices in cartography, six geography students, and five domain experts. The usability of the space–time cube for novel application in crime mapping was addressed by Morgan [35]. Nine researchers and 10 mapping analysts were interviewed to find the best strategies to visualize crime scenarios. Kveladze [30] combined the interviews and eye-tracking tasks to check the influence of the cartographic design on the usability of the space–time cube. The evaluation by non-domain experts involved 22 participants, while the study with domain experts and non-experienced users involved seven participants per group.

Our study focused on the collection of qualitative data on the design of the space–time cube designed for the unique historical site. As the application supports a small number of particular users—researchers and future tourists of the Royal Castle in Warsaw—the sample size of four domain experts and 21 test users was adequate to identify problems and benefits of the space–time cube's design. The number of participants tested in each setup was small, because domain experts explained that the space–time cube is a novel technique for depicting cultural heritage sites. This approach also follows the guidelines of the London Charter. Whenever visualization methods are innovative or not likely to be understood within the relevant communities of practice, it is necessary to choose the technique that has been proven before to be successful. The space–time concept proved to be applicable for spatiotemporal visualizations in many domains connected to cultural heritage, such as museum studies [9], archaeology [11,12], or landscape visualizations [31,36]. Qualitative studies are a prerequisite in more controlled experiments, in which quantitative data are collected, and the results can be generalized over the large set of user profiles. Therefore, additional empirical design should be independent from the particular case study. The general usability tests of the space–time cube and the slider-based visualization could be performed following the previous experimental studies [23–27].

The space–time cube is a promising visualization technique for the cultural heritage visualization, as for the case study, its overall success rate in benchmark tasks was 70%. The observed increase in success rate for the space–time cube could be interpreted as a result of the additional complexity of this visualization. The users needed to invest more time in the exploration process, and had a chance to better understand the landscape characteristics. The most difficult benchmark task proposed in our study was the change assessment from the first question. The users spent the maximum of their time trying to count the destroyed objects and find temporal intervals. However, those users who performed the task with the space–time cube succeeded more often than another group. This might indicate that the space–time overview of the landscape continuum could be useful in the general change perception. The next identification task focused on finding the Grodzka Tower. This task was solved by all of the participants, and needed the least amount of time among all of the questions. Surprisingly, the false answers on the last question about the oldest building within the study area were obtained more quickly with the space–time cube than the slider-based visualization. We had expected users to benefit from the overview representation of the landscape to eliminate the uncertainty and ambiguity of this question. As the oldest times were always visible, we had supposed that the answer would be clearly and easily retrieved, and the success rate would be higher.

Our study also provided insights into the familiarity of the possible users with the spatiotemporal exploration tools. It is very likely that participants may have wrongly assessed their previous knowledge of spatiotemporal visualizations, and this may have led to some inconsistent results. Users who were the most familiar with the concepts performed significantly worse in the existence assessment, and generally speaking were not always faster in providing answers. Additionally, when taking the completion rate into consideration, experienced users failed significantly more often than people interacting with such visualizations for the first time. This question should be more specific in the future tests, to check whether the users have any previous knowledge about an investigated visualization technique. However, these results proved that the created space–time cube for the Royal Castle in Warsaw has a high learnability potential, as the non-experienced users found it easy to understand.

The additional insight about the task-oriented visualizations was contributed via the eye-tracking experiment and feedback session. The participants identified seven main design issues to be reconsidered and fixed in a redesign process. The remarks from the users on the design, interaction, and implementation issues were mostly confirmed by their characteristic gaze patterns. The need to adjust the time slider was visible as the high-gaze density in the bottom part of the screen, where the users were looking for the interesting timestamp. Also, the inconvenience in retrieving information from info-boxes was confirmed by the characteristic eye movement between the selected object and information panel. As expected, the users of the space–time cube benefited from the stacked prisms with historical landscapes. Layers made it easier to look through the dataset and relate objects from the different centuries. However, one design issue was not recorded during the eye-tracking test, although many users mentioned it in the feedback: the background orthophotomap appeared too distracting. This was not visible during the test, as the gaze patterns were focused more on the space–time cube content. In the similar applications, users should be provided with the opportunity to select the basemap, which they preferred. This finding is in line with the ICOMOS Charter, which recommends visualizing the landscape, natural environment, and geographical setting around the integral parts of a historical site.

When asked about preferences, similar percentages of the users in each group tended to prefer the opposite visualization. The participants performing benchmark tasks on the slider-based animation preferred the space–time cube, while the space–time cube users were more keen on the slider-based visualization. One of the reasons for this change could be the amount of time that the users invested in the exploration. The participants who spent a lot of time on analytical operations within the space–time cube were looking for a simpler, time-saving solution. On the other hand, the users who were only able to see a temporal section of the landscape quite enjoyed having all of the data in one place. They found the cube to be a neat tool for discovering how and where changes happen, as looking at the cube from the different angles showed more clearly where additions had been made and buildings had been destroyed. It implies that with a short familiarizing time and positive experiences with spatiotemporal visualizations, even non-expert users are capable of becoming interested in more complex systems such as the space–time cube, if they are designed accordingly.

5. Conclusions

Deriving spatiotemporal characteristics of the cultural landscapes in a form of the space–time cube seems to be one of the techniques to create task-oriented landscape representations. The process of creating exploratory tools took into consideration specific benchmark tasks inspired by the domain experts. From their perspective, the space–time cube was also of interest for the non-expert stakeholders. Therefore, the usability of the visualization was examined with 21 potential users, originating from various disciplinary domains. The evaluation sessions covered benchmark tasks, feedback session, and eye-tracking. The performance of the space–time cube was compared with another representation technique and measured for correctness, response time, and satisfaction.

After the evaluation, the following conclusions can be drawn for similar future developments. If the presented landscape covers a timespan of few hundred years and the historical objects to be visualized are pre-selected, the space–time cube can provide a good overview of the landscape changes. As a consequence of the design of the cube, users will spend more time in the exploration processes, and therefore will get a better overview of the landscape phenomena. For the study case tested, the users expressed their interest in extending the functionalities of the cube. They would have liked to have more information in the info-boxes, particularly in the form of historical drawings and contemporary photographs of the castle. While the landscape objects were simplified in their shape and color, the users reported a need to see more realistic or photorealistic textures on the buildings. Similar spatiotemporal visualizations need to be designed with greater care, as overlapping objects or size and shape manipulations blur the depth cues. Our future work will focus on the usage of other interactive functionalities such as selection for improving insights into the space–time cube content. The prospect of being able to experience the landscape changes serves as an impulse for implementing the space–time cube in the augmented reality environment.

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