Cartography M.Sc.

Master thesis

Space-Time Cube Visualization in a Mixed Reality Environment

New Approaches to Support Understanding Historical Landscape Changes

Maria Turchenko

Technical University of Munich

Technische Universität Wien
Vienna University of Technology

Technische Universität Dresden

University of Twente. ITC

2018

Space-Time Cube Visualization in a Mixed Reality Environment

New Approaches to Support Understanding Historical Landscape Changes

submitted for the academic degree of Master of Science (M.Sc.)
conducted at the Department of Civil, Geo and Environmental Engineering
Technical University of Munich

Author:	Maria Turchenko
Study course:	Cartography M.Sc.
Supervisors:	Dr.-Ing. Mathias Jahnke (TUM)
	Dr. Corne P.J.M. van Elzakker (University of Twente)
Additional reviewer	M.Sc. Edyta P. Bogucka (TUM)
Chair of the Thesis Assessment Board:	Prof. Dr. Liqiu Meng

Date of submission: 14.09.2018

Statement of Authorship

Herewith I declare that I am the sole author of the submitted Master’s thesis entitled:

“Title of your thesis”

I have fully referenced the ideas and work of others, whether published or unpublished. Literal or analogous citations are clearly marked as such.

Munich, 14.09.2018 Maria Turchenko

Acknowledges

First, I would like to express my gratitude to my first supervisor Dr.-Ing. Mathias Jahnke for the guidance, useful comments, remarks and patience through the research process of this master thesis.

I am grateful to my second supervisor Dr. Corne Van Elzakker for the useful feedback on my research proposal and midterm presentations.

I am grateful to my additional reviewer M.Sc. Edyta Bogucka for her engagement, encouragement, advices and inspiration in my research.

I would like to thank M.Sc. Juliane Cron, Program coordinator, for her support, care and help with any study-related questions.

In addition, I would like to thank all the staff of the Chair of Cartography at the Technische Universität München for their cooperation and help with my research.

Also, I would like to appreciate all the participants in the user study for finding time and especially every person, who helped me to find these participants.

Finally, I thank my family and friends for their emotional support even though they were far away during my study.

Abstract

Mixed reality is rather new technology, but already aroused interest of the cartographers and other specialists from geo-visualization domain due to its promising natural ways of interaction with data visualizations. The current research of its applicability to the cartographic visualizations, including spatiotemporal visualizations, is limited and needs further investigation.

The general goal of the thesis is to investigate the applicability of the mixed reality environment in the domain of spatiotemporal representations on the example of the space-time cube. The research is narrowed down to the implementation of the space-time cube for the depiction of the cultural landscape changes.

The virtual mixed-reality hologram of the space-time cube representing cultural landscape changes based on the case study of the landscape of the Royal Castle in Warsaw for the HoloLens headset is developed. The elements of the space-time cube suitable for this thematic domain are defined. Cartographic principles and map elements are integrated into the visualization. Visual variables are implemented in regard to mixed reality rendering specificity. Interactivity of the application attempts to make use of novel interaction possibilities of the mixed reality, such as gaze, gesture and voice input.

For the usability evaluation of the developed space-time cube hologram the empirical study is conducted among 20 participants. The evaluation is performed within the developed application and does not compare it to any other visualization. It explores and evaluates the overall comfort of interactions with the hologram, perception of the visual component of the space-time cube, determines advantageous features and limitations of the technology. It is found that the limitations are mostly connected with the current development of the mixed reality technology and the device used for visualization. The interaction through gaze, gesture and voice have positive feedback from the users, but still need time to get used to them. Regarding the visual constituent further research should be performed in terms of transparent rendering of the hologram and changing of the visual contrast with changing of the surrounding working space.

Keywords: space-time cube, spatiotemporal, mixed reality, cultural landscape changes, visual variables, cartographic design principles, virtual hologram.

Table of Contents

List of figures

List of Tables

List of Abbreviations

MR	Mixed Reality
AR	Augmented Reality
VR	Virtual Reality
STC	Space-Time Cube
3D	3-Dimensional
2D	2- Dimensional
GIS	Geoinformation systems
DTM	Digital Terrain Model

1 Introduction

1.1 Background and motivation

Studying and understanding the landscape changes is one of the important issues for such fields as land management, land-use planning, ecology, or archeology. According to the European Landscape Convention (Council of Europe, 20.X.2000), "*landscape means an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors*". Referring to this definition, both natural and man-made features of the surrounding space constitute a landscape. Nowadays research on the cultural landscape, where the changes are influenced by man-made, economic factors, is one of the directions of the landscape studies (Luc, Somorowska and Szmańda, 2015). As all landscape features are geographically related and subject to some changes over time, the visualization of these changes demands both spatial and temporal dimensions. There are several methods for spatiotemporal visualizations and one of them is the space-time cube (STC), which could be considered as a useful tool for providing spatiotemporal overview. The idea of the space-time cube was first introduced by Hägerstand within his time geography theory (Hägerstraand, 1970). The x and y axes, located in horizontal plane, provide space component, while vertical z axis represents time. The thesis will address the STC visualization and will not go into details with other spatiotemporal visualization techniques. STC was implemented in various fields of application, which will be further illustrated in the following chapter. The usability and effectiveness of STC for dealing with spatiotemporal data was researched in comparison with another visualization methods. The influence of visual design on the STC content comprehension was investigated at the University of Twente (Kveladze, 2015; Kveladze, Kraak and van Elzakker, 2013; Kraak, 2003). The STC approach was applied to landscape changes visualization by Moylan (2001) and Bogucka and Jahnke (2017).

With the development of the computer technologies and virtual reality (VR), new visualization environments - augmented and mixed realities, have appeared. This technological progress resulted into the usage of these environments for the 3D interactive visualizations in different fields and stimulated the research about their interaction capabilities and perception (Bach et al., 2018). Thus, there were already attempts to visualize spatial data using mixed reality technology with different levels of immersion (Paelke and Brenner, 2007; Yim et al., 2016).

The thesis focused on the applicability of the mixed reality, also known as a hybrid reality, which is characterized by the merge of real world and virtual objects and their interaction with each other in real time. User interface for the mixed reality experience is provided by the special displays. History of the first displays for merging of the real and virtual worlds goes back to the beginning of 1990s, and such displays did not always provide immersive mixed reality as they were monitor-based (Milgram and Kishino, 1994). Modern hybrid displays are built into the head-mounted devices, giving the user an immersive experience and a natural way of interaction, as it is declared by the producers of such headsets. One of the MR headsets represented on the today's MR market is Microsoft HoloLens (Figure 1.1). The thesis will focus on the MR visualization for the Microsoft HoloLens basis headset.

Figure 1.1 Microsoft HoloLens Headset.[1]

The thesis will investigate possible incorporation of the space-time cube visualization technique into a mixed reality environment. Although space-time cube representations on the computer screen have been used and studied as one of the tools for spatiotemporal data analysis in visual analytics. The possibility and practicability of its transfer into the MR environment remains a question to investigate. New MR application of the STC should keep positive features reported in the literature on the STC and possibly expand its interactive capabilities to the new level of interaction freedom, inherent for the MR headsets.

1.2 Research identification

1.2.1 Research objectives

General goal of the thesis is to determine the applicability of the mixed reality environment in spatiotemporal mapping and the main interaction possibilities which affect its success.

Research objectives: Firstly, the thesis aims to investigate how the space-time cube can be visualized in a mixed reality environment. Secondly, the thesis will explore what are the advantages and disadvantages of such immersive mixed reality integration. The third research objective is to investigate the way of usability evaluation of space-time cube in mixed reality.

1.2.2 Research questions

According to the introduced research objectives, the research questions could be defined to structure the investigation process. The research questions assigned to each of the research objected are presented below.

Research objective 1:

To investigate how to visualize the space-time cube in the mixed reality environment.

Research questions:

How to visualize the elements of the space-time cube?

[1] "Wikimedia Commons," 2018, https://commons.wikimedia.org/wiki/File:Ramahololens.jpg, accessed August 2018.

Which cartographic principles can be transferred into the STC hologram?
How the visual variables could be applied within STC hologram?
Which interactions with the space-time cube could be integrated within the mixed reality device?

Research objective 2:
To explore what are the advantages and disadvantages of such immersive mixed reality integration.
Research questions:
What are the benefits of the mixed reality STC visualization?
What are the disadvantages or limitations of the mixed reality STC visualization?

Research objective 3:
To investigate the way of usability evaluation of space-time cube in mixed reality.
Research questions:
Which methods of usability evaluation are suitable for the STC visualization in mixed reality?

1.3 Outline of the thesis

The thesis is structured in seven chapters and 4 appendices . The first chapter is an introductory part of the thesis giving information about the background and motivation, as well as identifying the research objectives and research questions. The second chapter on the state of the art provides overview of related works and domain literature in three aspects: STC visualizations, usability of the STC as a geovisualization and usability studies in MR. The third chapter is dedicated to the methodology of the development of the STC virtual hologram, its interactive features and design of the user study. The implementation of the methodology to the case study, as well as data background is represented in the fourth chapter. Fifth chapter focuses on the evaluation of the case study implementation through user study. The results of the evaluation are given in the sixth chapter, which is followed by conclusions and outlook for the future research in the seventh chapter.

2 State of the art

The state-of-the-art section of the thesis focuses on the literature review regarding the general theory and applications of the space-time cube visualization, including investigation of the existing examples of the STC in the landscape depiction domain, as well as geovisualizations in MR. The usability evaluation of the STC in the scope of this thesis integrates two parts: usability studies on the space-time cube and usability studies of the mixed reality 3D visualizations.

2.1 Space-Time Cube and Landscape Changes

The notion of the space-time cube was first developed by Hägerstrand (1970) within his time geography concept. Initially the STC was used to visualize individual movements in space and time (Figure 2.1). Space was represented by two horizontal axes, as in traditional maps, while vertical axis was used for the temporal factor. The main elements presented within the STC model were:

- space-time paths – trajectories of the individual in the space and time, which projection on the horizontal axes plane gives a footprint of an individual's path;
- stations - time periods when the individual wasn't changing his location in space;
- space-time prisms – the 3D volume along all three axes of space and time, showing the possible distance, to be reached by an individual in one direction and to return back in a specific time interval.

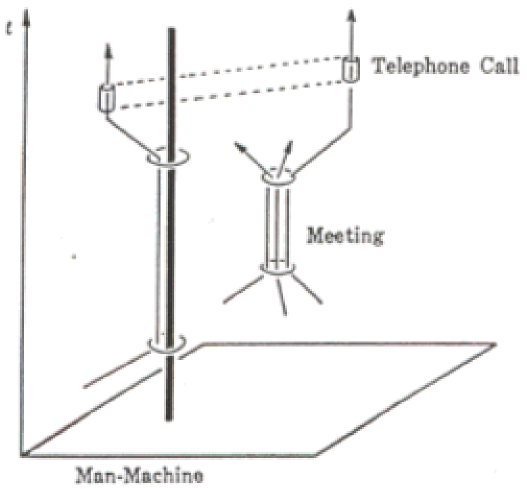


Figure 2.1 Space-time cube represented by (Hägerstrand, 1970).

First visualizations of the STC were limited to manual drawings. Thus, the 3D STC representation was static, and it was time consuming and effortful to explore data within space-time cube from different perspectives and angles (Kveladze, 2015). With the development of the computers, interactive 3D visualizations become possible and the STC became a more popular tool for spatiotemporal data visualization in different fields.

Kraak (2003) investigated the applicability of the STC for geovisualizations. He distinguished the functionalities needed for the STC exploration according to the expected user cases. Thus, the main functions to be presented were determined as a manipulation of the STC in space to allow changing the views on the content of the STC. Such functionalities are rotation along all axes, extraction of information on demand and filtering presented information and elements. The result of this work was a the “space-time cube’s viewing environment” framework (Kraak, 2003), which consisted of a main working view and three additional views to improve the user experience: 2D view, 3D view and attribute view. These views provided the possibility to adjust the main view of the environment. With the use of the attributive view it is possible to determine which and how additional data will be represented in the STC, such as base map or digital terrain model, time intervals, and space-time paths with visual attributes. Kraak (2003) considered STC as a tool mainly for visualization of people’s and objects’ movements in space and time, but also suggested that it could be used for monitoring movement-related events and related posterior analysis of the these events, as well as for archeological studies. Linking additional views with relevant visualizations is considered to be a possible option to modify the cube’s functionality for each specific case.

Another research on the applicability of the space-time cube in spatiotemporal data exploration was performed in Fraunhofer AIS (Andrienko, N., Andrienko, G., Gatalsky, P., 2003; Gatalsky, Andrienko and Andrienko, 2004). The STC technique was implemented within the Frauenhofer AIS software for event data analysis in an overview scale. This tool was developed for the pattern exploration of the events datasets. Events, considered as points or stations in time, were suggested to be presented as circles or another suitable visual symbol, in the 3D space of the STC. To visualize additional attribute variables of the events, the usage of visual variables such as size and color was proposed. The interactions implemented within the software included: STC views manipulations, selection of objects in multiple linked views, information extraction from the STC view or from attributes of the events, and changing or scaling of the displayed time interval to deal with overloaded and complex data representations. The developed visualization also used a base map for geospatial orientation. The pattern detection was suggested to be performed by the analysis of the 3D clusters of events, shaped in different structures and forms, such as example vertical or inclined lines of consequent events. The authors emphasize the relevancy of the linked views for interaction with STC and data analysis.

Li (2010) applied the space-time cube for analysis of the eye-movement data (Li, Çöltekin and Kraak, 2010). The novelty of this work was the possibility to move base map along the time dimension and see the position of the gaze on the base map at any time, which was supposed to provide better background for the analysis. Additionally, authors linked the space-time paths of the eye movement with additional multi-media annotations. Another prominent feature of the work was the attempt to include the visual information seeking mantra into the STC model (Shneiderman, 1996), thus providing additional functionality for the tool. In 2013 the exploration of the usage of the STC in the field of ecology was performed, taking as a case study visualization and analysis possibilities of animal moving behavior (Baas, 2013).

Kveladze (2015) explored the applicability of the STC for the spatiotemporal datasets from different domains, analyzing design principles of the STC, cartographic principles and their possible influence on the STC representations, implementing user centered design, as well as giving feedback about limitations of the STC. The author came to a conclusion that different tasks and cases demand different visual design and interactivity. Regarding the limitations of the STC, the most important issue for today's 3D intractable visualizations is the big amount of data, which can result in overloading the limited cube's extent.

In 2017 Bach, Dragicevic, Archambault, Hurter and Carpendale explored STC as a basis for another temporal data visualizations, and represented a classification of these visualizations based on the possible operations on STC (Bach et al., 2014). STC in this context was considered as a conceptual model not only for spatiotemporal data, but also for temporal representation of abstract data. The main difference between the presented STC model and Hägerstrand's (1970) model is that time axis had a horizontal direction, pointing from left to right, instead of vertical direction. As a result, authors developed a descriptive taxonomy of time-linked visualizations based on five main operations for data processing within conceptual model of STC, namely extracting, flattering, filling, geometry transformation and content transformation (Figure 2.2). The concept of the developed taxonomy consists of the idea that any 2D or 3D temporal visualization can be considered as a part of the STC model containing the whole temporal dataset. Extraction operations over STC model can result in point, curve, volume or surface subtraction from the whole STC model, and can be performed both in time and data axes directions, as well as in any oblique direction. Flattering uses the aggregation function within the chosen plane and it could be orthogonal (along one of the STC model axes) or oblique – freely located within 3D space. Filling operations use interpolation function to fill missing data in chosen curve, plane or volume within STC. Geometry transformation changes the shape of the STC model using shifting, rotation, scaling and bending along time and space axes and planes. The last operation, content transformation, adjusts the content of the STC without changing its geometry. For example, different visual variables can be applied, data can be aggregated, clustered, filtered, etc. The proposed taxonomy was aimed to structure the existing temporal visualization techniques and to illustrate the resulting visualizations of the various operations on the STC.

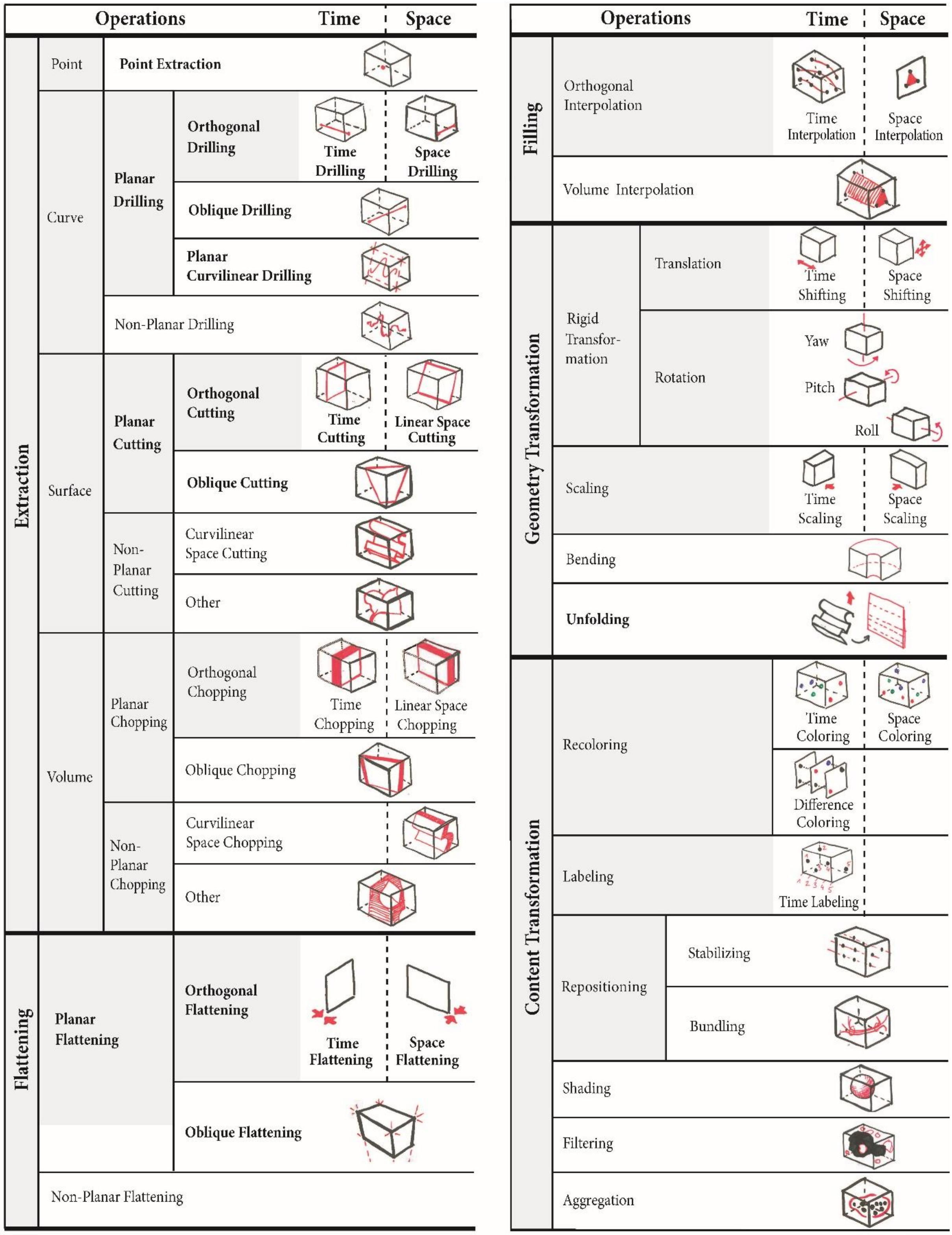


Figure 2.2 Illustrations for the taxonomy of elementary space-time cube operations represented by Bach, Dragicevic, Archambault, Hurter and Carpendale (Bach et al., 2014).

In 2001 Moylan implemented the STC approach for depicting landscape change (Moylan, ca. 2001). Based on this approach the *landscape history model* was developed, with the *cell* as a basic element of the model (Figure 2.3). The position of the cell represented a spatial component, and the attribute of a cell provided information about landscape type change in accordance with a landscape classification. Information about landscape types and their change over time was based on the historical documents. To reflect the time, each layer of cells was assigned a particular time interval.

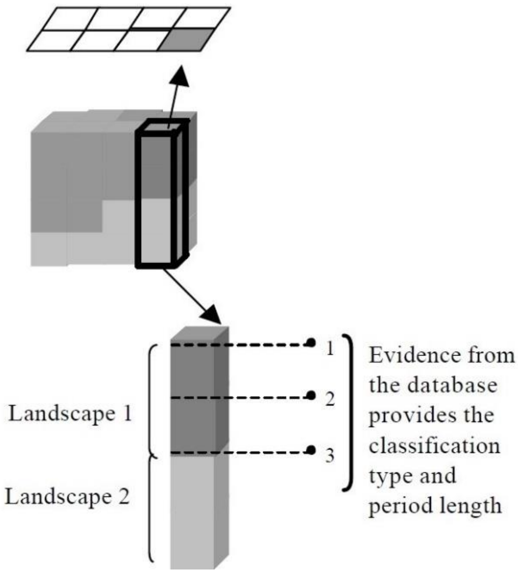


Figure 2.3 Historical Landscape Model based on the Space-Time Cube principle (Moylan, ca. 2001)

Later the STC approach was implemented for the visualization and analysis of temporal data on the cultural landscapes (Bogucka and Jahnke, 2017) and was followed by its usability testing (Bogucka and Jahnke, 2018). Thus, the main elements of the STC were chosen considering the specificity of the investigated city landscape of the Old Town in Warsaw. As the landscape features do not move or change significantly in a small time interval, it was not appropriate to implement the notions of the space-time paths. Instead of that landscape features were shown based on the idea of a space-time stations - the 3D objects corresponded to landscape features: buildings, water bodies and green areas. The time axes was showing not a continuous time, but time intervals equal to the century, represented as space–time prisms. This allowed to implement two dimensions of both time and height within the vertical axis of the STC. In order to connect the locations of the landscape features between the space-time prisms authors developed the idea of space-time links, which were shown as vertical lines intersecting the space-time prisms (Figure 2.3).

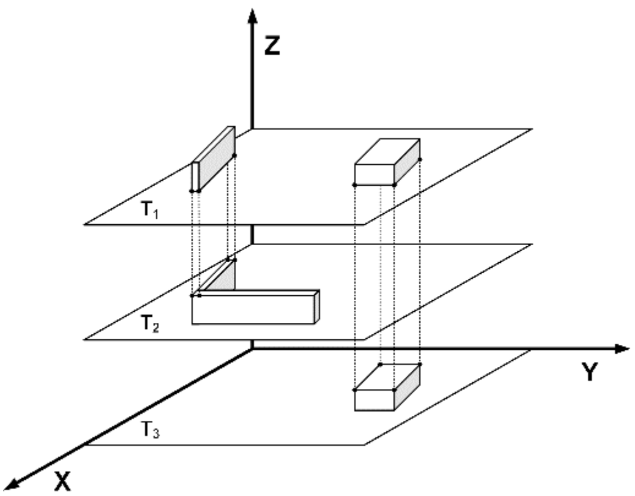


Figure 2.4 The model of the space-time cube developed by Bogucka and Jahnke for the domain of cultural landscape investigation (Bogucka and Jahnke, 2017).

The reviewed literature allows to conclude that the space-time cube visualization technique has been and can be adapted and applied in completely different domains. The elements and controls of the STC can be tailored accordingly to the specific task and case. The additional positive feature, which can be convincing for the further STC applications and research, is the development and emergence of new technologies as a base for creating a novate STC environment and thus broadening the STC interactivity and analysis capability.

2.2 Elements of the Space-Time Cube

The first research objective covers the investigation on how to visualize the STC in MR. The first step to answer this question is to determine which elements of the STC were reported in the literature within the application domain.

Table 2.1 provides the summary of the STC elements used for specific data visualizations. It is observable that space-time paths were used only for the movement data and were not applied to the landscape changes studies. Base map, with some differences, was used in all cases. For the study of landscape changes Moylan (2001) used an element, which he defined as the STC cell. The cell indicated the landscape type, such as urban or agricultural. The position of the cell was coordinated with the land parcel in the real world. The time interval allocated to one cell was equal to one year. Thus, no specific landscape features were presented in the STC created by Moylan. Such representation can be suitable for the land-use pattern determination of the large territories, but it does not provide a detailed understanding of the local landscape. Another idea, implemented by Bogucka and Jahnke (2017, 2018), was based on more detailed cultural landscape feature visualization. The authors included four landscape features into STC visualization, namely buildings, water bodies, defensive walls and gardens. They were classified as space-time prisms, although did not completely correspond to the initial notion of space-time prisms introduced by Hägerstrand (1970). The landscape features in space-time prisms represented the real landscape objects, which were located at the specific place in real landscape without any movement within specific time interval. Although they were not presented as point objects in space, they had the spatial footprints of the real objects in the x and y axes, and additional height attribute along the time axis. In both cases of STC landscape changes visualizations, the time was represented not as a continuum, but with time intervals. In Moylan's STC (2001) each level of cells represented new time interval, while in the STC of Bogucka and Janke (2017,2018) time interval was assigned the value of one hundred years. To provide better perception of the landscape features in space-time prisms the authors added the ground slice for each time interval. Additionally, the base map was used as the foundation of the STC. Another novel element introduced within cultural landscapes STC model were the space-time links, which coordinated the location of the historical landscape features in the today's landscape. Space-time links were presented as vertical lines connecting the landscape features corners through time dimension. Such approach, represented by Bogucka and Jahnke (2017, 2018) could be used for visualization of landscape with different levels of detail or generalization.

While analyzing the base map implementations within overviewed STCs, it is worth to mention the base map moveable along time axis, which was introduced in the eye-movement study of (Li, Çöltekin and Kraak, 2010). This approach can be transferred into the landscape changes STC. Thus, the base map can be presented at every ground slice, or it could be changed according to the historical period of the specific ground slice.

Table 2.1 Elements of STC implemented within previous research.

Case study / Elements of STC	Movement of individuals or groups of individuals	Geographically related events	Eye-movement data	Landscape changes	Animal behavior analysis
Space-time paths	Hägerstrand (1970) Kraak (2003)		Li, Çöltekin, and Kraak (2010)		Baas (2013)
Space-time path footprint	Kraak (2003)				
Stations	Hägerstrand (1970) Kraak (2003)	Gatalsky, Andrienko, and Andrienko (2004)	Li, Çöltekin, and Kraak (2010)		Baas (2013)
Space-time prisms	Hägerstrand (1970) Kraak (2003)			Bogucka and Jahnke (2017)	
Space-time links				Bogucka and Jahnke (2017)	
STC Cell				Moylan (2001)	
Base map	Kraak (2003)	Gatalsky, Andrienko, and Andrienko (2004)	Li, Çöltekin, and Kraak (2010)	Bogucka and Jahnke (2017)	Baas (2013)
Ground slices				Bogucka and Jahnke (2017)	
Space-time grid					Baas (2013)

Another interesting element, mentioned in the literature, is a space-time grid – a grid with geographical coordinates at every axes intersections, implemented along the time axes within a specific time interval, for example one month (Baas, 2013). The grid can have different spacing and can provide additional information about geographical location of the landscape features.

2.3 Cartographic Design Principles and Visual Variables in Space-Time Cube

2.3.1 Cartographic Design Principles

With the development of thematic maps production, cartographers tried to clarify and classify the process of map design. Among the first in this sphere was Robinson (1995), the author of the book "Elements of Cartography". Later the cartographical principles were investigated by other cartographers: Madej (2000), Tyner (1992), Slocum (2004), Dent (2009).

The design principles in cartography are based on the manipulations with map elements and their allocation to provide meaningful map representation. Map elements are identified as the main entities, which constitute any thematic map. These entities are classified according to their visual and perceptual weight in the map representation and allocated to different visual significance levels. Thus, the assignment of the map elements to different visual levels results into vertical visual hierarchical organization of the levels. Besides, several elements can be attributed to one visual level. Such case refers to a planar arrangement of the map elements (Dent, 2009). Table 2.2 presents the elements of the thematic map according to the place in hierarchy (from the highest to lowest) and their main cartographic design characteristics.

Table 2.2 Map elements and their characteristics. Map elements represented in the table according to their weight in visual hierarchy, from the most (on the top of the table) to the least visually influential.

Map element	**Characteristic**
Figure, theme or subject area (mapped area)	Visual center of the map; First in the map elements hierarchy; Sizing and positioning
Title and subtitle	Should describe the content or theme of the map; Title should draw attention of the user and have more visual emphasis than subtitle
Map legend	Legend label should be coordinated with the map topic; Legend content should explain map symbolization
Map scale	Could be represented as scale bar, relative fraction, labelled graticule
Orientation	North arrow should be used on the maps with scale and projections, which doesn't influence on the straightness and parallelism of meridians; Graticule and grid is another possibility to provide orientation
Borders and neatlines	Provide separation of the map content from surrounding area and help user to focus on the content
Names and labeling	Should be readable, size of the font should correspond with feature weight
Credits	Data source, authorship, license, date

Map element	Characteristic
Graticule or grid	Used to identify location in geographic coordinates by the parallels and meridians lines depiction
Map symbols	The main element of the map to represent thematic or geographic features
Map inset	Secondary map area: Provide map overview for locating of the current view; Enlarging of the specific map area; Representing additional maps

The cartographic design principles mentioned in the literature aimed to produce a good communicative map. Tyner (Tyner, 1992) delineated five main guidelines to pursue in the map design process, including clarity of the map, order, balance, contrast and unity. Later Madej (Madej, 2000) extended the notions of the clarity, referring to it as legibility, contrast, discussing visual contrast, figure-ground contrast, and order as a hierarchical organization. The summarized information about cartographic design principles and their possible implementation techniques is given in the Table 2.3.

Table 2.3 Summary of the cartographic design principles.

Cartographic principle	Aim	Possible techniques
Legibility (Clarity)	• Emphasize important • Eliminate unnecessary • Create unambiguous representation of main pattern • Ensure legibility of map symbols, easiness in differentiating of map symbols and readability of labels	• Appropriate associative map symbols; • Appropriate size of the symbols; • Readable typefaces; • Efficient label placement;
Visual contrast	• Provide good visual contrast between map elements • Draw user's attention to the relevant map elements and symbols • Avoid visual monotony	• Contrast of light-dark, thin-thick, light-heavy; • Contrast in size, intensity, shape, color;
Figure-ground contrast	• Visually emphasize the relevance of figure (main content of the map) in the foreground from the rest map space (ground)	• Different detail levels; • Drop shadow; • Bigger size of map symbols; • Difference in color value; •

Cartographic principle	Aim	Possible techniques
Hierarchical organization (Order)	• Logical coherent arrangement of the map elements	• Stereogrammic organization: visualized content subdivided into different classes, where the classes hierarchically organized at different levels; more important classes of map features can be placed on top of others; • Extensional organization: ordering of the content within one class using size variations of map symbols; • Subdivisional organization: refers to a subdivision within one class;
Balance	• Coordinate graphic and visual weight of all map elements and features • Visual center is considered slightly above the actual center of the map • The map should be presented in the largest possible scale to avoid predominance of unfilled white space •	• Graphic weight could be influenced by darker or lighter color value (bright colors are heavier than dark colors), density of map elements; • Visual weight depends on arrangement and size of map elements: the further element from the visual center the heavier its weight in visual perception; elements in the upper right corner of the map are heavier than in the lower left corner; separate elements are heavier then groups of the elements;
Unity	• Provide visual perception of the map as a single visualization	• Harmonic interrelation of all map elements

2.3.2 Visual Variables

The first exploration on graphic symbols in the map and their visual perception goes back to 1967, when French cartographer Jacques Bertin published a book “Semiologie Graphique”, where he represented a theory about visual variables – graphical elements of the map. The first English translation of the book was published in 1983. He defined seven visual variables, namely location, size, shape, orientation, color hue, color value and texture (Bertin and Berg, 2011). Lately this list was extended by Morrison (Morrison, 1984), by adding color saturation and arrangement, and by MacEachren (MacEachren, 1995), by adding visual variables of crispness, resolution and transparency, which are characterized by digital graphic emergence. The notion of visual variables implies one’s ability to percept graphic content visually, with the sight, rather than through thinking. Bertin also defined four levels of organization: associative, selective, ordered and quantitative. These levels were characterized by different visual, perceptual and understanding properties of the variables. Thus, at associative level visual variables are percepted by a human eye with the same level of significance and can be grouped in accordance to the visual variable. At selective level human eye can distinguish one visual variable from another and select map objects with one specific visual variable. Ordered level of organization allows sequential ranking of the visual variables between two opposite states. Quantitative level of organization provides understanding of some numerical values behind the visual symbol. Later the theory of visual variables was summed up by Roth (Roth, 2017). Figure 2.5 represents the overview of visual variables.

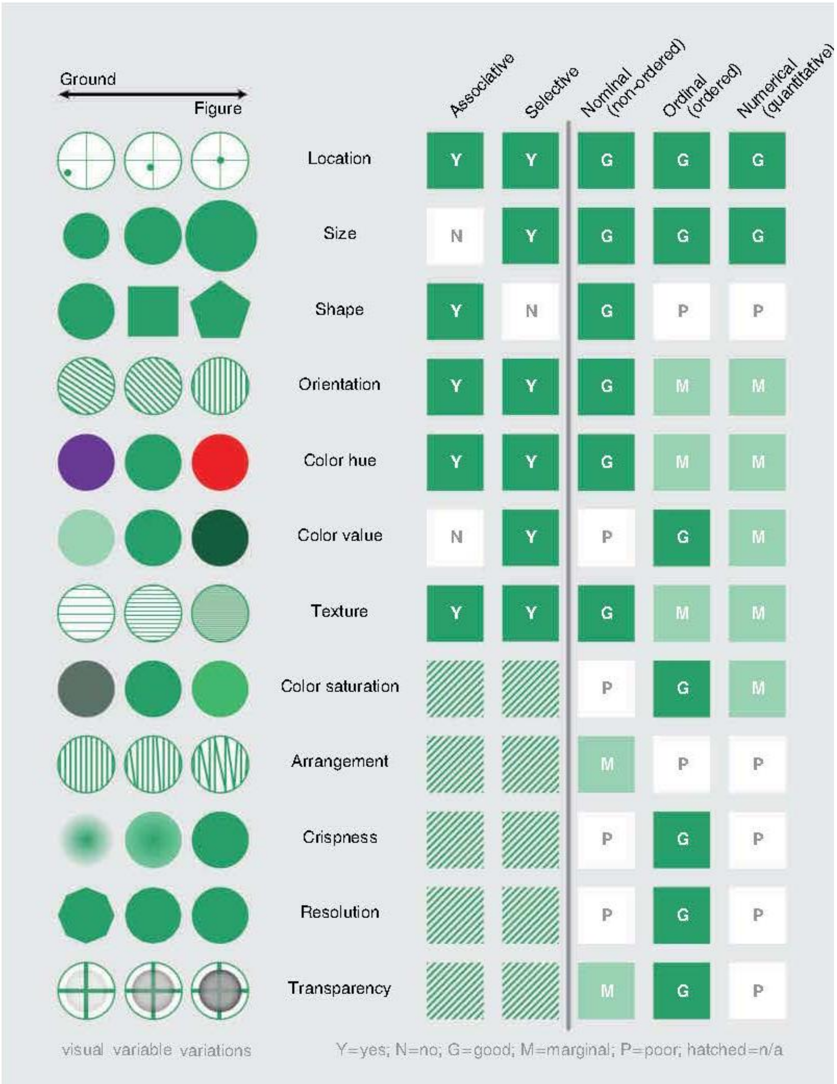


Figure 2.5 Visual variables and their properties in respect to the organizational levels (Roth, 2017).

2.3.3 Visual Variables in the STC

According to Kveladze, Kraak and van Elzakker (Kveladze, Kraak and van Elzakker, 2018) available research on implementation of visual variables in STC visualizations was quite narrow. Most of it focused on color hue, color saturation, size and transparency. The authors tried to extend existing research and explored five visual variables in the context of the STC applications (Kveladze et al., 2018) - color hue, color value, color saturation, size and orientation, united with transparency and shading, what resulted in ten pairs of visual variables. The research was conducted within movement datasets and visual variables were applied for the space-time paths.

Bogucka and Jahnke (Bogucka and Jahnke, 2017) suggested the implementation of the following visual variables in the STC for the cultural landscapes changes: color hue, transparency, edge enhancement, shape, size and pattern.

2.4 Cartographic Interactions

For modern cartographic representations interactiveness is a necessary feature to explore map's content. The area of interactions with maps or map-like representations was widely investigated by researches providing taxonomies of interaction operators, interaction objectives and operands. Roth (Roth, 2013) discussed the interaction issues in the field of cartography. He investigated basic interaction constitutes in the exploration process of cartographic representations and referred to them as interaction primitives. Roth emphasized that humans "*experience interactions*", rather than use them. That is why it is important to focus on the interaction design with map content. The interaction design can be based on the objectives of interactions, on operators available for implementation and on operands, the objects to interact with. Table 2.4 represents the implemented operations in the reviewed space-time cube visualizations. Based on the interactivity implemented in the space-time cubes in different domains, the possible objectives, operators and operands for the mixed-reality space-time cube interactivity were defined. The results are presented in the Table 2.5, while Tables 2.6 and 2.7 explain the characteristics of the selected potential objectives and operators.

Table 2.4 Interactions implemented within selected STC visualizations.

Case study / Interactions	Movement of individuals or groups of individuals	Geographically related events	Eye-movement data	Landscape changes	Animal behavior analysis
Manipulating viewpoint	Kraak (2003)	Gatalsky, Andrienko, and Andrienko (2004)		Bogucka and Jahnke (2017)	Baas (2013)
Time filter: select time interval/timespan	Kraak (2003)	Gatalsky, Andrienko, and Andrienko (2004)		Bogucka and Jahnke (2017)	
Zooming in time dimension		Gatalsky, Andrienko, and Andrienko (2004)	Li, Çöltekin, and Kraak (2010)		
Zooming overall STC		Gatalsky, Andrienko, and Andrienko (2004)	Li, Çöltekin, and Kraak (2010)	Bogucka and Jahnke (2017)	

Case study / Interactions	**Movement of individuals or groups of individuals**	**Geographically related events**	**Eye-movement data**	**Landscape changes**	**Animal behavior analysis**
Selection by attributes		Gatalsky, Andrienko, and Andrienko (2004)			
Querying data (information-on-demand)	Kraak (2003)			Moylan (2001) Bogucka and Jahnke (2017)	
Manipulations with base map	Kraak (2003)		Li, Çöltekin, and Kraak (2010)		
Rotating STC	Kraak (2003)				
Switching additional attributes/layers on/off	Kraak (2003)		Li, Çöltekin, and Kraak (2010)		
Filter by attributes			Li, Çöltekin, and Kraak (2010)		
Filter by location			Li, Çöltekin, and Kraak (2010)		
Focusing camera on object				Bogucka and Jahnke (2017)	
Draggable axes to measure time and location	Kraak (2003)				
Linked annotations (multimedia data) on demand			Li, Çöltekin, and Kraak (2010)		
Dynamic linking with additional views	Kraak (2003)	Gatalsky, Andrienko, and Andrienko (2004)			

Table 2.5 Possible MR STC hologram interactivities in correlation with interaction objectives, operators and operands.

Possible objectives for interaction primitives in STC	Possible operators for interaction primitives in STC	Possible operands for interaction primitives in STC
• Identify • Compare • Locate • Distinguish • Categorize • Rank • Correlate • Re-order • Extract • Emphasize • Characterize distribution • Explore • Filter	• Highlight • Label • Object rotation • Linking • Manipulate objects • Overview • Zoom • Filter • Details-on-demand • Extract • Accessing extra information • Changing parameters of representation • Colormap manipulation • Viewpoint manipulation • Selection • Altering symbolization • Toggling visibility	• Data • Data representation • View • Time • Location • Object • Visualization structure

Table 2.6 Characteristics of the selected possible operators for interaction primitives in STC

Operators	**Characteristics**
• Highlight	Temporally change the visualization of selected objects
• Label	Display labels for the selected objects
• Object rotation	Rotate selected objects
• Linking	Linking additional views in such a way that manipulations with one view invoke correlated changes in other views
• Manipulate objects	Operating objects through interaction operators
• Overview	Provide a general view on the represented content
• Zoom	Map browsing with change in scale within the visualization space
• Filter	Limiting the visualized objects to those which satisfy specified conditions or characteristics
• Details-on-demand	Show additional information through interaction operators
• Extract	Filtering of the data to get specific data

Operators	Characteristics
• Accessing extra information	Show additional information through interaction operators
• Changing parameters of representation	Change the visualizations by usage of visual variables without changes in the represented content
• Colormap manipulation	Changing visualization by changing color-related visual variables
• Viewpoint manipulation	Changing the point of view on the visualization using map panning and zooming
• Selection	Direct selection of the objects
• Altering symbolization	Changing the graphical representation of the object
• Toggling visibility	Switch on/off the visual representation of the selected objects

Table 2.7 Characteristics of the selected possible objectives for interaction primitives in STC.

Objectives	Characteristics
• Identify	provide the objects with specific features, which can be used to clearly chose this object among others
• Compare	finding similarities and distinctions among two or several objects
• Locate	defines the position of the object in space
• Distinguish	the possibility to find the object, which differs from some group of objects
• Categorize	classification of objects to different groups in accordance to some object feature
• Rank	provides the ordering of the objects within a hierarchy according to some feature
• Correlate	institutes the connections between some objects
• Re-order	Changing the representation of a ranked or categorized data through a cartographic interface
• Extract	Filtering of the data to get specific data
• Emphasize	Visually mark out the object among others
• Characterize distribution	Create a statistics for the distribution of objects within classification
• Filter	Present only objects which have specified features or meet specific requirements

2.5 Space-Time Cube Evaluation

There are different methods which can be applied in space-time cube evaluation. The data collected in result can be classified to quantitative and qualitative.[4] The qualitative data gives insights about how the people use the application, what is easy to deal with and what is hard. It helps to reveal the problematic features and the way that can fix it. The researcher usually can

[4] Christian Rohrer, "When to Use Which User-Experience Research Methods," 2014, https://www.nngroup.com/articles/which-ux-research-methods/, accessed September 2018.

observe users' actions directly, ask them direct questions about their experience or ask for an audio feedback, such as thinking aloud. With quantitative data researcher can answer the questions of how many and how much and get the usability metrics based on user tasks performance. In result the quantitative methods provide numerical data, such as percentage of the correct answers or time of task performance. Thus, it could be used for comparative evaluation between two different applications or between two versions of application. According to the ISO 9241-11 (ISO International Organization for Standardization, 2018) the notion of usability addresses "*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 of use*". Thus, it discusses how user friendly is the evaluated system and its attributes to achieve user specified tasks. The document defines three main usability metrics: effectiveness, efficiency and satisfaction. The definitions of the metrics provided by the ISO 9241-11:2018 are the following:

- *Effectiveness*: the accuracy and completeness with which users achieve specified goals;
- *Efficiency*: the resources expended defined in relation to the results achieved;
- *Satisfaction*: the comfort and acceptability of use.

It is worth to mention that the first edition of the ISO 9241-11:1998 was currently reworked into the second edition, and the definition of efficiency is now not related to accuracy and completeness with which users achieve goals.[5]

According to Kveladze, Kraak and van Elzakker (2013) most of the usability studies performed with the STC visualization were comparative, where the effectiveness of the STC was evaluated with respect to other visualization techniques, and were not taking into consideration cartographic design principles. Trying to fill this gap, the above mentioned authors proposed a conceptual framework for evaluating the usability of the STC, which included visual design aspects of the STC content together with user-centered design of the working environment. The framework consisted of six phases, where the early phase involved domain experts to develop a visualization workflow and design guidelines, which were verified in the later phases. Developed workflow and design were evaluated, together with the STC working environment with linked views to other visualizations techniques.

This study was later followed by more detailed exploration of effectiveness and efficiency of visual variables and depth cues within the STC visualization (Kveladze, Kraak & van Elzakker, 2018). The study took into consideration five visual variables, namely color hue, color value, color saturation, size and orientation, and the shading and transparency depth cues. The study investigated interrelation between the level of data complexity and the appropriate visual design for the STC. For this purpose, the experiment was conducted with two different movement datasets with different content complexity and the tasks were correlated with information seeking mantra

[5] "ISO 9241-11:2018, Ergonomics of human-system interaction — Part 11: Usability: Definitions and concepts," https://www.iso.org/obp/ui/#iso:std:iso:9241:-11:ed-2:v1:en, accessed September 2018.

(Shneiderman, 1996). In particular, the visual variables and depth cues were applied to the space-time paths. The results showed that some combinations of visual variables and depths cues proved themselves good for simple datasets exploration, but not appropriate for complex data, and vice versa. Additionally, some combinations were showing good visualization capabilities for the overview of the STC content, while being less effective for the zoomed views. The design combinations, which did not show good results for an overview, also were not beneficial for zooming level. As a result, the authors made recommendations on different design combinations to be used for specific operations on STC content, such as locate and distinguish, estimate, locate and compare. The results of the study are represented in the Table 2.8.

Table 2.4 Recommendations on the use of the design options for task execution (Kveladze, Kraak & van Elzakker 2018).

Data complexity	Visual variables & Tasks	Qualitative				Quantitative					
		Colour hue & thin st-path	Colour hue & thick st-path	Colour hue & shading	Orientation & shading	Colour saturation & thin st-path	Colour saturation & shading	Colour value & thin st-path	Colour value & thick st-path	Colour value & shading	Size & shading
Simple datasets	Locate	–	+	++	–			–	–	++	+
	Distinguish	–	+	++	–						
	Estimate	+	++	–	–			–	–	++	+
Complex datasets	Locate	+	+	++	–	+	++	–		–	
	Distinguish	+	+	++	–						
	Compare					+	++	–		–	

☐ Not Evaluated – Not Recommended + Recommended ++ Most Recommended

One of the comparative studies on the STC, relevant for the topic of the thesis, was performed by Bogucka and Jahnke (2018). The STC visualization of cultural landscape (Bogucka and Jahnke, 2017) was tested in comparison with the time slider-based visualization of the same dataset, which aimed at investigating efficiency, effectiveness and satisfaction of the STC. The two interactive visualizations had the same interface and design. The experiment included the performance of the data retrieval tasks suggested by the domain experts, and free exploration of the visualization.

The reviewed usability studies of the STC have touched the efficiency, effectiveness of the STC visualization technique, as well as some design issues. Although, the experiment involved limited design options and the further research of visual cartographic design of the STC should be conducted. Another possible direction of the research is to establish new working environments for the STC, which became possible due to technological progress in computer science. One of such novel working environments to explore is mixed reality.

2.6 Mixed Reality Visualizations

The concept of a *mixed reality (MR)*, also called a hybrid reality, has emerged as a result of development of virtual reality technologies. The term of mixed reality was first presented by Paul

Milgram and Fumio Kishino in 1994 within their work on *a "taxonomy of Mixed Reality Visual Displays*". It is referred as a part of a "*virtuality continuum*" between real environment on one side of the continuum and virtual environment on the other side of the continuum (Milgram and Kishino, 1994), where the notion of virtual environment, or *virtual reality (VR)*, implies to the completely artificial computer-generated world in oppose to the real physical world. This means that *mixed reality represents a merge of real world and virtual digital objects, which both exist in the real physical space and interact with each other in real time*. It is necessary to distinguish this term with the concepts of augmented reality and augmented virtuality. Thus, *augmented reality (AR)* is a part of "*virtuality continuum*", where elements of real, physical environment are augmented by the computer-generated information. Such augmenting information can be an audio, visual, or haptic input. This means that although real world is supplemented by digital overlay, it stays central in perception. The concept of *augmented virtuality* implies virtual world, which is supplemented by real-world objects, such as, for example streaming of video from web-camera (Milgram and Kishino, 1994).

The application range of mixed reality today is characterized by its broadness and universality. It can be used in different fields, from science, analytics, and business to entertainment. The main current limitation of its usage is its novelty and relative high price, which means that it is not as widespread and common as traditional desktop computers. Nevertheless, mixed reality was already investigated in terms of its usage for deploying geospatial visualizations.

The first implementation of the MR displays in the GIS domain goes back to the emerging time of the MR. The main distinctive feature of such applications was not a head-mounted display, but a tablet-like display. Due to this fact such devices had no immersive factor and were closer to the AR. Thus, Paelke and Brenner (2007) developed a MR interactive device, called GeoScope, for on-site visualization of GIS data (Figure 2.6). The device was mounted on the geodetic tripod and had an MR display in the front part and a camera on the back side. It was equipped with a GIS software based on the ArcObjects from ESRI and stored in the memory of the GIS database. The virtual objects from the database were added to the view from the camera in the real time, thus providing additional geospatial virtual information to the real-world objects within the camera view on display. The device interactivity helped user in identifying selected objects in a real world by added information, localizing objects and user's position, and provided the guidance and navigation. (Paelke and Brenner, 2007)

Figure 2.6 The GeoScope Prototype (Paelke and Brenner, 2007).

Due to today’s fast technological development, new technical devices in the spheres of AR, VR, and MR are becoming affordable for more and more users. This users’ growth leads to the growths in the applicability research of these devices as well.

The researches from the University of Calgary, Canada suggested a framework for visualization of complex data with Microsoft HoloLens and Microsoft Kinect 2 (Yim et al., 2016). Microsoft Kinect 2 is a technology for body movements tracking, which allows to enlarge the interaction possibilities of the HoloLens by adding custom natural gestures to the two of default HoloLens gestures. Described framework was implemented for the disaster analysis case study - flood mapping (Figure 2.7). Digital terrain model (DTM) was used to create a 3D map of the area with additional rivers being represented as 3D volumes. The corners of the map were coordinated with the real longitude and latitude, which allowed to add any location-based data to the virtual map. The map provided the necessary information for the flood monitoring at the large information screen, and the interactivity based on the natural custom gestures provided the functionality to simulate the flood events in the area. The virtual map could be extended in such a way that users can walk through it, thus providing an immersive experience. The model had a visual feedback, such as changing of the color of the towns’ names which were in the danger of flooding, and shared experience feedback, which means that several people can explore and interact with the virtual map in the same time. These features of natural ways of interaction, immersive environment and shared experience were considered as a framework for visualizing any large heterogeneous datasets in MR.

Figure 2.7 3D virtual map in mixed reality (Yim et al., 2016).

Recent research included a comparative user study about interaction possibilities of 3D visualizations on computer screen, on AR tangible displays, and with MR head-mounted displays (Bach et al., 2018). The investigation was focused on the efficiency of tangible interactions with MR 3D virtual holograms within current MR technology. The authors suggested that MR technology can provide better insights for exploration of the 3D visualizations compared to the today's conventional computer desktop visualizations due to the sense of immersiveness and stereoscopic perception of the 3D virtual holograms in MR, without separating the user from the real world, as well as the higher degree of interaction freedom, such as moving around hologram or placing hologram in preferred position in the physical space. The research explored in this context three main questions: stereoscopic perception of 3D content, MR interactions with high degrees of freedom, and spatial proximity of physical space for interaction and perception. Among the testing environments of MR head-mounted display, HoloLens was considered as the environment with the highest values for all three mentioned aspects. Traditional computer was characterized with the lowest values for these aspects. Tangible AR displays and handheld tablet supposed to have same high level of degree of freedom as HoloLens, but lower level of proximity and 3D perception. For all environments the same datasets of point clouds were used as a technique suitable for different spatial visualizations. The result showed that tablet-based AR had the lowest precision and time for performing the tasks, as well as the least comfort in usage according to the users' feedback. The computer screen visualization proved to have a good efficiency and precision. The immersive MR had advantages in spatial understanding and stereoscopic perception, although it did not scored the fastest solving time for most of the tasks within the study. Authors suggested that the way of the interaction in MR, involving body and head movement, take more time than computer mouse movement with a hand. Another conclusion made in the study is that ease of using computer desktop visualization can be explained by the fact that most of the users were accustomed to the 3D desktop CAD programs, while HoloLens was a new device for them with different ways of interaction. But with time and additional training in MR headset usage, it is possible to improve the interaction process with MR holograms. Additional interesting feature of the study was that users were moving a lot with HoloLens, but they did not mention the fatigue from this process. On the contrary, users reported tiredness from the AR tablet visualizations, although most of them were seated and not moving with the whole body.

To sum up, modern mixed reality headsets, such as HoloLens, can provide a novel working environment for the STC exploration. Due to the relative newness of the MR and immersive MR headsets, the usability issues of spatial visualizations in MR are still an open question. Although the research performed in this domain demonstrated that MR is harder to handle comparing to computer desktop applications, it proved that MR provides new 3D perceptual quality of virtual holograms and interactions with them. Thus, the visual design and interactivity features of the 3D virtual holographic visualizations of spatial data are still to be explored. In connection with the STC research, an attempt to transfer already discussed visual and interactive STC design recommendations, as well as find out new appropriate guidelines based on the cartographic principles and design rules, can be a promising challenge to investigate.

2.6.1 Colors and Visual Perception in Mixed Reality

Due to the additive color nature of the MR displays, visual rendering of the holographic objects and colors differs from the computer screen rendering[6]. Black color with an RGB values of (0,0,0) is rendered as completely transparent, while white color is the brightest. This means that darker colors within MR displays are harder to visual presumption because of the higher degree of transparency compared to brighter colors. Another factor influencing the MR holographic visualization is the physical environment: lighting of the room, visual contrast of the background dependent on the materials and colors in the user's room. Important feature of the MR hologram to be considered is that the color can separate to its constituents when the hologram is moving or the user moves his head. Moreover, the large objects rendered with bright solid color may become blotched due to different lighting conditions in the room and visually distracting due to its very bright visualization. To avoid these problems Microsoft gives recommendation to test the MR hologram deployed within HoloLens during the development stage.

2.7 Interactions in Mixed Reality

The interactivity of the MR hologram is determined with the characteristics and technical possibilities of MR headset. According to Microsoft HoloLens documentation, current version of the HoloLens is developed with two main hand gestures, voice and gaze input for interaction with MR holograms.[7] Gaze, which is defined as headset direction in space, is used to select objects to interact with. To help user with understanding of this process and making it more precise, it is suggested to use cursor for the MR holographic application. Cursor is a point, or any other visual point-based visualization, which is always visible and locates user gaze in MR space. Figure 2.7(a) shows the example of the cursor. The gestures implemented within Microsoft HoloLens called Air Tap and Bloom.

Air tap gesture mechanism has an analogy with mouse-click action for a computer. To perform air tap on some specific object within MR hologram user should select an object with a gaze. To provide the clarity, which object is selected, the hologram should have a visual feedback, like changing of the courser look or changing the color of the object. The examples of the cursor with feedback are given at the Figure2.8 (b) and (c). Once the object of interaction is selected, user should do the air tap gesture:

- place hand in front of HoloLens;
- raise index finger up – this is a ready position, or ready state, which HoloLens can detect;
- press the index finger down to tap;

[6] "MicrosoftDocs/mixed-reality," https://github.com/MicrosoftDocs/mixed-reality/blob/master/mixed-reality-docs/color,-light-and-materials.md, accessed September 2018.
[7] "MicrosoftDocs/mixed-reality_Gestures," https://github.com/MicrosoftDocs/mixed-reality/blob/master/mixed-reality-docs/gestures.md, accessed September 2018.

- quickly raise the index finger back up.

The visual representation of the air tap gesture is given at the Figure 2.9. Other possibilities to make an air tap is the usage of HoloLens clicker or voice command, speaking “Select”.

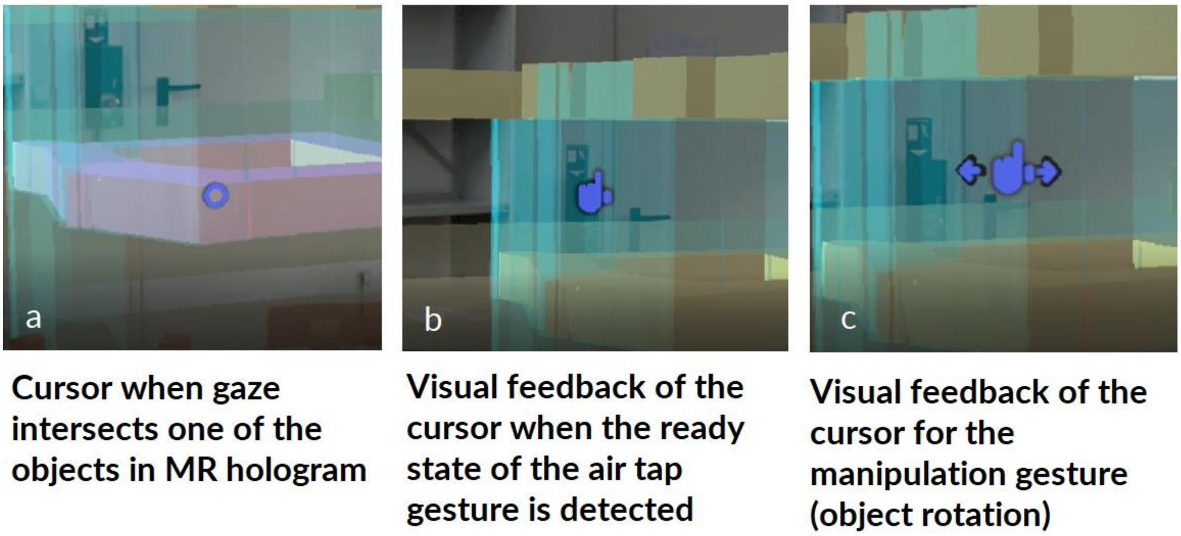


Figure 2.8 Cursor in MR holographic application.

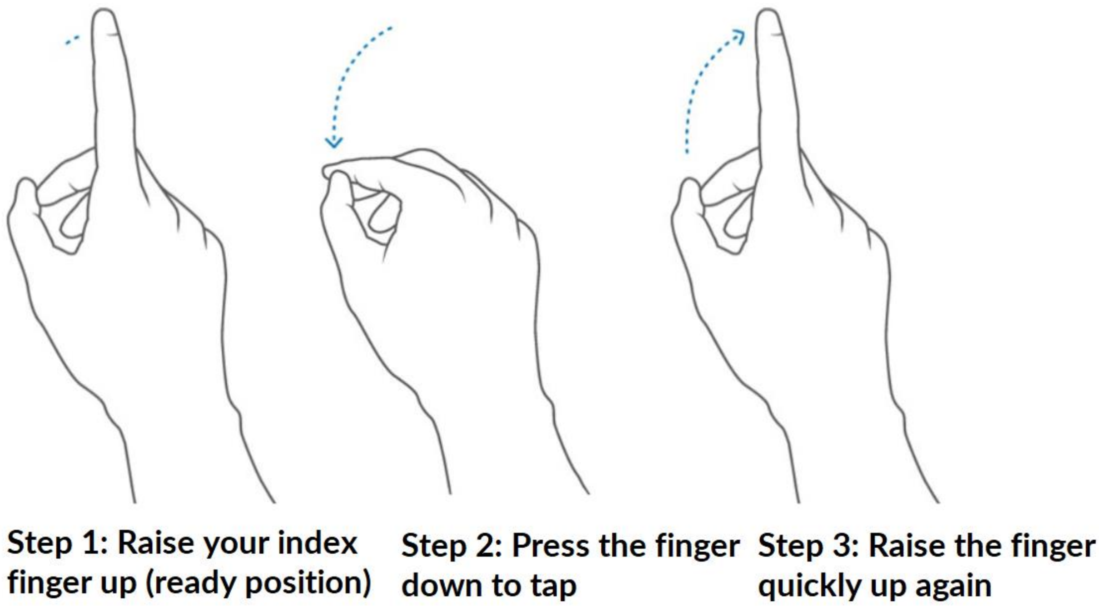


Figure 2.9 Air tap gesture.

The bloom gesture is used to open the main menu or to close the application. To perform it the user should close the palm with fingers pointed up and closed together, and then open the palm. The gesture is illustrated on the Figure 2.10. Another way to open the main menu is to say a voice command: “Hey Cortana, go home”.

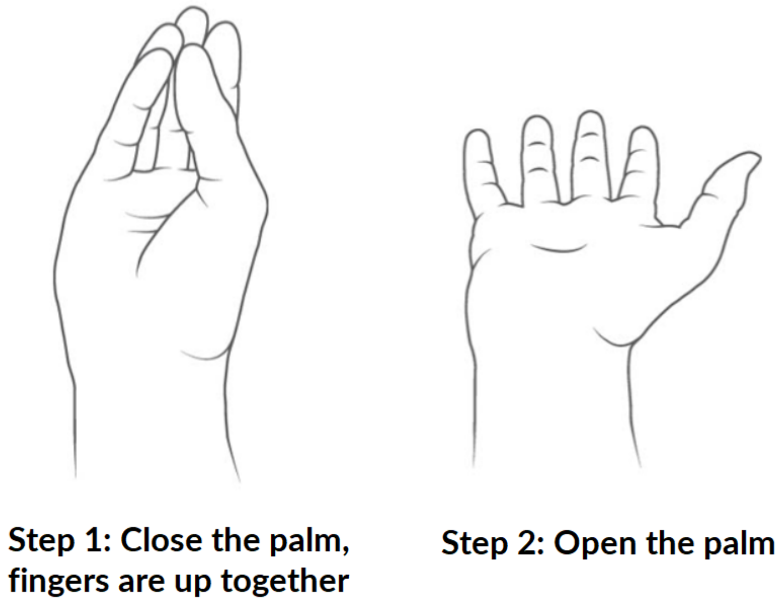


Figure 2.10 Bloom gesture.

The HoloLens technology allows to make recognizable also the combinations of gestures such as double air tap, for example. In addition, HoloLens recognizes composite gestures to provide higher level of interaction complexity. There are three composite gestures embedded into HoloLens technology, namely tap and hold gesture, navigation and manipulation.

Tap and hold gesture is used for such interactions, as scroll, drag, zoom. The gesture is based on the air tap, but once the index finger is pressed down, it should be kept in this position. At the same time the movement of a hand in MR space is tracked by the HoloLens and used to control the operations mentioned above. Tap and hold serves as a basis for manipulation and navigation gestures. The type of a gesture used in application is specified in the scripts within application development. Manipulation gesture is used for moving, resizing or rotating of the MR hologram and it provides the reaction of the hologram to the user's hand movement with the correlation of 1:1 between input and output. Navigation gesture can be used for scrolling, dragging and zooming the hologram in 2D MR space, as well as in 3D MR space. It can create a scrolling, zooming or rotation with increasing velocity. To start the gesture user should perform tap and hold gesture and then move the hand in any direction within a virtual 3D cube, which center is located at the initial tap position.

All hand gestures can be replaced with the HoloLens clicker. Moreover, the MR hologram can react to the voice commands, which can be customized during application development.

Furthermore, it is possible to extend the default HoloLens gestures by integrating Microsoft Kinect 2 technology, which is based on the special Kinect sensors. This sensors track body movements and allow to create completely new gestures for the interactions with HoloLens holograms, for example two hands can be used for resizing of a hologram. Such technology was investigated within research in the University of Calgary, Canada (Yim et al., 2016).

3 Methodology

The methodology chapter represents the research approach and the workflow chosen to pursue the research goals. As it was stated in the introduction chapter, the main research goal is to investigate the applicability of the MR environment for the spatiotemporal representations on the example of the space-time cube. To define the scope of the thesis, the research is focused on one particular application of spatiotemporal visualization, namely space-time cube for depicting landscape changes. Figure 3.1 represents the research workflow.

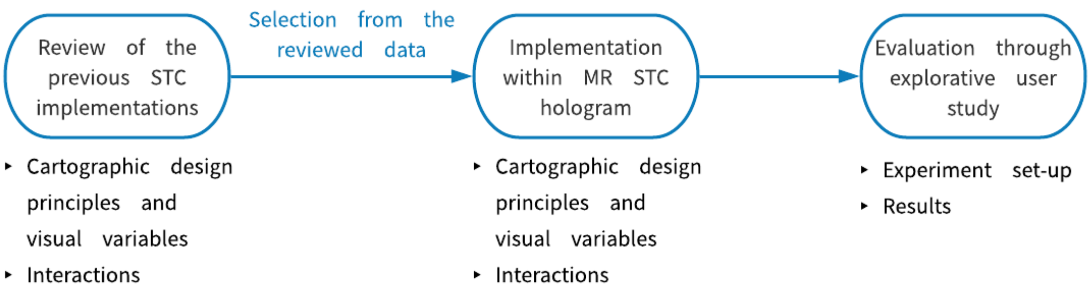


Figure 3.1 Research workflow.

The methodological part investigates existing cartographic design principles and visual variables and proposes their new implementation within mixed reality hologram. Moreover, the proposed methodology includes an overview of interactions with map representations and possible interactive features in the mixed reality. As a result, the interactive properties of the mixed reality space-time cube hologram are defined. Finally, suitable usability evaluation method for the mixed reality space-time cube hologram is proposed.

3.1 Space-Time Cube Hologram Development

3.1.1 Elements of the Space-Time Cube within Mixed Reality Hologram

After reviewing latest developments of the STC, the feasible STC elements to be implemented within MR STC hologram and possible visualization methods are specified in the table 3.1. The aim of the implementation of the reviewed space-time cube elements in the mixed reality hologram is to attempt extend their previous implementations by suggestion new visualization and interaction features. The most thematically close space-time cube implementation is the one performed by Bogucka and Jahnke (Bogucka and Jahnke, 2017). That is why it was assumed suitable to apply the resembling main elements configuring the basis of the space-time cube hologram for the cultural landscape changes depiction. In particular, it is space-time prisms representing landscape features, space-time links and ground slices. Base map was widely used and proved its usefulness in space-time cube visualizations (Kraak, 2003; Gatalsky, Andrienko, and Andrienko; 2004; Li, Çöltekin, and Kraak, 2010; Bogucka and Jahnke 2017, 2018; Baas, 2013). In the reviewed cases base map was located at the bottom of the space-time cube. In two visualizations the were interactive features of this element – possibility to move base map along time axis (Kraak, 2003; Li, Çöltekin, and Kraak, 2010). Considering the mixed reality environment and the fact that there is no stable base for the hologram, such as earth surface of the 3D globe (Bogucka and Jahnke, 2017, 2018) and the hologram can be placed anywhere in the surrounding space, it was suggested to place the base map on the ground slices of the space-time cube hologram. Space-time grid was introduced in Baas's space-time cube for animal behavior tracking (2013). It has an advantage of the better geographical location estimation. The potential incorporation of this element to the mixed reality space-time cube visualization for the cultural landscape changes depiction can be done by showing space-time grid at the bottom of the cube, or at each ground slice. Such feature could be useful for locating of the landscape features in real world geographical coordinates. The characteristics and visualization methods given in the Table 3.1 reflect the aspects discussed above and expand them to the potential of mixed reality application.

Table 3.1 STC elements, which can be implemented within MR STC hologram for historical landscape changes representation.

STC element	**Characteristics**	**Way to visualize within MR STC hologram**
Landscape features (space-time prisms)	Buildings, water bodies, green areas, additional features important for the specific case study (for example roads, railroads, bridges, etc.)	Landscape features footprints extruded to the relative height
Space-time links	Connections between landscape features locations through the time dimension	Vertical lines through main border points of the landscape features like in Bogucka and Jahnke STC (2017, 2018) or semi-transparent vertical volume having a landscape feature footprint as a base shape
Ground slices	Ground base for the landscape features for each time interval	Horizontal plane within each time interval
Base map	Base map at the bottom of the STC or at each ground slice for better geospatial orientation of the landscape features	A scaled texture of a map or orthophoto image assigned to the ground slice
Space-time grid	Grid with geographical coordinates at the bottom of the cube or at each time interval slice	Grid of lines with given coordinates

The scope of the thesis includes practical development and evaluation of the mixed reality hologram of the space-time cube hologram for cultural landscape changes depiction. As it is a novel area for such visualization only the basic elements were chosen to be implemented: landscape features (buildings and water bodies), space-time links, and ground slices. Visualization methods which chosen for these elements are represented in the Table 3.2. The selection process of the methods was based on the capabilities of the 3D mixed reality holographic visualizations.

Table 3.2 Space-time cube elements to be implemented within MR hologram.

Space-time cube element	Visualization method
Landscape features: buildings	3D cuboids derived from the buildings' footprints through their extrusion
Landscape features: water bodies	3D volumes derived by extrusion of the water bodies footprints
Space-time links	Transparent 3D volumes connecting buildings' locations through the whole time dimension of the STC
Ground slices	Semi-transparent planes at the basement for buildings and water bodies of each time subinterval

3.1.2 Cartographic Principles in the Space-Time Cube Hologram

The transfer of cartographic principles discussed by Tyner (1992) and Madej (2000) into a mixed reality space-time cube hologram can provide better user experience of the STC application. Map elements arrangement constitutes the cartographic representation and thus can be embedded into the 3D space-time cube mixed reality application, considering space-time cube as a spatiotemporal cartographic visualization technique. The map elements and their characteristics were reviewed in the State of the Art Chapter. Each map element and principle was examined for its potential applicability in the space-time cube visualization for landscape changes and mixed reality application of the space-time cube which will be developed in the scope of the thesis. As the reviewed literature does not referred to this issue, the embedding techniques of the cartographic principles were based purely on the author suggestions. The map elements and cartographic principles selected as suitable for implementation in space-time cube hologram are listed in the Table 3.3 and Table 3.4 respectively. Additional notes column for the cartographic principles presents the ideas of how to achieve the goals of each principle in the holographic space-time cube application.

Table 3.3 Map elements and their implementation within the mixed reality space-time cube hologram.

Figure, theme or subject area (mapped area)	Space-time cube itself	3D space-time cube
Title and subtitle	Written on the starting welcoming screen of the application	Title on the starting screen of application
Map legend	Given next to the space-time cube	Interactive map legend next to the 3D space-time cube
Map scale	Could be represented as labelled graticule or grid	*No implementation*
Orientation	Could be provided by a north arrow or by graticule/grid	North arrow
Names and labeling	Labeling of the landscape features can be provided on demand	Names of the landscape features given at the info-windows showing on air tap
Credits	Could be given within welcoming screen or provided via tapping on the specific button in user interface	*No implementation*
Graticule or grid	Could be implemented on the ground slices	*No implementation*

Table 3.4 Implementation of cartographic principles within MR space-time cube hologram.

Cartographic principle	**Aim**	**Additional notes**
Legibility (Clarity)	• Intuitive and understandable color scheme • Readable text with appropriate text size and color • User-friendly interface and instructions within the MR STC holographic application	• Color scheme chosen with ColorBrewer web instrument[10] and adapted to mixed reality • Contrast colors for text: dark text should be placed only on the white background; for other backgrounds white color will provide good contrast; • Build-in instructions
Visual contrast	• contrast between MR STC hologram elements	• Contrast colors for text: dark text should be placed only on the

[10] "ColorBrewer: Color Advice for Maps," 2016, http://colorbrewer2.org/#type=sequential&scheme=BuGn&n=3, accessed September 2018.

Cartographic principle	Aim	Additional notes
		white background; for other backgrounds white color will provide good contrast; • Contrast in size, intensity, shape, color;
Figure-ground contrast	• contrast between MR hologram and background (taking into consideration a non-static background depending on the working environment - room)	• Different color hues or color values (white color and other bright colors give better contrast than dark colors) • Different rendering techniques for the object materials
Hierarchical organization (Order)	• Vertical hierarchy of time slices (time subintervals)	
Balance	• Initial position and size of the hologram comfortable for visual perception • Balanced spacing between centuries to provide comfortable user experience	
Unity	• Harmonic position of the legend, control elements, menu and settings buttons	

3.1.3 Visual Variables in Space-Time Cube Hologram

Visual variables are the inalienable graphic elements of the map as they constitute the cartographic visualization and symbology. Thus, the use of visual variables in the space-time cube, as one of the cartographic representations, is an inherent process. Though only few visual variables were investigated in the space-time cube development process. These are color hue, color value, color saturation, size and orientation, transparency and shading (Kveladze, Kraak and van Elzakker, 2018). Bogucka and Jahnke (Bogucka and Jahnke, 2017) in their space-time cube for the cultural landscapes changes suggested to use also edge enhancement, shape and pattern. The color hue and color value are universal visual variables which can be used in various cases and applications, as well as transparency. Although transparency in mixed reality environment could be perceived ambiguous as the mixed reality holograms possess some degree of transparency by themselves. Size in different applications can be visualized differently, e.g. in the space-time cube for movement data it can be implemented as varying width of the space-time paths shading (Kveladze, Kraak and van Elzakker, 2018), while space-time cube for landscape changes will not have space-time path as a constituent element, but the size variable can be implemented towards other elements, like landscape feature height. Concluding, the visual variable of color hue, color value, transparency and size are seemed feasible for mixed reality space-time cube for cultural landscapes. Additionally, the usage of the texture variable can enhance the landscape features representation and perception as this variable can provide associative, more natural look of these features. For each selected potential visual variables for the mixed reality hologram were suggested the ways of usage within the space-time cube hologram and potential difficulties, which may occur in the mixed reality visualization due to the additive color rendering of the mixed reality devices (Table 3.5). For the practical part of the thesis the visual variables were defined according to the selected earlier elements of the space-time cube (Table 3.6).

Table 3.5 Potential implementation of the visual variables within MR STC hologram

Visual variable	**Potential usage in the MR STC hologram**	**Possible difficulties in the implementation of the MR visualization**
Color hue	• as associative variable to visually categorize landscape objects into the groups, such as water, green areas, roads, etc. • as selective variable to provide possibility of visual selection of the objects possessing same characteristic • to emphasize some specific landscape features	• darker color hue will be visually represented as more transparent compared to brighter color hue • to visualize black color the RGB values should be different from (0,0,0) and should correspond to dark grey color hue • the white color hue will be the brightest within the MR hologram and it should be used wisely in order to provide comfortable visual contrast of the whole hologram
Color value	• as ordered variable to provide sequential categorization of the objects	• the potential differences in transparency for different color values should be considered
Transparency	• to enhance visual perception and comprehension of STC content to avoid visual clutter	• should be used carefully due to the inherent transparency of the MR holograms
Texture	• to provide associative or selective perceptions of the specific landscape features, e.g. to assign one texture to the buildings with the same specific characteristic or to emphasize specific buildings among others.	• suitable resolution, mapping and filtering should be applied during the development stage in order to avoid aliasing effect on the borders[11]

[11] "MicrosoftDocs/mixed-reality," https://github.com/MicrosoftDocs/mixed-reality/blob/master/mixed-reality-docs/color,-light-and-materials.md, accessed September 2018.

Visual variable	Potential usage in the MR STC hologram	Possible difficulties in the implementation of the MR visualization
Size	• to emphasize some specific landscape features among other, or to provide additional quantitative characteristic of some group of landscape features.	• should be comfortable for user to visually percept objects and interact with them

Table 3.6 Implementation of the visual variables in the MR space-time cube hologram for the depiction of landscape changes.

Visual Variable	Implementation within MR STC for landscape changes depiction
Color hue	• Color schemes for buildings classification • Buildings highlighting (with bright color for gaze selection) • Associative color hue for water bodies and ground slices
Color value	• Water bodies highlighting • Color scheme for buildings classification
Transparency	• Two variations of the ground slices: • 90% transparent • 10% transparent
Size	• Assign different height to the buildings which were built and destroyed at the same time subinterval, and thus having the same location within the STC and creating visual clutter within time subinterval • Spacing of time subintervals

3.2 Interactive Features of the Space-Time Cube Hologram

The investigation of the previous space time-cube variations shows that the manipulation of the viewpoint on the space-time cube is the most frequent interactive feature. It was implemented for movement data (Kraak, 2003), depiction of geo-related events (Gatalsky, Andrienko, and Andrienko, 2004), animal behavior (Baas, 2003) and landscape changes Bogucka and Jahnke (2017). This interactivity provides better exploration experience of the data, and can be implemented within mixed reality as rotation and dragging of the space-time cube hologram. Due to the possible complications with hand gesture interacting within novel mixed reality technology it is suggested to add possibility to reset the cube's rotation to its initial state. Zooming overall space-time cube was also an interactive feature used by several researchers in order to provide both overview and detailed levels for the data exploration (Gatalsky, Andrienko, and Andrienko, 2004; Li, Çöltekin, and Kraak, 2010; Bogucka and Jahnke, 2017). This interactive feature can be transferred to the mixed reality hologram as well.

Highlighting of the features with the gaze operation was chosen as user should have visual feedback about his gaze position in the mixed reality, otherwise it would be problematic to distinguish the object for interaction. Querying data and showing it on demand was used by Kraak (2003), and specifically for landscape changes space-time cubes by Moylan (2001) and Bogucka and Jahnke (2017). This feature provides the possibility to get additional data which is not visually represented all the time and avoid visual clutter in space-time cube. Space-time links were for the first time implemented by Bogucka and Jahnke (2017), but they were not interactive. The suggestion to make them displayed on demand only is based on the attempt to reduce visual clutter. Filtering was implemented in the eye-movement data visualization (Li, Çöltekin, and Kraak, 2010). Filtering was based on location and attributes of the data. The implementation of such operation in the mixed reality space-time cube for landscape changes can be adjusted and be performed in the time dimension - filtering of time subintervals. Re-ordering of the time subintervals is proposed as additional extending functionality, that can adjust visualization according to user's preferences or needs. Switching additional layers on/off and manipulating with the base map was used in both Kraak's space-time cube (2003) and the one from Li, Çöltekin, and Kraak (2010). Additional layers provide customization of the visualization. In the MR space-time cube for landscape changes this can toggle on/off of the base map and space-time grid, as well as changing the base map styles for the user needs adjustment. The possible interactive features for a mixed reality space-time cube hologram can be defined based on the potential operands (space-time cube elements or features). The suggested potential interactions and their implementation methods are listed in the Table 3.7. The selected interactive feature for the implementation within mixed reality space-time cube hologram within the scope of the thesis for landscape changes depiction are represented in the table 3.8.

Table 3.7 Potential interactions within MR space-time cube hologram based on the possible operands.

Operand	**Interaction**	**Potential implementation**
Landscape feature	Highlighting with the gaze	• Change of the color hue / color value, when the user's gaze intersects the landscape feature's location in 3D MR space
Landscape feature	Show information on demand	• Open/close info-window for the landscape feature on the air tap, when the feature is selected with the gaze
Space-time links	Show space-time links on demand	• Toggle visibility of the space-time links through the button on the info-window for the landscape feature using air tap gesture
Space-time cube	Rotation of the space-time cube in horizontal/vertical plane	• Start/finish rotation by voice command • Start/finish rotation by tapping on the specific button • Rotation through interaction with a bounding box

Operand	Interaction	Potential implementation
Space-time cube	Resetting the rotation of the space-time cube to its initial position	• Reset the position of the space-time cube via specific button in user interface/via voice command
Space-time cube	Proportionally changing the size of the space-time cube (scaling)	• Start/finish scaling by tapping on the specific button • Start/finish scaling by voice command • Scaling through interaction with a bounding box
The whole MR space-time cube application	Dragging the hologram in any direction and at any point of the MR 3D space	• Start/finish dragging by voice command • Start/finish dragging via specific button in user interface
Color scheme	Switching between several color schemes	• Via specific button in user interface • Via voice command
Time subintervals	Filtering visualized time subintervals	• Toggle visibility of each separate time subinterval (ground slice with landscape features) via specific buttons in user interface
Time subintervals	Re-ordering of the time subintervals along the time axis: from the contemporary landscape time subinterval on the top of the STC to its positioning at the bottom of the STC and vice versa	• Re-order of the time subinterval via specific button in user interface/via voice command
Sub-intervals spacing	Changing of the height between two ground slices	• Via specific button in user interface/via voice command
Space-time grid	Toggle space-time grid on/off	• Via specific button in user interface/via voice command
Base map on the ground slices	Toggle base map on/off Switching between different base map styles	• Via specific button in user interface • Switching between different styles of base map: orthophoto image, historical map, contemporary map etc.

Table 3.8 Implementation of the interactions in the MR space-time cube hologram for the depiction of landscape changes.

Interaction	**Implementation within MR STC for landscape changes depiction**
Highlighting with the gaze	• Change of the color hue / color value, when the user's gaze intersects the landscape feature's location in 3D MR space
Show information on demand	• Open/close info-window for the landscape feature on the air tap, when the feature is selected with the gaze
Show space-time links on demand	• Toggle visibility of the space-time links through the button on the info-window for the landscape feature using air tap gesture
Rotation of the space-time cube in horizontal/vertical plane	• Start/finish rotation by voice command • Rotation through interaction with a bounding box
Resetting the rotation of the space-time cube to its initial position	• Reset the position of the space-time cube via specific button in user interface
Proportionally changing the size of the space-time cube (scaling)	• Scaling through interaction with a bounding box
Dragging the hologram in any direction and at any point of the MR 3D space	• Start/finish dragging by voice command • Via specific button in user interface
Switching between several color schemes	• Via specific button in user interface
Filtering visualized time subintervals	• Toggle visibility of each separate time subinterval (ground slice with landscape features) via specific buttons in user interface
Re-ordering of the time subintervals along the time axis: from the contemporary landscape time subinterval on the top of the STC to its positioning at the bottom of the STC and vice versa	• Re-order of the time subinterval via specific button in user interface

3.3 Mixed Reality Space-Time Cube Hologram Evaluation

According to the investigated literature there are two ways for the space-time cube evaluation: comparative and exploratory usability study (Kveladze, Kraak and van Elzakker, 2013). Comparative study demands to perform quantitative evaluation in order to get in result numerical values to compare, such as time user needed to accomplish with tasks or the percentage of the correct answers of the user. Such study is aimed to evaluate efficiency and effectiveness of application. The example of such study is the experiment conducted by Bogucka and Jahnke for the cultural landscape changes space-time cube (2018). In this study space-time cube effectiveness and efficiency were explored in comparison to the other computer screen spatiotemporal visualization. As it was mentioned in the State of the Art chapter, mixed reality is a new technology and most of the users are not used to it, comparing with the computer-mouse working environment. Bach, Sicat, Beyer, Cordeil, Pfister (2018) conducted a comparative study between mixed reality and computer desktop visualizations. The findings of the research proved that the novelty of the mixed reality technology influences on the time, users need to accomplish tasks, slowing down the interaction process, which is not an issue for the computer applications. Due to that fact it is decided to make an exploratory user study of the MR space-time cube hologram for the landscape changes depiction. The study will consist of three parts. First part is an introduction of the user to the Microsoft HoloLens and interactions within its working environment in general and within space-time cube holographic application. Second part includes tasks performance by the user, providing audio feedback of his actions within mixed reality environment – thinking aloud. The second part of the study will be recorded in the video format, using the HoloLens functionality. The video will include only view of the user, his voice and hologram within the user's view. During the third part of the study user will be asked to fill in the questionnaire about his experience within space-time cube hologram. Additionally, the time of the task performance will be tracked. It will be used to define, if there are any factors, such as previous mixed reality experience, which are influencing on the time of the task performance. The study will investigate the comfort of the interactivity of the space-time cube within mixed reality, perception of the visual variables and advantageous features and limitations of the mixed reality for the space-time cube implementation.

4 Case Study

4.1 Royal Castle in Warsaw

The practical implementation of the methodology is based on the case study of the Royal Castle in Warsaw, Poland (Figure 4.1). Due to its eventful history, artistic values and symbolic meaning, it is considered as one of the most recognizable landmarks of Warsaw and the country itself. With approximately 600.000 visitors per year, museum of the Royal Castle prepares multimedia exhibitions and explores new possibilities for visualizing its history and collections.

The territory of the Castle includes the castle's building and the adjoining constructions and outbuildings (Figure 4.2). The Castle serves as a good example for cultural landscape changes depiction, as it has undergone many transformations in its appearance during its existence period since fourteenth century till nowadays. Its initial construction was held in 14^{th} century. Later in 16^{th} and 17^{th} centuries the castle was re-built and enlarged. During the World War II the site was completely destroyed (Figure 4.3), and only reconstructed in 1971. Restoration works were based on the historical plans, maps and images of the Old Town in Warsaw from the 17^{th} century. Additionally, to fulfil defensive and representative functions of residence, different types of water bodies were incorporated into the neighboring landscape. In the 14^{th} century castle was surrounded by moats, which were lately eliminated. The Vistula river, a key element of Warsaw's panorama, changed its flow channel after 17^{th} century. In 1980 the Old Town of Warsaw was registered as a UNESCO World Heritage Site. Thus, this part of Warsaw's landscape can be considered as an illustrative case study for the thesis.

Figure 4.1 Royal Castle in Warsaw nowadays. [12]

[12] "Category:Royal Castle, Warsaw - Wikimedia Commons," 2018, https://commons.wikimedia.org/wiki/Category:Royal_Castle,_Warsaw, accessed September 2018.

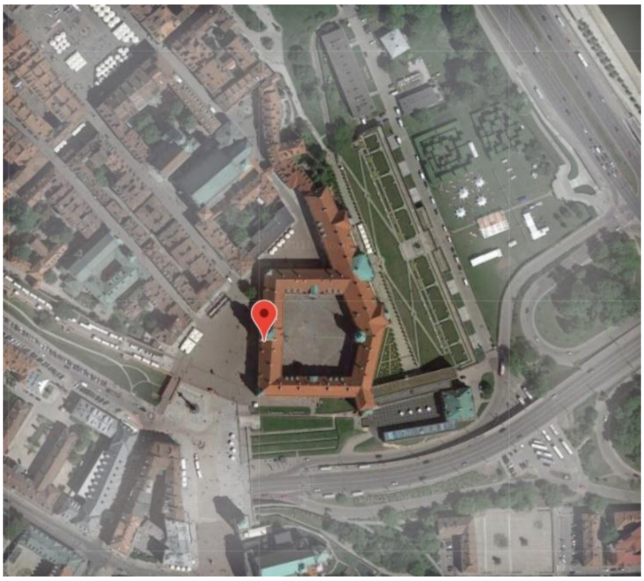


Figure 4.2 Royal Castle in Warsaw and adjoining buildings nowadays. [13]

Figure 4.3 Royal Castle in Warsaw after World War II. [14]

4.2 Microsoft HoloLens

Microsoft HoloLens is built on the principle of usual glasses, having two waveguides lenses instead of normal ones. However, HoloLens is not just a simple pair of glasses, but a headset with built-in computer with Windows 10 operational system. It has a light sensor, cameras for understanding

[13] "The Royal Castle in Warsaw - Google Maps," https://www.google.de/maps/place/The+Royal+Castle+in+Warsaw/@52.2479783,21.0137297,17z/data=!3m1!4b1!4m5!3m4!1s0x471ecc661b455407:0x2019a146fb49c9be!8m2!3d52.247976!4d21.015256, accessed September 2018.

[14] "File:Castleinwarsaw1947.jpg - Wikimedia Commons," 2018, https://commons.wikimedia.org/wiki/File:Castleinwarsaw1947.jpg, accessed September 2018.

of the surrounding space, a high definition camera and four microphones. The work of HoloLens from battery should last up to 2-3 hours.[15]

The HoloLens displays have additive nature and due to this feature the visualization in HoloLens MR is completely different comparing to computer screen or VR. The displays add light to the light of the real world, which results in rendering of virtual 3D objects, holograms, in the real-world space. Virtual 3D holograms do not have any physical resistance. Made of light, they can be seen from different angles and points of view. As the rendering principle is additive, the light colors are rendered bright, while the dark colors are less visually perceptible and more transparent. The black color is rendered completely transparent within HoloLens displays. HoloLens has an ability to scan the surrounding space and to create meshes for detected surfaces and objects of the physical world. Virtual holograms can be placed anywhere in the scanned real environment and can interact with the real surfaces and objects, such as walls, tables, etc. The methods of interaction with MR headset are announced as tangible and more natural compared to the computer mouse or touch screen interaction. HoloLens also provides immersive experiences without complete suppression of the real environment, as it is in typical VR applications. Thus, according to Microsoft HoloLens documentation user can interact with the hologram by means of gestures, gaze (the point of interaction is the point where the user's gaze is directed), using hands and voice as controls. It is worth to mention that gaze direction is determined by the direction of the whole headset, not by the eye tracking technology.[16]

4.3 Data Processing

The data used for the case study implementation was provided by the Chair of Cartography at the Technical University of Munich. The initial format of the data was ESRI shapefile (*.shp). The dataset contained footprints of landscape features such as buildings, water bodies and green areas. The software used at this stage of data processing was ArcGIS 10.5. The attribute table of the shapefile included the information about the years of construction and destruction for each landscape feature (Figure 4.4). Due to the temporal frequency of changes, it was decided to make time subinterval of the space-time cube equal to one century. That is why all the footprints were classified according to their temporal attributes into seven classes, with the precision of one year:

1. 14th century: 1301 – 1400
2. 15th century: 1401 – 1500
3. 16th century: 1501 – 1600
4. 17th century: 1601 – 1700
5. 18th century: 1701 – 1800
6. 19th century: 1801 – 1900
7. 20th century: 1901 – 2000

[15] "HoloLens hardware details - Mixed Reality," 2018, https://docs.microsoft.com/en-us/windows/mixed-reality/hololens-hardware-details, accessed August 2018.

[16] "What is a hologram? - Windows Mixed Reality," 2018, https://docs.microsoft.com/en-us/windows/mixed-reality/hologram, accessed August 2018.

The 21st century was not represented in the space-time cube hologram, as there was no significant changes in the landscape since the end of the 20th century.

Table

footprints_for_thesisPicture

FID	Shape *	Name	FolderPath	Base	BeginTime	EndTime	Shape_Leng	Shape_Area	Type
12	Polygon ZM	Entrance gate	Buildings/XIV century	15	1339	1818	0,000412	0	Buildings
13	Polygon ZM	Entrance gate	Buildings/XIV century	15	1339	1818	0,00039	0	Buildings
14	Polygon ZM	Grodzka Tower	Buildings/XIV century	15	1301	1572	0,000623	0	Buildings
15	Polygon ZM	Zuraw Tower	Buildings/XIV century	15	1301	1560	0,000461	0	Buildings
16	Polygon ZM	Outbuilding	Buildings/XIV century	15	1301	1400	0,000456	0	Buildings
17	Polygon ZM	Outbuilding	Buildings/XIV century	15	1301	1400	0,000476	0	Buildings
18	Polygon ZM	Outbuilding	Buildings/XIV century	15	1301	1400	0,000421	0	Buildings
19	Polygon ZM	Curia Maior	Buildings/XIV century	15	1400	1572	0,001442	0	Buildings
20	Polygon ZM	Curia Minor	Buildings/XV	15	1450	1944	0,000478	0	Buildings
21	Polygon ZM	Princess house	Buildings/XV	15	1450	1944	0,000483	0	Buildings
22	Polygon ZM	Baths	Buildings/XV	15	1450	1600	0,000393	0	Buildings
23	Polygon ZM	Castle kitchen	Buildings/XV	15	1450	1600	0,000373	0	Buildings
24	Polygon ZM	Palace	Buildings/XVI	15	1501	1619	0,00089	0	Buildings

0 (1 out of 46 Selected)

footprints_for_thesisPicture

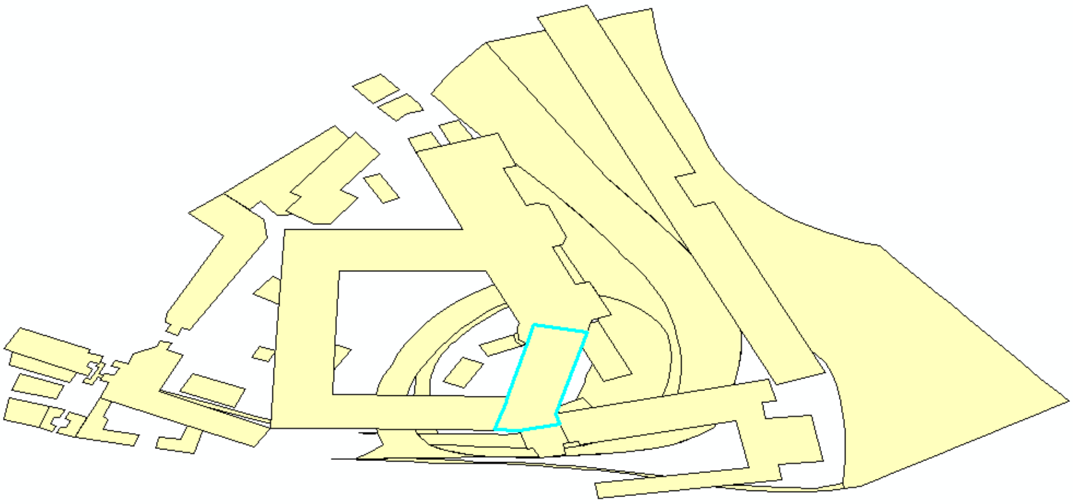


Figure 4.4 Shapefile with landscape features' footprints opened in ArcMap software together with their attribute table.

Based on the classification, the additional shapefiles were created and imported to the ArcScene 10.5 software. The ArcScene was used to extrude footprints and create the 3D model of the space-time cube for the case study (Figure 4.5). At this stage the initial spacing between time subintervals, as well as the height of buildings, water bodies and ground slices was set.

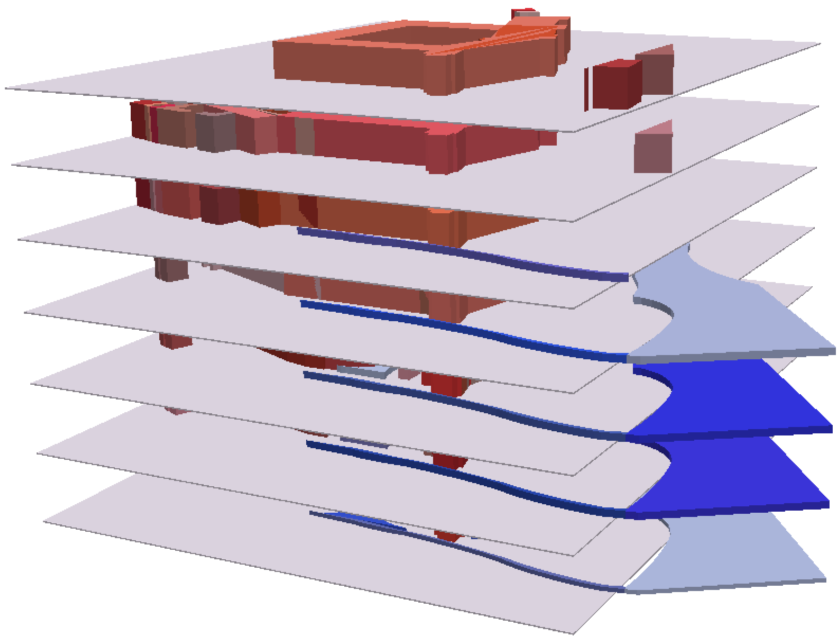


Figure 4.5 The model of the space time-cube for landscape changes depiction of the Royal Castle in Warsaw created in ArcScene software.

In the next step all elements of the space-time cube were classified according to their unique identification number and exported to the Blender software. Blender was used to re-mesh 3D models of the space-time cube elements in order to achieve their better visualization in the HoloLens hologram. The re-meshed model was imported to the Unity 2018.1 software as an asset for the space-time cube hologram project. The necessary technical condition for the developing for the mixed reality was Windows 10 operating system as the Windows 10 SDK (software developer's kit) is required.[17]

Unity was used for assigning materials for the elements of the hologram and scripting the interactive features of the hologram. For using all the possibilities of the mixed reality during the development stage a mixed reality toolkit 2017.2.1.4 was additionally installed to the Unity project.[18] All the remaining adjustments and improvements of the STC model, such as changing the height or the scale of the elements, creating additional elements of the user interface and interaction features, were made within Unity. Scripts were coded in the C# programming language and assigned to the objects within Unity platform. Code editing was performed in the Microsoft Visual Studio 2017 software. This software was also used for installing the developed space-time cube application to the HoloLens headset.

The overall data processing workflow is represented on the Figure 4.6.

[17] ."Install the tools – Mixed Reality." 2018. https://docs.microsoft.com/en-us/windows/mixed-reality/install-the-tools, accessed September 2018.

[18] ." MixedRealityToolkit-Unity uses code from the base MixedRealityToolkit repository and makes it easier to consume in Unity." https://github.com/Microsoft/MixedRealityToolkit-Unity, accessed September 2018.

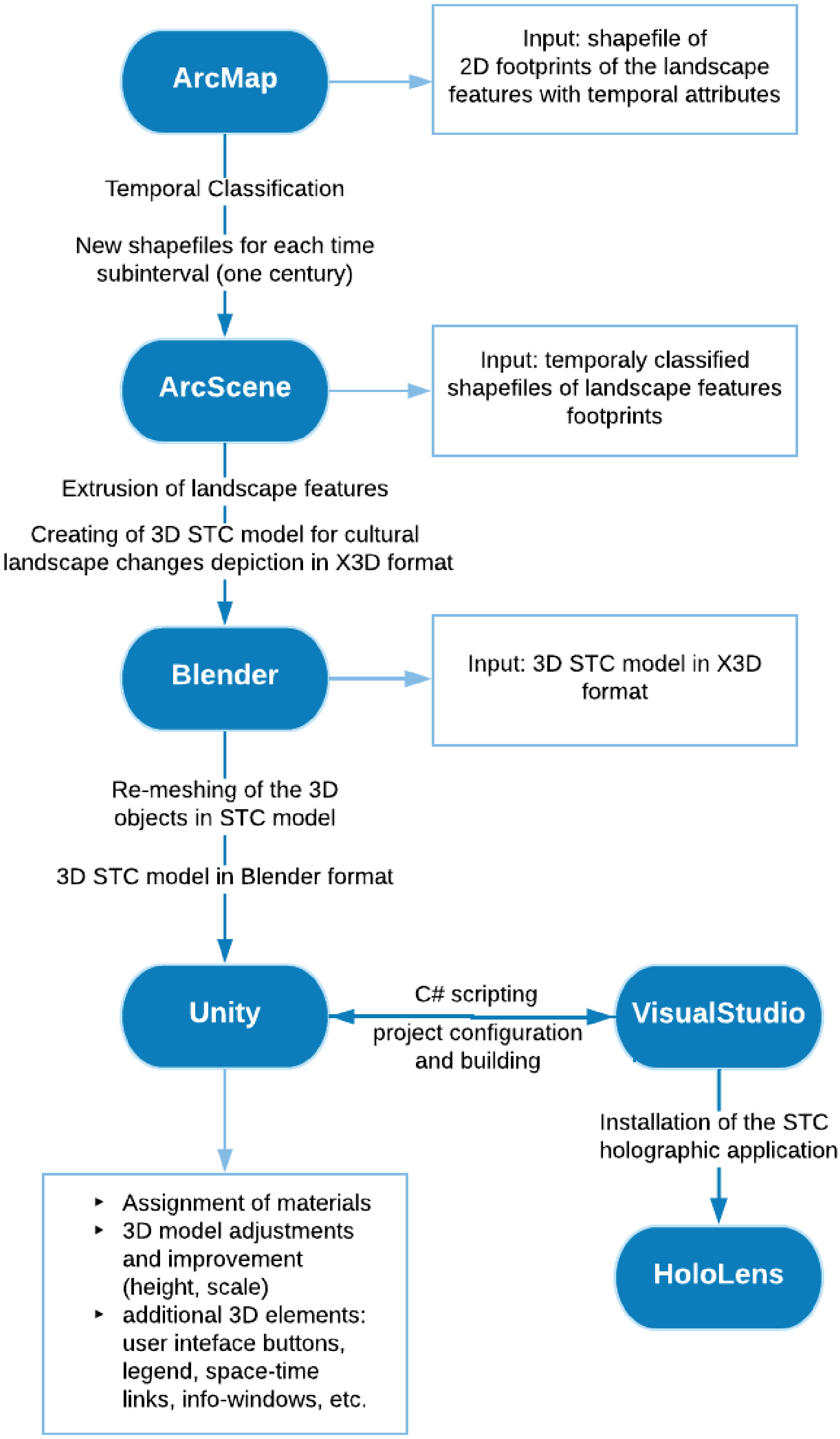
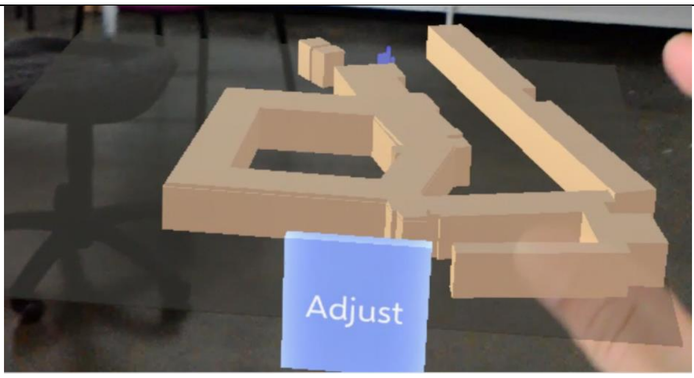
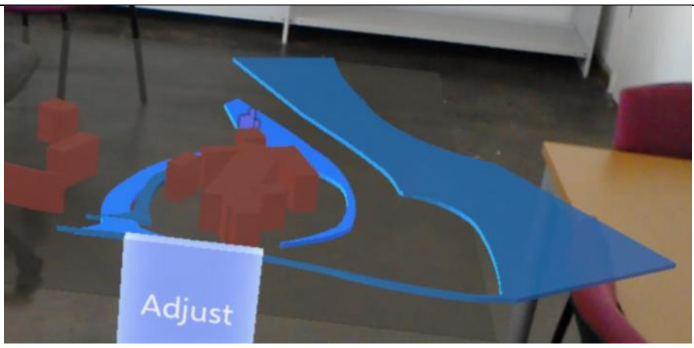
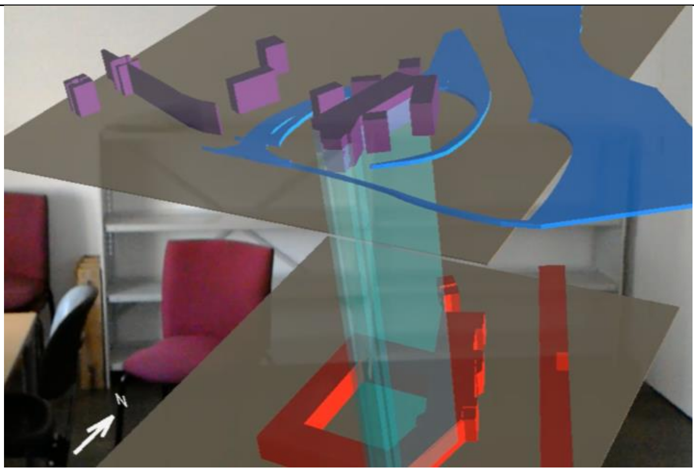


Figure 4.6 Data processing workflow.

4.4 Implementation

The mixed reality hologram of the space-time cube is based on the implementation process described in the methodology. Space-time cube consists of landscape features (buildings and water bodies), ground slices and space-time links. The information about the elements of the space-time cube and the examples of their visual representation are summarized in Table 4.1. The space-time cube hologram has some generic map elements as well, namely figure (main content), title, legend, orientation hints and interactive labeling. The examples of these elements are shown in the Table 4.2.

Table 4.1 Visualization of the space-time cube elements.

Space-time cube element and its associated visual variables	Visualization of the space-time cube elements in the mixed reality environment
Landscape features: buildings 3D cuboids derived from the buildings' footprints through their extrusion **Visual variables:** Color hue for buildings' classification Size (different height and width for the buildings existing at the same place in different years during the same time subinterval – century; left building on the figure)	
Landscape features: water bodies 3D volumes derived by extrusion of the water bodies footprints **Visual variables:** Color hue Color value (for highlighting)	
Space-time links Transparent 3D volumes connecting buildings' locations through the entire time dimension of the STC **Visual variables:** Transparency	

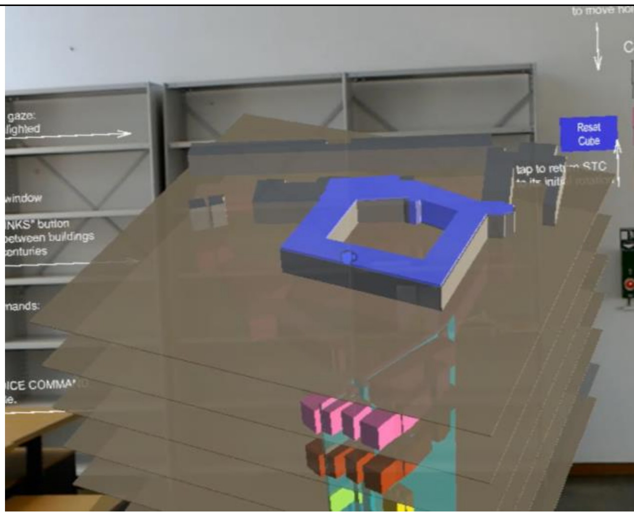
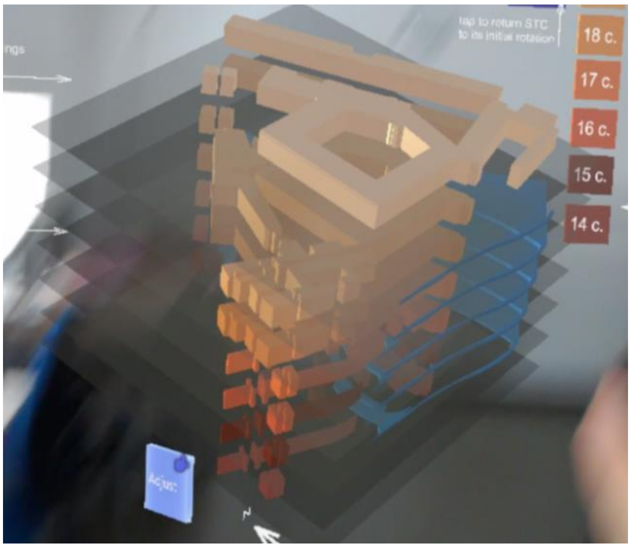
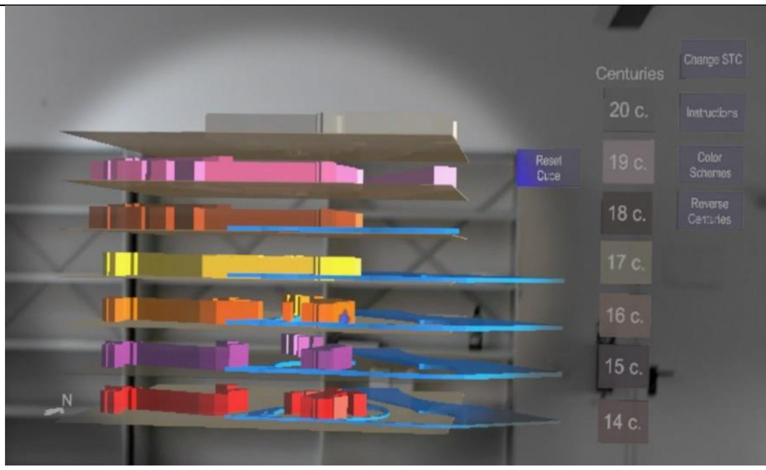
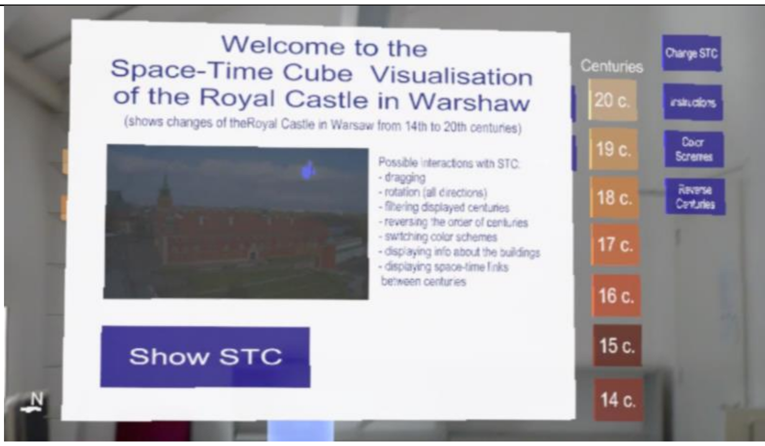
Space-time cube element and its associated visual variables	**Visualization of the space-time cube elements in the mixed reality environment**
Ground slices Semi-transparent planes at the base of the buildings and water bodies foreach time subinterval **Visual variables:** Transparency 1. 10% transparent ground slices 2. 90% transparent ground slices	 

Table 4.2 Map elements implemented in the MR space-time cube hologram.

Figure: **3D space-time cube**	

<table>
<tr><td></td><td></td></tr>
<tr><td>Title and subtitle:

Title on the starting

screen of application</td><td>


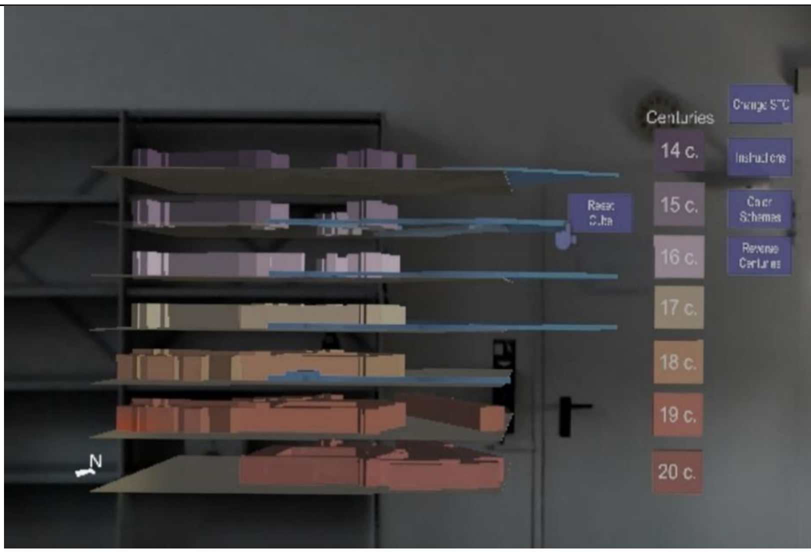
</td></tr>
<tr><td>Map legend:

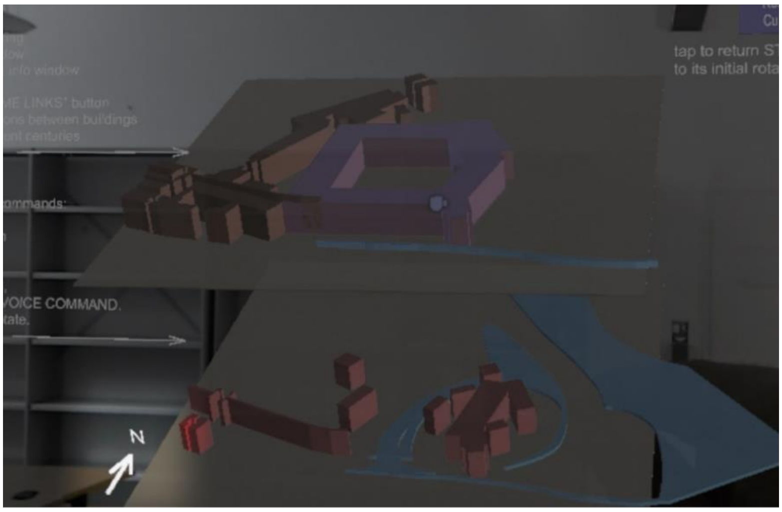
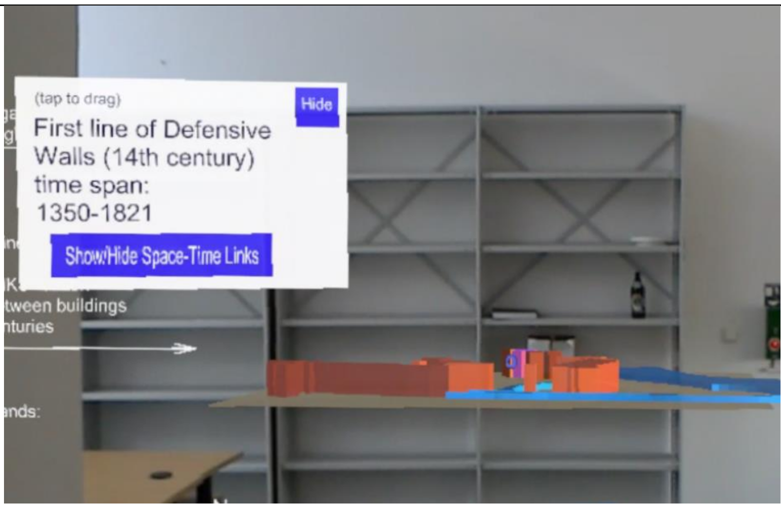
Interactive map

legend next to the 3D

space-time cube</td><td>


</td></tr>
</table>

<table>
<tr><td></td><td></td></tr>
<tr><td>Orientation:
North arrow</td><td>


</td></tr>
<tr><td>Names and labeling:
Names of the landscape features given at the info-windows showing on air tap</td><td>
</td></tr>
</table>

The development of the space-time cube hologram for the cultural landscape changes depiction considered the cartographic design principles. Thus, it was attempted to achieve legibility, good visual and figure-ground contrast, clear hierarchy, balance and unity of the hologram.

The *legibility*, or clarity, principle has several aspects to be described. Firstly, an understandable color scheme was chosen based on the ColorBrewer toolkit[19] and adapted to the mixed reality environment. Adaptation was required due to the different visual appearance of the colors in the HoloLens display rendering, which wereadditionally influenced by specific rendering settings in Unity. As a result, three main color schemes for the space-time cube were created: diverging (Figure 4.7), sequential (Figure 4.8) and qualitative (Figure 4.9).

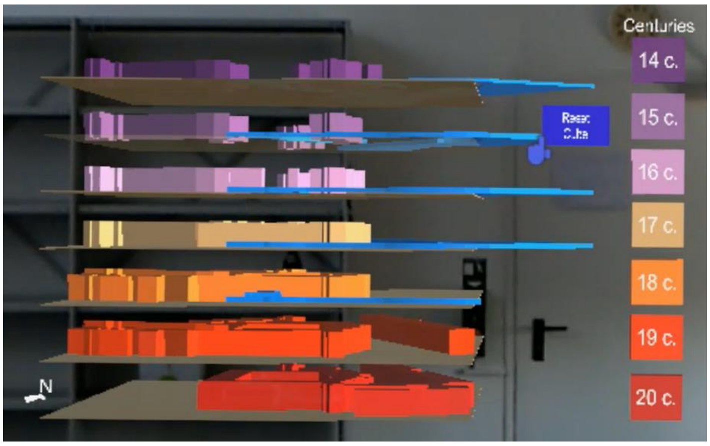


Figure 4.7 Diverging color scheme in MR STC.

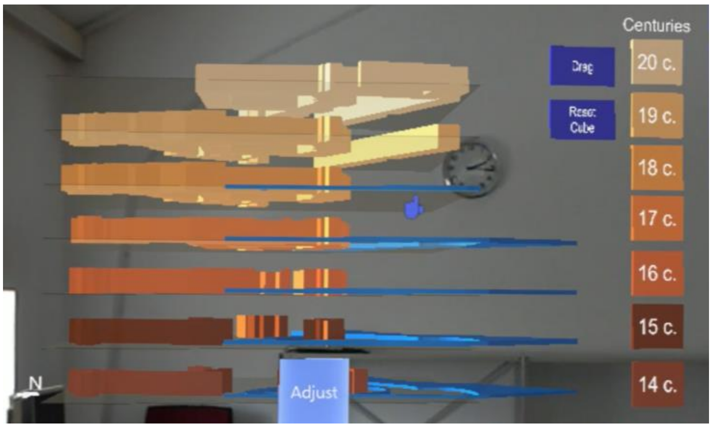


Figure 4.8 Sequential color scheme in MR STC.

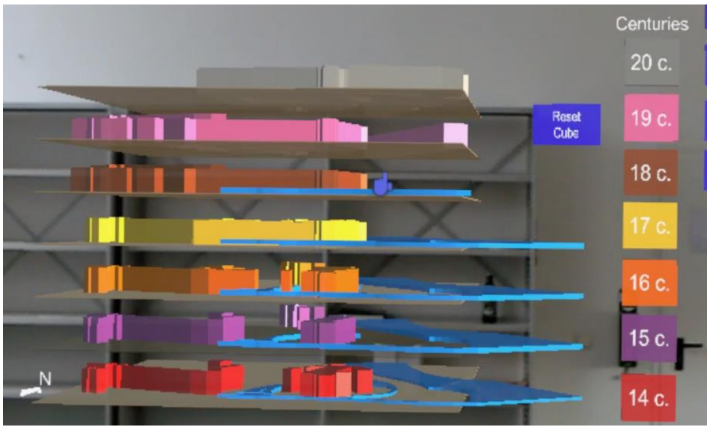


Figure 4.9 Qualitative color scheme in MR STC.

[19] "ColorBrewer: Color Advice for Maps," 2016, http://colorbrewer2.org/#type=sequential&scheme=BuGn&n=3, accessed September 2018.

Another aspect of legibility principle was to prototype the application with a readable text container, understood as appropriate text in suitable size and color (Figure 4.10).

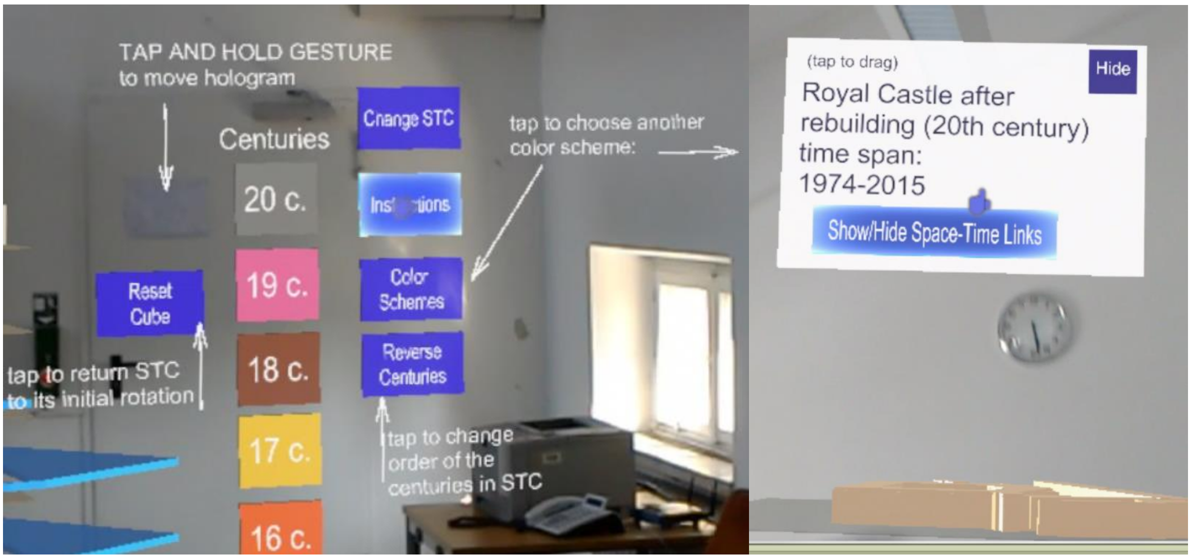


Figure 4.10 Examples of the text visualization in MR STC.

Furthermore, user-friendly interface should be provided for the users. The familiarization with the cube is possible through overall positioning of the interface buttons and build-in instructions with the possibility to switch them off and on. Interface hints are explained with white text around the hologram with arrows showing the elements correlated with the text (Figure 4.11).

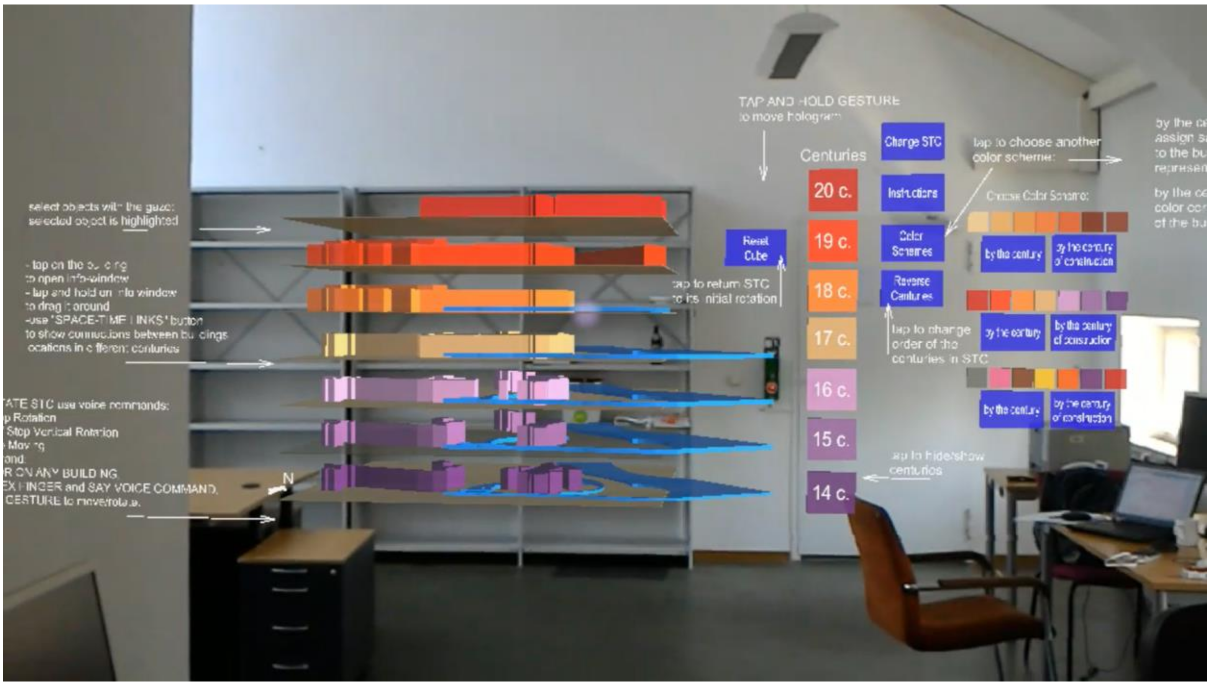


Figure 4.11 User interface and instructions for the MR STC hologram.

The next cartographic principle, which influenced the development of the space-time cube hologram, is *visual contrast*, or contrast between MR STC hologram elements. The main issue for this aspect was to provide the good contrast colors for the text containers: dark text on the white background, white text on the other backgrounds (Figure 4.12).

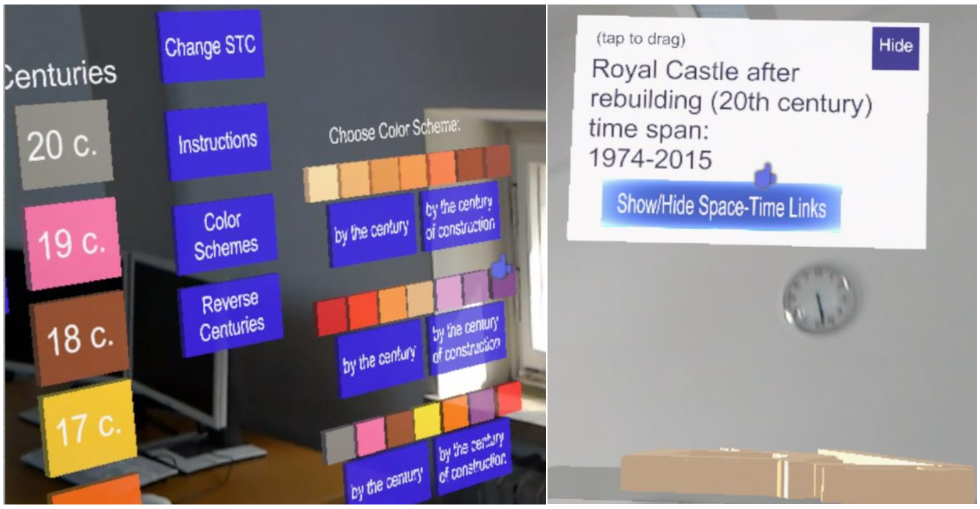


Figure 4.12 Contrast text colors in MR STC hologram.

The notion of the *figure-ground contrast* is related to the contrast between MR hologram and the background itself. It should preferably consider a non-static background, which further depends on the working environment and conditions, such as room and lighting. Different lighting in the same room results in different contrast levels for the same visualization (Figure 4.13 a, b). Different color hues also provide different contrast depending on the background, e.g. wall color can influence the visual perception of the visualization (Figure 4.14).

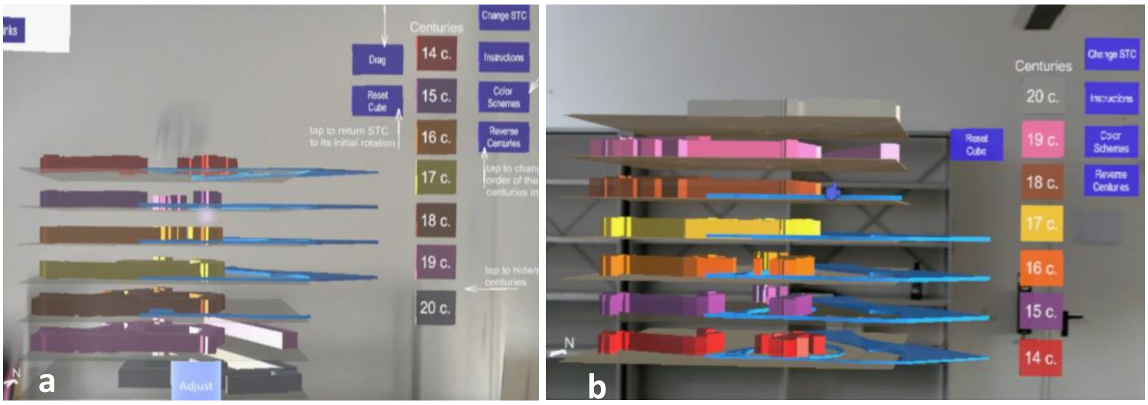


Figure 4.13 Influence of the working environment on the figure-ground contrast.

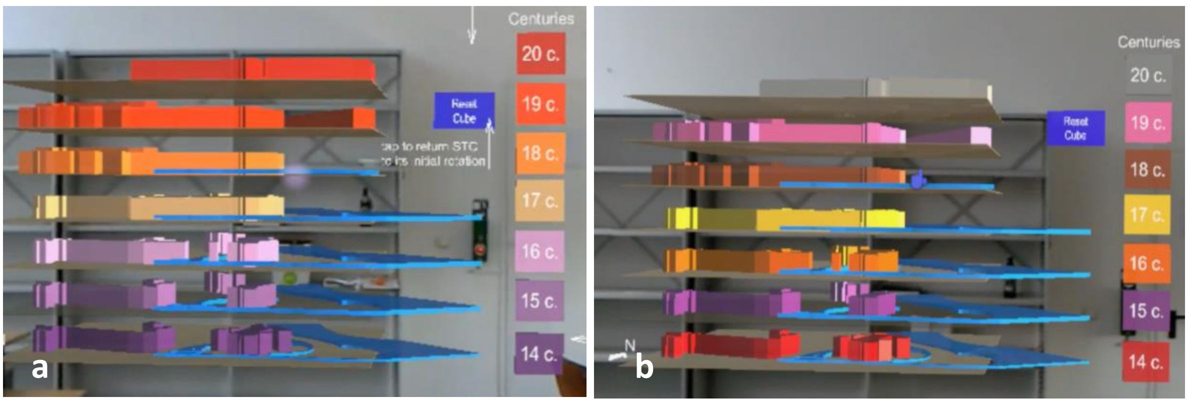


Figure 4.14 Good contrast for 20th century coloring scheme (a) and poor contrast for 20th century coloring scheme with the same background wall (century coloring scheme has similar color hue as the wall color) (b).

Specific color hues or color values also have better influence on the figure-ground contrast, e.g. white bounding box and bright color values provide better contrast with the background (Figure 4.15).

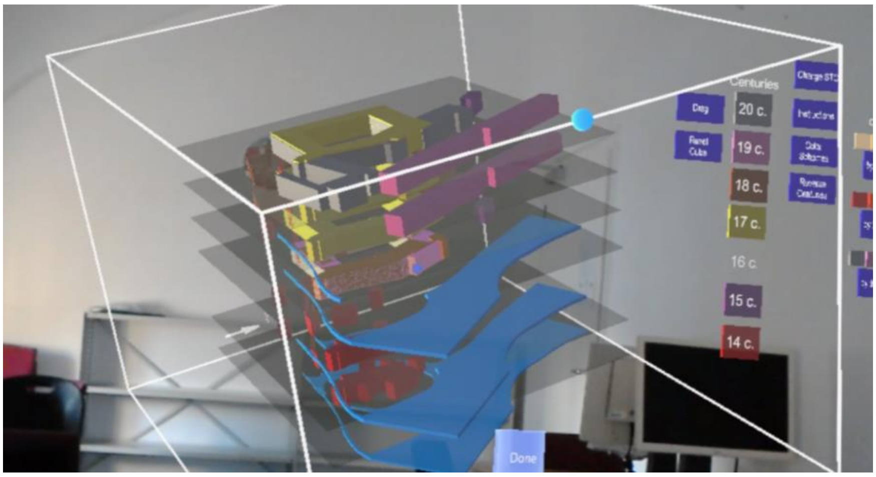


Figure 4.15 Influence of the color hue and color value on the figure-ground contrast.

Different rendering techniques for the object materials resulted in different contrast. 90% transparent ground slice (Figure 4.16, a) had poorer contrast than 10% transparent ground slice (Figure 4.16, b) and non-transparent rendering of the buildings and water bodies.

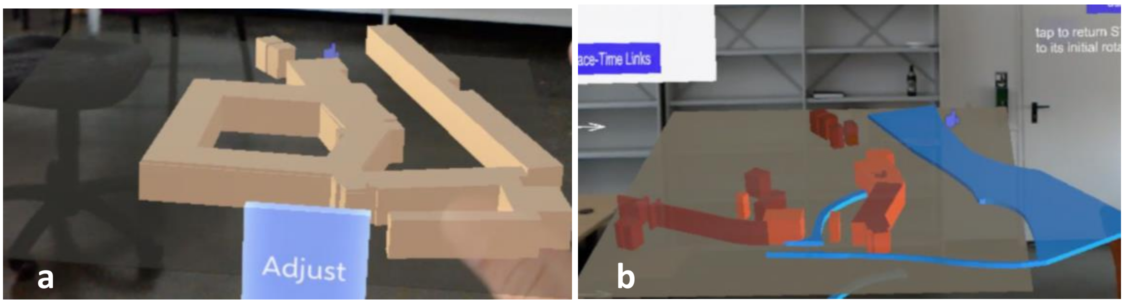


Figure 4.16 Influence of the different rendering techniques on the figure-ground contrast.

The *hierarchical organization* of the space-time cube hologram was presented as a vertical hierarchy of time slices - time subintervals equal to one century (Figure 4.17). Vertical legend supplemented the vertical order of the hologram.

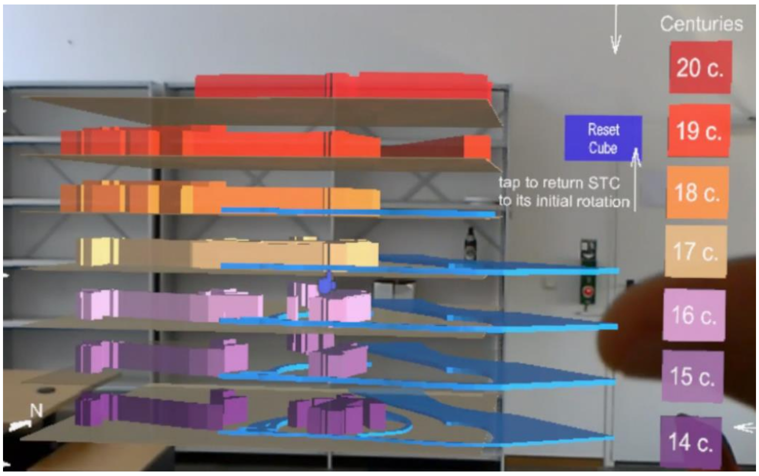


Figure 4.17 Vertical hierarchy of the MR STC hologram.

Balance was reached by initial position and size of the hologram which were comfortable for the visual perception and placed 2 meters in front of the user. Size of the starting screen fits into the HoloLens MR display, which allowed the user to visually perceive the whole hologram at once (Figure 4.18).

Figure 4.18 Starting screen of the MR STC application.

Balanced spacing between centuries provided comfortable user experience. The spacing from the final version of the space-time cube hologram is represented on the Figure 4.19, while Figure 4.20 (a, b) shows previous spacing variations.

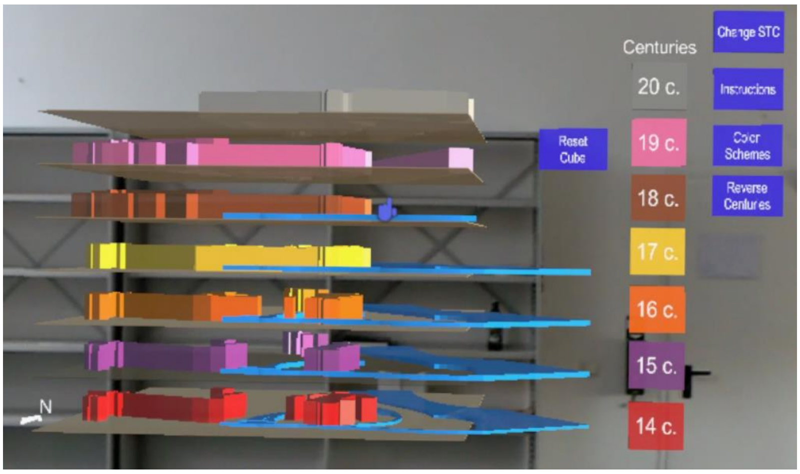


Figure 4.19 Spacing of the time subintervals.

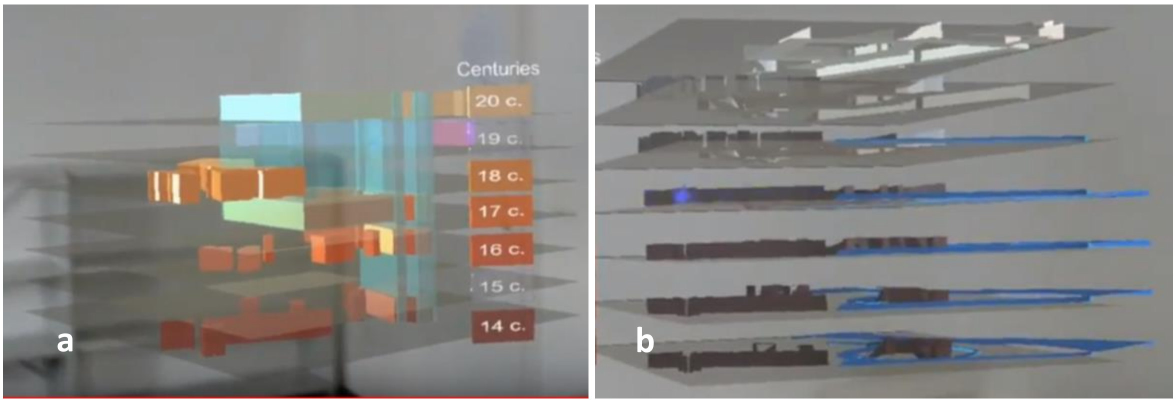


Figure 4.20 Previous spacing variants: (a) relative high buildings - easy to interact, hard to distinguish between time subintervals; (b) relatively small height of the buildings – hard to interact with.

The principle of *unity* resulted in harmonic position of the legend, control elements, menu and settings buttons – vertical legend and controls were located on the right next to 3D space-time cube (Figure 4.21 a). Alternative color schemes were extended further to the right (Figure 4.21 b).

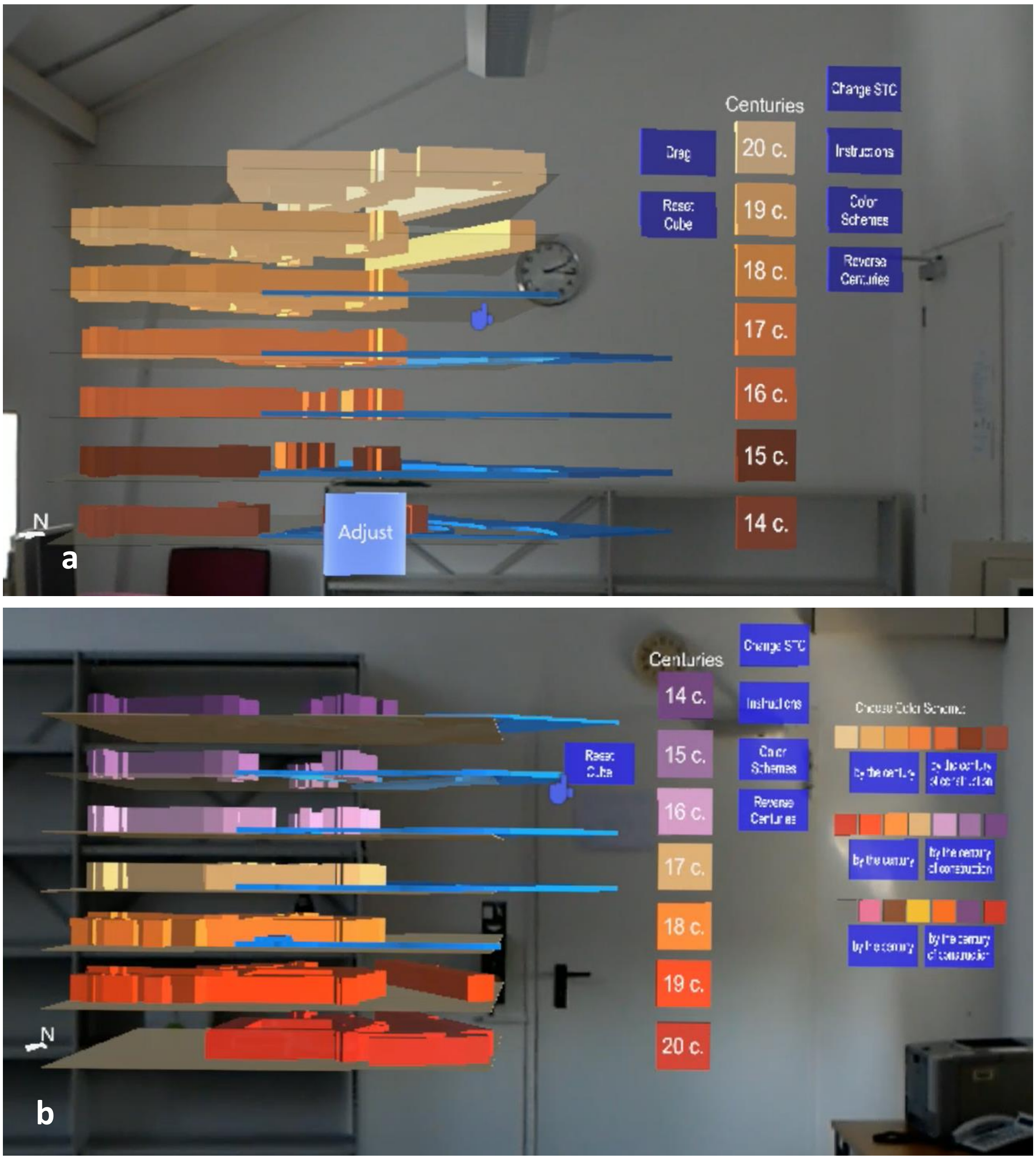
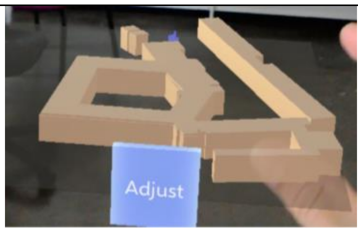
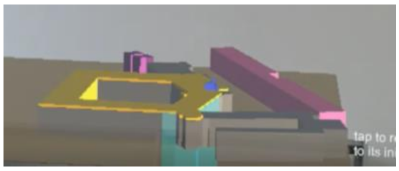
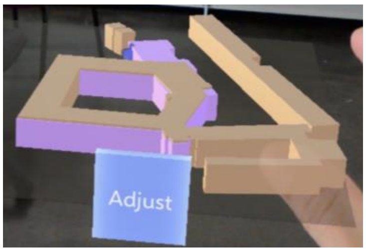
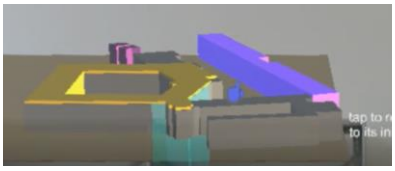
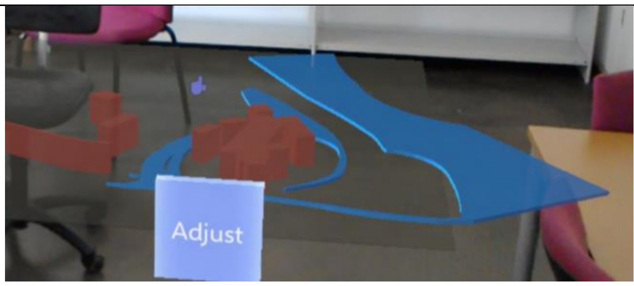
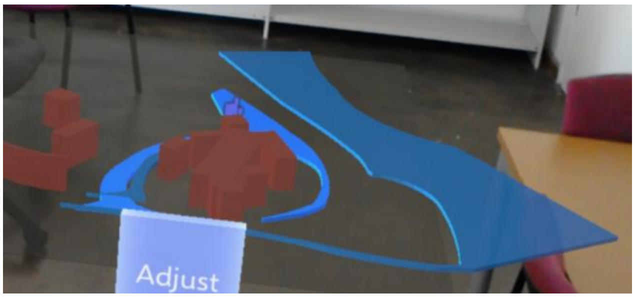
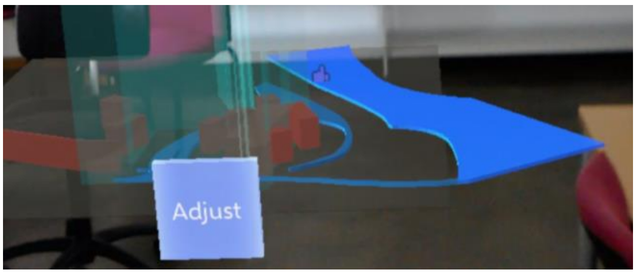


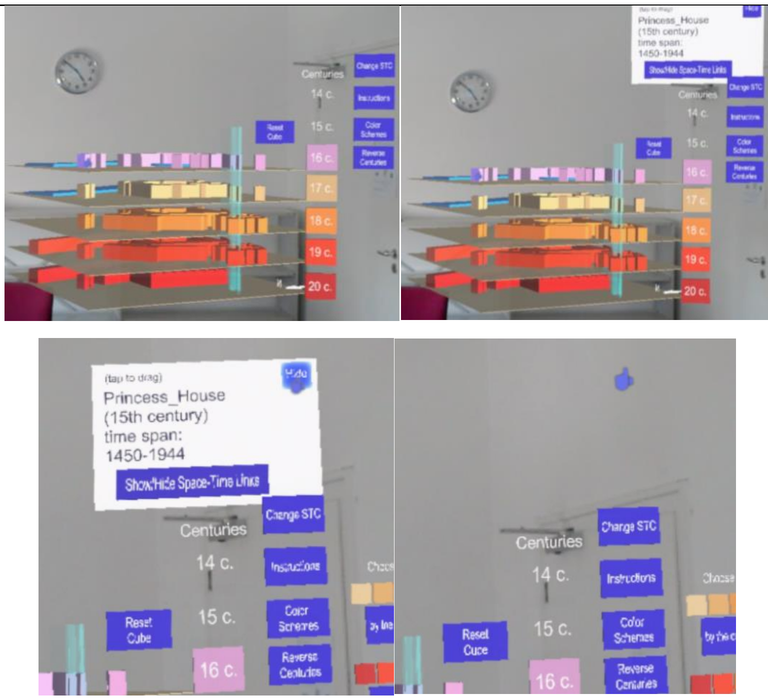
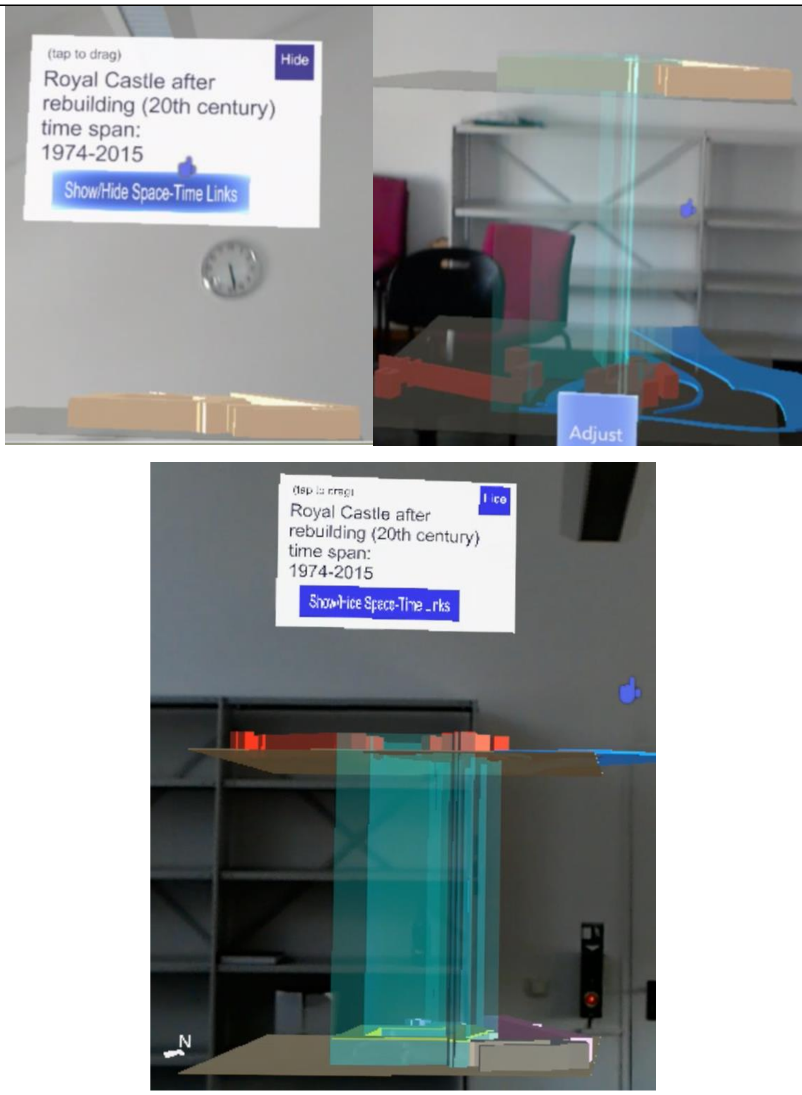
Figure 4.21 Overview of the user interface and its controls.

Implementation process involved experimenting with different visual variables, such as color hue, color value, size of the space-time cube elements and degree of transparency, before the final holographic application was introduced. In initial visualization the transparency was used only for the ground slices, because the hologram in general possess a certain degree of transparency due to the rendering technology of the HoloLens. However, transparency was still be used for the space-time links to achieve visual connections between the buildings in different time subintervals. Interactive legend elements had full transparency except for the borders, where the filtering of the time slices was done. The visual representation of this feature is given within the interactions' summary table (Table 4.3). Color hue was used for buildings' classification through several variations of the color schemes (diverging and qualitative), which are represented on the

Figures 4.7 and 4.9. For the sequential color scheme, the visual variable of color value was used as well (Figure 4.8). Both color hue and color value were used for the interactive features of the space-time cube hologram – highlighting of the objects with the gaze. The full list of interactions and their visual representations are given in the Table 4.3.

Table 4.3 Implemented interactive features within MR space-time cube hologram.

Interaction	Implementation within MR STC for landscape changes depiction
Highlighting the building with the gaze: Change of the color hue, when the user's gaze intersects the landscape feature's location in 3D MR space. **Visual variables**: Color hue	    
Highlighting the water body with the gaze: Change of the color value, when the user's gaze intersects the landscape feature's location in 3D MR space. **Visual variables**: Color value	  

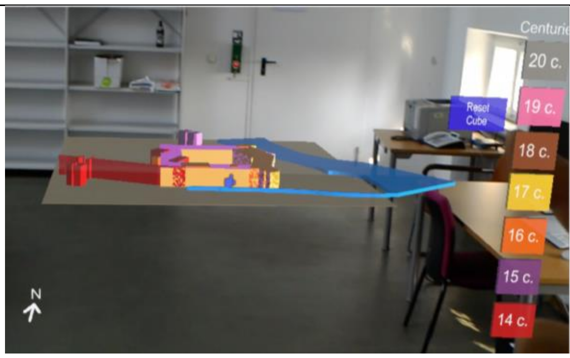
Interaction	Implementation within MR STC for landscape changes depiction
Show information on demand (interactive labeling): Air tap on the landscape feature. When the feature is selected with the gaze, info-window with feature's name, century of construction and years of existence is opened. To close the info-window user should tap "Hide" button in the upper right corner of the info-window.	
Show space-time links on demand: User has a possibility to toggle visibility of the space-time links through the button "Show/Hide Space-Time Links" on the info-window for the landscape feature using air tap gesture. **Visual variables**: Transparency	

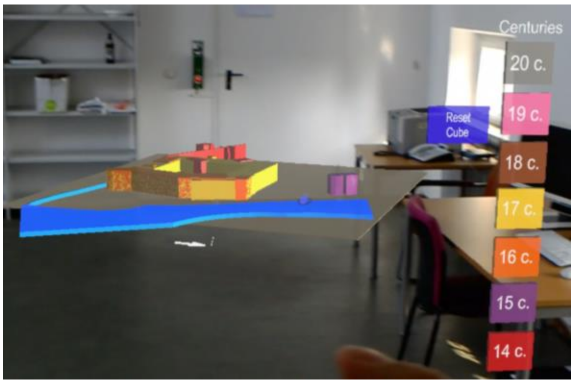
<table>
<tr><th>Interaction</th><th>Implementation within MR STC for landscape changes depiction</th></tr>
<tr><td>

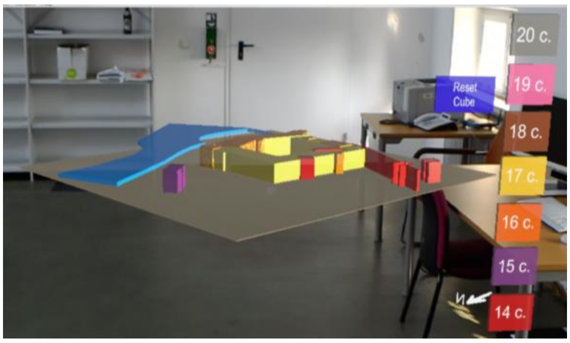
Rotation of the space-time cube in horizontal plane via voice command:

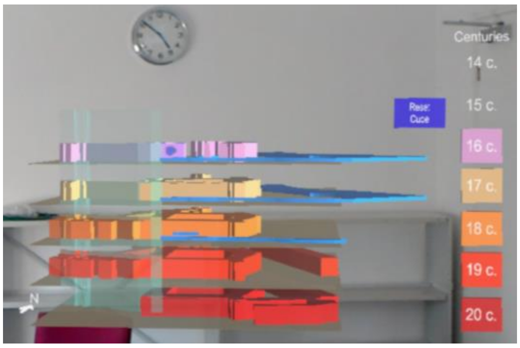
1. User should say voice command “Rotate Cube”.
2. Tap and hold one of the landscape features within the cube.
3. Move the hand in the direction of the desired rotation.
4. To stop rotation user should say the voice command “Stop Rotation”.

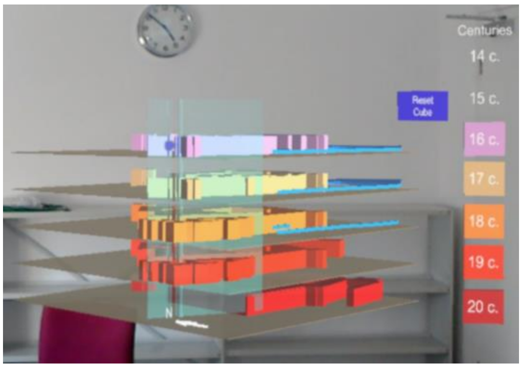
</td><td>



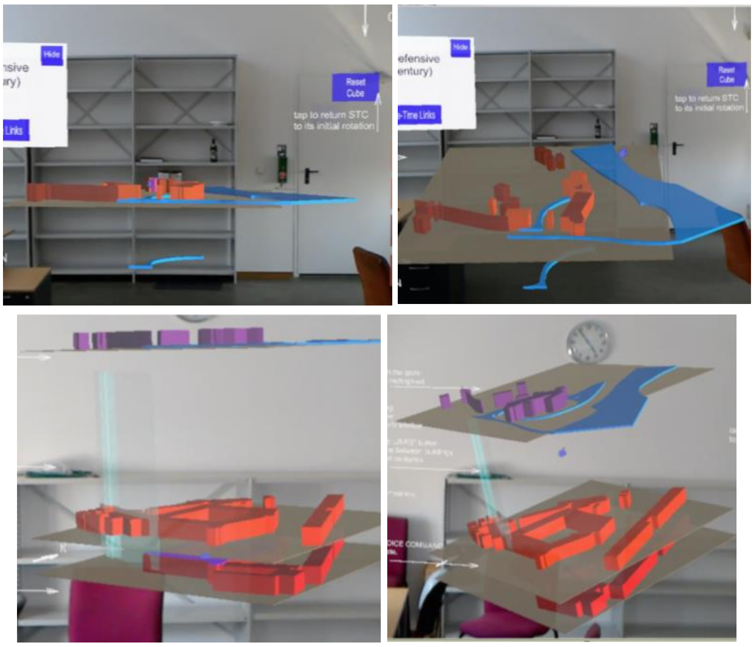
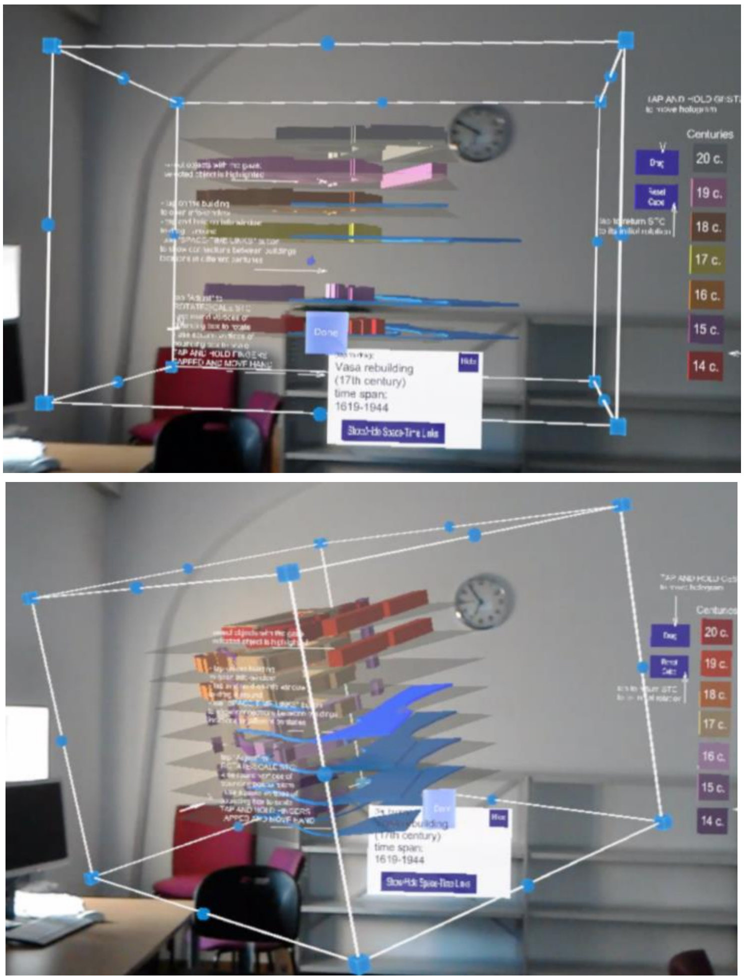




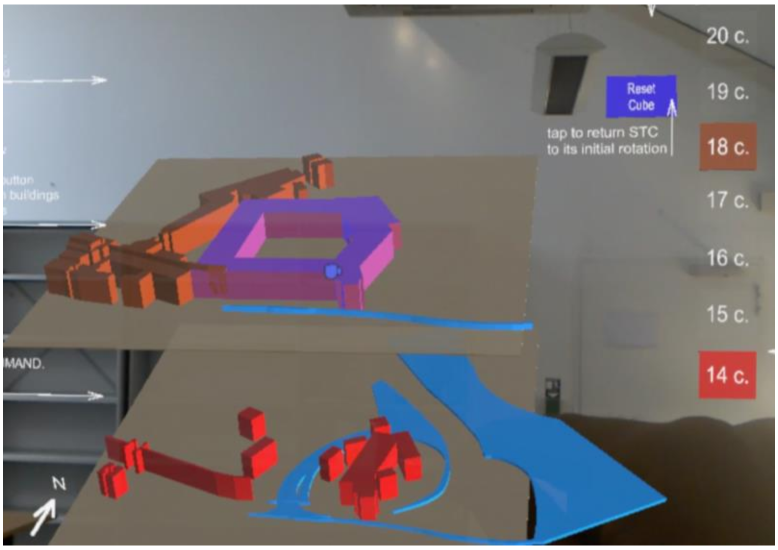


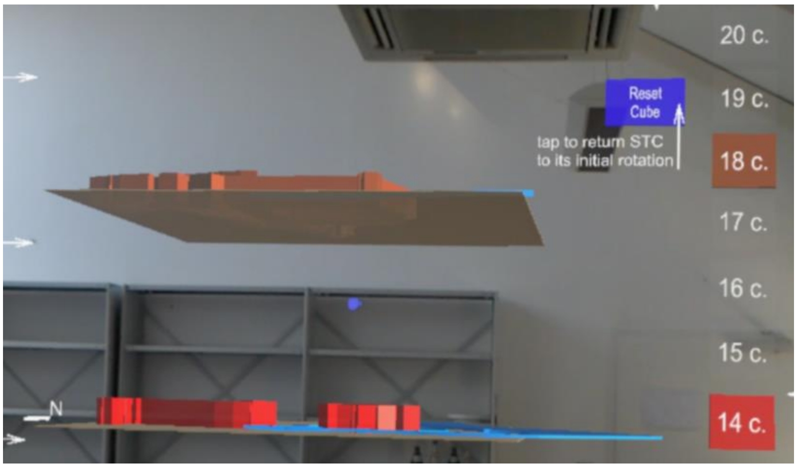


</td></tr>
</table>

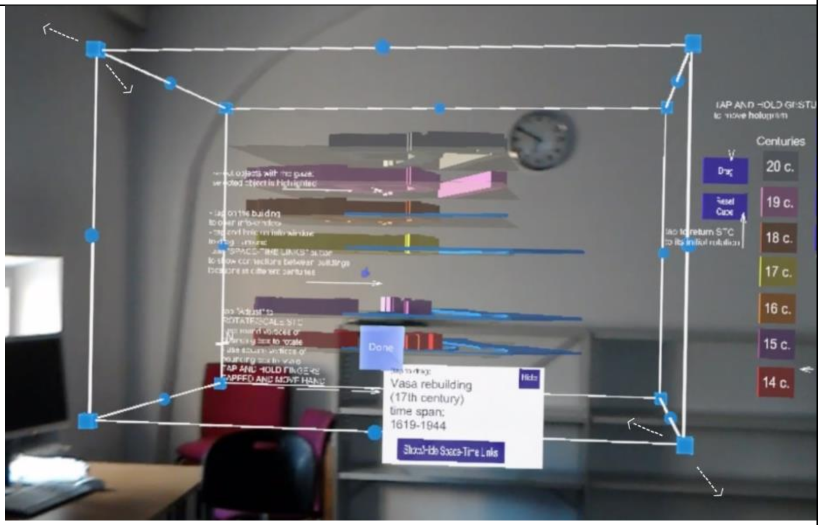
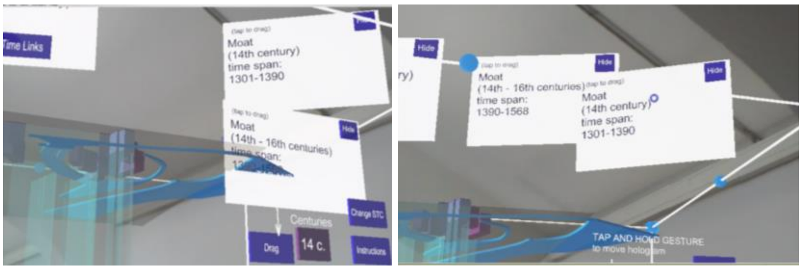
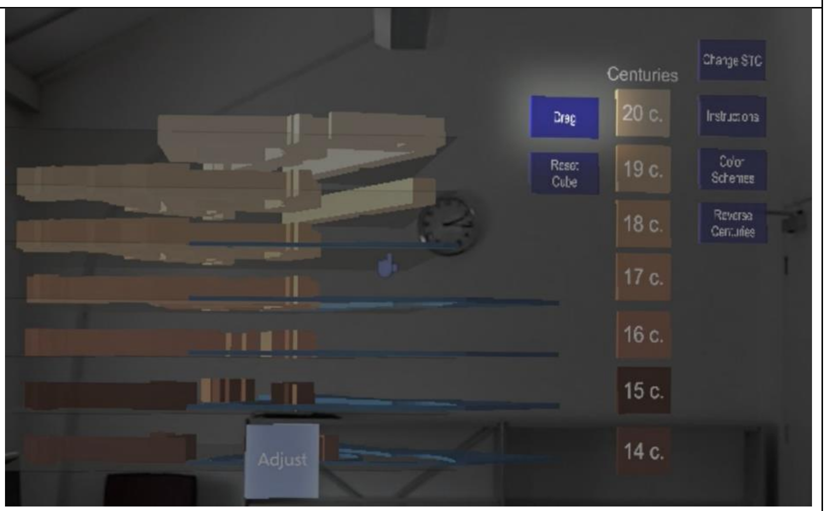
<table>
<tr><th>Interaction</th><th>Implementation within MR STC for landscape changes depiction</th></tr>
<tr><td>Rotation of the space-time cube in vertical plane via voice command:
1. User should say the voice command “Vertical Rotation”.
2. Tap and hold one of the landscape features within the cube.
3. Move the hand in the direction of the desired rotation.
To stop rotation user should say the voice command “Stop Vertical Rotation”.</td><td></td></tr>
<tr><td>Rotation of the space-time cube in horizontal and vertical plane through interactions with bounding box:
Round vertices in the middle of the lines are used for rotation of the cube. User should tap and hold, and then move his hand in the 3D space to rotate the cube.</td><td>
</td></tr>
</table>

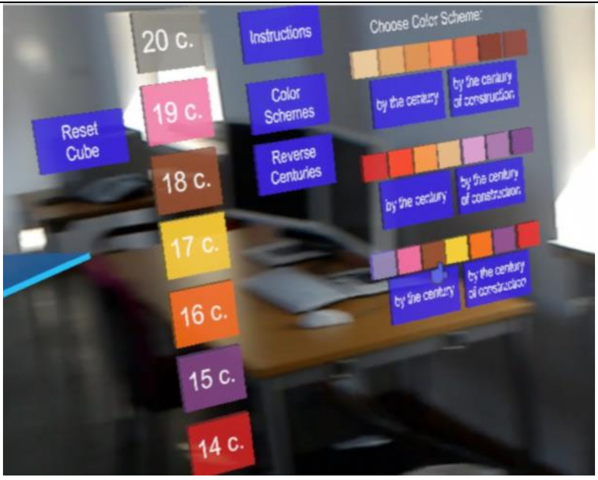
<table>
<tr><th>Interaction</th><th>Implementation within MR STC for landscape changes depiction</th></tr>
<tr><td>Resetting the rotation of the space-time cube to its initial position
Tapping “Reset” button in user interface</td><td>

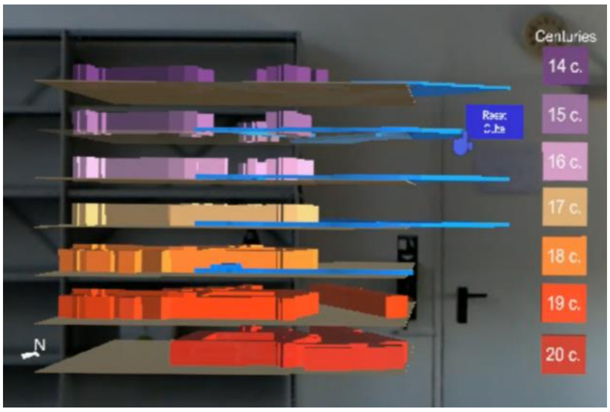


</td></tr>
</table>

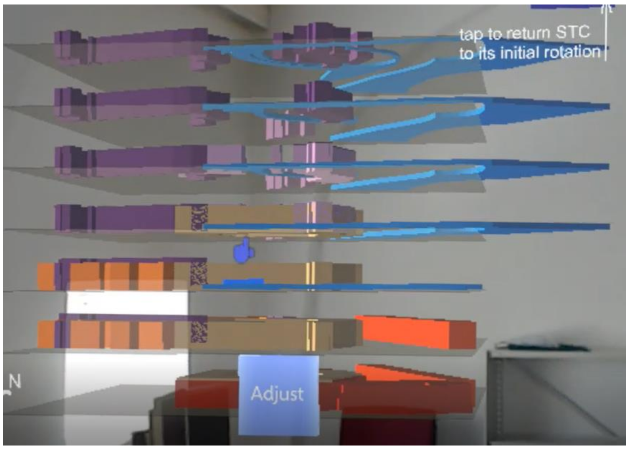
<table>
<tr><th>Interaction</th><th>Implementation within MR STC for landscape changes depiction</th></tr>
<tr><td>Scaling of the space-time cube through interaction with a bounding box:
Square vertices in the corners of the bounding box are used for the scaling of the cube by tapping and holding the vertex, and then moving the hand towards the center of the cube to make the cube smaller and away from the center to enlarge it.</td><td></td></tr>
<tr><td>Dragging info-window in any direction and at any point of the MR 3D space by tapping and holding on it</td><td></td></tr>
<tr><td>Dragging the hologram in any direction and at any point of the MR 3D space
• By tapping and holding “Drag” button
• By voice command:
4. User should say the voice command “Move Cube”.
5. Tap and hold one of the landscape features within the cube.
6. Move the hand in the direction of desired rotation.
To stop rotation user should say the voice command “Stop Moving”.</td><td></td></tr>
</table>

<table>
<tr>
<td>Switching between several color schemes by tapping “Color Schemes” button. Three color schemes are implemented within MR STC application with two options for each color scheme. First option “By the century” colors the buildings existing in the whole time subinterval in the same color. The second option “By the color of construction” colors the buildings according to the time subinterval (one century), in which they were constructed (the temporal precision for the landscape features existence in the initial data was 1 year).</td>
<td>


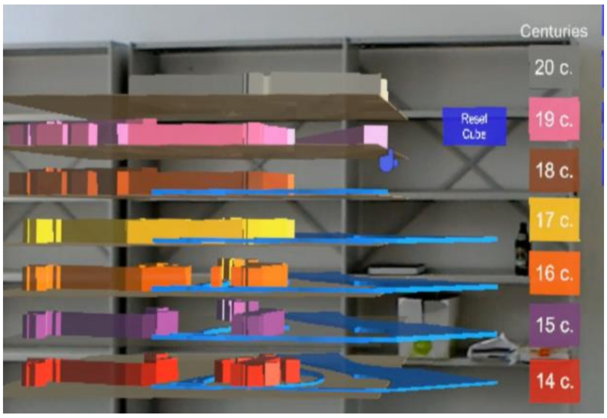
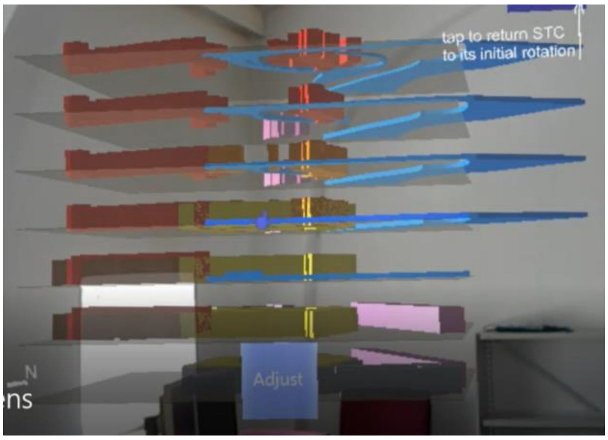
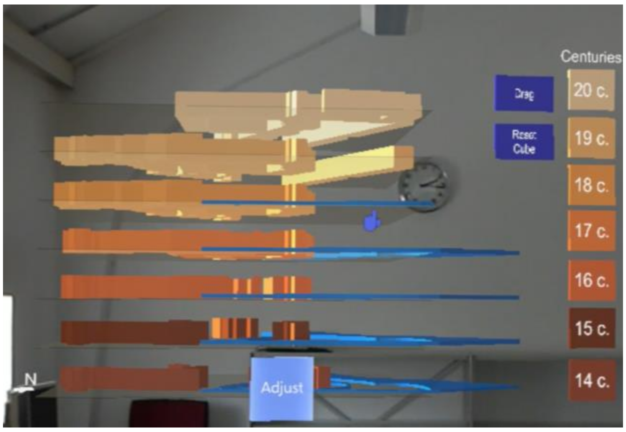
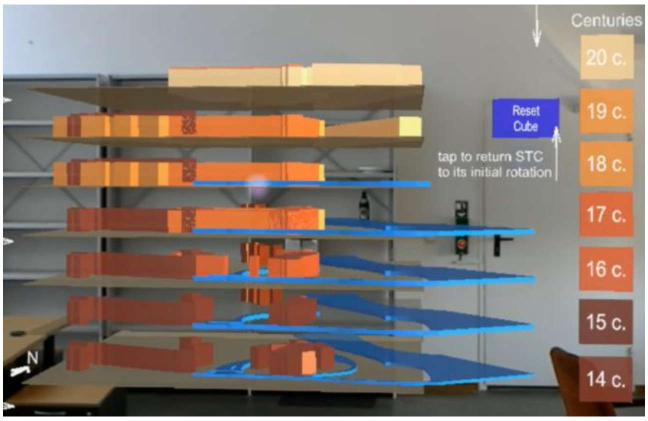
1. Diverging color scheme by the century:



2. Diverging color scheme by the century of construction:



</td>
</tr>
</table>

	3. Qualitative color scheme by the century:  4. Qualitative color scheme by the century of construction:  5. Sequential color scheme by the century:  6. Sequential color scheme by the century of construction: 

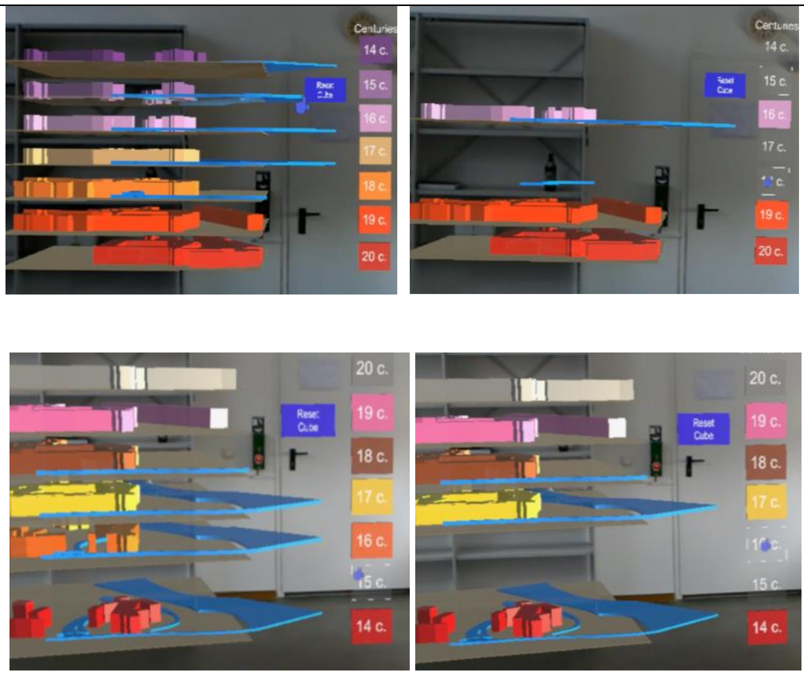
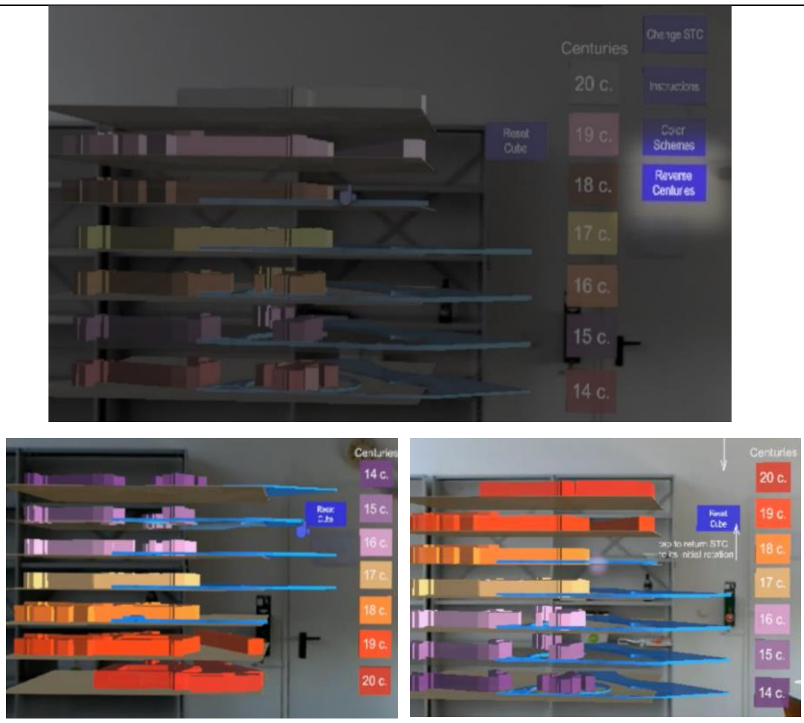
Filtering visualized time subintervals: Toggle visibility of each separate time subinterval (ground slice with landscape features) by tapping correlated legend element in the user interface. The correlated legend element changes its visual representation to completely transparent with non-transparent border. **Visual Variables**: Transparency	
Re-ordering of the time subintervals along the time axis by tapping "Reverse Centuries" button: Changes the order of the time subintervals (centuries) from the contemporary landscape time subinterval on the top of the STC to its positioning at the bottom of the STC and vice versa.	

Table 4.3 Implemented interactive features within MR space-time cube hologram

In the final application two variations of the space-time cube are represented. First has 90% transparent ground slices, which provide good visibility of the buildings located below through the ground slices. Another distinctive features are the rotation of the space-time cube using a bounding box around it and dragging of the hologram by tapping and holding "Drag" button. Additionally, space-time cube can be scaled via bounding box. The second variation of the space-time cube has 10% transparency of ground slices, which makes the below located buildings harder to distinguish. The rotation and dragging of this variation of the space-time cube is operated by the voice commands, and it has no scaling function.

5 Evaluation

As it was mentioned in the State of the Art Chapter, the space-time cubes were mostly evaluated in comparison to other visualizations. One of such study was performed by Jahnke and Bogucka (2018) in terms of efficiency, effectiveness and satisfaction with the space-time cube visualization relative to slider-based temporal visualization. Both visualizations were made on the computer desktop and have the same visual style, but the study did not concentrate on the visual design issues. On the other hand, Kveladze, Kraak and van Elzakker proposed a framework for the space-time cube design evaluation and its user centered design (2013), which was followed by the investigation of the influence of visual variables and depth cues on the space-time cube effectiveness and efficiency (2018). The usability testing of the mixed reality visualization for the HoloLens headset was performed Bach, Sicat, Beyer, Cordeil, and Pfister (2018). Although it did not have a space-time cube as a technique for testing, it has a thesis-related aspect. The researchers investigated the efficiency of mixed reality hologram in comparison to desktop computer and tangible augmented reality visualizations in relation to the three issues: stereoscopic perception of 3D content, MR interactions with high degrees of freedom, and spatial proximity of physical space for interaction and perception. Although mixed reality environment showed good results in visual and space perception, the desktop environment showed the fastest results. The authors concluded that the reason for this could be broad experience with computer interaction among the users, which is explained by current wide usage of this technology, and lack of experience with mixed reality devices. Also, the researchers discovered the tendency for the resulting time improvement among the users, who had regular additional training with mixed reality.

Considering the findings of this study, it was suggested that any comparative study of the space-time cube in mixed reality with the space-time cube visualization in more usual and familiar environment, such as computer-mouse system, will result in the better performance of the computer-mouse system. That is way it was decided to perform an exploratory evaluation of the mixed reality space-time cube hologram.

5.1 Evaluation Goals

The empirical evaluation study aims to explore the visual design aspects of the space-time cube in mixed reality and their perceptional comfort for the user, and interactive possibilities of the space-time cube, which became possible due to the immersive mixed reality environment; and to investigate advantages and disadvantages or limitations of the mixed reality technology in regard to space-time cube visualization.

5.2 Materials and Participants

Experiment was held within HoloLens headset provided by the Chair of Cartography of the Technical University of Munich. The developed space-time cube mixed reality application was installed to the device through the Microsoft Visual Studio 2017 software. The applications had two variations of the space-time cube with some differences in visual design and interactivity. The first variation had 90% transparency of the ground slices, sequential color scheme, classified by the century, as default. Rotation and scaling of the space-time cube were performed through bounding box, dragging of the hologram – through tapping and holding "Drag" button. The second variation had 10% transparency of the ground slices, which made them almost opaque, and qualitative color scheme, classified by the century, as a default. Rotation and dragging operation was performed by means of voice commands, no scaling possibility was given.

The user testing of the hologram was conducted among the users with different professional background and different levels of acquaintance with mixed reality environment. Overall, there were 20 participants, 12 males and 8 females with age range from 21 to 41, with 65% between 25 and 34 years old. The participants came from different professional backgrounds, such as cartography, geoinformatics, BML management, informatics, computational mechanics, mechanical engineering, environmental geography, geoscience, computer science, transformational systems and psychology. The cartography background was the most repeated and accounted 40 % among all participants.

5.3 Evaluation Methodology

Before conducting the final study, two pre-studies were performed, which helped to define the final experiment process. The user study was performed in three steps:

1. Introduction of a technology to the user and explanation of all interactive features of the application. The user had possibility to try each interaction during this part and explore color schemes.
2. Performance of the given tasks while using the application. The user was asked to think aloud and to comment, as well as ask questions and help if there were any problems with interaction process. This part was recorder as a video within HoloLens display via special holographic camera of the HoloLens. It captured the view of the user, the hologram, and the user's voice. Additionally, the time spend for each task was recorded.
3. Filling questionnaire about user's experience.

The first part of the study aimed to explain the participants the order of the study, get them acquainted to the mixed reality, try functionality of the application and freely explore the hologram. This stage was necessary as most of the participants needed to be introduced to the gestures of interaction within HoloLens application. The introductory part took 10 to 15 minutes, depending how fast the participant remembered the air tap gesture and the selection with the gaze in the hologram.

For the second part four tasks were defined, which should provide the possibility to test all the interactive features implemented and to deal with all space-time cube elements. The hypothetical workflow for task performance was developed in order to make sure that the user will pay attention to all space-time cube elements and features (Table 5.1).

Table 5.1 User study tasks.

Task	Hypothetical interaction workflow	Potential features of the space-time cube hologram to be tested
What was the most Northern building in the 16th century?	• Distinguish the northern direction • Rotate STC horizontally/vertically • Use filtering of the time subintervals through interactive legend • Air tap on the building to get the information about the building • Name the building	• Rotation of the cube • Filtering of the centuries • Highlighting of the buildings with the gaze • Retrieving information on demand • North Arrow perception
Which water bodies in 14th century were located at the same place as the Royal Castle after rebuilding in 20th century?	• Find the Royal Castle in 20th century • Open information about Royal Castle • Show space-time link for the Royal Castle • Filter unnecessary centuries • Reverse STC • Chose the water bodies which intersect with space-time link • Open water bodies information • Name water bodies	• Perception of the space-time links • Highlighting of the water bodies with the gaze • Filtering of the centuries • Highlighting of the buildings with the gaze • Retrieving information on demand
How many buildings from 14th century were represented in 18th century?	• Switch to the color scheme by the century of construction • Distinguish the buildings from 14th century • Possibly use space-time links and vertical rotation • Open information and name the buildings	• Different color schemes perception • Highlighting of the buildings with the gaze • Vertical rotation of the cube • Space-time links perception
Name the oldest buildings existing in 17th century.	• Use filtering of the centuries • Use color scheme by the century of construction • Distinguish the buildings from 14th century • Open information about the buildings and name them	• Different color schemes perception • Highlighting of the buildings with the gaze • Retrieving information on demand and comparing

The participants were divided into four groups. First group performed all four tasks on the first variation of the cube. Second group performed tasks on the second variation of the cube. Third group started with the first variation of the cube for first and second tasks and then switched to the second variation of the cube for the third and fourth tasks. Fourth group performed first and second tasks on the second variation of the cube, and third and fourth tasks on the first variation of the cube. There were no time limits to accomplish the tasks. As it was not possible to see user's view of the hologram for anyone else except the user, participants were asked to give the answers

to the questions aloud. They were asked to proceed to the next task after giving the correct answer to the current task. The time user spent to each task was recorded for further analysis.
For the third stage of the experiment the questionnaire was developed. The questionnaire focused on several aspects. First aim of the questionnaire was to collect statistical data of the participants' background, such as field of occupation, age and acquaintance with the mixed reality environments. Then participants were asked to mark the interactions they used for each task in order to see which range of functionalities they were using. Other questions were dealing with overall comfort and easiness of the space-time cube hologram usage and the comfort of the methods for rotation, dragging and scaling of the cube. Part of the questions was devoted to the visual variables perception and usefulness in the hologram. Such questions were based on the Likert scale. The last section of the questionnaire had two open questions about the positive features of the mixed reality experience and about the limitations and features, which can be improved in the space-time cube hologram.

5.4 Experiment Set-Up

The experiment was conducted in the Eye-tracking Lab at the Technical University of Munich. The room served as a good location for the holographic application usage, as it is required enough shade space without large windows with incoming light. The room corresponded to that conditions, that is way it was possible to perform the study during any time of the day. Participants could choose if they wanted to stay, sit or move around the hologram during the study. Only one person at a time was participating in the study. The reason for this was the necessity to give instructions to each participant individually and make sure that the participant understood how to perform HoloLens gestures. Also, participant was saying his answers aloud and it was required to follow his answers and the whole task performing part and to track the time spend to each task. For the participants dealing with two space-time cube variations additional instructions and time to explore were given after switching to another variation. This time was mostly limited to 5 minutes as the difference in interaction with the cube's variation was only in the rotation, dragging and scaling the cube. Every participant was using default gestures built-in HoloLens technology, such as air tap and tap and hold. The bloom gesture was not used by the participants as it served for closing the application. The way of interactions through hand gestures and not by a HoloLens clicker was chosen in order to see how comfortable participants feel about such more natural way of interaction. The HoloLens has a built-in constraint for video length of 5 minutes time. For this reason, the tester had to check the time already spent by the user and to ask to start recoding the video from HoloLens over again. After finishing the tasks, participant was asked to return HoloLens to the tester and to fill in the questionnaire.
The whole evaluation procedure took from 30 minutes to 50 minutes. Each participant was given the same information about the purpose of the study and its workflow. Before starting the introductory part of the study each participant signed "The Consent to Participate", where he agreed with the procedure of the experiment. The instruction part of the space-time cube application was introduced by the tester orally, when the user already put on the HoloLens

headset and started using the application. The individual oral explanation of the instructions was made due to the fact that during pre-studies participants were exploring instructions by themselves and did not pay attention to all the functionality of the space-time cube hologram. The user followed the introduced instructions and then he was asked to explore the hologram by himself and when ready, start with the tasks. It was made in such a way to make sure that each participant has tried all interactive possibilities of the space-time cube, which are planned to be evaluated.

5.5 Processing of the Evaluation Data

There were several types of data collected after the evaluation experiment: statistical data about participants, Likert scale data about user experience, list of interactions and time spent for each task by each participant and video records of the participants' task performance within HoloLens application. Additional notes were made if the participant was moving around the hologram in the process of interaction or stayed in same place. The video records were recorded as an additional material for analysis.

6 Results

The collected data from the questionnaire was organized within Microsoft Excel worksheet and processed there. Additionally, the MS Access table was created for summing up the data about interactions performed by the participants and spent time. In order to proceed the data some SQL queries were performed.

6.1 Interactivity

As it was marked in the user study description, the experiment participants were divided into four groups and dealt with different variations of the space-time cube, either with one of the variations for all four tasks or switching the variation after two tasks to another. The results showed that in general the participants dealing with both variations of the space-time cube holograms performed the tasks a bit faster than those who were dealing only with one variation (Figure 6.1). The analysis of the participants with previous mixed reality experience show that their distribution among the four testing groups were uneven and their percentage is higher for the groups dealing with both space-time cube variations (Figure 6.2).

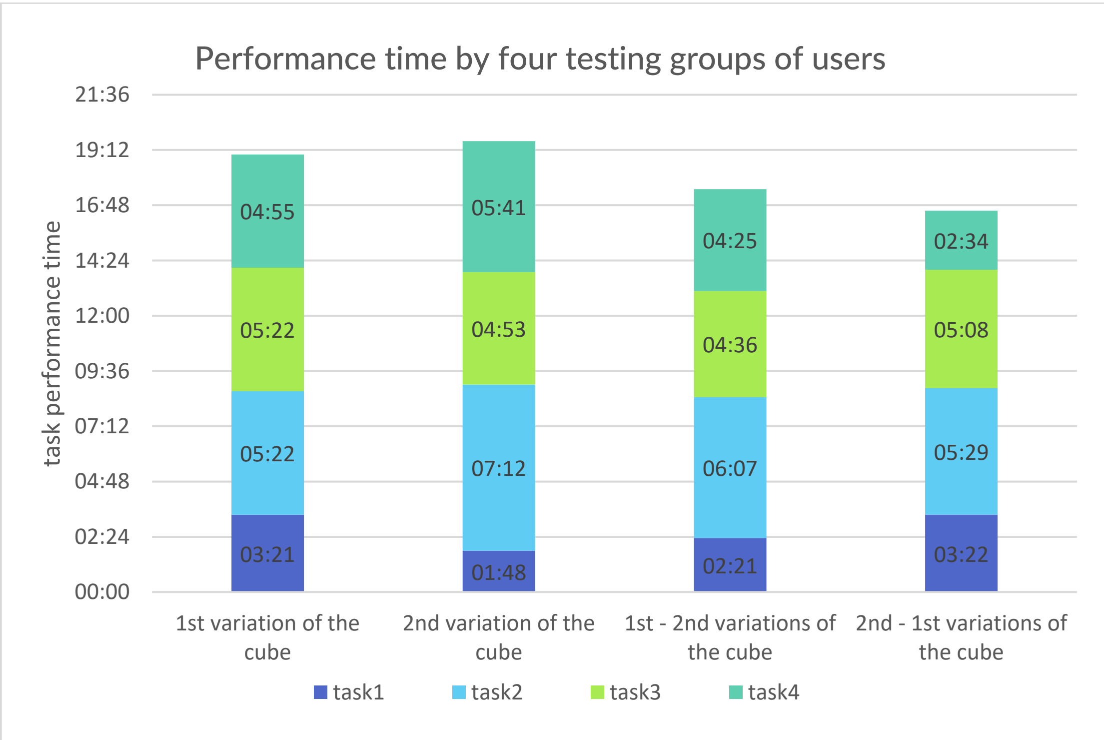


Figure 6.1 Overall task performance time by four user group, dealing with different variations of the space-time cube hologram.

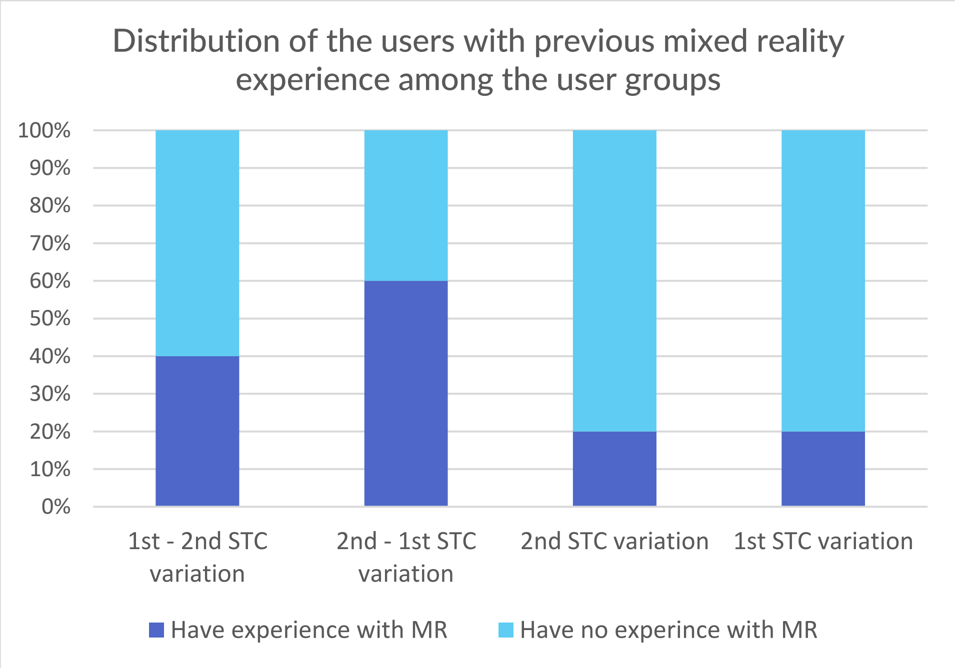


Figure 6.2 Distribution of the users with previous mixed reality experience among the user groups.

The analysis of the recorded video showed that the main slowing down factor for the participants was unusual hand gesture interaction. Sometimes the hologram was not reacting to the users' gesture, because the hands were situated out of the HoloLens gesture detection area or the gesture was performed not exactly as it should be detected with the device. These is reflected in the findings of the experiment that the participants, who had previous experience with mixed reality, had better time performance comparing to those without any mixed reality experience (Figure 6.3).

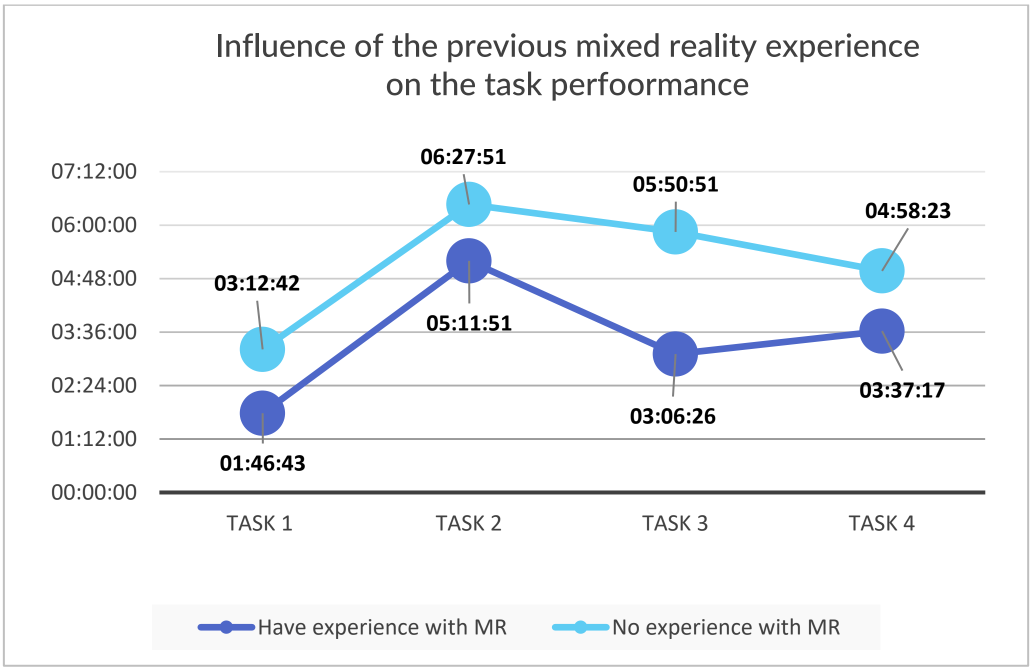


Figure 6.3 Influence of the previous experience with mixed reality on the tasks performance.

In general, all participants managed to give the correct answer for the first task (identify the most northern located building). The analysis of the video material showed that for the first task part of the users did not notice the north arrow in the hologram, but suggested that the furthest from the user border of the space-time cube represents northern part. Although later in the process of performing the task every participant mentioned that he found north arrow. Another finding regarding this aspect, is that the quickest answers were given by the participants, who at first distinguished the north direction by discovering north arrow in the hologram.

For the rest tasks part of the participants identified the correct landscape features partly or with the help of the tester. Thus, for the second task, identification of the water bodies which existed in the 14th century at the location of the Royal Castle building in 20th century, five participants out of twenty had difficulties. The third and fourth tasks suggested that the users can apply color scheme by the century of construction for better visual classification of the buildings regarding their historical foundation time. The analysis of the interactions used showed that for the third task, counting buildings constructed in 14th century and still represented in 18th century, most of the participants got correct answers by displaying space-time links for the buildings from 14th century, filtering all unnecessary centuries and rotation the cube vertically. Only one participant experienced difficulties with identifying correct building and spend the longest time on the task (13 minutes), while the shortest time for the correct answer was a bit more than 1 minute and average performance time was around 4 minutes. For the fourth task, naming the oldest buildings existing in 17th century, 15 participants managed to identify all the correct buildings and 5 participants had difficulties. The analysis of the performed operation showed that 80% of the users switched the coloring of the buildings by the century of construction, and only 25% of the users were displaying space-time links. The overall frequency of the interactions performed by the participant for each task is represented in the Figure 6.4.

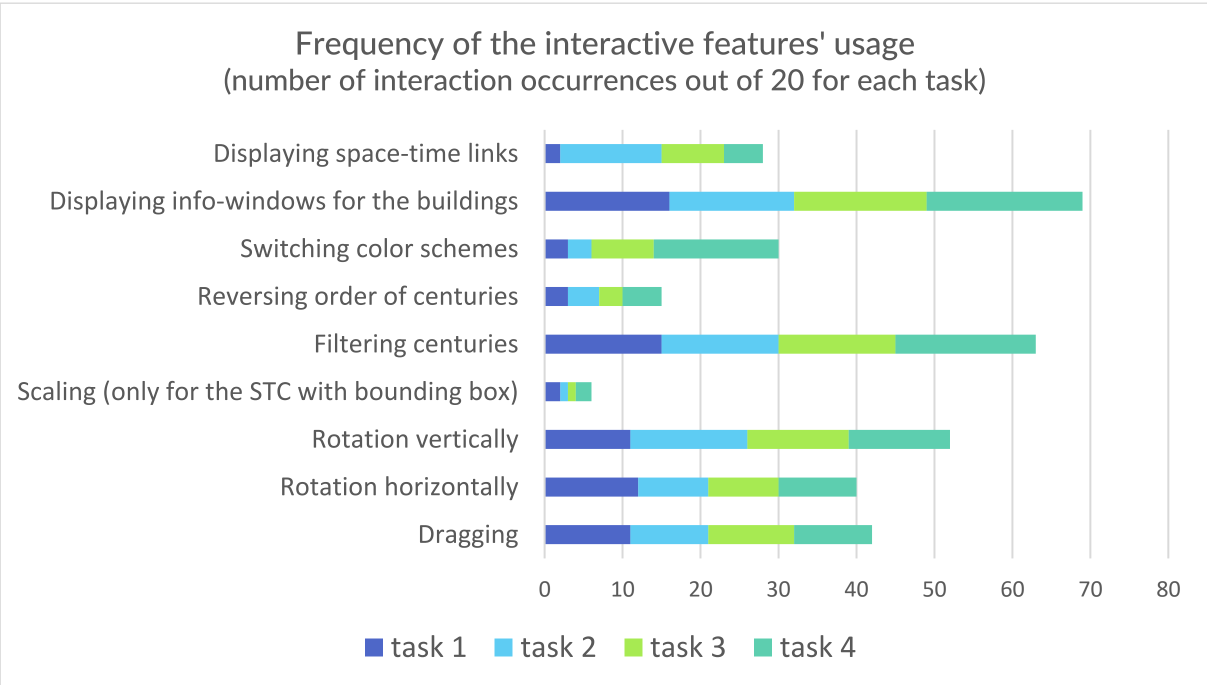


Figure 6.4 Frequency of the interactive features' usage in regard to each task.

The figure 6.5 shows the frequency of performing interactions for each task in percentage. The most frequently used operations are colored in green and the seldom used operations are represented with reddish colors. Thus, scaling the space-time cube and reversing the order of the century slices were using less than 30% of the participants through all tasks. Displaying info-windows and filtering centuries are the most used operations in all study tasks and were performed by more than 70% users. Rotation, both vertical and horizontal, as well as dragging hologram function were applied between 40% to 60% of the participants for all questions. Meanwhile switching color schemes and displaying space-time links have the most uneven distribution through the task performance. Space-time links were mostly performed for the second and third tasks, while color scheme switching had the highest applications for the fourth and third tasks respectively (Figure 6.5).

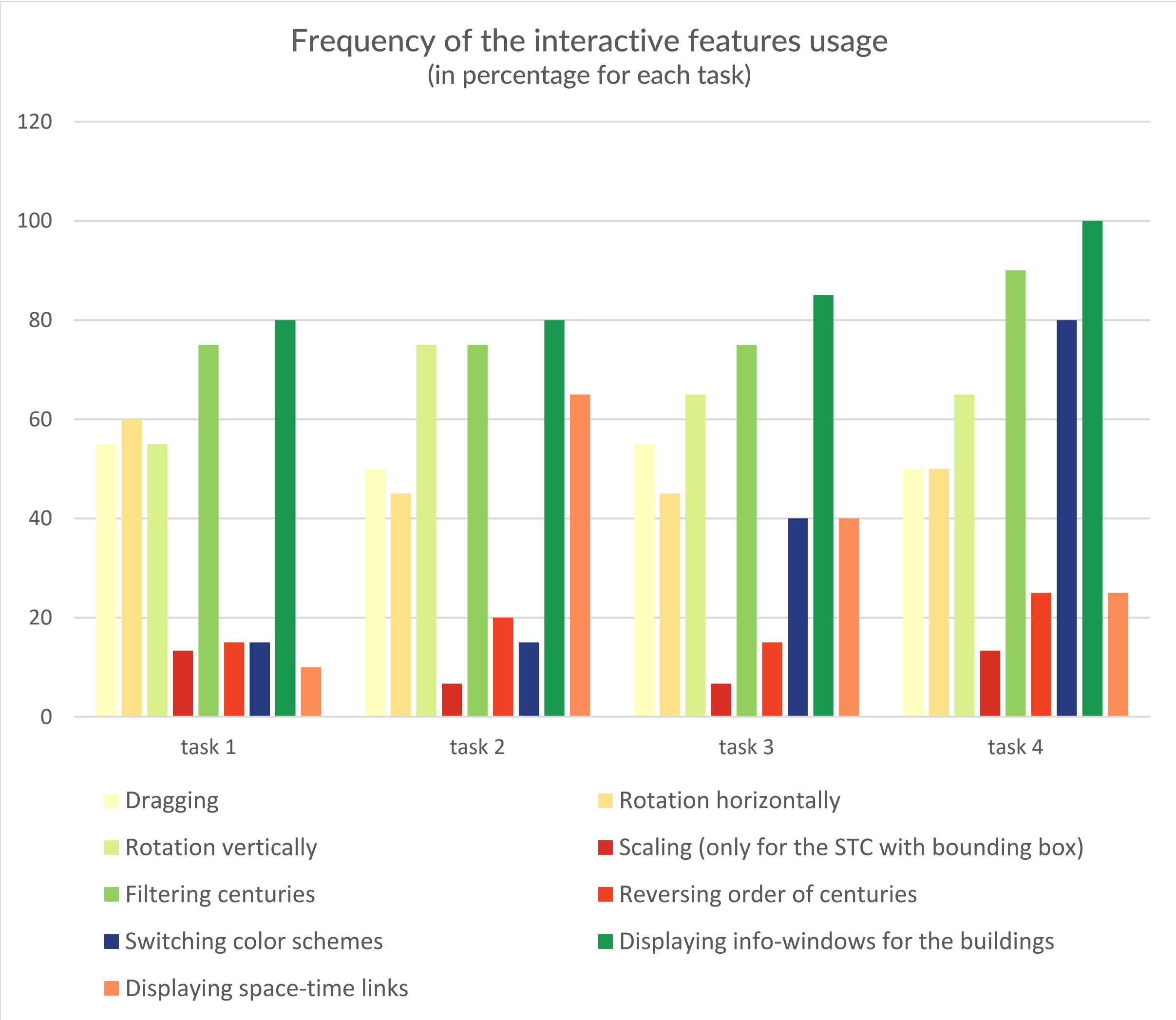


Figure 6.5 Frequency of the interactive features usage (in percentage for each task).

The general navigation process through the hologram was estimated by participants almost with all variations of the Likert scale from difficult (1) to easy (7). Although the overall trend has the middle values, with the 60% of the users (Figure 6.6). One of the specifically mixed reality features, the selection of the objects with the gaze, was tested in the experiment for the level of its comfort. The distribution of the users' opinions shows that this feature is considered as easy for usage by around 30% of the participants and difficult by 20% of the participants, while the rest of the users gived neutral evaluation of its easiness (Figure 6.6). Dealing with small objects by the gaze selection and hand gesture is another issue of the mixed reality interactivity. The experiment indicated that 50% of the users found this interactive operation difficult to accomplish. Only less than 10% of the participant estimated it as quite easy, with value 6 on Likert scale from 1 (difficult) to 7 (easy) (Figure 6.6).

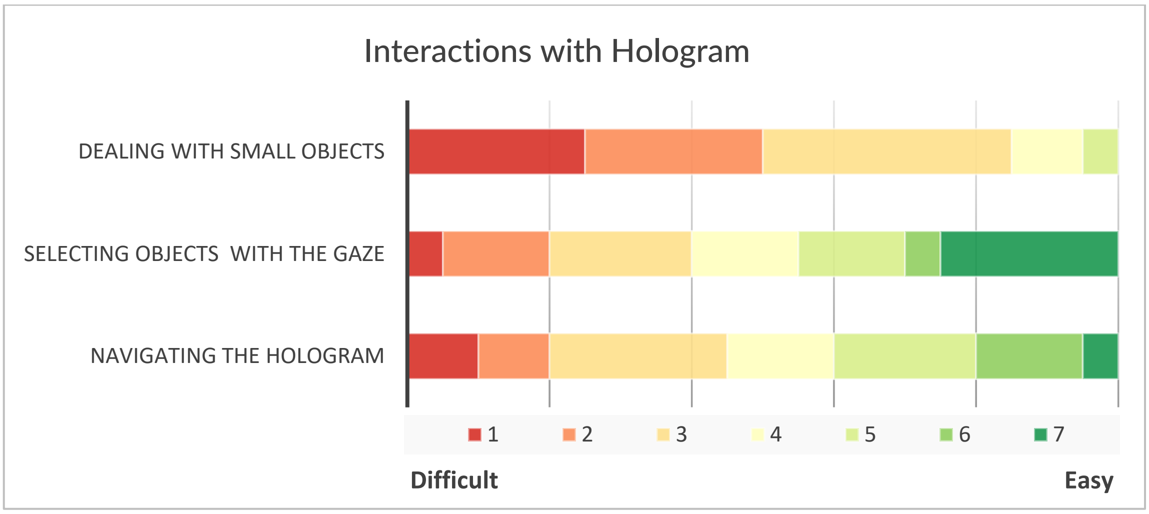


Figure 6.6 Comfort of interaction in mixed reality.

Two variations of the tested space-time cube holograms had differences in the mechanisms for rotating, moving and scaling the cube -using bounding box around the cube or voice commands. Half of the participants performed the study on both variations and were asked to estimate the comfort of both methods from "difficult to deal with" (1) to "easy to manage" (7), as well as name the preferred method. Seven out of ten users selected interaction using bounding box ass more comfortable. This trend is also reflected at the graph representing Likert data distribution for these interaction methods (Figure 6.7).

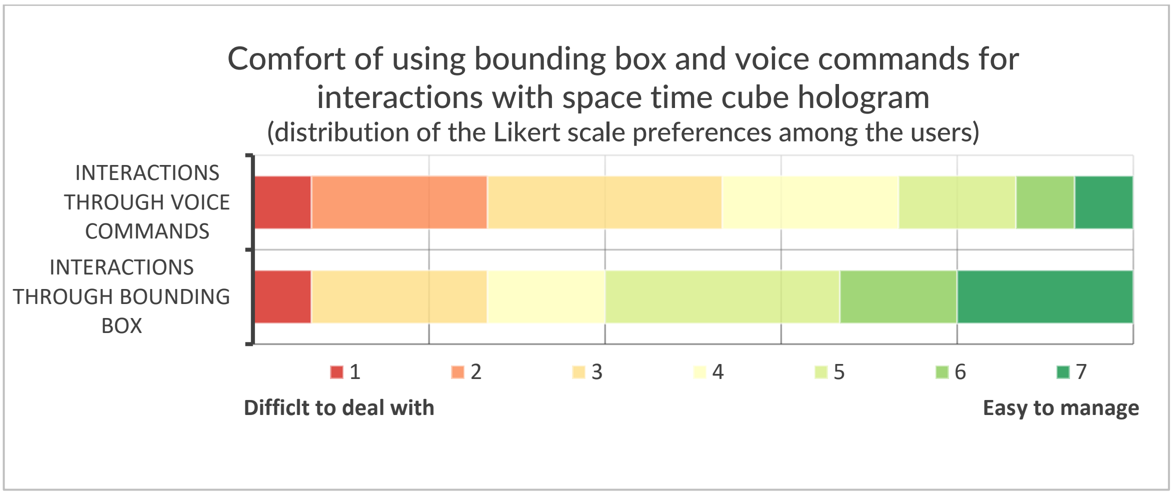


Figure 6.7 Comfort of using bounding box and voice commands for interactions with space time cube hologram (distribution of the Likert scale preferences among the users).

6.2 Visual Variables

Another aspect which was explored in the study is the perception of the visual components of the space-time cube hologram. Thus, the participants were asked questions about the color schemes of the space-time cube, coloring method for the buildings and the transparency of the ground slices. There were three color schemes represented within the hologram: sequential, qualitative and diverging. Half of the participants marked qualitative color scheme as the most suitable and helpful for the tasks performance. Diverging color scheme was selected by 30 % of the users. And sequential counted only 15% (Figure 6.8). Fifteen participants out of twenty found the coloring of the buildings by the century of construction more informative and comfortable for tasks performance than by the century of existence. Two users liked both coloring methods useful, one user preferred the coloring by the century of existence and two users did not give an answer (Figure 6.9).

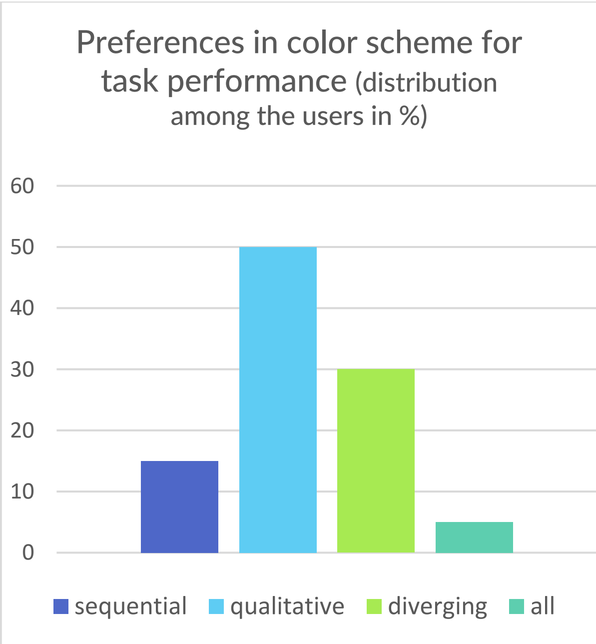


Figure 6.8 Preferences in color scheme for task performance (distribution among the users in %).

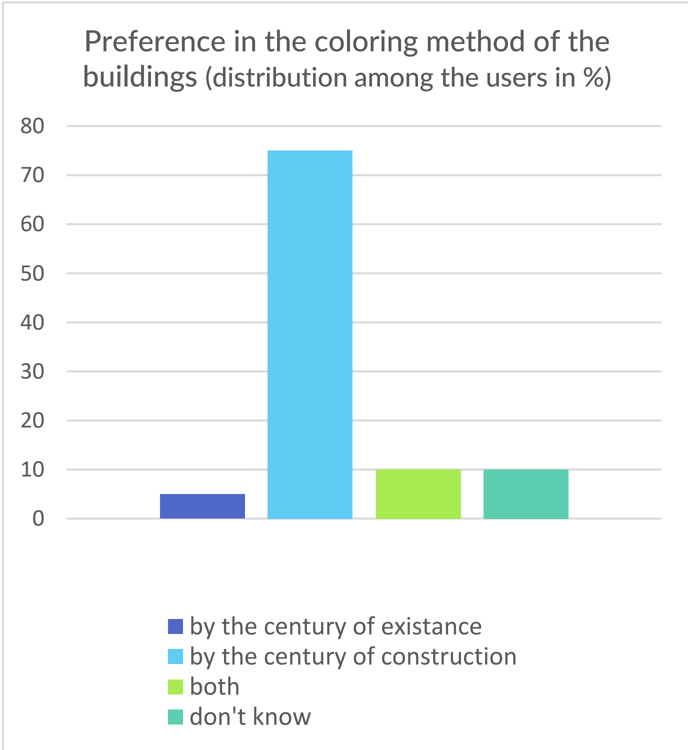


Figure 6.9 Preference in the coloring method of the buildings (distribution among the users in %).

Most of the answers about the high degree of transparency of the ground slices among the users, who were using the first variation of the cube for all the tasks or only for two of them (fifteen users) were mostly positive, and only less than 10% of these users marked it as a distracting feature of the space-time cube (figure 6.10). The opinions about the transparency of the ground slices of the participants, who were dealing with two cubes (ten users out of twenty), are divided into three almost equal categories: 4 participants preferred 90% transparent ground slices, 3 participants preferred 10% transparency and 3 participants did not notice the difference while using the space-time cube hologram (Figure 6.11).

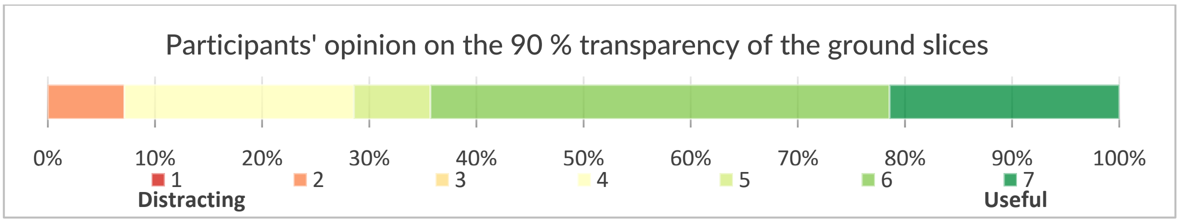


Figure 6.10 Participants' opinion on the 90 % transparency of the ground slices.

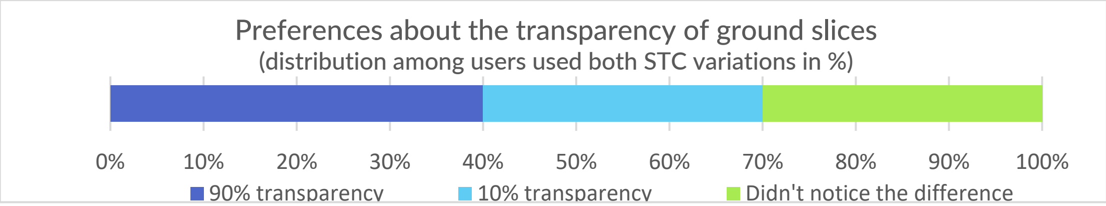


Figure 6.11 Preferences about the transparency of ground slices (distribution among users used both STC variations in %).

Visual contrast between the hologram and the background, which is surrounding space of the room, was marked as good by 85% of the participants with only one person, who gave poor contrast as a feedback. Spacing between the centuries slices was acknowledged as balanced by 90% of the users.

Additional analysis was made to explore if the gender preferences differ for the color scheme selection or for the interaction method with the space-time cube. The equal percent of the women chose the qualitative and diverging color schemes as the most suitable, while the men preferred qualitative color scheme. The trend, discovered in the interaction method preference, is the same for both men and women – both preferred interactions through bounding box to the voice commands method (Figure 6.12).

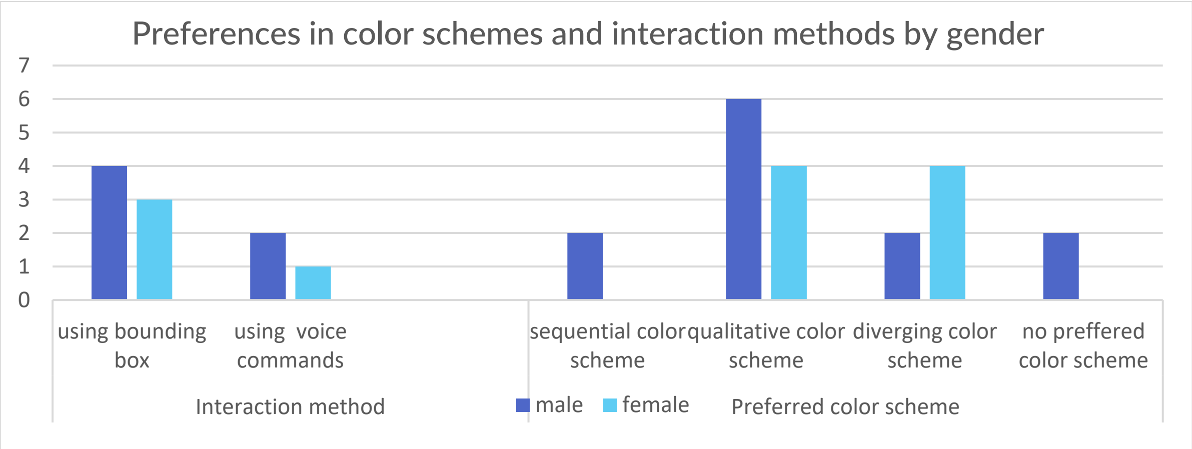


Figure 6.12 Preferences in color schemes and interaction methods by gender.

6.3 Advantages and Limitations

Analyzing the answers of the participants for the open questions about the features they liked in the mixed reality space-time cube application and the features and limitations, which can be improved, the advantages and limitations of the landscape space-time cube hologram can be suggested. The participants described their experience as “an absolutely new way to discover history”, “easy and natural way of interaction”, “feeling of future technology”. Thus, among the most mentioned positive features of the application are interactiveness and functionalities, 3D perception and navigation, possibility to move around, easy and natural way of interaction though hand gestures and gaze selection, visual appearance and alternative color schemes. Among other advantageous aspects of the space-time cube implementation were named user-friendly interface, novelty of the technology, enjoyable user experience and understandable instructions, voice commands, simplicity and informativeness. Also, users noted the good experience with movable info-windows and filtering functionalities (Figure 6.13).

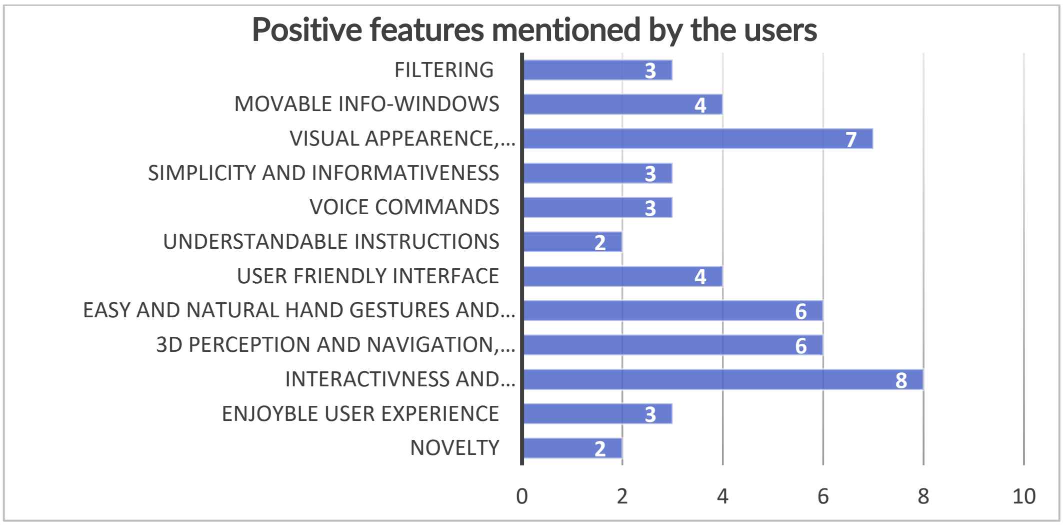


Figure 6.13 Positive features mentioned by users.

The most prominent limitation defined by the experiment participants is selection of the small objects with the gaze, which is hard to accomplish. Furthermore, several users mentioned that they needed at first some time to get used to the hand gestures and start interacting with the hologram more effectively. The rest limitations marked by users are mainly connected with the limitations of the HoloLens technology. Thus, limited size of the holographic screen and therefore small angle of view was mentioned. Two participants mentioned long response time for the voice commands and hand detection, and two participants suggested to use HoloLens clicker instead of hand gestures for interactions. Finally, one user marked poor contrast for the whole visualization, which was later fixed. The reason for this was accidental clicking on the button on the headset itself when putting on the headset. Moreover, sometimes users noticed shaking of the whole hologram when the video capturing started.

For the further development and improvement of the application, mainly users suggested the improvement of interactivity and then of visual component. Regarding interactivity the participants proposed to improve the vertical rotation process, as sometimes the cube went the opposite direction to the hand movement; add zooming feature for small objects; implement scaling and rotation functions without bounding box; and improve the initial positioning for info-windows in order to avoid overlapping of the info-windows and visual clutter. The ideas suggested for the visual improvement included extension of the color schemes and finding better visual design decision, adding realistic textures and shapes for the landscape features, animation to show historical changes and improving the highlighting of the elements.

6.4 Discussion

The performed empirical user study was aims to answer the question about:

- visual design aspects of the mixed reality space-time cube hologram;
- interactive possibilities of the mixed reality space-time cube visualization;
- advantages and disadvantages or limitations of the mixed reality space-time cube visualization.

The main finding about interaction with mixed reality hologram concerns the previous mixed reality experience of the participants. The users with such experience demonstrated faster task performance comparing to the user without such experience, which corresponds with the conclusions made in the study conducted by Yim, Loison,Fard, Chan, McAllister and Maurer (2016). The researches inferred that with the regular training in the mixed reality environment the time for performing tasks reduces. This can be explained by the observation made due to the analysis of the video material collected in the experiment with the space-time cube hologram. Participants without previous experience with mixed reality performed air tap gesture and tap and hold gesture not always correct and needed time to adjust to it. Or they placed their hand out of the area of the hand detection sensor of the HoloLens. The time performance results for the four user groups showed faster time for the groups which participants dealt with two variations of the space-time cube. Though it could be suggested that these participants need more time due to the switching from one variation of the cube to another and necessity to adjust to the new method of interaction (bounding box or voice commands). The opposite behavior can be explained by the distribution of the users with mixed reality experience among testing groups – groups which worked with both cube variations had higher percentage of experienced in mixed reality users.

The video records can also reveal the problems, which experienced the users while performing the second task (identification of the water bodies which existed in the 14th century at the location of the Royal Castle building in 20th century). The correct answer for the task included two water bodies names, and both were called “moat”, but they had different time span of existence within the same, fourteenth, century. The users get confused, because the info-windows for both water bodies were appearing at the same initial position within hologram and both info-windows had “Moat” as a header. Part of the users were tapping on one identified moat in the hologram and then looking to the info-window and closing it. Then they were tapping on another identified moat and looking for its info-window, and seeing the same header – “Moat”, but not paying attention to another information given, such as time-span of the water bodies. The participants who successfully managed with this task were dragging info-windows around and placing them in such positions, that they could see both info-windows at a time. This difficulty probably led to the partly correct answers, naming only one moat, and to the longer times of task performance. Another difficulty in this task was the relatively small size of the water bodies – moats. For some participants it took time to select them with the gaze and tap to open info-window. To conclude, it is necessary to find the better way for placement of info-windows without overlapping as not always the user remembers about the possibility to move it aside.

Dealing with the small objects in the spacetime cube hologram is another aspect demanding further exploration. It was hard for the participant to focus the gaze on small element. Possible explanation to this is that the device, HoloLens, does not use the eye-tracking technology for gaze direction recognition, but only tracks the direction of the headset front part. Due to this, the zooming feature for the small objects was proposed by the test participants as the way to improve the application.

In general, all the functionality was proven to be appropriate and suitable for the application and navigation through the hologram did not make too much complications. The preference of the interactions using bounding box can be explained by the slow voice recognition within the application, which can be clearly seen in the captured video material. Further work can be done to improve voice recognition commands and making the interactivity working with these commands, such as rotation, smoother.

The investigation of transparency variable applied in the hologram ground slices showed that almost one third of the participants did not notice the difference in the transparency degree of 10% and 90%. The overall trend represents that transparency was considered useful for ground slices, which allows to conclude that transparency visual variable can be applied in the mixed realty. The color schemes were positively evaluated by users, pointing that qualitative color scheme was the most suitable for solving tasks, as well as color classification of the buildings by the century of construction as these techniques provided better visual distinction among different classes.

The main advantages of the space-time cube visualization in mixed reality can be defined as following:

- 3D perception and navigation, possibility to move around;
- natural way of interaction though hand gestures and gaze selection;
- interactiveness and wide functionalities range;
- enjoyable user experience and visual appearance;
- control through voice;
- novelty and the feel of the future technology.

The following features can be attributed to the limitations and disadvantages:

- focusing of the gaze on the small objects;
- hand gestures demand time to get used to them;
- limited size of the holographic screen of the headset and limited field of view on the hologram;
- long response time for the hand detection and voice recognition (probably influenced by the available free random-access memory of the device, which is responsible for the fast responses of the computer systems);
- poor contrast within brightly lighted spaces.

Conclusion and Outlook

This thesis was aimed to determine the applicability of the mixed reality environment in spatiotemporal mapping on the example of the space-time cube depicting the cultural landscape changes and the its interactivity potential. To achieve this aim the research attempted to define how to visualize space-time cube in mixed reality, an evaluation technique was suggested and visual and interactive aspects of the hologram, together with advantages and limitations of such visualization were evaluated.

The development environment for the mixed reality consists of Unity and Visual Studio software installed on the Windows 10 platform. The software needed to create a 3D model of space-time cube before importing it to Unity depends on the initial data format and available software for 3D modelling.

Within the space-time cube hologram developed for the cultural landscape changes depiction the following elements were embedded: space-time prisms for landscape features depiction, space-time links and ground slices.

The explorative empirical study was performed to evaluate the developed space-space time usability. The results showed that mixed reality provide a new way of interaction with the space-time cube representation, by extending the visualization from a computer screen to the 3D surrounding space, allowing moving around the hologram like any other object in the real world and get better 3D perception of the cube and its elements. The interaction through gestures, gaze and voice exposed both favourable and unfavourable aspects. While selection with the gaze perceived by users a natural way of interaction with element of the cube, it was hard to focus gaze on small objects. Hand gestures were comfortable for the users experienced with mixed reality and difficult for those without such experience. In order to profit from the voice commands in mixed reality application better voice recognition should be implemented, which is dependable on the device's technical features.

The visual variables of color hue and color value proved to be useful in the hologram of the space-time cube. Meanwhile the usage of the transparency did not provide accurate conclusion about its applicability in mixed reality, as part of the users did not notice the difference between different degree of the transparency for the ground slices of the space-time cube. This visual variable, as well as the size variable should be further investigated for the mixed reality applicability.

Furthermore, the thesis attempted to integrate cartographic design principles into the mixed reality space-time cube. Visual and figure-ground contrast was proven to be good. Although, the suggestion can be made that such results were a consequence of the dark lighting conditions in the experiment room. In connection to this further research should be conducted on the influence of the lighting conditions on the figure-ground contrast. The legibility principle was achieved through color schemes of the hologram, readable text and user-friendly interface, which was mentioned in the users' answers for the open question about positive features of the space-time cube hologram. The spacing of the space-time cube ground slices was evaluated as balanced. The implementation was aimed to provide comfortable and balanced initial position and size of the hologram by placing it two meters ahead of the user and fitting into the field of rendering of the HoloLens, but further research should be done in this direction.

The limitations of the mixed reality environment for the space-time cube application are defined by technology of the device: the size of the holographic screen through which user see the hologram; gaze recognition as a head movement tracking, not an eye-tracking resulting into difficulties with the selection of the small objects; predefined hand gestures recognized by the device which users should at first train to perform; slow voice recognition and response to the voice commands; poor contrast within bright light of the surrounding space. It can be assumed that these limitations will be eliminated with the development of the mixed reality technologies and construction of the improved model of the HoloLens. Also, these limitations can not be taken as a cornerstone for the visualizations within other mixed reality headsets.

The advantages of visualizing space time cube in mixed reality can be defined by the specific capabilities and functionalities of the technology: a better 3D perception of the cube due to the placement of the 3D hologram into the natural environment and possibility to walk around and see it from various angles; the potential of the natural interactions methods through gaze, voice, hands, which most likely be improved in the future; enjoyable interaction process and "feel of the future technology".

The field of mixed reality is a new sphere for spatiotemporal visualizations in general and its applicability can not be fully evaluated by the performed study and demands further investigation. The future research in this area can focus on the following aspects:

- influence of the usage time of the HoloLens on the effectiveness and efficiency, as well as tiredness of the user; these criteria can limit the potential usage of the device by the professionals engaged into the mixed reality exploration of the thematic spatiotemporal data;
- influence of the lightning conditions of the surrounding space on the visual contrast, on the 3D perception and on the effectiveness and efficiency; the performed study was held in one room with static and rather dark lightning conditions;
- implementation and evaluation of the realistic textures and shapes for landscape features for the cultural landscape changes space-time cube visualization;
- further research and evaluation on the transparency visual variable;
- research on the comfortable positioning of the space-time cube hologram.

8 Literature

Andrienko, N., Andrienko, G., Gatalsky, P. “Visual Data Exploration Using Space-Time Cube.” In *Proceedings of the 21st International Cartographic Conference (ICC).* Durban, 2003.

Baas, Maarten. “Space-time cube analyses of animal behaviour.” Master’s dissertation, Wageningen, The Netherlands, 2013.

Bach, Benjamin, Dragicevic, Pierre, Archambault, Daniel, Hurter, Christophe, and Carpendale, Sheelagh. “A Review of Temporal Data Visualizations Based on Space-Time Cube Operations: Eurographics Conference on Visualization (EuroVis 2014).” In *Eurographics Conference on Visualization (EuroVis 2014),* 2014.

Bach, Benjamin, Sicat, Ronell, Beyer, Johanna, Cordeil, Maxime, and Pfister, Hanspeter. “The Hologram in My Hand: How Effective is Interactive Exploration of 3D Visualizations in Immersive Tangible Augmented Reality?” *IEEE Transactions on Visualization and Computer Graphics* 24 (2018): 457–467.

Bertin, Jacques, and Berg, William J. *Semiology of graphics: Diagrams, networks, maps / Jacques Bertin ; translated by William J. Berg*. 1st ed. Redlands, Calif.: ESRI; London : Eurospan [distributor], 2011.

Bogucka, Edyta, and Jahnke, Mathias. “Feasibility of the Space–Time Cube in Temporal Cultural Landscape Visualization.” *ISPRS International Journal of Geo-Information* 7, no. 6 (2018): 209.

Bogucka, Edyta P., and Jahnke, Mathias. “Space-Time Cube - A Visualization Tool for Landscaoe Changes.” *Kartographische Nachrichten Journal of Cartography and Geographic Information* 4 (2017): 183–191.

“Category:Royal Castle, Warsaw - Wikimedia Commons.” 2018. https://commons.wikimedia.org/wiki/Category:Royal_Castle,_Warsaw, accessed September 2018.

Christian Rohrer. “When to Use Which User-Experience Research Methods.” 2014. https://www.nngroup.com/articles/which-ux-research-methods/, accessed September 2018.

“ColorBrewer: Color Advice for Maps.” 2016. http://colorbrewer2.org/#type=sequential&scheme=BuGn&n=3, accessed September 2018.

Dent, Borden D. *Cartography*. 6th ed. Boston [u.a.]: McGraw-Hill Higher Education, 2009. http://opac.ub.tum.de/InfoGuideClient.tumsis/start.do?Login=wotum&Query=540="0-07-294382-3".

“European Landscape Convention.” In *European Treaty Series.* Florence.

"File:Castleinwarsaw1947.jpg - Wikimedia Commons." 2018. https://commons.wikimedia.org/wiki/File:Castleinwarsaw1947.jpg, accessed September 2018.

Gatalsky, P., Andrienko, N., and Andrienko, G. "Interactive analysis of event data using space-time cube." 2004.

"HoloLens hardware details - Mixed Reality." 2018. https://docs.microsoft.com/en-us/windows/mixed-reality/hololens-hardware-details, accessed August 2018.

"ISO 9241-11:2018, Ergonomics of human-system interaction — Part 11: Usability: Definitions and concepts." https://www.iso.org/obp/ui/#iso:std:iso:9241:-11:ed-2:v1:en, accessed September 2018.

ISO International Organization for Standardization. *Part 11: Usability: Definitions and concepts,* 2018.

Kraak, Menno-Jan. "The Space-Time Cube Revisited from a Geovisualization Perspective." In *ICC 2003 : Proceedings of the 21st international cartographic conference: cartographic renaissance.* Durban, South Africa: International Cartographic Association (ICA), 2003.

Kveladze, Irma. "Space time cube design and usability." Dissertation, Entschede Netherlands, 2015. https://research.utwente.nl/en/publications/space-time-cube-design-and-usability.

Kveladze, Irma, Kraak, Menno-Jan, and van Elzakker, Corné P.J.M. "Cartographic design and the space-time cube." *The Cartographic Journal (*2018).

Li, Xia, Çöltekin, Arzu, and Kraak, Menno-Jan. "Visual Exploration of Eye Movement Data Using the Space-Time-Cube." In *Geographic information science: 6th international conference, GiScience 2010, Zurich, Switzerland, September 14-17, 2010 : proceedings / Sara Irina Fabrikant … [et al.] (eds.),* edited by Sara Irina Fabrikant. Berlin: Springer, 2010.

Luc, M., Urszula Somorowska, and Jacek Bogusław Szmańda, eds. *Landscape Analysis and Planning: Geographical perspectives*. Cham, Heidelberg, New York, Dordrecht, London: Springer, 2015.

MacEachren, Alan M. *How maps work: Representation, visualization, and design / Alan M. MacEachren*. New York, London: Guilford Press, 1995.

Madej, Ed. *Cartographic design using ArcView GIS*. 1st ed. Albany, NY: OnWord Press, 2000.

"MicrosoftDocs/mixed-reality." https://github.com/MicrosoftDocs/mixed-reality/blob/master/mixed-reality-docs/color,-light-and-materials.md, accessed September 2018.

"MicrosoftDocs/mixed-reality_Gestures." https://github.com/MicrosoftDocs/mixed-reality/blob/master/mixed-reality-docs/gestures.md, accessed September 2018.

Milgram, Paul, and Kishino, Fumio. “A Taxonomy of Mixed Reality Visual Displays.” *IEICE Trans. Information Systems* vol. E77-D, no. 12 (1994).

Morrison, J. L. “Applied cartographic communication: map symbolization for atlases.” *Cartographica* 21, no. 1 (1984): 44–84.

Moylan, Elizabeth. “Mapping Landscape Change: Space Time Dynamics and Historical Periods.” ca. 2001. http://www.geocomputation.org/2001/papers/moylan.pdf.

Paelke, Volker, and Brenner, Claus. “Development of a Mixed Reality Device for Interactive On-Site Geo-visualization.” 2007.

Roth, Robert E. “Cartographic Interaction Primitives: Framework and Synthesis.” *The Cartographic Journal* 49, no. 4 (2013): 376–395.

Roth, Robert E. “Visual Variables.” In *The international encyclopedia of geography: People, the earth, environment, and technology / editor-in-chief, Douglas Richardson ; general editors, Noel Castree, Michael F. Goodchild, Audrey Kobayashi, Weidong Liu, Richard A. Marston,* edited by Douglas Richardson, Noel Castree, Michael F. Goodchild, Audrey Lynn Kobayashi, Weidong Liu and Richard A. Marston. Chichester, West Sussex, UK: Wiley Blackwell, 2017.

Shneiderman, B. “The eyes have it: A task by data type taxonomy for information visualizations.” 1996.

Slocum, Terry A. *Thematic cartography and geographic visualization*. 2nd ed. Upper Saddle River, N.J.: Pearson Prentice Hall, 2004.

“The Royal Castle in Warsaw - Google Maps.” https://www.google.de/maps/place/The+Royal+Castle+in+Warsaw/@52.2479783,21.0137297,17z/data=!3m1!4b1!4m5!3m4!1s0x471ecc661b455407:0x2019a146fb49c9be!8m2!3d52.247976!4d21.015256, accessed September 2018.

Tyner, Judith A. *Introduction to thematic cartography*. Englewood Cliffs, N.J.: Prentice Hall, 1992.

“What is a hologram? - Windows Mixed Reality.” 2018. https://docs.microsoft.com/en-us/windows/mixed-reality/hologram, accessed August 2018.

“Wikimedia Commons.” 2018. https://commons.wikimedia.org/wiki/File:Ramahololens.jpg, accessed August 2018.

Yim, Dianna, Loison, Garance Nicole, Fard, Fatemeh Hendijani, Chan, Edwin, McAllister, Alec, and Maurer, Frank. “Gesture-driven Interactions on a Virtual Hologram in Mixed Reality.” 2016.

Appendix A: Consent to Participate in a User Study

Consent to Participate in a User Study

Technical University of Munich

Thank you for finding time for the user test, which is conducted by **Maria Turchenko**, master student of the Technical University of Munich. It is organized within my work on the master thesis with the topic **"Space-Time Cube Visualization in a Mixed Reality Environment – New Approaches to Support Understanding Historical Landscape Changes"**.

The test will consist of 3 parts. The first part is an introductory part to Microsoft HoloLens headset and its interaction gestures. Second part is the test itself (exploring the space-time cube hologram itself and answering 4 questions while using the hologram), followed by the third part – a short questionnaire.

I aimed to perform an exploratory research on the usability of the created hologram to evaluate the applicability of the mixed reality to the spatiotemporal visualizations. For these reasons your interactions with hologram will be recorded on the video within HoloLens. The video will capture only your hand performing the gestures, your view within HoloLens and your speech. You are kindly asked to think aloud during the test stage to provide a better understanding of your interactions and motivations within the test.

Confidentiality and Rights

This study is anonymous and is not aimed to collect or retain any personal information. All the records and data gained from the test will be anonymized and used only within the work on my master thesis research with the possible subsequent publication of the thesis on a conference or in a journal.

The decision to participate in this study is entirely up to you. You may refuse to take part in the study at any time. You have the right to ask questions about this research study and to have those questions answered by me before, during or after the research.

Consent

- I have been informed on the procedure and purpose of the study and my questions have been answered to my satisfaction.

I have volunteered to take part in this study and agree that during the study information is recorded (audio and video as well as my interaction with the system). This information may only be used for research purpose with the possible subsequent publication of the thesis on a conference or in a journal.

- I understand that my participation in this study is confidential. All personal information and individual results will not be released to third parties without my written consent.
- I understand that I can withdraw from participation in the study at any time.

Subject's Name : ____

Subject's Signature: ________________________ Date:__________________

Appendix B: Questionnaire for the participants dealing with two cube's variations

Questionnaire (for the participants dealing with two cubes)

Please mark one number in the continuum for each question that best represents your experience.
Please mark one option for the multiple choice questions.

1. What is your field of study/occupation (e.g. geography, economics etc.)?

____

2. Your age: __________ **3.** Gender: Female ☐ Male ☐

4. Do you have previous experience with mixed reality: Yes ☐ No ☐

5. Please mark the interactions you used for the tasks performance:

	Task 1	Task 2	Task 3	Task 4
Dragging				
Rotation horizontally				
Rotation vertically				
Scaling (only for the STC with bounding box)				
Filtering displayed centuries via legend				
Reversing the order of centuries				
Switching color schemes				
Displaying info about the buildings				
Displaying space-time links between centuries				

Task 1: What was the most northern building in the 16th century?

Task 2: Which water bodies in 14th century were located at the same place as the Royal Castle after rebuilding in 20th century?

Task 3: How many buildings from 14th century were represented in 18th century?

Task 4: Name the oldest building existing in 17th century.

6. Navigating the space-time cube hologram was:

Difficult	1	2	3	4	5	6	7	Easy

7. The controls and buttons for the space-time cube holograms were:

Confusing	1	2	3	4	5	6	7	Clear

8. The contrast between the background and the elements of hologram was:

Bad	1	2	3	4	5	6	7	Good

9. Which rotation/dragging of the space-time cube hologram were more comfortable to perform?

a. with voice commands ☐

b. with bounding box ☐

10. Rotation/scaling by means of bounding box was:

Difficult to deal with	1	2	3	4	5	6	7	Easy to manage

11. Switching between rotation/dragging by means of voice command was:

Difficult to deal with	1	2	3	4	5	6	7	Easy to manage

12. The transparency of the ground slices was:

Distracting	1	2	3	4	5	6	7	Useful

13. Which transparency degree of the ground slices did you liked more?

a. transparent ☐

b. almost opaque ☐

14. The selection of objects with the gaze was:

Difficult	1	2	3	4	5	6	7	Easy

15. Which color scheme did you like the most for performing the tasks?

a. first (sequential from deep brown to yellow) ☐

b. second (diverging from dark violet to brown) ☐

c. third (qualitative – distinct colors) ☐

16. Which coloring of the buildings was more informative and comfortable?

a. by the century of existence ☐

b. by the century of construction ☐

17. Spacing between the centuries was:

Too small	1	2	3	4	5	6	7	Too large

18. Dealing with the small objects within the hologram was:

Difficult to deal with	1	2	3	4	5	6	7	Easy to manage

19. What did you like about the application the most?

____

____

____

____

____

____

20. What could be improved?

____

____

____

____

____

____

Thank you for your time!

Appendix C: Questionnaire for the participants dealing with the first cube's variation

Please mark one number in the continuum for each question that best represents your experience.
Please mark one option for the multiple choice questions.

1. What is your field of study/occupation (e.g. geography, economics etc.)?

____

2. Your age: __________ **3.** Gender: Female ☐ Male ☐

4. Do you have previous experience with mixed reality: Yes ☐ No ☐

5. Please mark the interactions you used for the tasks performance:

	Task 1	Task 2	Task 3	Task 4
Dragging				
Rotation horizontally				
Rotation vertically				
Scaling (only for the STC with bounding box)				
Filtering displayed centuries via legend				
Reversing the order of centuries				
Switching color schemes				
Displaying info about the buildings				
Displaying space-time links between centuries				

Task 1: What was the most northern building in the 16th century?

Task 2: Which water bodies in 14th century were located at the same place as the Royal Castle after rebuilding in 20th century?

Task 3: How many buildings from 14th century were represented in 18th century?

Task 4: Name the oldest building existing in 17th century.

6. Navigating the space-time cube hologram was:

Difficult	1	2	3	4	5	6	7	Easy

7. The controls and buttons for the space-time cube holograms were:

Confusing	1	2	3	4	5	6	7	Clear

8. The contrast between the background and the elements of hologram was:

Bad	1	2	3	4	5	6	7	Good

9. Rotation/scaling by means of bounding box was:

Difficult to deal with	1	2	3	4	5	6	7	Easy to manage

10. The transparency of the ground slices was:

Distracting	1	2	3	4	5	6	7	Useful

11. The selection of objects with the gaze was:

Difficult	1	2	3	4	5	6	7	Easy

12. Which color scheme did you like the most for performing the tasks?

d. first (sequential from deep brown to yellow) ☐

e. second (diverging from dark violet to brown) ☐

f. third (qualitative – distinct colors) ☐

13. Which coloring of the buildings was more informative and comfortable?

c. by the century of existence ☐

d. by the century of construction ☐

14. Spacing between the centuries was:

Too small	1	2	3	4	5	6	7	Too large

15. Dealing with the small objects within the hologram was:

Difficult to deal with	1	2	3	4	5	6	7	Easy to manage

16. What did you like about the application the most?

____

____

____

____

17. What could be improved?

Thank you for your time!

Appendix D: Questionnaire (for the participants dealing with the first cube only)

Please mark one number in the continuum for each question that best represents your experience.
Please mark one option for the multiple choice questions.

1. What is your field of study/occupation (e.g. geography, economics etc.)?

____

2. Your age: __________ **3.** Gender: Female ☐ Male ☐

4. Do you have previous experience with mixed reality: Yes ☐ No ☐

5. Please mark the interactions you used for the tasks performance:

	Task 1	Task 2	Task 3	Task 4
Dragging				
Rotation horizontally				
Rotation vertically				
Scaling (only for the STC with bounding box)				
Filtering displayed centuries via legend				
Reversing the order of centuries				
Switching color schemes				
Displaying info about the buildings				
Displaying space-time links between centuries				

Task 1: What was the most northern building in the 16^{th} century?

Task 2: Which water bodies in 14^{th} century were located at the same place as the Royal Castle after rebuilding in 20^{th} century?

Task 3: How many buildings from 14^{th} century were represented in 18^{th} century?

Task 4: Name the oldest building existing in 17^{th} century.

6. Navigating the space-time cube hologram was:

Difficult	1	2	3	4	5	6	7	Easy

7. The controls and buttons for the space-time cube holograms were:

Confusing	1	2	3	4	5	6	7	Clear

8. The contrast between the background and the elements of hologram was:

Bad	1	2	3	4	5	6	7	Good

9. Rotation/scaling by means of bounding box was:

Difficult to deal with	1	2	3	4	5	6	7	Easy to manage

10. The transparency of the ground slices was:

Distracting	1	2	3	4	5	6	7	Useful

11. The selection of objects with the gaze was:

Difficult	1	2	3	4	5	6	7	Easy

12. Which color scheme did you like the most for performing the tasks?

g. first (sequential from deep brown to yellow) ☐

h. second (diverging from dark violet to brown) ☐

i. third (qualitative – distinct colors) ☐

13. Which coloring of the buildings was more informative and comfortable?

e. by the century of existence ☐

f. by the century of construction ☐

14. Spacing between the centuries was:

Too small	1	2	3	4	5	6	7	Too large

15. Dealing with the small objects within the hologram was:

Difficult to deal with	1	2	3	4	5	6	7	Easy to manage

16. What did you like about the application the most?

____

____

____

____

17. What could be improved?

Thank you for your time!