Technische Universität München
Department of Civil, Geo and Environmental Engineering
Chair of Cartography
Prof. Dr.-Ing. Liqiu Meng

Master's Thesis

Online visualization of multi-dimensional spatio-temporal data

Visualization of weather data of Germany in a large time scale

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Statement of Authorship

I confirm that this master's thesis is my own work and I have documented all sources and material used.

16.04.2018, Dresden

Keni Han

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Abstract

Time has always been a challenge for cartographers to visualize in maps. Many methods to visualize the time parameter in maps have been proposed, including animated maps, static time map series. The evolvement of computer technologies has offered opportunities for cartographers to map using various media, which has meanwhile brought the need of developing novel visualization methods. Among the mapping media and technologies, web mapping has become rather important and popular, thanks to its wide accessibility to the users and its flexibilities.

The overall goal of the thesis is to develop methodolody to visualize multi-dimentsional spatio-temporal data, and to fill in the gap of assesing the performance of the applied techniques. An interactive map that combines animated map, static map, and chart to present multi-dimensional spatio-temporal data is built, with the help of up-to-date web mapping technologies. In the case study, weather data of Germany is applied, owing to its characteristics of multi-dimension and time-sensitivity.

For the purpose of accessing the utility and usability of the map, map evaluation is conducted. The evaluation is based on the theoretical background of eye-tracking technique and analysis. Users are gathered to view the map in two major phases of free-examination task and goal-directed task, during which their eye-movements are collected, as well as the response to the designed questions. The evaluation results contain area of interst analysis, performances among different groups of users, accuracy and efficiency when the users answer the questions. Threfore, conclusions are drawn based on the results, including user preference, utility of each component in the map, gender difference, etc.. It is found that animated map and chart generate different types of information in a spatio-temporal scenario. Animated map generates information regionally, while chart renders better overall and quantitative information. The usage of animated map longer than a possible time threshold could cause congnitive overload for the users. Concerning the gender of the users, animated map is more appealing to female, while chart is rather preferred by male than female.

Keywords: multi-dimensional, spatio-temporal, web mapping, animated map, map evaluation, map utility, eye-tracking technique

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1 Introduction

1.1 Background

Over the years of development of cartography, visualizing time has always been a challenge. This challenge of mapping multi-dimensional reality on a two-dimensional presentation has remained an on-going topic for cartographers (Bruggmann and Fabrikant, 2016; Silverio and Jaquet, 2012). Scientists proposed two forms of dynamic phenomena in the maps to present the changes over time, which are qualitative and quantitative phenomena, and these forms are sometimes combined. Such forms will have different approaches regarding visualization. Koussoulakou and Kraak (1992) proposed that there are three primary methods to present dynamic phenomena: single static map, static map series, and animated map. In this thesis, a novel method will be proposed to visualize the chosen datasets, based on the characteristics of the datasets, the characteristics of the target users, as well as the current trend of cartography.

As for the media for presenting maps, due to the fast evolvement of web-based technology and programming languages, web-based cartography has become more critical and much more accessible to cartographers. This development also gives opportunities to cartographers to visualize dynamic geographic phenomena vividly. Because of its abundant possibilities of functionalities and flexibilities, web-based visualization is preferred by many cartographers as the platform to map geographic phenomena, which at the same time gives an easier and more direct access to the users to explore. Meanwhile, according to a survey that MURAKOSHI (2006) conducted about the role of online maps, it was found that web maps were easier to use than paper maps.

In the last few decades spatial data (e.g., satellite images, administrative geographic data, Open Street Map, Google Map) has vastly increased in volume, offering an excellent opportunity for researchers to explore the data and map previously unrevealed information. At the same time, the growing size and complexity of the datasets increases the difficulty of finding and visualizing useful information. Owing to the vast amount of data, it is no longer practical or useful to let the data “speak for itself”, instead, data visualization needs to apply a pattern to reveal the vital information for users (Andrienko et al., 2008). Which part of the information to visualize and how important the information is very much depend on the categories of the datasets and the goal of visualization.

Map evaluation serves as a tool to see if the map is efficient and effective. During the process of evaluation, new problems or findings may be revealed. The need to assess the usefulness and usability of geovisualization tools is increasing as various types of user interactions in maps emerge (Muntz et al., 2003). The map usability and utility are usually tested, and such assessments also focus on the usefulness, and performance of a tool. Meanwhile, the preference and behaviors of the users can also be collected to shed light on further design of the maps. Eye tracking technique and analysis have been proven to be useful techniques in user research. By using eye-tracking data, researchers can discover how long and how often a user looks at a particular area of interest, as well as the length and speed of the eye movements (Duchowski, 2007; Holmqvist et al., 2011). However, it remains a challenge for the cartographers to design efficient evaluation methodologies to reveal the problems and performances of the maps.

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1.2 Research goals

The overall goal of the thesis is to develop methodolody to visualize multi-dimentsional spatio-temporal visualization data, and to fill in the gap of the performance of applied techniques. The objectives of the goal are: 1) summerizing and proposing suitable methods to visualize data in a multi-dimentsional spatio-temporal scenario; 2) applying these techniques by a proper medium, which is web map application in this case; 3) testing the usability and utility of the techniqes applied. The detailed objectives are listed as below.

Based on a literature review, the map design decisions should be drawn, which serve as the theoretical basis for the building a map application.

- Find suitable and available datasets. These datasets should also be well comprehensible and understandable to the general public.
- Find a proper way to visualize spatio-temporal data. Temporal data is predominately for scientific use. The task of this thesis is to make the visualization accessible and comprehensible to the general public.
- Take the users' needs, the purpose and user characteristics into account to choose an adequate visualization technique.

For the purpose of testing the map usability and utility of the applied methods and the users' preferencae, the following objectives should be met:

- Find methods to test the map usability and utility.
- Obtain the users' preference when viewing this map.
- Based on users' performances, evaluate the usage of the techniques applied, and test if the predicted goals of the techniques are achieved.
- Find out different needs from different groups of users and analyze the possible reasons for the differences.

Concerning the result of the map, the following objectives should be addressed.

- Take both theoretical background and evaluated results into consideration to find and adopt a proper methodology to visualize the temporal data.
- Discover unrevealed possibilities for an interactive map.

1.3 Research questions

The first procedure is to summarize the existing multi-dimensional spatio-temporal data visualization methods, then to apply one or more methods to the final visualization. The question lies in how to organize all parameters in this multi-dimensional scenario and how to find a balance among the relationships between the parameters and time clearly. How can one present a vivid visualization that focuses on change? What is the most appropriate generalization of time?

Map evaluation may prove challenging because of the likely uncertainties of working with users. These uncertainties lie in the procedure of tracking the users' behaviors and user recruiting. The results are highly related to the evaluation methods adopted. It therefore relates to the following questions: How do users' differences affect the effectiveness of spatio-temporal visual displays? What kind of techniques to apply to collect the users' reaction to the map? How to adapt the users' feedback into further map design?

1.4 Overview of contents

The thesis consists of two major aspects, which are data visualization and map evaluation.

In the first chapter, an introduction and overview of the work are stated. The research goals and questions are presented as well. The related work is written in the chapter of state of art, which consists of three major parts, including data description, visualization method, and map evaluation. The third chapter includes the description of the datasets, data retrieving and processing. The fourth chapter focuses on the methodologies adopted and case study. Based on what has been learned from the reviewed literature and the related study, the suitable techniques are chosen for the datasets. Moreover, the used software, programming language, and APIs are also described. Map evaluation is stated in chapter six, including the evaluation goals and procedures, etc.. The results of the evaluation are stated in chapter seven, while discussion of the results is contained in chapter eight. The ninth chapter contains the summary of the study and outlooks of the study. The last chapter includes the appendix.

2 State of art

This study covers research backgrounds from three major aspects. The first part contains the visualization of the data, the media to visualize, and the possible techniques. Secondly, the methods to evaluate the map are introduced. The evaluation methods are based on the theory and basis of map usability and utility. At last, the data to be applied is researched, where its properties and usages are mentioned.

2.1 Data visualization

To develop methodologies to visualize the multi-dimensional spatio-temporal data, the thesis need to focus on the characteristics of the data into consideration, as well as the medium to present the data. As for the aspect of multi-dimension, current scientific visualization methods will be summarized. There has been a lot of research which propose and suggest proper methods to visualize spatio-temporal data, and they will be discussed in the second part. The methodologies concerning the two aspects have to be merged and applied in the of the web map design. The state of art of web mapping concerning its role in modern cartography and its usages is presented in the last part.

2.1.1 Multi-dimensional data visualization

In the last decade, there has been enormous progress in scientific visualization (Max, 2005). However, the visualization of multi-variate continuous three-dimensional (3D) data, especially when the data is also time-dependent, remains an excellent visualization challenge. Recent studies have depicted a change in visualization from a classical approach—which focuses on small and isolated information—to visualization of data on a massive scale with dynamic data (Fuchs and Hauser, 2009). Due to the slight but distinct difference between multi-variate and multi-dimensional data, the visualization techniques are dependent on their properties. It is important to understand the datasets and apply the right methods. In this study, multi-dimensional data is chosen. Fuchs and Hauser (2009) summarized the techniques identified to deal with multi-dimensional datasets, and a few selected techniques among them which are of potential relevance to the geographic environment are as follows:

- Glyphs (also referred to as icons) are a powerful communication item. A large number of data dimensions can be incorporated into the attributes of a single shape or symbol.
- Hybrid/multi-method visualization is the application of several visualization techniques for the same image.

- Interaction is probably the most important tool for understanding complex data. Interactions modify viewing parameters, transfer function manipulation, seeding point selection, culling, queries, graphical model exploration, region of interest selection and many others.
- Layering and Fusion have been used extensively in scientific visualization to show multiple items.
- Multiple Views present the information in several different views that encourage comparison, give contrast and help to generate a correct understanding.
- n-D viewing is based on defining hyperplanes on the high dimensional volume or direct projection. This is done very often for time-varying datasets, where time-coherency can be exploited for compression and acceleration.
- Reduction of dimension and de-noising can remove unwanted details in the data and remove obscuring structures that hinder the process of understanding.

Multi-method and interaction techniques are mainly applied in the case study, which will be discussed more in the chapter of methodologies and case study.

2.1.2 Spatio-temporal data visualization

As for highly multi-dimensional data visualization, Skupin and Fabrikant (2007) relate spatialization with the systematic transformation of high-dimensional datasets into lower-dimensional, spatial representations for facilitating data exploration and knowledge construction, with the usage of spatial metaphors. The role of spatial metaphors, including geographic metaphors, is also central to the narrower definition of spatialization developed in the GI Science literature over the last decade (Skupin and Fabrikant, 2007). The search for patterns, relationships, and trends in a temporal GIS environment is commonly accomplished by computational methods supported by the graphic display of intermediate and final analysis results. Other methods are relying more on visual interpretations in an environment where the user has possibilities to interact with the data and/or the display can be considered complementary to the computational ones (Blok et al., 1999). Apparently, the more powerful method is the combination of both graphic display and interactions, which requires that GIS and scientific visualization environments are well integrated. With the development of the GIS software and web-mapping, this combination is now possible.

Different strategies can be used to address to present spatio-temporal data (Monmonier, 1990), where a range of options for the graphic display of quantitative spatial-temporal data is proposed, as shown in Table 2-1.

Table 2-1: A conceptual framework for the visualization of geographic time-series data (Monmonier, 1990)

Time-series graphs with place names or other geographic metaphors	
Single static maps	Temporal symbols; temporal aggregation; focused measurements; “dance maps”; change maps; generalized maps focusing on transition and or diffusion
Multiple static maps (and graphs)	“Chess maps” (juxtaposition); cartographic cross-classification arrays (with maps and statistical graphics)
Single dynamic maps	Sequenced symbols (accretion); temporal sequences of views; symbols suggesting motion (pulsating directional symbols)
Multiple dynamic maps (and graphs)	High-interaction graphic analysis: scatterplot brushing; geographic brushing; temporal brushing
	Programmed sequences of “interesting” or “meaningful” view: authored video animation; “projection pursuit”; “grand tour”; “atlas touring”

When trying out approaches for representation and exploration of spatio-temporal data, Andrienko et al. (2003) propose two concepts to depict the visualizations, one of which is ”when - what + where”, while another is “what + where - when”. The first concept depicts identification tasks that have the goal to determine characteristics of spatial objects or locations at a given moment or moments. In this task, a software system must be able to visualize data referring to a particular user-selected time moment. The latter depicts the goal as determining the time moment(s) when specific characteristics of objects or locations occur. The characteristics of objects or locations (known information) need to be set as query constraints and time (unknown information) set as the query target. They combine the two tasks in the design of one map software. Static map and animation are applied to solve the first task, while time-series graph is used to achieve the second. They found that using the time-series graph; one can easily determine at what time moments the attribute value for a given object was the highest or the lowest as well as when the highest or the lowest value among all objects was attained.

Koussoulakou and Kraak (1992) concentrate how the users understand and communicate with the spatio-temporal map. In this study, to obtain some concrete evidence of the response of users to spatio-temporal map displays, a map-user test was conducted. Animated maps and respective static ones depicting the same subjects were presented to the users and evaluations were conducted. The results indicate that although the correctness of answers is not influenced by the type of map (i.e., static or animated), the users perceive faster from animated map displays (Koussoulakou and Kraak, 1992).

However, it is not always enough to show the changeability with a series of static maps of other forms of maps. Monmonier (1992) argued that in some cases, a standard map component needs to be combined with another graphical component to identify the associations between different variables. These extra components can be both interactive or non-interactive. Climate studies and natural hazards monitoring are examples of domains where such a "multi-component" approach could be useful (Opach et al., 2011). This type of combination is widely used in natural environment visualizations, especially in presenting climate change or natural hazards. In a web cartographic environment, Jenny et al. (2006) proposed methods to combine different information visualizations with maps, including presenting seismic events on a map as well as in profile and visualizing volcanoes with the temperature presented in a diagram.

2.1.2.1 Animated Map

Although animated map seems to be emerging in the last few decades, its application has existed as long as the map itself. It is widely recognized that static maps have limitations in depicting temporal data. However, due to the technical hurdles and the lack of importance of animation, there has been a failure by cartographers to grasp the significance and necessity of cartographic animation, which was lamented upon by researchers in the early 1990's (Campbell and Egbert, 1990). The broad application and popularity of computers and internet have spurred the re-appearance of map animation. In its simplest form, a cartographic animation can consist of only two maps, which are viewed in quick succession, to depict a trend or a pattern that would not be apparent if the maps were viewed individually (Peterson, 1999).

For the realization of an animated map, a 4D cartographer has to deal with scale, data classification, visual hierarchy, and many other problems discussed at length in the literature of traditional print cartography (Gersmehl, 1990). 4D here means mapping with the dimension of time. Gersmehl (1990) also summarized nine metaphors for map animation:

- Slideshow. Animation is an orderly but attention-grabbing sequencing of dissimilar still images - maps, photographs, diagrams, etc.
- Teleprompter. An orderly set of nested lists, and therefore a straightforward scrolling of key words or phrases can be a useful visual reinforcement for their spoken message.
- Pointer. If words are arranged on the screen so that their position is part of their message, then the program is an example of the pointer metaphor.

- Flipbook. This metaphor has its root in a set of stapled cards that are held in one hand, bent slightly with the thumb o! the other hand, and then released in rapid sequence.
- Sprite. Animations of this kind have an assortment of small and simple-to-draw objects moving along a restricted set of paths on the screen.
- Stage and play. These programs structure an animated sequence as a stage with backdrops and actors
- Color Cycling. In this kind of program, the animator uses a special 'brush' to lay down a specified series of colors with each stroke.
- Metamorphosis. A metamorphosis program is designed to make it easy to change the shapes or other features of rather complex individual objects.
- Model and camera. These programs define objects as sets of three-dimensional coordinates for key vertices. They then construct the intervening surfaces, add texture to the surfaces, calculate highlights and shadows, define paths for movement of both object and camera, and then encourage you to go out for a long lunch while they render the commands for a three-second animation into visible form.

These metaphors are widely applied and act as the basics of map animation, also in many modern media. The design of map animation shares many common rules and principals with traditional map design, but because of its unique form and the revealed information, there is a difference of visualization regarding visual variables. Bertin (1981) identified seven main categories of visual variables: position, size, shape, value, color, orientation, and texture. In addition to these variables, animation affords a number of additional and potentially very powerful visual attractants, such as sudden appearance, vibratory motion, color change, flashing, and fringing of foreground objects or graying of the background information (Gersmehl, 1990).

2.1.2.2 Chart

In most cases, diagrams are applied in the region of the map, acting as a visual variable of a map. As a more statistic-oriented presentation, the combination of the chart is prevalent in cartography, and the method to make a chart map exist in many software and APIs (e.g., Google map API, ArcGIS for Javascript API). Andrienko et al. (2003) adopts the usage of time-series graphs to address the task of “what + where - when.” With the help of time-series graphs, users can easily determine at what time moments the attribute value for a given object was the highest or the lowest, as well as when the highest or the lowest value among all objects was attained and an example from this research is shown in Figure 2-1.

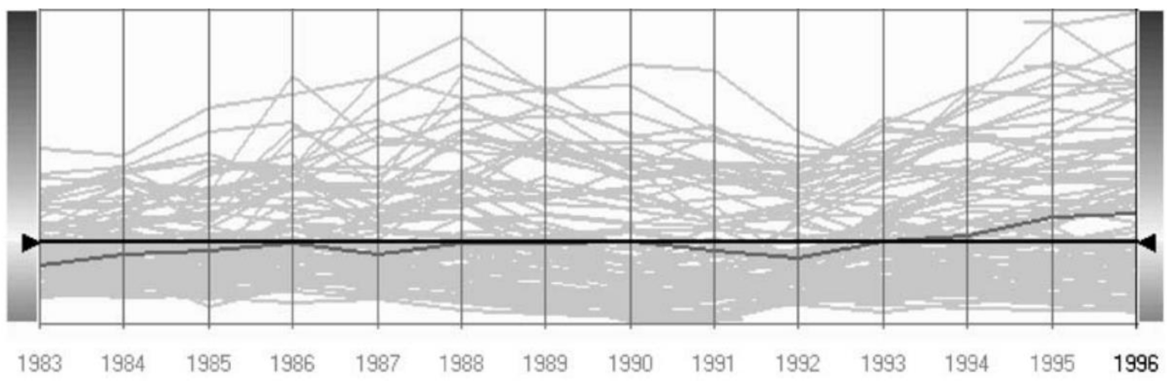

Figure 2-1: The appearance of the interactive time-series graph in the mode of comparison to a particular attribute value. The value is represented on the graph by a straight horizontal line. Through the map display, the user may select some geographical object and compare its value path (it is highlighted in the graph) with the line for the specified reference value (Andrienko et al., 2003).

2.1.3 Web mapping

Presently, we can define three categories of mapping applications, each with a different audience, and having various functions and requirements. There is a definite link between audience, tasks, functional requirements and development team skills in each category. These three categories are desktop GIS, online GIS, and web mapping. Mainstream applications of web mapping have only been emerging in recent years. However, the technology that makes web mapping available has been around for decades. The widespread availability of digital mapping technology has led to increased use of web-based maps, which is reflected in the frequent utilization of map pages in many search engines. The technological developments have provided new tools and techniques for designing interface and interactivities with the websites. The Internet has become an immensely valuable information resource and has been widely recognized recently as an essential means to quickly disseminate information and acquire spatial data from diverse sources (Plewe, 1997). The form of the maps had been evolved with the improvement of cartography and technology; Howard and MacEachren (1996) predicted that digital maps are becoming the norm—replacing static paper maps in applications from way finding to scientific research. Cartography is about the design and production of maps. Web cartography is as well, whereas only the medium is different. Web mapping sites, or simply web maps, are interactive maps that are accessed through a web page (Mitchell, 2005).

The medium of web and internet brought new functionalities to maps. They are not only used in a natural environment to show locations and geographic information. The users can navigate, search, and play a role in the geospatial data infrastructure needed to search for and disseminate geospatial data(Couclelis, 1998). In contrast to traditional maps, web maps give more accessibility and more direct access to users. The world wide web offers the benefits of flexibility and ubiquity and reduces the costs and risks of obsolescence and isolation (Anderson and Moreno-Sanchez, 2003). The development of the world wide web and many internet GIS programs provide proprietary ways to allow users to quickly access, display, and query spatial data over the web (Green, 1997; Plewe, 1997). Compared to static printed maps, screen-based spatial maps can efficiently be processed, updated, and analyzed interactively by users or designers. Modern maps are no longer used for mere presentation, but as an interactive and individual exploration of temporal and non-temporal spatial data, very much reflecting personal tastes and preferences (Fuhrmann and Kraak, 2001). Peterson (1995) implemented simple dynamic mapping and animation. The advantage of this approach is that JavaScript programs can be interpreted by most browsers. The language is straightforward and can be used by non-programmers. The possibilities of mapping on the web are changing all the time; what cannot be mapped today possibly will be mapped tomorrow. Köbben and Kraak (1999) summarized a few options and experiences with web maps as follows:

- The depiction of movement & change.
- Maps combined with other graphics, sound, and moving images, which are multimedia maps.
- Virtual worlds: an alternative view from the traditional generalized and symbolized maps we know.
- Maps to scientifically explore spatial data: this exploratory cartography will create an environment where geoscientists can work to solve their problems and make new discoveries.

Kraak and Brown (2003) pointed out that there are two types of web maps: static and dynamic maps. Both can be view-only or interactive. It is important to find a suitable form to present the geographic data. Except for the advantages of a web map, there are still hurdles that exist which need to be addressed for better visualization. Kraak and Brown (2003) suggest some limitations that should be taken into consideration regarding web map:

- Finding web maps and geodata. The source of the geodata and maps, and the methods to find the existing web maps and geodata.
- Language. Even world wide web can be accessed worldwide, the language is a limitation since it can’t be in every language.
- Accessibility for everyone? There sometimes exists restrictions or limitation for the users who can use the map.
- Web maps and fee of geodata. Some of the geodata on the internet are not free, which affects the fee of the web map that created using these data.
- Internet access. Most of the web maps require internet access.

- Speed of data transfer. When transferring, loading data simultaneously as loading the map, how fast will it be? Will it the reduce the performance of the map or the user' experience?

These limitations are also fully considered in the process of the web map design in this thesis. Despite all the problems and limitations, the web map is still growing to be the dominant medium of mapmaking.

To facilitate the build and design of web map, some commercial GIS programs or government agencies are developing tools, APIs, prototypes, standards for web mapping, and web GIS. There also exists standards from OGC available concerning web mapping (e.g. WMS, WMTS, WFS). Most GIS vendors propose solutions for internet mapping by their existing packages.

2.1.4 User interface design

Howard and MacEachren (1996) suggested three principles for the design of interfaces to geo-referenced data, and these principles are summarized in a hierarchical approach to interface design with conceptual, operational, and implementational levels. This hierarchical approach leads designers from questions about the goals and users of the system to the creation of tools to accomplish those goals. Then, designers are led to questions regarding interface controls that allow effective interaction with the tools. Although interactive maps in various media and platforms are emerging, not all the interactive maps can efficiently be used. This ineffectiveness varies across platforms. Users become more and more aware of the shortcoming and restrictions, which leads to the topic of user-centered design. To address the problem, Roth et al. (2015) suggests a term “interface success” (i.e., does the interactive map work?) from the perspectives of cartography, GIScience, and visual analytics.

User-Centered design can provide financial benefits for the system developer with reduced production costs, decreased support costs, reduced costs in use, and improved product quality (Earthy, 1996). The ISO 13407 standard—human-centered design processes for interactive systems—gives instructions to achieve user needs by utilizing a user-centered design (UCD) approach throughout the entire lifecycle of a system (ISO, 1999). The user-centered design and usability engineering methods have a fundamental role in designing applications for new technical environments, which involve entirely new ways of interacting (Nivala et al., 2007). UCD has increasingly been recommended for interactive maps (Fuhrmann and Pike, 2005). However, preliminary evidence suggests that UCD may not be common in practice, despite the desire of interactive map users to be more involved in the conceptualization, evaluation, and refinement of their interactive mapping systems (Roth, 2015).

2.2 Map evaluation

Roth et al. (2015) summarized "The three U's of interface success" , where utility, usability, and user are included. For a success interface design, these three components should be well considered, following a process of user-centered design with the interface evaluation in the end.

2.2.1 Map usability and utility

The reason for the emergence of usability is the focus on users. The users might belong to different groups, such as professionals, decision-makers, students, tourists, or children. Owing to the various and large number of groups, the design of the map should be based on the targeted users, known as user-centered design. Another reason usability is emerging is that with the developments in hardware and software, new innovative methods for geovisualisation have evolved. Usability is defined in the ISO 9241 standard as 'the effectiveness, efficiency, and satisfaction with which specified users achieve specified goals in particular environments' (ISO, 1997). Usability describes the ease of using an interface to complete the user's desired set of objectives (Grinstein et al., 2003). Nielsen (1992) listed five measures of usability, which have been adopted by the Usability.gov website[1]:

- Learnability (how quickly users understand the interface without prior use);
- Efficiency (how quickly users can interact with the interface once learned to complete the desired tasks);
- Memorability (how well users can return to an interface and pick up where they left off);
- Error frequency and severity (how often users make mistakes and how fatal they are, respectively);
- Subjective satisfaction (how well the users like the interface).

While the first four measures of usability primarily evaluate work productivity, the latter describes the user's engagement with the interface and general impression, an aspect of usability essential for promoting buy-in and improving uptake of an interactive map.

Usability engineering—a term used to describe methods for analyzing and enhancing the usability of software—is an approach to help design products that take into account the new technical environments and user requirements (Nielsen, 1994). With many applications of usability, several researchers have also noticed the lack of usability engineering in cartographic visualization, for instance, MacEachren and Kraak (2001), Fuhrmann and Pike (2005), Nivala et al. (2007). As with graphical user interfaces in software engineering, maps can also be regarded as user interfaces, enables the possibility to apply the usability

[1] Usability.Gov. http://www.usability.gov

engineering into the field of cartography. Peterson (1995) suggests that the word interface can be related to maps in two ways: first, maps are interfaces to the world and, second, composed of UI elements. The map layout, including the elements of legend, color, and visual variables can be regarded as elements of a UI. It is also suggested that with the multimedia characteristics of the internet, web map can be seen as interfaces (Kraak and Brown, 2003). MacEachren and Kraak (2001) observe some challenges to address for cartographers, where it is suggested that with usability, the emphasis is on delineating the advantages and disadvantages of the increasing array of geovisualization methods and technologies in a wide range of contexts for a wide range of users. The researchers have tested the usability of well-scaled mobile maps for consumers (Van Elzakker, 2005). However, to take the usability approaches into the product is not always straightforward. Nivala et al. (2007) stated usability evaluation methods adopted from software engineering are used for the development of applications in other areas, which is challenging to be applied in the field of geovisualization.

In contrast, utility describes the usefulness of an interface for completing the user’s desired set of objectives (Nielsen, 1992).

As for evaluating the usability and utility of a map, there has been a lot of related researchers. These researchers focused on printed maps and on-screen maps which includes mobile maps, web maps, and map application. Iterative evaluation sessions allow usability researchers to identify most usability problems (Nielsen, 1994). Questionnaires, videos, conversation with the users, mouse-clicking are widely used usability evaluations. Owing to the massive amount of usability rules that researchers had proposed, which made it hard to apply the rules correctly, Nielsen (1994) suggested that the evaluation could reveal usability problems, and many of the remaining issues can be revealed by the simplified thinking-aloud test. Whitefield et al. (1991) provided a classification of evaluation methods on two dimensions: whether or not real users are involved and whether or not the interface has been implemented. The usability testing and evaluation methods are also adopted in the field of map evaluation. Koussoulakou and Kraak (1992) experiment on the use of animated maps in comparison to static maps for analyzing spatio-temporal data. They detected no significant difference concerning the users’ ability to retrieve correct information and perceive temporal trends. Andrienko et al. (2003) present an “operational task typology” to characterize the suite of tasks that a user may need to complete with interactive visualization. It includes three axes along which benchmark tasks vary: the cognitive operation, search target (the information content under consideration, including space, time, and attribute, or “where?”, “when?”, and “what?” questions), and search level (an additional aspect of the information content considering the percentage of all map items under consideration along a continuum of elementary to general). The result of the operational task typology is a three-dimensional solution space from which example benchmark tasks can be derived for utility evaluation. There is another approach to test the utility of a map, which is to assess the quality of analytical products acquired by the user when employing the interactive map. Such analytical products vary according to the user’s overall goals and may include the hypotheses generated by the interface, knowledge constructed while using the interface, or decisions made with the support of the interface (Roth et al., 2015).

2.2.2 Map interface evaluation

These evaluation procedures are often conducted based on an empirical study and interviews. However, sometimes users’ thoughts do not quite equate to their feedback. This can be particularly relevant in highly interactive systems used to solve complex problems, when people might not be able to fully verbalize their own complex inference-making. A viewer’s cognitive load might become so high during task completion that verbal reports or think-aloud protocols interfere with the quality of inference making (Çöltekin et al., 2009). Eye movement recordings, on the other hand, can offer additional unobtrusive evidence of overt user behavior. Eye movement recordings are frequently viewed as a window into internal cognitive processes (Bojko, 2006). By learning the eye-movements of the participants, we could be able to compensate the excessive cognitive load, and preventing them from self-reporting. Standard usability evaluations methods, such as testing, inspection have been users in traditional map presentations. However, more recent research papers suggest the need for better, more suitable map evaluation methods, demonstrating that the traditional methods “may no longer be suitable for the growing range of map users, usage scenarios, and digital map devices,” (Nivala et al., 2008) in particular with new interactive visualizations (Koua and Kraak, 2004).

2.2.3 Eye tracking technology

Eye tracking is a technology that tracks the exact point at which a user's gaze is fixated on a screen (Nielsen and Pernice, 2009). Eye tracking technology has emerged for years in various usages, which have been extensively researched regarding the knowledge of eye movements. The eye does not rotate about a fixed center, but this is not of practical importance for most measurement application (Park and Park, 1933). Also, it does not move smoothly over the visual field. Instead, it makes a series of sudden jumps, called saccades, along with other specialized movements (Haber and Hershenson, 1973). The saccade is used to orient the eyeball to cause the desired portion of the visual scene falls upon the fovea. It is a sudden, rapid motion with high acceleration and deceleration rates. More typically, a saccade is followed by a fixation, a period of relative stability during which an object can be viewed. A fixation is when eyes are stationary at a given threshold of approximately 50 to 500 milliseconds (Irwin, 2004). The usage and importance of eye tracking technology have been noticed by many researchers in the field web interaction design, as well as the GI and cartography(e.g., Goldberg and Kotval (1999)). Goldberg and Kotval (1999) pointed out that eye movement analysis provides valuable quantitative and qualitative information on both stages of visual search and thereby complements SEE metrics.

Early in 1970, Steinke (1987) applied information of map usability gathered by eye movements to understand the relation of map reading and map design. During the following decades, the usage trend seemed to decrease. With the price of eye tracking devices going down and the faster development of interactive digital maps, this method has become widely used. Mainly, there are two major parts in an interactive digital map: geographic presentation and the user interface. The application of eye tracking technology provides a better understanding of how people use static small-multiple displays to explore dynamic geographic phenomena. It also helps to illuminate how people make inferences from static visualizations of dynamic processes for knowledge construction in a geographical context (Fabrikant et al., 2013). Opach et al. (2013) applied an eye-tracking experiment, based on the well-designed empirical model, to evaluate the usability of a multi-component animated map. This study can examine which particular components attract users’ attention in sequence and whether display effectiveness can be characterized by users’ viewing behaviors. This thus identifies visual behavior patterns that result in performance differences between participants, using multi-component animated maps.

For the visualization and analysis of eye movement data, there exists a range of techniques. The most straightforward of those provide a simple plot of the pupil’s horizontal and vertical coordinates against time. Other techniques plot raw eye movements in 2-D with the stimulus image as the background. Again, this method is still extensively used by researchers and is one of the easiest-to-implement techniques of the visualization (Duchowski, 2002). There is another more advanced tool, which is called fixation map (Figure 2-2). The fixations are presented as circles, and the saccade is depicted as lines connecting the circles. Another modern visualization is the heatmap, which shows how much users look at different parts of a web page. The example in Figure 2-3 is from a website's "About Us" pages. The heatmap shows users' tendency to read in an "F" pattern, and their focus on information that's presented in bulleted lists (Nielsen and Pernice, 2009). It shows how much users looked at different parts of a web page. Areas where users looked the most are colored red; the yellow areas indicate fewer fixations, followed by the least-viewed blue areas. Gray areas didn't attract any fixations. The opacity of the heatmaps can also be changed to meet the needs. For the purpose of analyzing and applying the data, the question lies in where, how, how long, and how often participants gaze at each element of the map during the task, which then allows researchers to reveal the performances as well as problems of the map interface and its components. It provides added value to the process of systematically evaluating interactive map interfaces, by taking the effectiveness and efficiency into consideration.

Figure 2-2: Fixations visualized as circles (University of Trier)

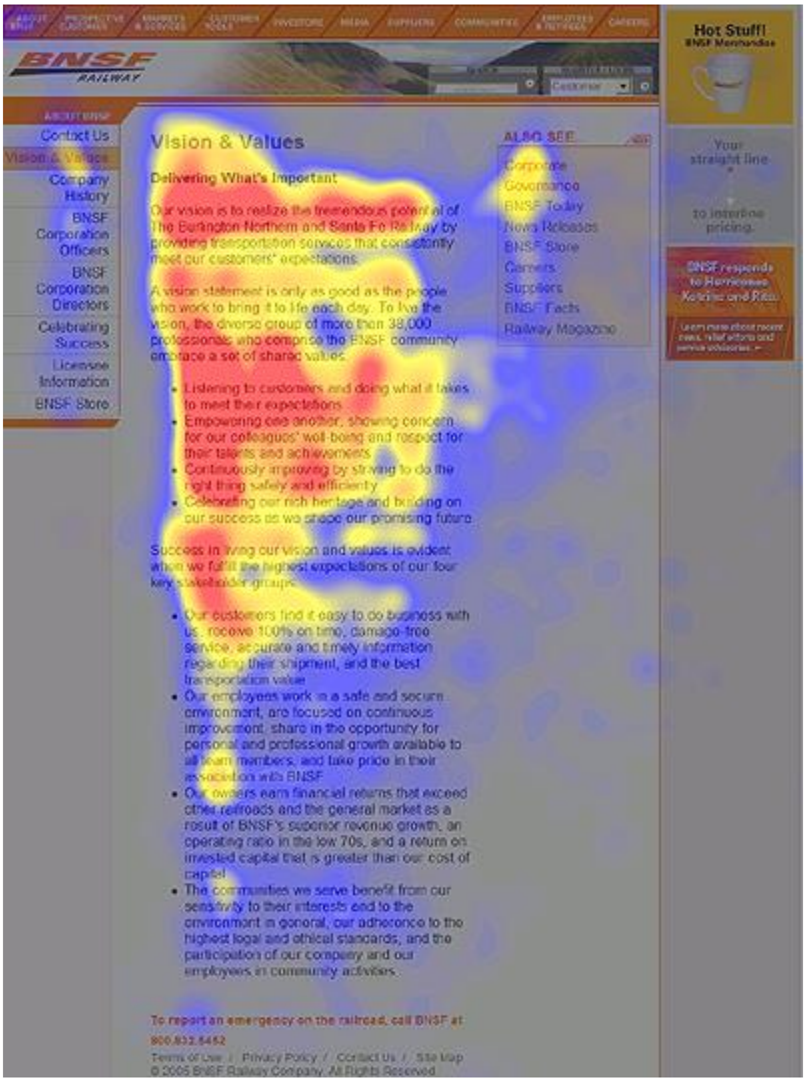

Figure 2-3: 'Heatmaps' are visualizations showing where people spent the most time looking on a web page.

2.3 Categorization of data

2.3.1 Multi-dimensional data

Fuchs and Hauser (2009) distinguish the types of complex volumetric data, depicted below:

- Multi-variate data is a general description of a type of information where each data item x is represented by an attribute vector such that x = (a1,..., an).
- Multi-dimensional data is a special case where some of the attributes are independent of each other and are related to physical dimensions such as space or time.

Whether data is multi-variate or multi-dimensional is related to its structure and the relation of data items to the physical world (Fuchs and Hauser, 2009).

2.3.2 Spatio-temporal data in GIS and cartography

Parkes and Thrift (1980) distinguish geography from geometry, because in geography, space is indivisibly coupled with time. The world that maps represent is dynamic. Many users and researchers of geographic information are interested in spatial dynamic, or changes over time in the locational and attribute components of geographic data. One goal of GIS is that they could be capable of tracing and analyzing, as well as visualizing the changes in spatial information. An atemporal GIS obscures the processes that cause states to change from one to the next, making dynamics of the modeled world challenging to analyze or understand. A temporal GIS would trace the changes of the state of a study area, storing historical and anticipated geographic states and patterns (Kucera, 1992, pp. 4-5). GIS and cartography are essential means to reveal the dynamic changes both naturally and socially, which act as a suitable environment for the identification of patterns and relations in the spatio-temporal process. Many researchers have already integrated the factor of time in GIS or maps. The spatial-temporal data is widely applied in the field of detecting the change of the natural environment, climate dynamics, historical events, land use change detection, and human geography. In the early stage, Cliff and Ord (1981) examined change through time by scanning a sequence of maps, searching for systematic autocorrelation structures in space-time in order to specify "active" and "interactive" processes. Later, more and more researchers in the field of geography put more work into time geography and GIS (e.g., Pred (1984)).

Unlike geographic data, the additional dimension of spatio-temporal data makes it different and unique in many aspects in a GIS, including information extraction, data storage, and data visualization. Many types of research (e.g., Langran (1993)) had primarily revealed that the representation of phenomena in time, as well as space, is significantly more complicated and difficult than their representation in space alone. For such database, the goal is to make the time dimension accessible to users. Clifford and Warren (1983) describe such a database as "a model of the dynamically changing world," in which data are never 'forgotten.' Based on

Blok (2000), three type of spatio-temporal data was classified according to the kind of changes occurring over time:

- Existential changes, i.e., appearance and disappearance.
- Changes of spatial properties: location, shape or/and size, orientation, altitude, height, gradient, and volume.
- Changes of thematic properties expressed through values of attributes: qualitative changes and changes in ordinal or numeric characteristics (increase and decrease).

It is essential to determine which type of spatio-temporal data to visualize, since different types require different techniques, owing to their characteristics and different information to reveal. Besides, the characteristics of the user group also has impact on which techniques to apply.

3 Data preparation for the experiment

This chapter is contains data description and the processing procedures. The data structure is firstly described. Then the content goes into details about how to process them to fit in this scenario for the later visualization.

3.1 Raw data

In this case, weather data is chosen as the topic of visualization, based on three reasons. These reasons vary from the characteristic of weather data, the visualization of climate change data, as well as the public perception of climate change, and they are explained in the following three paragraphs.

Weather data has various weather parameters, which meets the goal of visualizing multi-dimensional data. Moreover, its strong relationship with time and space makes it reasonable to visualize the data in a spatio-temporal way. These characteristics of weather data will make it natural and comprehensible for the users to view this map and to gather information. To advance the process of visualizing weather data, it is crucial to understand the difference between weather and climate. Weather is what conditions of the atmosphere are over a short period, and climate is how the atmosphere "behaves" over relatively long periods of time (Dunbar, 2015). That means, in a sufficient time scale, visualizing weather data can show the change and tendency of climate change. Meanwhile, with increasing computing power, there have been markedly rising amounts of simulation datasets of climate change. Visualization is a crucial technology for analyzing and presenting climate simulations and observations as well as related social and ecological data (Nocke et al., 2008).

The heterogeneity of climate change, including spatial, temporal, and multi-dimensional aspects require a variety of exclusive visualization methods. Climate change is a vast topic worldwide which has gained increasing interest from both scientists and decision-makers. Visualization and publicity of climate data will significantly benefit the users. Many reports, web-applications[2][3], predictions, literatures are concerning the visualization of climate change, most of which focus on usage for scientific usages, and do not offer good users' experience. In this case, one of the primary aims of building the web map application is to make it accessible to the general public, as well as to provide the possibility of successful interaction and user-experience.

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[2] http://geology.com/sea-level-rise/

[3] http://sdwebx.worldbank.org/climateportal/

Another reason for choosing climate data to visualize counts for the public perception of climate change. Climate change rather seems to be a topic which has been widely discussed and reported, than an issue that is closely related to their lives. Most of the current studies are related to the impact of climate change on human beings or ecological communities in a large scale, but neither on the concept of climate change nor on people's awareness of the fact of climate change. The outcome of this case study could also reveal statistical changes of climate as well as gain the users' perception of climate change.

Based on these aspects, weather data is chosen to be applied in the case study, which is climate data Germany from Deutscher Wetterdienst[4]. All the climate datasets are downloaded from the DWD Climate Data Center (CDC)[5.] The server provides the climate data at hourly, daily, monthly, annual or multi-annual resolution, depending on the specific weather parameter. Many parameters are available on the server, e.g., air temperature, soil temperature, precipitation, humidity, pressure, visibility, solar irradiance, sunshine duration, cloud cover, wind speed and direction. All the datasets have various resolutions. Over 400 climate stations have been contributing the data to generate and zip the datasets. The major datasets from the server are gridded fields, which are in raster format and have different resolutions for different periods of time. Records from near-surface weather stations are the foundation of climate research (Peterson and Vose, 1997).

3.1.1 Selected climate parameters

There is no need to visualize or proceed all the datasets that are offered, considering the aim the research and the capability of a web application. When selecting the proper datasets to visualize, there are a few aspects to consider, including which climate parameter, which resolution and which time periods are most relevant. Two characteristics of the datasets are taken into consideration. First, is the data interesting or understandable to the users? That the general public might not be familiar with the climate parameters mentioned above must be taken into account. Second, has this climate parameter significantly changed during a particular period? This aims at revealing the facts of climate change and enhancing the users' perception.

Based on the first aspect, temperature and precipitation very common to people's everyday life. Thus, the climate parameter "Temperature" and "Precipitation" are chosen. By talking with some of the participants who lived in Germany for a long time, it was found that the significant changes of snow cover days in winter has drawn their attention. For the typical and significant

[4] © Deutscher Wetterdienst. Link: https://www.dwd.de/EN/Home/home_node.html.

[5] ftp://ftp-cdc.dwd.de/pub/CDC/

climate changes in Germany, the following aspects and literature are taken as criteria to choose the parameters. Extreme heat events, such as heat days (T > 30ºC) or heat waves (intervals of more than three days during which the maximum daily temperature lies above a certain high threshold, relative to the specific temperature standard of the weather station) exhibit a definite trend (Schröter et al., 2005). The number of ice days (maximum temperature < 0 °C), however, has not changed significantly (Becker et al., 2012). The probability of occurrence of heat days in July and August has risen over the last one hundred years, and especially markedly over the previous twenty years at almost all weather stations in Germany (Schröter et al., 2005). During 1900-2000, yearly average precipitation rates increased by 9%. During this period, precipitation decreased slightly in the summer (by 3%). During spring, autumn and winter precipitation increased by 13%, 9%, and 19%, respectively (Schröter et al., 2005). Based on these findings, the parameters temperature, precipitation, temperature in July, ice days, snow cover days, and precipitation in winter are chosen for visualization.

3.1.2 Structure of the datasets

Except for the temperature datasets in July, which are monthly-averaged data, and precipitation datasets, which are seasonally-averaged data, the rest of the data is annul-averaged.

All of the raw datasets are in the format ESRI-ASCII-grid. The spatial reference is 3-degree Gauss-Kruger zone 3, Ellipsoid Bessel, Datum Potsdam (central point Rauenberg), EPSG:31467. It contains a table of 654 x 866 numbers. Each row goes from West to East. The first row is the northernmost one (654 values with four digits). Missing values are marked with -999[6]. All the definitions of the climate parameters, as well as their temporal coverage, are shown in Table 3-1.

Table 3-1: Chosen climate parameters, their definitions, and the temporal coverages[6]

Climate parameter	Definition	Temporal coverage(year)
Temperature	The annual mean of the monthly averaged means daily air temperature in 2-meter height above ground.	1881 - 2016

[6] The description of each dataset is presented alone under the its folder on the ftp server. Here is the link to the introduction to annual air temperature mean: ftp://ftp-cdc.dwd.de/pub/CDC/grids_germany/annual/air_temperature_mean/DESCRIPTION_gridsgermany_annual_air_temperature_mean_en.pdf

Precipitation	The annual sum of monthly total precipitation given in millimeter.	1881 - 2016
Ice days	The number of days of ice days. Definition of ice day: maximum air temperature < 0°C.	1951 - 2016
Snow cover days	The number of days with snow cover. Definition of snow cover: snow depth >= 1 cm at morning reading (nowadays 7 UTC).	1951 - 2016
Hot days	The number of days of hot days. Definition of the hot day: maximum air temperature ≥ 30°C.	1951 - 2017
Temperature in July	Mean of the monthly averaged mean daily air temperature in 2-meter height above ground,	1881 - 2017
Precipitation in winter	The seasonal sum of total precipitation given in millimeter.	1882 - 2017

Uncertainties are caused by the interpolation method and erroneous or missing observations. When comparing grid fields for different years, it should be considered that the measurement network has changed over time.

The spatial resolution of all the datasets is 1km*1km, and temporal resolution is one year. That means that each data including the average data in a year of a specific climate parameter.

The grids are based on the DWD station data (Kaspar et al., 2013), which are interpolated in space with the gridding method described below. For each month, the gridding routines were applied to the monthly means. The monthly means were derived from the respective daily means of the stations. In 2008, the grids were calculated back to 1881 with quality-controlled station data which were digitized by 2008. Since 2008, the grids are extended monthly. The gridding method is based on height regression and Inverse Distance Weight (IDW): The station density allows for a linear regression between topographic height and climatological parameters within a region and varies somewhat between the regions in Germany (Maier and Müller-Westermeier, 2010).The regression coefficients were determined separately for each month, based on the monthly means recorded 1951-1980. By using these interpolated regression coefficients, the station values are reduced to the reference height and attributed to the grid cells. In case several stations refer to a grid cell, the mean was taken. In a second step, the values at reference height were interpolated horizontally to cover the grid (weighted with the inverse square distance). Finally, in a third step, the values at reference height are transformed to values corresponding to the topographic elevation using again the spatially variable regression function. This is done with the DWD digital topographic height model. When grid cells contain a station, the value of the latter merely is interpolated vertically to the height of the grid cell[7].

3.2 Data retrieving and processing

Two forms of temporal data as proposed by Langran (1993) are event and data of the current state. In this case, data of the current state will be used.

The generalization of the data regarding time resolution is crucial in this study. Langran (1993) proposed two occasions:

- Create a time slice by identifying the states of all data in an area as of the given moment. Generalize the time slice to the desired spatial resolution.
- Create a time slice that is a generalization of a timespan, i.e., generalize to a desired temporal resolution. Then generalize to the desired spatial resolution.

The method applied to the datasets in this study falls into the second case, which is the generalization of a timespan. The reason lies in the collection method of the data and the users' perception.

3.2.1 Data retrieving

Owing to the fact that a vast number of datasets to be downloaded and stored, an automatic retrieving procedure is conducted with Python code. To gain access to the datasets on the FTP server, the package ftp/ftplib is applied.

Few Python packages are used in this process, and the major ones are shown in Table 3-2.

Table 3-2: The major Python packages that are used in the process of data retrieving

Python package	The function used in this case
FTP/ftplib	Login to the FTP server, download data from the server.
gzip	Unzip each dataset and write them into a new file.
folders	Check the existence of a folder and create new ones.

[7] This part of the description applies for all the datasets. Here is one of the description files: ftp://ftp-cdc.dwd.de/pub/CDC/grids_germany/monthly/air_temperature_mean/DESCRIPTION_gridsgermany_monthly_air_temperature_mean_en.pdf

The downloaded datasets are in the format of .gz, which will have the format of ESRI-ASCII-grid-format with the extension of .asc after being unzipped. These data can be processed directly by Esri desktop software. Based on the description of Esri: A grid is a raster data storage format native to Esri. There are two types of grids: integer and floating point. Integer grids are used to represent discrete data and floating-point grids to represent continuous data[8]. The grids of the datasets are integer grids, where one grid stands for a square of 1km×1km on the ground, while one dataset stands for the average data of one year.

3.2.2 Data processing and analyzing

For the major parts of the data processing, tools provided by ArcGIS Pro are applied. However, none of these procedures are executed in the ArcGIS Pro desktop. Instead, they are programmed in Python with the help of ArcPy, which has access to all the available tools in ArcGIS Pro. This approach minimizes the repetitive process for the datasets. Considering the number of datasets, this saves time and simplifies the procedure. All Python packages applied in this procedure are listed in Table 3-3.

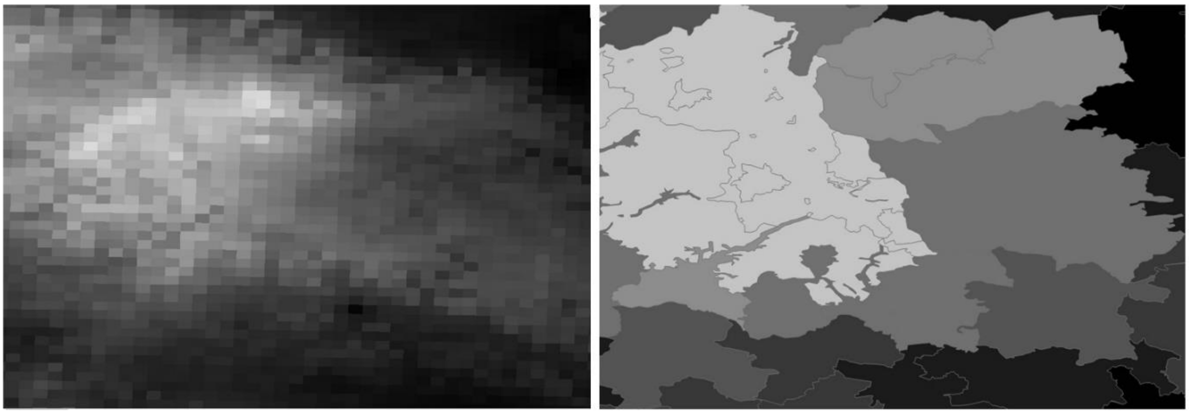
Table 3-3: The major Python packages used in data processing and analyzing

Python package	The function used in this case
arcpy	Geographic data editing and analysis, e.g., spatial join, zonal statistics, define projection. Managing the geographic files, e.g., create a new file, copy and paste the file.
pandas	Datasets organizing, data summarizing.
Matplotlib/pyplot	Data visualization.
dbf	Table storage and editing.

When imported into ArcGIS Pro, raster datasets do not have a geographic reference. The projection, as pointed out in the data description, is 3-degree Gauss-Kruger zone 3, Ellipsoid Bessel, Datum Potsdam (central point Rauenberg), EPSG:31467. The tool of Define Projection in ArcGIS Pro was applied to assign the raster datasets with a geographic reference.

[8] http://desktop.arcgis.com/en/arcmap/10.3/manage-data/raster-and-images/esri-grid-format.htm

The resolution of the raster datasets is 1km×1km, which makes the visualization of them quite slow in ArcGIS Pro. Considering the abilities of the web browser and the internet speed, it would also take quite a long time to load the amount of data and to render it on the monitor. In this case, generalization is needed. Raster data generalization is the process of enlarging and resampling cells in a raster format("GIS Dictionary: generalization,"). Concerning geographic data generalization, Peter and Weibel (1999) point out three elements to consider in a generalization process, where the first element concerns the specification of so-called generalization constraints. This refers to, conditions of geometric, topological, semantic, and Gestalt nature, which govern the process of categorical map generalization. For the purpose of presenting the map in the way that is relatable to the map readers' knowledge of the study area, the datasets are generalized based on administrative boundaries. In this case, a vector file that contains the geographic information in the level of the administrative region of the county, referred to as Landkreis in German. The vector file was accessed from Open Data and Services from Bundesamt für Kartographie und Geodäsie.
The administrative levels are nationwide and based on the governmental administrative district level. The applicable scale of the vector data is 1: 250,000. The generalization is the process that the vector polygons would take the place of the raster grids, where the vector polygon obtains a new value filling in a new field, which is the average of all the girds inside and on the border of the polygon. This procedure could be executed by the tool called Zonal Statistic in ArcGIS Pro. One part of the study area is shown in Figure 3-1, demonstrating the process of generalization.



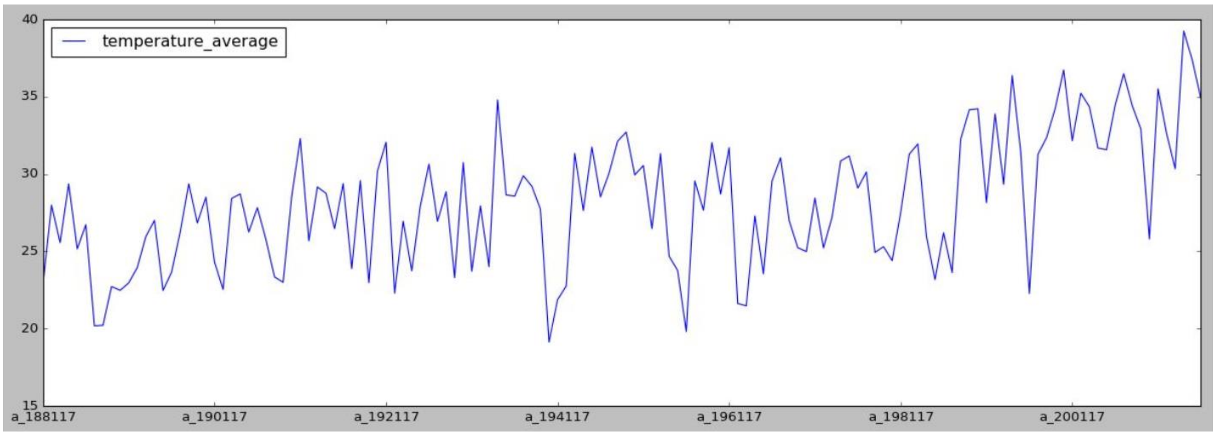
(a)The original raster grids. The colors are decided by the value of the grid, are also stretched.

(b) The generalized vector dataset of this region. The colors are decided by the values of the polygons, classified by natural breaks.

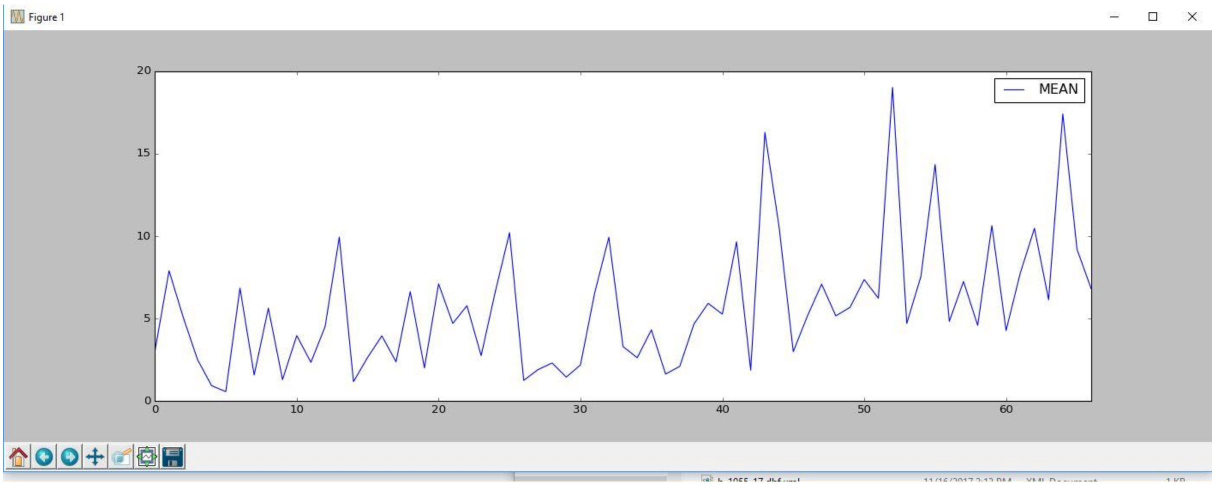
Figure 3-1: The original raster dataset and the generalized data. Visualized in ArcGIS Pro. both depicting the precipitation of 1881 in a part of the study area.

At the same time, another scale of generalization is also performed. The difference lies inthe shapefile that is used for generalization, which is a polygonal vector of Germany. All the raster girds in one raster file will be generalized into one polygon, with only one value calculated from all the points of one dataset. This procedure aims at collecting the average weather data in a year of Germany, whose results are used in rendering a chart demonstrating the change of one climate parameter, as well as giving an overview or insight to the users. Meanwhile, before designing the map, these datasets are also used to examine the data, to check if the trend of the climate parameter worth visualizing.

After being generalized, each dataset will generate a table with the extension of .dbf, which includes the attributes of the original vector file. Each climate parameter contains many raster datasets. The Merge function is applied here to join all the tables into one table. The entries in the table are the attributes of the vector geometries, which can be joined together to complete the vector file. At last, all the generalized values of one climate parameter are stored in one single vector file, where each field represents the average weather data for one year. Few of the raw plots of the weather data are shown in Figure 3-2. These plots are not visible to the users.



(a) The average temperature from 1881 to 2017. The unit of the y-axis is Celsius.



(b) The average number of hot days from 1951 to 2017.

Figure 3-2: Plots of the average weather data in Germany during the available timescale.

The workflow of the procedures is shown in Figure 3-3. This is the standard workflow of datasets that belongs to one climate parameter; datasets of different climate parameters are processed separately.

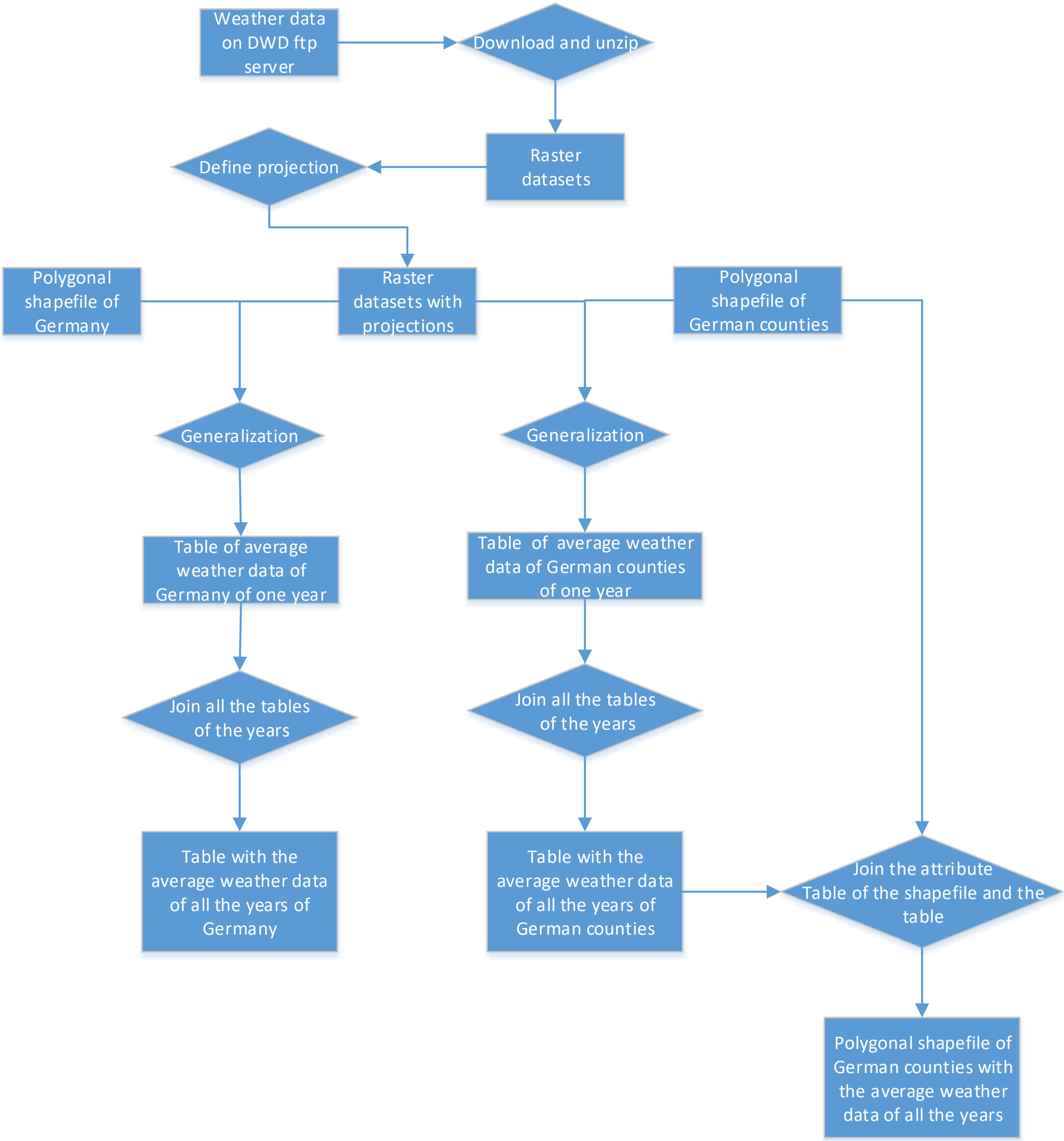


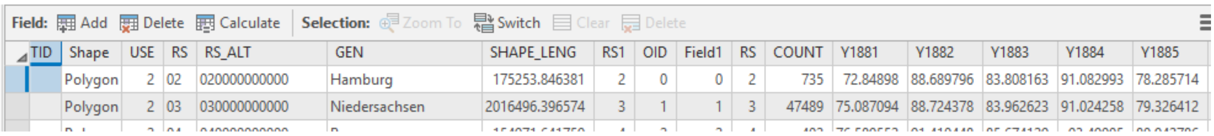
Figure 3-3: Workflow of data processing

3.2.3 Data storage

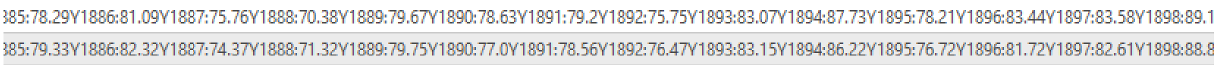
When trying to find a way to better store the temporal data, few options in ArcGIS Pro were found. The methods of data storage also affect the visualizing quality and possibilities of the current visualization tools, which are discussed in section 4.4. Few examples in Figure 3-4 demonstrate the three different methods of saving temporal data.

- Feature with years of weather data saving in separate fields, as shown in (a).

- Feature with years of weather data saving in one field, as shown in (b).
- Feature with years weather data saving in one field, where rows separate the years, with one more field for saving the date, as shown in (c).



(a) Data of years in separate fields.



(b) Data of years in one field.

(c) Data of years in separate rows.

Figure 3-4: Examples of how the temporal data are saved in a shapefile, visualized in ArcGIS Pro.

The three storage methods are all experimented. From what we have experienced, there are few properties for each method. The first is relatively easy to understand for the database designer or the users, while it could be time-consuming to retrieve data from field to field when few APIs or software are used. The second requires distinctive separation between one year of data to the next, which needs more time to program this format. Depending on the efficiency of the code in the retrieving programming language, this might take slightly less time to retrieve data than the first method. The third method is an Esri-recommended method to store spatio-temporal data. Data that is stored in this way can be easily visualized as temporal data with a time slider in ArcGIS Pro. The feature layer whose attributes are organized in this way can also be visualized without further programming in the Web App Builder for ArcGIS (Developer Edition). This method is not useful in this application because all of the data entries in one field have to be used when rendering a layer.

All the outputs are saved in the format of shapefile, which was handled as a feature layer in the ArcGIS API for JavaScript. For the purpose of giving the ArcGIS API for JavaScript access to the feature layers, the feature layers are uploaded to ArcGIS Online.

4 Methodology and case study

This chapter goes into details of the methods adopted in this study, which are based on the state of art in chapter two. The chosen software and tools for processing the datasets as well as visualizing them are depicted here. Then the visualization form for the multi-dimensional spatio-temporal data is stated along with the technical descriptions of how the presentations are achieved. The last part is the map evaluation, where the goals and the methodologies are suggested based on the related work, including the detailed evaluation procedure and task design. Since the methods adopted during the entire process depend on the datasets chosen in the study, the methodologies and how they are applied in the case are demonstrated in parallel.

4.1 Software and applied APIs

Today, several commercial desktop GIS software systems dominate the geographical information (GI) industry, while the emergence of web GIS and cartography add to the complexity. It is unlikely that all GIS applications will use the same software (Tarnoff 1998). Different software designs, data models, and database storage structures exist in these software; thus, geographical databases based on these designs cannot communicate without data conversion. Conversion tools must be developed to transfer data from one format to another in order to exchange information and share computational geo-database resources among heterogeneous systems. Two problems arise in sharing heterogeneous spatial data through data conversion: (1) Data becomes inaccurate after data conversion. This is an essential issue for time-critical applications because accurate and up-to-date information is a basic and essential requirement. Inaccurate information after data conversion may lead to poor decisions and time-critical applications usually cannot correct the poor decisions. (2) Time is wasted on data conversion. Time and money must be allocated to develop the data conversion tools (Zhang and Li, 2005). Thus, it is the best case to find software or a tool that allows easier and lossless conversion among the data types with the help of programming languages.

Esri products and Python

In order to proceed to the datasets, software, API, and the programming language need to be chosen. Due to the vast number of datasets, together with their characteristics of space and time, compact and robust GIS software is crucial. There are many commercial and open-source GIS software options currently available. The primary products include ArcGIS, QGIS, GRASS GIS, SuperGIS, SAGA GIS, JUMP GIS, etc. Each of them has its own analyzing abilities and specializes in specific aspects of visualization. In the study, the ability to process large numbers of datasets is necessary, which also needs to be fast-to-use and stable. At the same, the various and strong possibilities of visualization are also important. After taking a more in-depth and detailed look into many of the software mentioned before, ArcGIS Pro provided by Esri is chosen to be the processing software. Esri's ArcGIS platform includes many integrated components, such as desktop applications, databases, image and web services, cloud applications, and data along with mobile and web applications. ArcGIS Pro is Esri's latest addition to the existing GIS platform (Tripp Corbin, 2015, p. ix). The geographical analysis and procedure including define projection, spatial join, etc., are all processed by ArcGIS and its Python API, ArcPy. ArcGIS Pro has powerful analyzing abilities for geographical information, and it offers abundant ready-to-use functionalities, which can give a compact and complete processing workflow for data-processing in this case.

ArcPy is a Python site package that provides a useful and productive way to perform geographic data analysis, data conversion, data management, and map automation with Python[9]. All the analyzing tools that ArcGIS Pro offers can be converted into Python code, with the help of their description in the tool reference documentation[10]. This allows all the geographic procedures to be done quickly, by the preference of the order and combination of all the tools.

Another critical reason why ArcGIS Pro is chosen is that it provides various visualization tools and methods, both web-based or desktop-based. In this case, the online visualization services are used. The reason why this is important was discussed in the first paragraph of this part. The usage of Esri products reduces the time and complexity of data conversion, as well as data storage and transport. Programming in Python also allows automatic downloading and other non-geographic analysis, also with the help of other Python packages. The version of Python is 3.5.3. Python is developed under an open-source license and is relatively easy to pick up[11]. The Python Package Index (PyPI) hosts thousands of third-party modules for Python. Both Python's standard library and the community-contributed modules allow for more possibilities. The powerful and massive number of available packages from Python makes it simple and easy to process the data in all the aspects without programming from a very low level. The used packages include pandas[12], matplotlib.pyplot[13], etc..

HTML and Javascript

To visualize the processed data online, HTML and JavaScript are applied. JavaScript is an interpreted programming language with object-oriented capabilities, which is most commonly

[9] http://pro.arcgis.com/en/pro-app/arcpy/get-started/what-is-arcpy-.htm
[10] https://pro.arcgis.com/en/pro-app/tool-reference/main/arcgis-pro-tool-reference.htm
[11] https://www.python.org/
[12] https://pandas.pydata.org/
[13] https://matplotlib.org/api/_as_gen/matplotlib.pyplot.plot.html

used in web browsers. In this context, the general purpose core is extended with objects that allow scripts to interact with the user, control the web browser, and alter the document content that appears within the web browser window (Flanagan, 2006, p. 1). With the help of the ArcGIS API for JavaScript, it is quite easy and practical to visualize maps online, along with many pre-defined features as well as the freedom to design the web application as needed. It is designed to maximize users' productivity by building engaging, web mapping applications. The API combines modern web technology and powerful geospatial capabilities enabling the users to create high-performing apps and smarter visualizations of the data[14].

Hypertext Markup Language (HTML) is the standard markup language for creating web pages and web applications. With Cascading Style Sheets (CSS) and JavaScript, it forms a triad of cornerstone technologies for the World Wide Web (HTML,2018, in Wikipedia).

Part of the web page design was based on Materialize. Materialize is a responsive front-end framework. The framework was designed based on Material Design by Google. Material Design is a design language that combines the classic principles of successful design along with innovation and technology. Google's goal is to develop a system of design that allows for unified user experience across all their products on any platform[15].

4.2 Web-map application building

Before selecting how to represent spatiotemporal data, one must examine carefully what is to be presented. 'Temporal' is a loose term that embraces progression of states, recording of events and description of timespans. It is possible to take a valid spatiotemporal data structure and implement it in a way that does not describe the desired information (Langran, 1993).

The overall goal of the study is to represent stored spatio-temporal data in a way that conforms both to human conceptualizations of the world in space-time and geographic theory and to statistical demands for accuracy and flexibility in visual presentation. As for the aspect of human conceptualization, the animated map is used. Owing to the research that is mentioned showing the users' interest in animation in terms of the spatio-temporal map. the details of the implementation of the animated map are presented below. The characteristics of the datasets should also be taken into consideration. Since climate data is used in this study, the widely-used and suitable visualization methods for climate data should be referenced. In many cases, the multi-dimensional properties of climate data are of interest, typically in combination with spatial and/or temporal reference of the data.

[14] https://developers.arcgis.com/javascript/3/
[15] More information about Materialize and Material Design: http://materializecss.com/about.html

Map and charts are the major parts of the web map application. To build the map visualization as needed, including the map animation, there are few technical hurdles to overcome. Besides, the design of the web map application is also fundamental, in terms of making the map easy to use, as well as meeting the demands of map evaluation described in the later chapter.

Both static map and the animated map are presented in one area. The map contains two parts, one is the base map provided by Esri, and the other part is the visualization of the feature layer. ArcGIS API for JavaScript 3.23 was applied for the visualization process of the map. There are two major versions of JavaScript APIs that Esri provided. Based on the capabilities of each API[16], and the focus of visualizing data in a 2-dimension, the version of 3.23 is chosen. When using this API, users have access to the ArcGIS Online contents, based on particular restrictions of using. It also offers a lot of visualization methods and possibilities, which are quite flexible and adaptive to the web browser. Table 4-1 listed the major classes from ArcGIS API for JavaScript 3.23 and other APIs that are applied, as well as how they are used.

Table 4-1: Major classes from the APIs to build the web map.

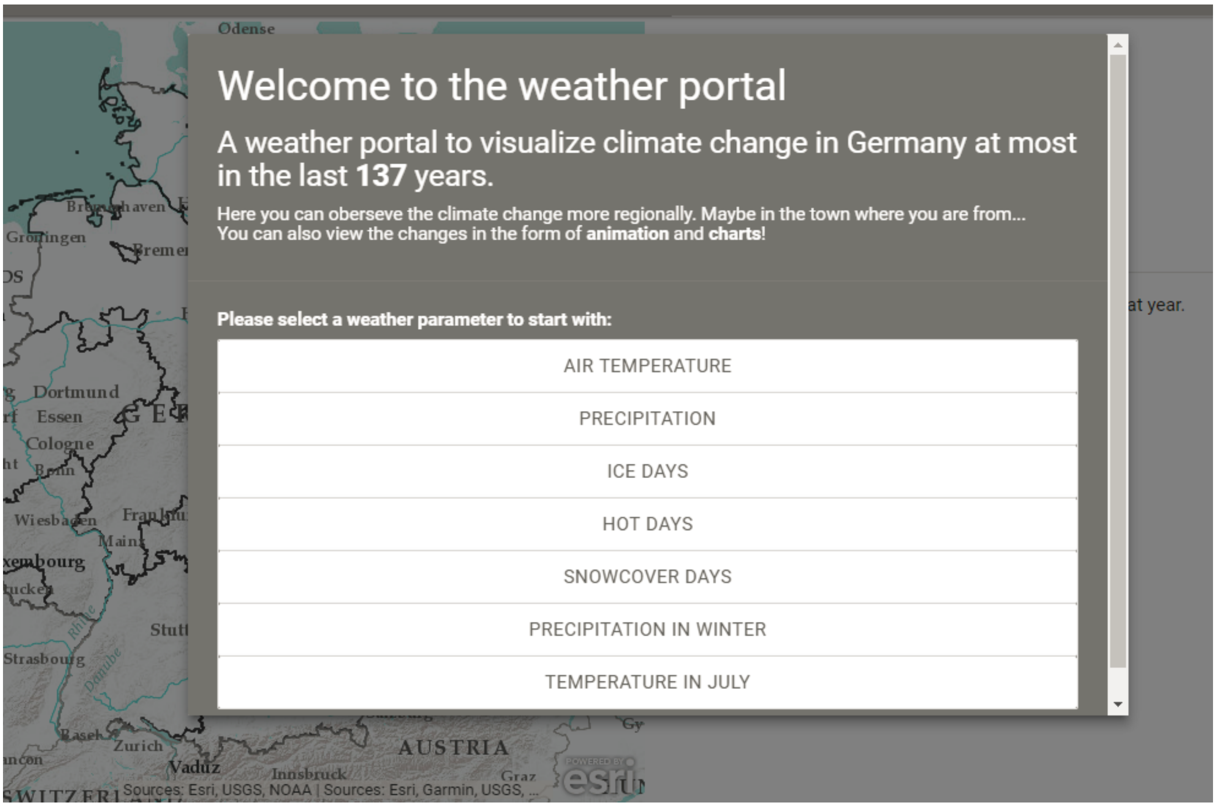
API	Classes	Methods and utilities in this case
ArcGIS API for JavaScript 3.23	esri/layers/FeatureLayer	Add the layers to the map, manage the layers to the map and set the renderer to the layer.
	esri/map	Set the map of the web application, including size and position. It is also the container for the feature layers.
	esri/renderers/SimpleRenderer	A major tool to visualize the feature layers. Set the symbology to the layer.
	esri/graphic	Create temporal geometry that includes the attributes, used for effect when hovering over one geometry.
	esri/dijit/Legend	Create and edit the legend of the map.
	esri/dijit/Search	Create Search widget.

[16] Choices between 3.23 and 4.6: https://developers.arcgis.com/javascript/latest/guide/choose-version/index.html

	esri/dijit/Basemap	Offer base maps of the map.
dijit	dijit/popup	Set the pop-up window for the geometries in the feature.

Base map “terrain” is used as the background of all target-visualized feature layers, along with feature layers that includes all the polygons of the federal states, whose polygons are all set without color and only the outlines are left. The background serves as the primary geographic information to the users in the map. The feature layer that contains the weather data is loaded as the preference of the users, while only one climate parameter can be observed at a time. All the available feature layers can be clicked and visualized at any time. A feature layer is loaded every time when the users trigger the alteration of the climate parameter, while the current layer will be deleted from the map container. The maximum and minimum scale of the map that can be zoomed in /out to is set in the code. The maximum scale was set based on the average size of the counties, since the resolution of the polygon features is county, while the minimum scale of the map is based on the extent of Germany.

As for the multi-dimensional part, there isn’t any sophisticated technique adopted. The various dimensions that the datasets have are entirely independent of one another, or the relations among the dimensions is not the primary goal of this study. Instead, the focus is concentrated on the relation, trend and changeability of one dimension over time. In this case, the different weather parameters stand for the multi-dimensions, which can be chosen on the top of the application, as well as a window when the first load in the application. This is shown in Figure 4-1.



(a) The starting window when firstly load into the application, showing the parameters to choose from.

(b) The parameter tabs on the top of the application, which can be clicked throughout the whole process of browsing.

Figure 4-1: the multi-dimensional approach of this web map application.

The design and process of visualization of in terms of spatio-temporal approach needed functionalities, are described in detail as below.

4.2.1 Animated map

Interactive forms of cartographic animation have existed for many years. The world wide web, now the primary form of distribution for cartographic animations, provides a number of tools for distributing interactive animations. These tools will likely play a significant role in the development of cartographic animation with the increased importance of the Web as a means of map distribution. In the future, most of the maps on the Web may actually be composed of multiple maps that can be viewed interactively as an animation (Peterson, 1999).

The animation technique adopted in this study foris based on the nine metaphors that Gersmehl (1990) proposed, where “Slideshow” was chosen. The animation consists of sequences of the static map, where the change from one map to the next based on specific speed.

Map animation is present in almost all geovisualization packages that deal with spatio-temporal data. Since JavaScript is applied and few of its APIs to build the animation, the method window.requestAnimationFrame() was mainly used. The major functions are listed below, along with the essential code. Andrienko et al. (2003) list five animation parameters to be considered when designing an animated map:

- Speed.
- Direction: backward or forwards.
- Extent.
- Moment/ intervals to include in animation
- Smoothness (creation of intermediate frames by means of interpolation).

In this case, the parameters of speed and direction can be directly set using the method window.requestAnimationFrame(), by setting the parameter in the method settimeout(), which is as shown below. The smoothness is not dealt with in this case. The speed for changing from on static map to the next is rather fast, which would make a relatively smooth animation in this time scale. The related code is shown below:

```
setTimeout(function () {
        if (!animating) {
          return;
        }

        value += direction; //set the direction as moving forward
        if (value > end) {
          value = start;
          direction = -direction;
        } else if (value < start) {
          value = start;
          direction = -direction;
        }

        setGapYear(value); //change the map display
        requestAnimationFrame(frame);
      }, 100);//set the change speed of two maps in a row as 100ms
```

Under the map container, there is a time slider with a play/pause button, allowing users to choose the year of the climate parameter and view an animation. When changing the year from one to another, the layer sets the field that the renderer is based on from one to another, where the function setRenderer() is used. To enable the animation, the function windows.requestAnimationFrame() is applied. The window.requestAnimationFrame() method tells the browser that one wishes to perform an animation and requests that the browser call a specified function to update an animation before the next repaint. The method takes a callback as an argument to be invoked before the repaint[17]. The method setRenderer() is the major functionality of the called function to apply the animation. The windows.setTimeout() method is applied to set the speed of the animation. It calls a function or evaluates an expression after a specified number of milliseconds[18]. However, it was found that owing to the internet speed, the ability of the monitor, and the scale of the map, when the same parameters for the functions above are inserted, the animation speeds still vary. In general, the animation speed is faster when either the map is zoomed into a bigger scale, when a monitor that performs better is being used, or when the internet is faster. When zooming the map or clicking a county in the map as the animation is playing, the animation will pause.

Harrower (2007) summarized that interactivity makes the animated map more engaging by requiring the user to do something other than passively watching a pre-defined sequence of content.

4.2.2 Chart

In most cases, climate change visualization is a type of visualization concerning both temporal and spatial dynamics. Some of the climate change visualization results or methods can also be adopted or referenced in this study. Many researchers in the field of climate simulation visualization have tried and summarized many tools and techniques. An interview conducted by Nocke et al. (2008) gains an overview of the requirements in the heterogeneous field of climate and climate impact research. It shows that standard 2D presentation techniques are most frequently used, where 90% researchers prefer time charts, 77% bar charts, 66% 2D maps, 56% scatterplots, and 2.5D and 3D visualization techniques are of minor importance only. At the same time, visualization technique features related to the (spatial) reference of the data are of high importance.

Most frequently, climate data is visualized in their temporal reference to identify temporal trends directly using time charts. As for the integration with the chart, Chart.js[19] was applied. The data to form the chats are either gained from the presenting shapefile or from the local

[17] https://developer.mozilla.org/en-US/docs/Web/API/window/requestAnimationFrame
[18] https://www.w3schools.com/jsref/met_win_settimeout.asp
[19] http://www.chartjs.org

table. Meanwhile, the chart is responsive to the map. Changing the map may affect the chart, and the events triggered in the chart also might change the map. When a layer is loaded, the average weather data of this climate parameter of Germany throughout the available time range will be drawn in the chart, along with the average weather data of Germany drawn in the same chart. The items in the legend for the chart are clickable, for deactivating or activating the weather data plots in two scales.

4.2.3 Functionalities

In this web map application, the scale the biggest scale can be zoomed in was decided by the average size of one county.

Query and Selection

Querying presumes that a software program is capable of answering users' questions concerning data under analysis (Andrienko et al., 2003). This also applied in a web map application. Andrienko et al. (2003) also pointed out two principals of how the query functionalities are going to fulfill the need of the users: (1) to provide the requested information in addition to what is already present on the screen; (2) to remove from the user's view the data that do not satisfy the query constraints. The former type of querying may be called ''lookup'' and the latter ''filtering''.

In the map container, there are also locate and home button, as well as a search box, and legend when a layer is loaded. As for the interactivities of the map, users can hover over the counties, then the information of this county and the weather data for the viewing year are presented in the pop-up window. At the same time, the polygon will be highlighted, which is also clickable. When a county is clicked, the chart will change accordingly, to the weather data that belong to the clicked county will be drawn in the chart.

4.2.4 User-interface design

Materialize, a CSS Framework based on material design is used for editing style of the map. One of the goals of the map evaluation is to test how they allocate they eyes in the static map, the animated map, and the chart. To ensure the users focus on the parts of the map to be evaluated, the other parts of the web application should not be prominent. Otherwise, the auxiliary parts will take up unnecessary gaze time of the users. As a result, the style of the other parts besides the map and chart must be understandable and straightforward. In Figure 4-1, the auxiliary parts of the web map application are highlighted with red frames.

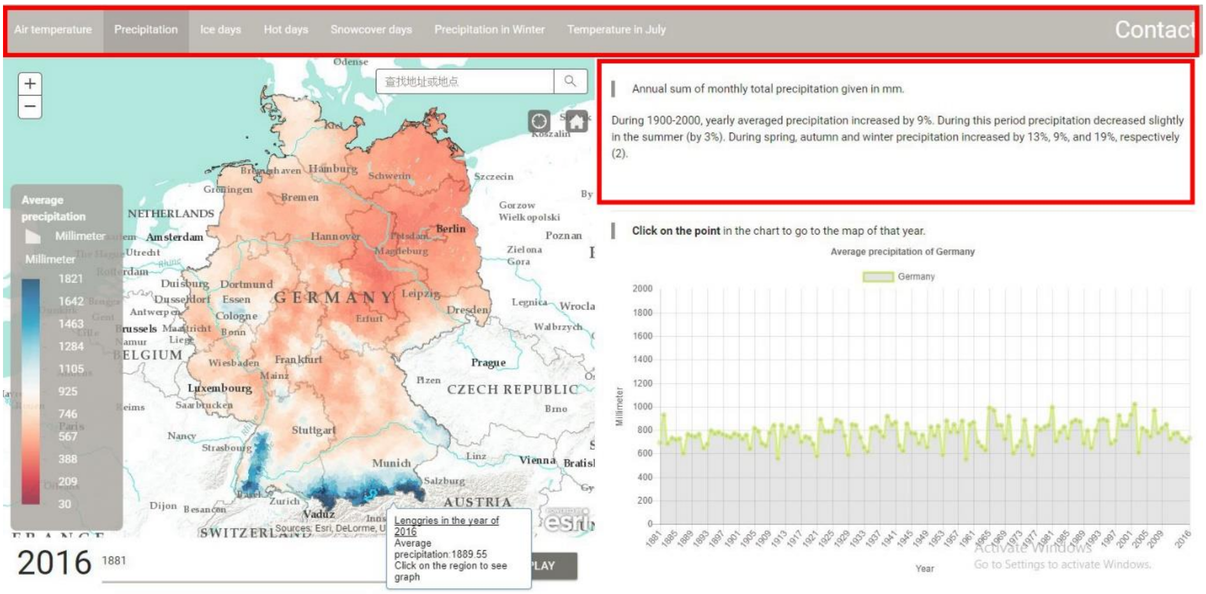


Figure 4-2: The finished web-application, where the supporting parts of the map are highlighted.

People tend to focus in the center of a screen. Thus, when trying to collect which parts interest them when they are viewing the map, the two major parts should be at similar positions. Map container takes up the left half of the application, while the chart takes up the right half of the map. The text which includes the explanatory information of the climate parameters and description takes up the part above the chats.

5 Map evaluation

The chapter is the map evaluation, where the goals and the methodologies are suggested based on the related work, including the detailed evaluation procedure and tasks design.

After designing the map, it is crucial to test if this combination, as well as the forms of visualization help users better perceive information.

The utility of the map is mainly evaluated, as well as the viewing behavior of the participants during different tasks. With the general goal, it could be testes which types of information and knowledge that each form of visualization generates. Concerning multi-dimensional spatio-temporal data visualization, chart and animated map are mainly adopted. Thus, map animation and chart in this map application are primarily evaluated, which means that the design of the evaluation procedure will be based on these two forms.

When talking about animated map, people always ask the question as: Are animated graphics better than static graphics? There is no surprise that the answers to these questions are always: “it depends.” In this case, the question is asked, when designing the evaluation procedure, is animated map better than static map? Or is animated map better than chart? This seems quite straightforward as a goal to set, while the answer will still be “it depends”. These are merely different map forms and visualizations and vary in many aspects. As Edsall et al. (1997) and Fabrikant and Goldsberry (2005) point out, the challenge is to understand how animation is different and for what kinds of data, users, and map-reading tasks it is especially effective. As a consequence, the utility of the map will be mainly tested, as well as the usage of each component, and if these forms of visualization are suitable for the data in this case.

In this study, the eye-tracking technique is applied. Nielsen and Pernice (2009) propose the “mind-eye hypothesis”, which indicates that people tend to look at things that they are thinking about. This technology has been used in many map evaluations. The use of eye tracking as an empirical research approach and the analysis of eye movement patterns captured during map reading process has been already discussed in the context of cartographic visualization (Steinke, 1987). This technology adds a powerful dimension to user research because it allows you to understand exactly what users see--and what they don't see (Nielsen and Pernice, 2009). The possibility of showing where the users’ eyes are focusing in a very small temporal resolution makes it a robust tool to get the tendency and habits of the map-readers, which also gives map-designer insights direct and detailed information about the performance of the current map and to benefit further design.

5.1 Evaluation goals

The goals and questions of the evaluation are shown as below:

- How do people allocate their eyes when they are viewing this multi-component map? Is there any difference when viewing without any tasks and viewing with tasks?
- Concerning the various parts of the map, which kind of information is generated by different parts of the map? Does the implementation of map animation or chart help the performance of the map?
- When users have tasks, how do the different viewing strategies influence their effectiveness and efficiency?

Eye-movement results, in this case, are collected to answer these questions. The most important results to obtain to meet the goals is the gaze duration of each part of the map.

5.2 Material and participants

The experiments were done in the Eye-tracking Lab located in Technische Universität München.

The eye-tracking device is provided by Gazepoint Analysis. Gazepoint Analysis provides a system for collecting and analyzing eye-gaze data. Gazepoint Analysis Standard Edition was used in this study, and it includes free with the GP3 eye-tracker and allows for basic screen capture with gaze overlay and heat map visualization as well as raw data export. Two software are applied for the experiment, and they are Gazepoint Analysis and Gazepoint Control. Gazepoint Analysis receives eye tracker data from Gazepoint Control. Gazepoint Control needs to run in conjunction with Gazepoint Analysis when collecting eye-tracking data. There are two modes of operation for Gazepoint Analysis, Collect Data mode and Analyze Data mode, the former one of which is to collect data when the participant is viewing the map, and the latter of which generated the gaze results. The map application is presented in Chrome.

24 participants have taken part in the evaluations. 11 participants are male, and 13 participants are female. The ages of the participants range from 20 to 30. 17 participants are currently studying Cartography, while the majors or jobs of the rest participants are informatics, economy, mechanic, and tourism. The nationalities of the participants vary, few of them are from Asia, including China Japan, Malaysia, and Kazakhstan, while the most of them are from Europe, including Germany and the UK, Greece, Spain and other European counties, and 1 participant is from the USA and 1 from Mexico. All the participants are very fluent in English, both speaking and reading.

The experiments were done in two monitors, operated on Windows 10 operating system.

The different parts in the map were assessed by the area where they located the map. However, map animation and static map took over the same area in the pre-set. Figure 5-1 shows the starting page when a user opens the application and starts the evaluation.

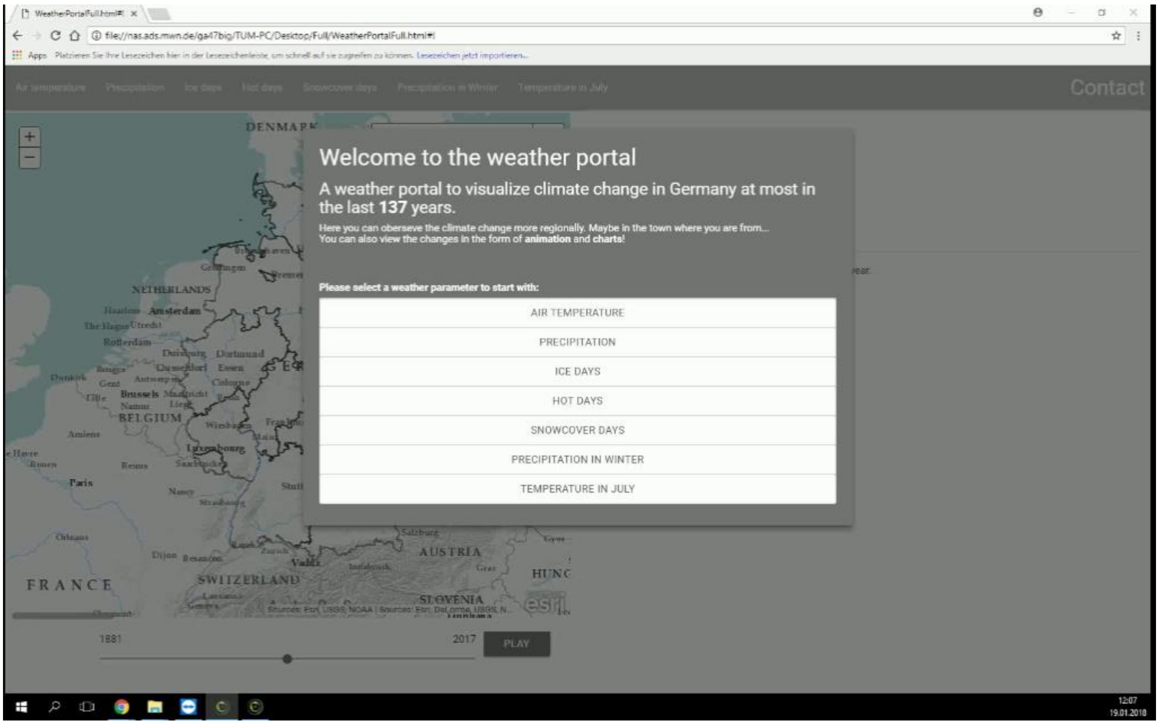


Figure 5-1: Starting page that the participant will view at the beginning of the evaluation.

For determining where the participants are viewing, all the four parts are separated by the percentage of the screen in four directions, as shown in Figure 5-2. The percentages are shown below Table 5-1. All the components are defined as rectangles. The gaze coordinates in the raw output were depicted as coordinated from (0,0) on the top left point to (1,1) on the bottom right point on the screen (*Open Gaze API* 2017). As a result, the coordinates of the rectangles are also recorded in this format.

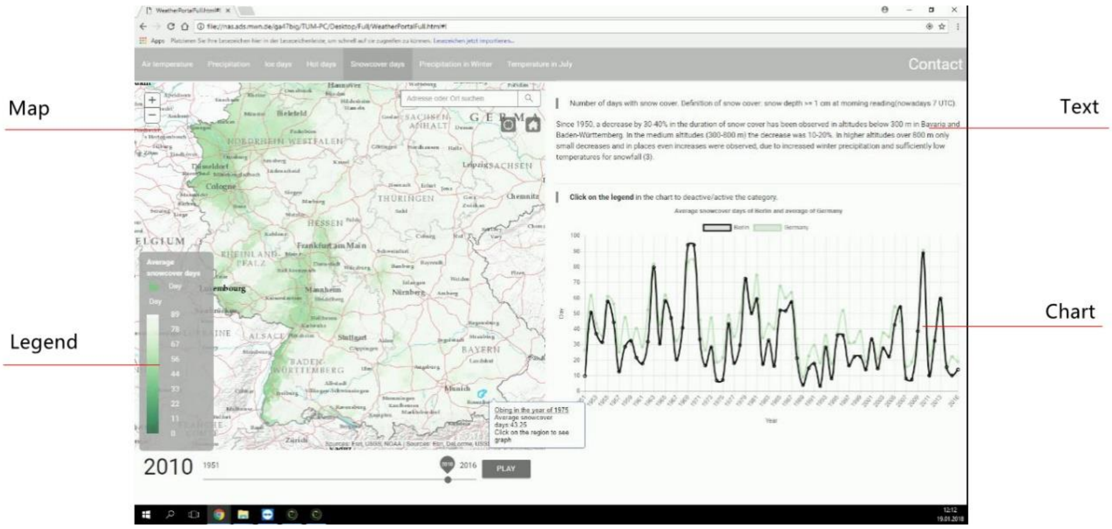


Figure 5-2: Screenshot of what participants view and parts of the map application.

Table 5-1: The coordinates that determine the rectangles of the parts in the map application

Part	Left	Right	Top	Bottom
Map	0	0.4927	0.1519	0.8574
Chart	0.5034	1	0.3504	0.8313
Legend	0.0077	0.0968	0.3566	0.8573
Text	0.5034	1	0.1519	0.3442

5.3 Evaluation methodologies

For the purpose of making sure that all the participants understand how to use this map application, the tester will spend 5 minutes in the beginning of the experiment to give instructions and description of the study. By doing this, the participants will focus on the information they need from the map application instead of spending time on trying out the functionalities. Otherwise, it will result in the case that the results do not reflect their real preferences correctly, as each participant needs a different length of time to get used to the functionalities.

To achieve the goal of understanding how people view a multi-component map, how long each participant has stayed on the part of the map application need to be calculated. Furthermore, the interests and the preference of the users are also essential to evaluate this map application. Thus, each participant is given 5 minutes to view the map without any task or indication. During the whole process, they are not told what to do or focus on. This is important to get the insights of users' habits and their preference of viewing strategy in a multi-component map application and is as well a technique to diagnose if the chosen forms of the map indeed interest them.

After that, they will be given 15 questions to accomplish the tasks, without time limits. In this case, how long they spend on each question will also be written down. As for the design of the questions, all the questions will be only a sentence, which is a statement in this case, and participants ought to choose "True" or "False" on the answer sheet. The main goal of this session is to evaluate which type of information that each part of map generates. Therefore, 3 types of questions are designed, which are important in a spatio-temporal scenario. The 3 types are "Regional trend", "Overall trend" and "Quantitative trend". The type of "Regional trend" indicates how the geographic events or occurrence change regionally, which in this case means that how the weather parameter changes over the depicted time from region to region. The type of "Overall trend" depicts how the geographical scenario changes over time in the whole region presented, which is Germany here. The difference between these two types is that the former one concentrates more on locational changes, while the latter emphasizes the changes over time in the largest picture possible. The third type "Quantitative trend" focuses on the statistical changes regionally or in a whole picture. 3 questions are designed for each type. At the same time, 2 questions are created for a new type which is the combination of two original types, which means 6 questions fall into 3 mixed types. Table 5-2 shows all the questions and the types they belong to.

Table 5-2: List of questions and the type they belong to, along with the right answer.

Number	Type	Question	Answer
Aa	Regional trend	Between 1881 and 2000, there were more years where <u>southern Bavaria in the Alps</u> has less average precipitation than <u>south-western Germany.</u>	False
Ab	Regional trend	Between 1881 and 2000, there were more years where north-western Germany has more precipitation than north-eastern Germany.	True
Ac	Regional trend	In comparison to the other four regions in the map below, the air temperature in southern Bavaria in the Alps had increased the most.	False
Ba	Overall trend	Between 2000 and 2016, 2007 was the year with the lowest number of snow cover days.	False

Bb		Between 1974 and 1984, the average number of ice days in Germany increased every year.	False
Bc		Between 1881 and 2017, 2014 is the year with the highest air temperature in Germany.	True
Ca	Quantitative trend	Between 2007 and 2017, Stuttgart always had more hot days than the average hot days of Germany.	False
Cb		Between 1881 and 2017, the annual average temperature in July in Berlin was not always over 17 Celsius degree.	True
Cc		Between 1881 and 2016, among the cities of Berlin, Kiel, and Munich, the average air temperature in Munich is the closest to the average temperature of Germany.	False
Da	Regional+ overall trend	Between 1881 and 2016, there are more years where Essen-Cologne-Bonn region has less precipitation than the average precipitation of Germany.	False
Db		Between 1881 and 2016, the southern Rhine basin has stayed the region that has the highest air temperature in Germany comparing to the other regions in the map below.	True
Ea	Regional+ quantitative trend	Between 1881 and 2017, the annual average temperature in July of southern Rhine Basin was more than 6 Celsius degrees higher than the annual average temperature in July of southern Bavaria in the Alps.	True
Eb		The average number of ice days in southern Bavaria in the Alps was always over 35 days	False
Fa	Overall+ quantitative trend	From 1986 to 2014, the average temperature of Germany had increased more than 2 Celsius degrees.	True

Fb		The average number of hot days between 1951 and 1960 was higher than the average number of hot days between 1961 and 1970.	False

In these statements, some cities and regions are also mentioned. All the locations are drawn on the same page of the question, with their names underlined, which gives a general idea of where the places are to the participants. This approach makes sure that all the participants are on the same knowledge level of the mentioned locations, which would minimize the redundant answering time caused by how well they are familiar with the regions. Moreover, the results are only useful when the participants answer the question with the correct climate parameter. Because of the number of climate parameters, it would be quite confusing and overwhelming for them when answering the questions. There are possibilities that the wrong parameters are used without being noticed. In order avoid this from happening, the climate parameter needed for one question and even the time range are clearly written and highlighted on the page. One example is shown in Figure 5-3.

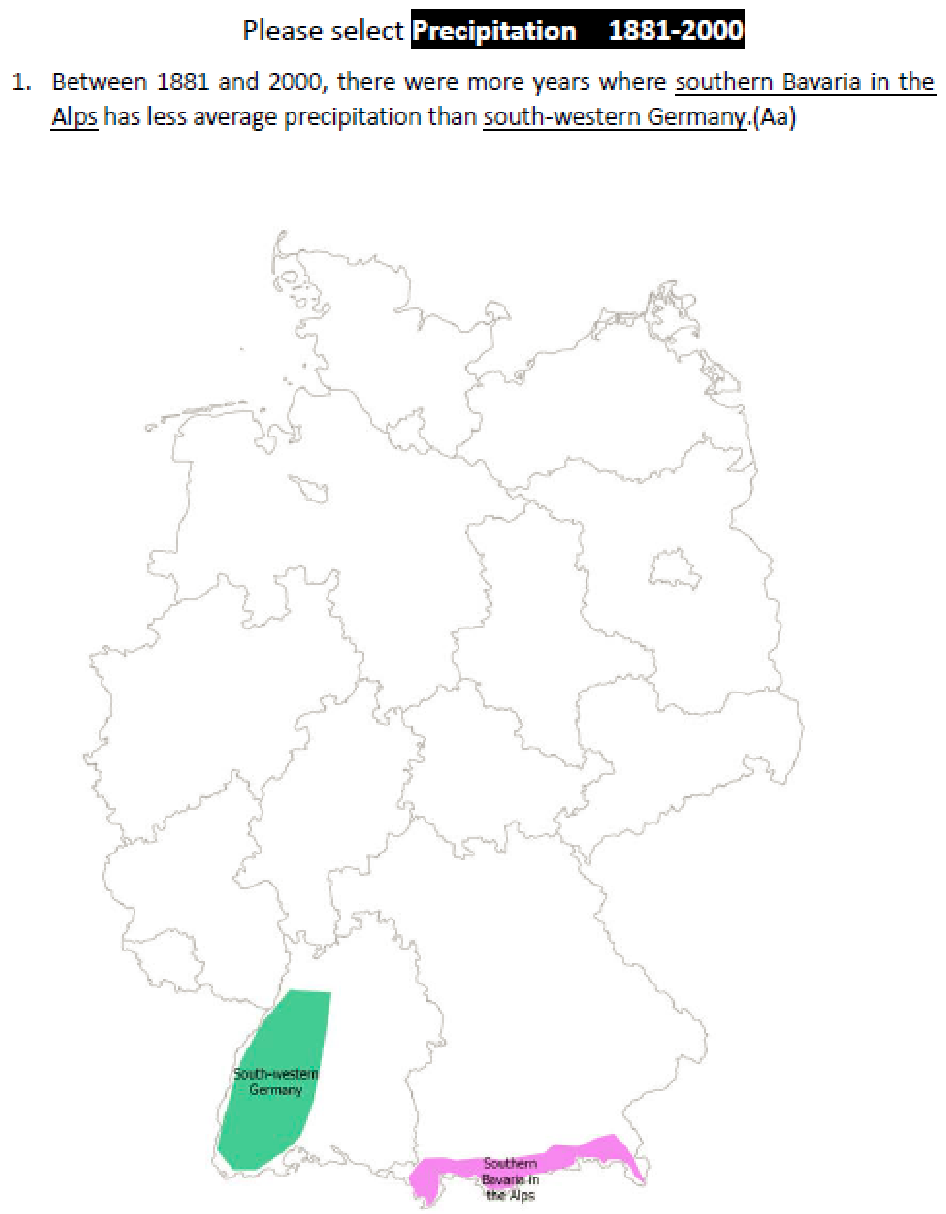


Figure 5-3: The page of one question with the underlined regions, which are also drawn on the map below, where weather parameter and year range are very much highlighted.

How familiar the participants are with the functionalities improves overtime, as well as the possibilities of finding better strategies for solving specific questions, which in return will affect their efficiency and effectiveness. Respectively, the order of the questions must be different for the participants, which makes sure that each type of questions gets the same summarize of order in the end. The orders of the questions are shown in Table 5-3.

Table 5-3: Three types of orders of the questions.

Number	Type	Order A	Order B	Order C
Aa	Regional trend	1	13	7
Ab		9	3	15
Ac		14	8	2
Ba	Overall trend	2	14	8
Bb		7	1	13
Bc		15	9	3
Ca	Quantitative trend	3	15	9
Cb		8	2	14
Cc		13	7	1
Da	Regional+ overall trend	4	10	6
Db		12	5	11
Ea	Regional+ quantitative trend	5	11	4
Eb		10	6	12
Fa	Overall+ quantitative trend	6	12	5
Fb		11	4	10

5.4 Project-set up

The experiments are done in the Eye-tracking Lab at Technische Universität München. The lab has six sets of eye-tracking devices, while only one was used. Most of the experiments are done during daytime, while the strong light coming from the light-bulb at night sometimes affect the ability of the device to catch the eye-movements.

Only one participant is tested at one time, as the tester needs to give instructions individually during to process, as well as to record how much time the participant spends on each question. During all the experiments, only the tester and the participant are in the lab, which is to guarantee that the participants are disturbed as less as possible, since time-duration for each task is the essential part of the results.

The operating system is Windows 10, and the browser is Chrome. There are two monitors used for the experiments. One monitor is for the participants to view the map, where Gazepoint Control is presented. Another one is for the tester, where Gazepoint Analysis is presented. This monitor is used to observe the participants' view process, and to keep track of the procedure as well as to give necessary instructions to the participants. The tester use another laptop to write down the starting- and end-time of the participant answering every question.

As mentioned before, there are three different orders for the 15 questions. Every question is printed on one single page, where the weather parameter and time range are highlighted. On the top of the questions, there is a page giving instructions to the users, which is also used to prevent the participant from reading the questions before the question session starts. At the same time, they are also given an answer sheet, where they could write down their information including name, gender, major or job, and nationality. Every 3 participants in a row are offered three orders of the questions.

5.5 Evaluation procedure

After welcoming the participants, the tester gave instruction and descriptions to the participant. The instructions and specifications to all the participants were all the same, which included the information below:

- The reason why we are doing this experiment, and the topic of the thesis.
- What is this map application, what are the functionalities? Including detailed description concerning each part of the map, and the interactivities. At the same time, the tester will demonstrate on the map application.
- The process of the experiment. Firstly, they will have 5 minutes to browse the map application as the free-examination task. Then they will be given 15 questions and answer them by the order. They are not allowed to change the answers after answering it.

After the instruction, they were asked to use the map for few seconds, to make sure all the participants were of the same knowledge level of the map application.

Before collecting data, the participants should calibrate their eyes. Gazepoint Control was opened on the monitor for the participant, while Gazepoint Analysis was opened on another monitor for the tester. Gaze control was needed to calibrate the eyes and record the eye-movements. Afterward, the free-examination task started, while Gazepoint analysis began to collect data. The participants were told to stop after 5 minutes and to start the goal-directed task. They were also told to put the question page away before answering the next question, which gave the signal to the tester about when they finish one question and start the next one.

During the process, they were informed by the tester to adjust their position to the eye-tracking device, when their eyes were out of the range of the device can reach or when the reflection from their glasses interrupted the collecting of eye-movements. The whole procedure lasted from 30 minutes to 50 minutes. They were also offered a piece of chocolate before they left.

5.6 Description and processing of the evaluation results

There are two types of output from Gazepoint Analysis, which are maps and raw data in the format of .csv. there are four types of maps that it renders, including fixation map, heat map, opacity map and bee swarm. The heat map is applied in the result. A heat map illustrates the general regions viewed by the user, shows how much users looked at different parts the of the map (Figure 5-4).

Figure 5-4: The heat map of one of the participants during the free-examination task, including the mouse-clicked points, generated by Gazepoint Analysis.

For the purpose of assessing the participants’ viewing behavior systematically and quantitatively, the raw-data output was used, where the gaze duration of the gaze points is recorded. As mentioned above, the examined parts of the map are divided by rectangles that defined by four lines on the map application, and the coordinates are the same as the coordinates in the exported file. The file that includes all the gaze fixation points is used, where each point is recorded by various coordinates and gaze duration, name, etc. however, only three of them are used, to determine how long the participants have stayed on each part of the map application during one task. The parameters used and the description of them are shown in Table 5-4.

Table 5-4: The parameters that are used to generate the gaze duration for each part of the map(*Open Gaze API* 2017).

Parameter ID	Description
POGD	The duration of the fixation POG(point of gaze) in seconds
FPOGX	The X-coordinates of the fixation POG(point of gaze).
FPOGY	The Y-coordinates of the fixation POG(point of gaze).

During free-examination task, gaze duration for each part will be summed up. During the goal-directed task, another dataset is used, which is the starting- and end-time of each question by the participants. All the fixation points of the second task are divided into sub-datasets based on the time slice of each question. Thus, the sub-datasets are evaluated and processed individually.

6 Results

Based on what has been collected from the evaluation procedure, the results of the two tasks are presented in this chapter. The first part of the chapter contains the result from the free examination task, where overall area of interest analysis and area of interest analysis based on gender are included. The second part contains the area of interest analysis of the questions and analysis based on users' accuracy of answering the questions. In both tasks, the usage of table, bar chart, as well as heat map serves as a clear and meaningful presentation of the results.

6.1 Free examination task

6.1.1 Overall area of interest analysis

Owing to the technical problems, the length of the recording of the first period cannot be precisely 5 minutes. The lengths range from 293 seconds to 343 seconds. Although the map and the chart are presented in the places that attract the users' eye as similar as possible, the content and form of visualization of these two parts determined that they could not take up space with the same size. In this case, to analyze how different parts of this map interest the users, it is crucial to take the percentage of the size of the components to the monitor into consideration.

Figure 6-1 is the heat map of the first period of the task, the gaze information of all the participants are added up for the presentation. The heat map scale is absolute 1 second. The size of the gaze points is 14% shown in the window of the analysis mode. Color mapping is usually selected so that the longer the observation, the warmer the color used to represent it. In this figure, we could see that most of the gaze points are placed in the map container, while the chart becomes the second part that users gaze the most. Users also tend to fix their small part of their attention on the time slider and the legend, as well as the description of each climate parameter.

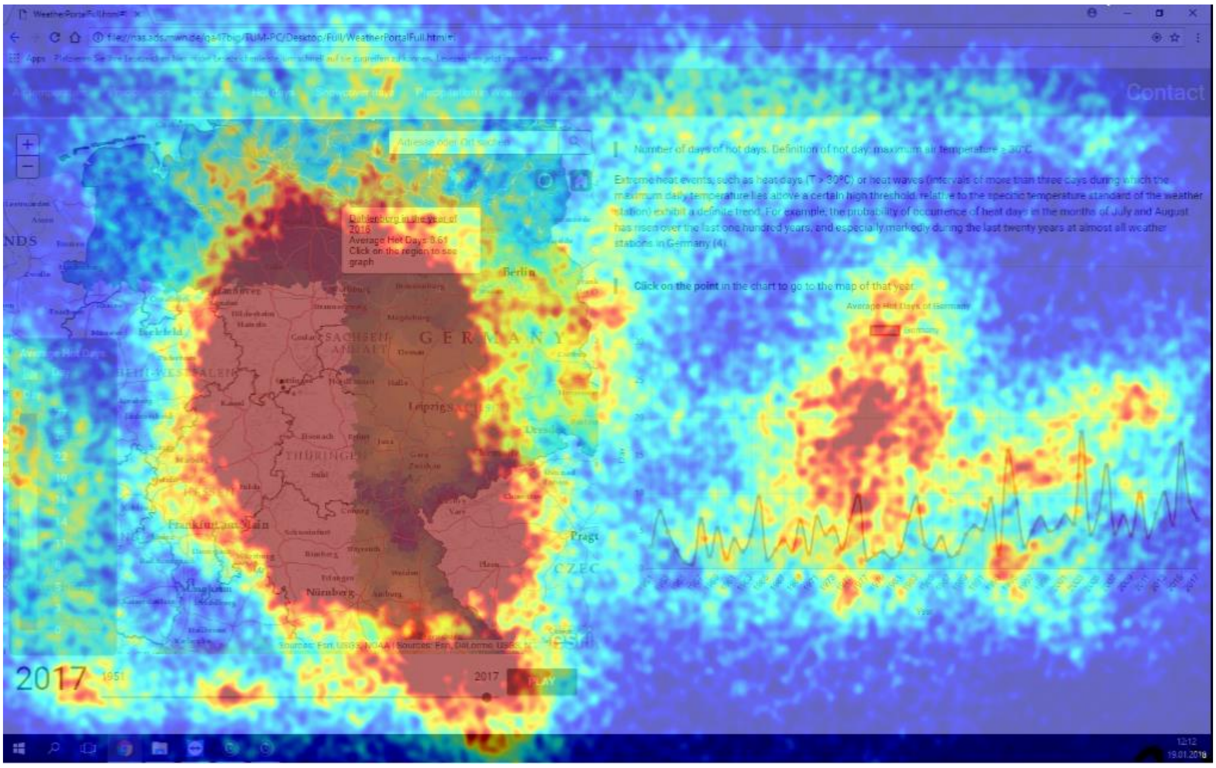


Figure 6-1: Heat map of the accumulation of all the 24 participants during the free-exanimation task. The heatmap scale is of absolute differences of 1 second.

A clear, thorough, and statistical area of interest analysis is shown in Table 6-1. As static map and animated map are in the same place, the term “map container” is used to demonstrate the statistic for the whole area. In the following tables and bar charts, map stands for the statistic for the whole area, while animated map and static map stand for two different status of the map. The component of the legend is also in the map container, so the fixation duration of legend was included in the duration of the map, and it is also included in the duration of animated map and static map, so that the duration of the legend is separated from the map container, and is analyzed as a single component.

Table 6-1: Total fixation duration of each component in the web map application during the free-examination period.

		Map container					
	Duration	**Map**	**Animated map**	**Static map**	**Chart**	**Legend**	**Description**
Mean	310.82	134.07	40.46	93.61	45.33	6.63	11.03

Standard deviation	12.86	39.01	30.72	48.93	27.73	4.54	13.16
Minimum	293.57	46.47	0.00	2.39	4.90	1.31	0.34
25%	302.30	102.17	14.00	53.41	27.60	3.00	2.99
50%	305.03	142.62	37.00	93.82	36.91	6.54	5.78
75%	320.60	161.87	58.75	132.70	63.31	9.04	14.71
Maximum	347.54	190.26	100.00	170.99	103.44	18.53	51.18

Table 6-2 depicts the average fixation duration of each component, along with the percentage of the whole duration, and the percentage of each component to the monitor. There are many factors that affect the fixation duration on each component, where the size of the component is one of the most important factors. For the purpose of revealing how well each component interests the participants and attracts the attention of the participants, the relation between the percentage of the duration and the percentage of its size to the monitor is calculated by applying dividing. In this case, the components that have a lower percentage of size but a higher percentage of duration are the components that the participants are more interested comparing to the others; they tend to have a higher ratio as well. As mentioned before, the component of animated map and static map are included in map container. It does not make much sense to take their ratios into consideration, where the map container should be considered as one component. Meanwhile, this does not affect the component of legend, while as mentioned before, it is calculated separately. As can be seen in the table, the map attracts the attention of the participants the most, where static map took more fixation duration than an animated map. the chart component comes afterwards.

Table 6-2:The percentage of each component to the monitor and the percentage of duration, and the relation between them.

	Map container					
	Map	**Animated map**	**Static map**	**Chart**	**Legend**	**Description**
% of the whole duration	43.13	13.02	30.12	14.58	2.13	3.55

% of the monitor	34.76	34.76	34.76	23.87	4.46	9.55
Relation between these two(ratio)	1.24	0.37	0.87	0.62	0.48	0.37

6.1.2 Area of interest analysis based on gender

To find out if there is a different preference of the participants based on gender, a statistical analysis where female and male participants are analyzed separately is needed. Among the 24 participants, 13 of them are female while 11 of them are male. Figure 6-2 depicts the average fixation duration of each component of female and male participants. There is no significant difference of fixation preference between female and male participants. Nevertheless, female participants tend to pay more attention to the map container, including the animated map and static map, while male participants spend more time on observing the chart comparing to female participants.

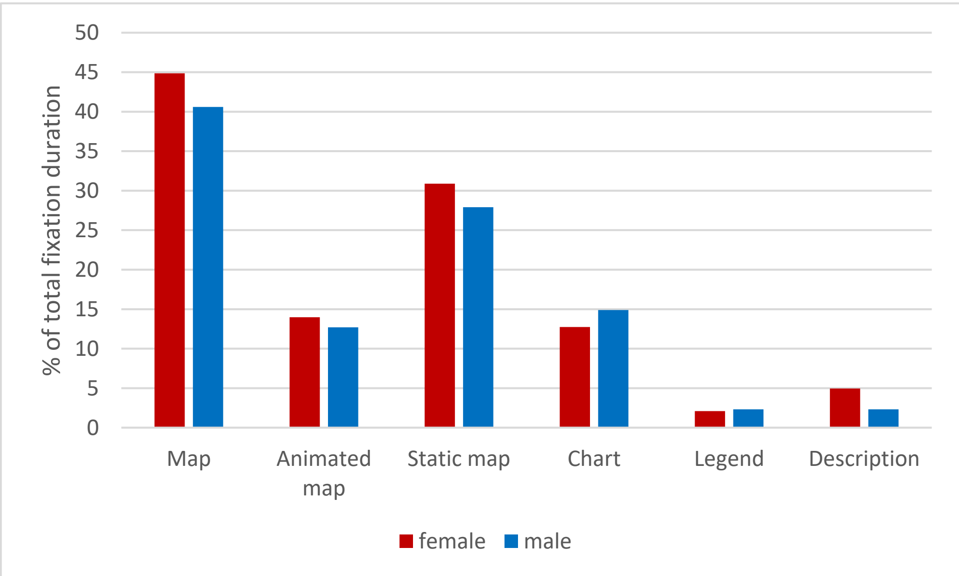


Figure 6-2: Average fixation duration of each component based on gender.

6.2 Goal-directed task

Due to technical problems, three of the participants are excluded from the result analysis. The questions in the goal-directed task are designed based on different categories, where the usages of animated map as well as chart are predicted. As a result, the overall area of interest analysis as demonstrated in 5.1.1 is not necessary. Instead, the fixation duration on each component based on the questions, as well as the accuracy of the answers are more important, which will be stated below.

6.2.1 Area of interest analysis based on questions

All 15 questions are designed based on the type of information that each component of the web application might generate. There is no need to analyze the questions one by one, where only the category they belong to matters. Thus, fixation duration on each component for each type of questions is summarized, as shown in Figure 6-3. The three types of questions are a regional trend, overall trend, and quantitative trend, and each of them has three corresponding questions. Meanwhile, the combination of every two categories creates three new categories, of which each has two corresponding questions. It can be seen in Figure 6-3 that for the questions that belong to the categories of regional trend and regional + overall trend, participants tend to use the animated map more. To get a clearer look of the three major categories, Figure 6-4 is presented. It is obvious that the animated map is preferred when dealing with the questions of a regional trend. The participants spent about 19% of total duration on animated map on questions of regional trend, about 9% of the time on questions of overall trend, and nearly 5% of the time on quantitative-trend questions. As for the chart component, people drew similar attention to it when solving the questions of quantitative and overall trend, which are both about 17% of the fixation duration. The participants also use the legend more when solving the questions of regional trend. In general, the component of description doesn't attract their attention much, less than 0.9% of the fixation duration of each question on average. Among the three mixed categories, participants tend to pay more attention to the animated map when solving the questions whose categories have regional trend, while they pay more attention to the chart when solving the questions whose categories have quantitative trend. Regarding quantitative trend, overall + quantitative trend and overall trend, less than 3% of the total duration was fixed on the animated map. Meanwhile, the fixed duration on the chart was never less than 6% of the total duration.

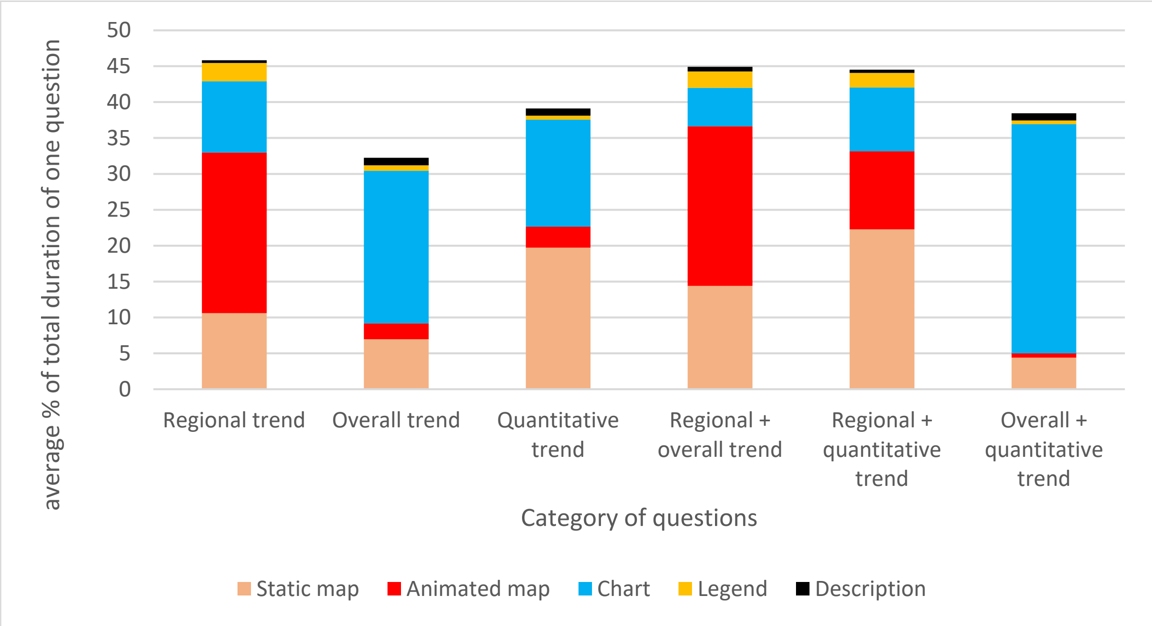


Figure 6-3: Average fixation duration on each component of each category of questions among all the participants.

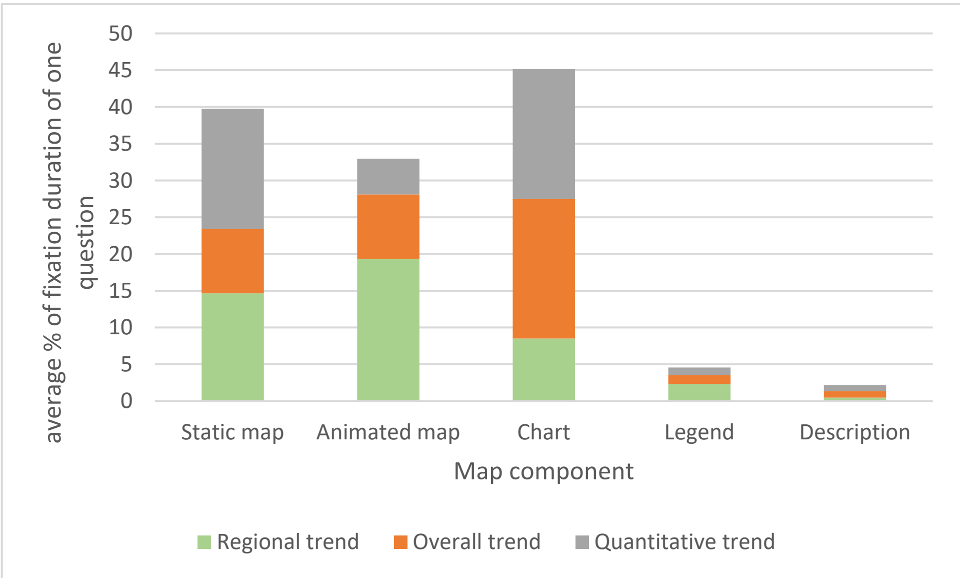


Figure 6-4: Average percentage of fixation duration of each major category of question among all the participants.

6.2.2 Area of interest analysis based on accuracy

As mentioned in chapter four, when answering each question, the participants also need to mark their confidence levels. The confidence assessment ranges from 1 to 5, where 1 corresponds to “not confident,” and 5 to “very confident”. However, there are very few questions from three participants that are marked with the number 1. Although no participants answered all the questions correctly, it is not important to take the confidence assessment into consideration. The answers from the participants will only be right or wrong, without the option of “I don’t know”. There are difficulty differences among all 15 questions; Figure 6-5 shows how many participants answer each question correctly and incorrectly. The number of the questions doesn’t stand for the order or categories of them.

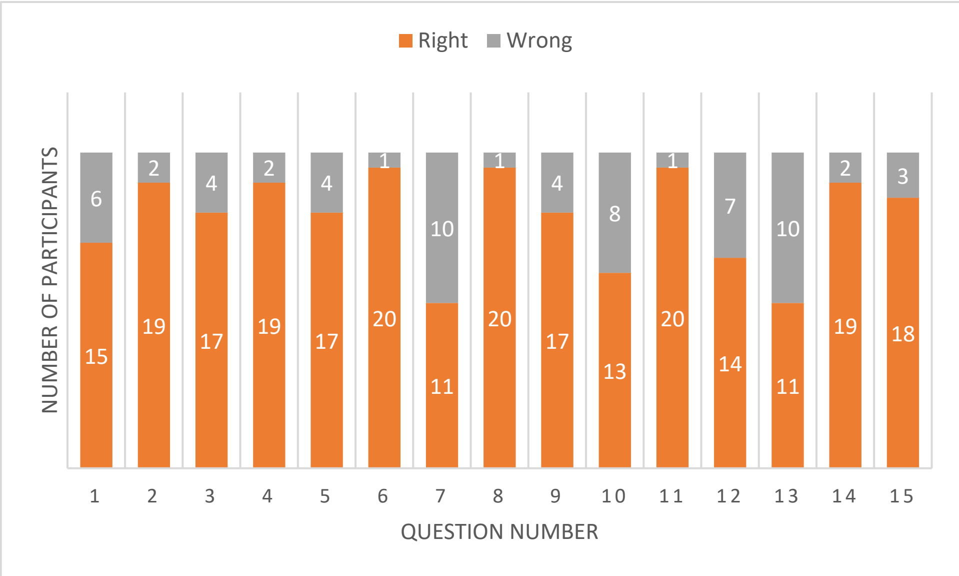


Figure 6-5: The amount of the participants who answer each question correctly or incorrectly.

The viewing strategy of the participants can possibly affect their accuracy. Based on the observation of the participants, they have different view preferences in terms of focusing component and focusing order. There are many factors that determined the accuracy of each question, here only the area of interest is analyzed, based on the average results from the participants who answer each question correctly as well as incorrectly. In this case, fixation duration is calculated instead of the percentage, where the duration can also reveal the difficulties of each category of the questions. The average total duration for each question and the number of participants who answered correctly and incorrectly are shown in Table 6-3. The number of participants whom answered incorrectly is less than the number of correct ones, while the incorrect participants spent on average more time on every question. Compared to other questions, the duration of one question has no relation to its accuracy.

For the category of regional trend and overall trend, the participants who pay more attention to the animated map tend to answer the question incorrectly. For overall trend as well as quantitative trend, the participants who gaze at the chart for a longer time tend to answer the questions correctly. The participants who answered the questions of overall + quantitative trend incorrectly averagely fix their attention on the components of chart and description more on average, except for which there isn’t a significant difference between the correct and incorrect performances of the three categories of regional + overall trend, regional + quantitative trend and overall + quantitative trend. It is also found that when it comes to the question from the categories of regional + quantitative trend, and regional + overall trend, static-map-duration of the incorrect participants is significantly longer than of the correct participants, while the animated-map-durations of both groups remain similar.

Table 6-3: Average duration, as well as the average number of participants that answer the question correctly or incorrectly of each question, grouped by correct and incorrect performances.

	Correct		Incorrect	
Category	Duration(s)	Number of participants	Duration(s)	Number of participants
Regional trend	101.16	17.00	108.58	4.00
Overall trend	49.80	18.67	56.08	2.33
Quantitative trend	69.86	16.00	74.48	5.00
Regional + overall	82.88	16.50	102.00	4.50
Regional + quantitative	83.19	12.50	88.74	8.50
Overall + quantitative	70.20	18.50	82.83	2.50

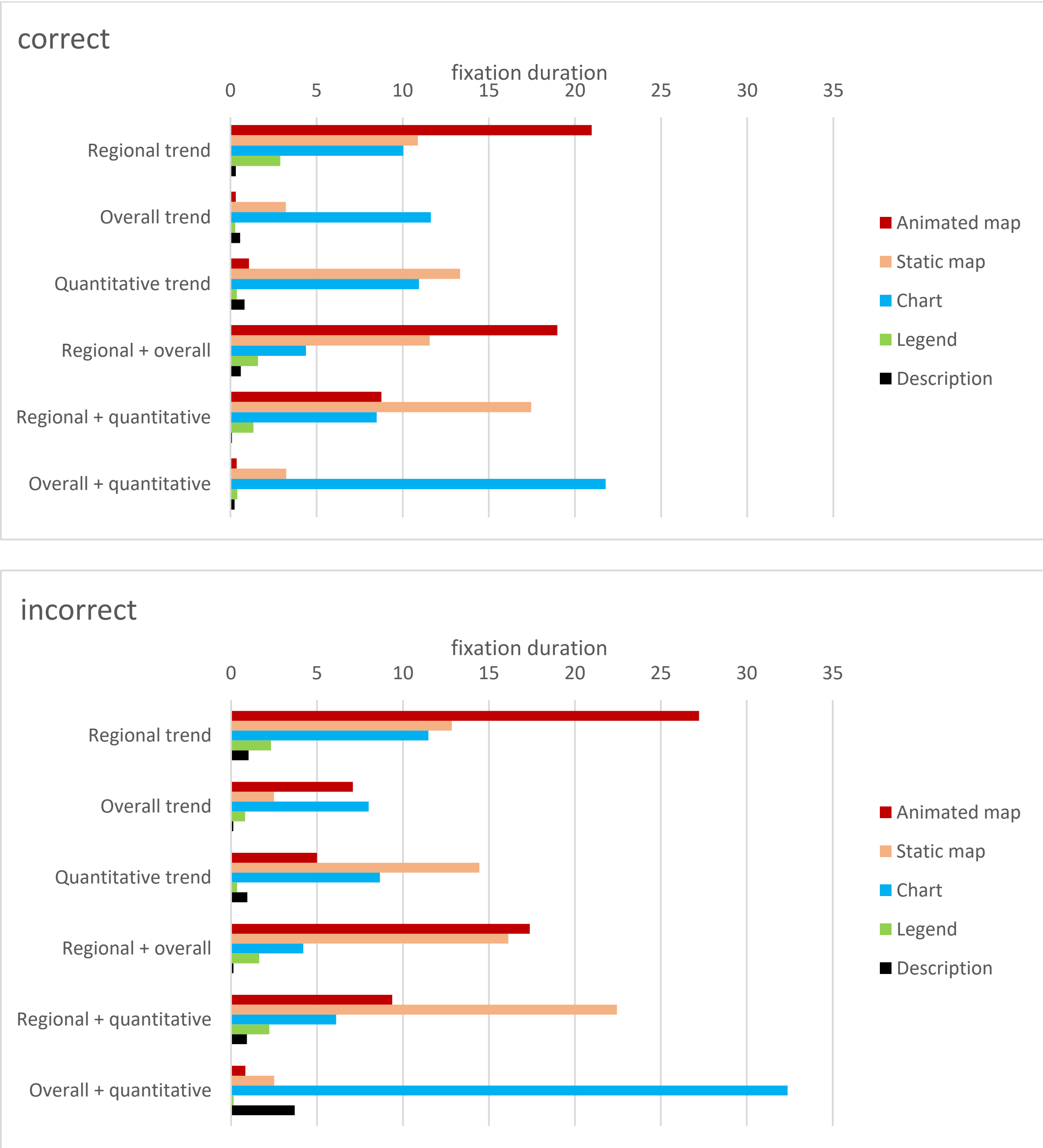


Figure 6-6: Average fixation duration for each category of questions, grouped by correct and the incorrect performances.

7 Discussion

An empirical study to evaluate the data visualization methods was employed, which was used to answer these questions:

- How do users allocate their eyes in the map application without tasks and with tasks?
- What kind of information do animated map and chart generate?
- How do the viewing strategies affect the accuracy and efficiency of the participants when they are performing the tasks?

With these three questions, a free-examination task and a goal-directed task were designed. The first task was designed to get the know the average using preference of the users, and the difference of groups. In the second task, 3 categories of information were chosen, which were regional trend, overall trend, and quantitative trend. The task aimed at finding out which type of information that each component generates.

In this case, the design of the evaluation tasks focused on the utility of the map.

7.1 Free-examination task

In the part of the free-examination task, without any guidance or instruction, the participants appeared to split their attention to all the components of the map. However, there existed significant difference of these components.

- Map container attracts the majority of participants' attention, considering the map container comprises the largest part of the web map application.
- The results also suggest that the application of animated map and chart are interesting and appealing enough.
- There is also distinction of viewing time on static map and animated map, the reasons are stated below.
- Women find map more interesting than men do, while men separate more of their attention on chart than women do.

It is not surprising that the map container attracted the participants' attention the most since the map container takes up the biggest part of the web map application. In the research that Wolfe and Horowitz (2004) conducted about what attributes guide the deployment of visual attention, they suggest that motion and color are the attributes that attract the viewers' attention without doubts. By default, the map shown in the application is static, while only by clicking the button can the animation be started, which counts for one of the reasons why participants spend more time on static map than animated map. Only one of the 24 participants did not play the animation in this procedure at all, which suggests that animated map do attract the participants' attention to a certain degree. A similar amount of time was spent on chart as the animated map, and the fact that all the participants fixed their eye-movement on chart for a relatively long time indicates the usage of chart help the spatio-temporal map reading. Ayres et al. (2005) point out that animated graphics have a greater potential than static graphics for saturating our limited working memory (WM), both because they are constantly changing and thus there is simply more to look at with less time to look at it, and also because the readers often need to remember previously viewed scenes in order to understand the current one. This also explains why the users tend to use animated map widely but spent less time on the animated map the static map.

During this period, both women and men prefer the map container the most for needed information, based on the ratio of the map size and the fixation duration. This was also predicted when designing this map, since the map gives a more vivid visualization together with spatial information, while charts with only statistics may appear to be less interesting. Studies also show there is a gender difference concerning information acquisition and map reading (Liao and Dong, 2017; O'Laughlin and Brubaker, 1998). Nevertheless, the results show that about 15% of the total duration is fixed on the chart, which is still promising. It is also notable that women spent more time fixated on map components than men, while men spent more percentage of time fixated on charts than women, which suggests that woman find maps more interesting than men, and men tend to find statistical visualizations more appealing than women. Other viewing preferences of different groups of people were not observed or not analyzed, owing to the small number of the participants from various backgrounds.

7.2 Goal-directed task

There are some reasons presented in the literature (Harrower, 2007) that conclude that while using complex animated maps, people do struggle to acquire information that the map conveys. Few findings in this task are shown below, and their explanations are stated afterwards:

1) Participants believe that animated map generates better trends in a spatio-temporal scenario regionally, and chart generates better trends quantitatively.

Despite the accuracy of the answers to the questions, the different information rendered by animated and non-animated charts is found based on the fixation duration that the participants spent on each question category. The animated map was widely and extensively used when they are dealing with the questions of regional trend. The chart was greatly applied when solving the question of quantitative trend. For the questions that belong to overall trend, it seems that the participants tend to use the chart more than the animated map, while the difference of these two is not as high as the difference of those in other categories.

2) The type of information that animated map appears to generate stays the same as users' preferences showed, which is regional trend.

3) The performances with inaccurate answers, also tend to take a longer time.

Performance is applied to describe the process of the participants answering one question, including their ability, skills, and results. When taking the accuracy and efficiency into consideration, it was found that there exists a noticeable difference between the groups of participants who were correct and incorrect on every question. The performances described in this case are categorized as ineffective performances.

4) However, participants who view the animated map for a longer time tend to have poorer performances. A threshold of viewing time on animated map could possibly be observed, as to achieve the best performance.

The situation depicted here happens to most of the categories of questions. To seek explanation, some previous research result may be taken into consideration. Many researchers argue the limitations and shortcomings of animated map. Harrower (2007) stated that when it comes to designing animated maps, the bottleneck is no longer the hardware, the software, or the database – it is the human user. The problem is not that map viewers are incapable of seeing the changes occurring on the animated map (i.e., perceptually), it is that they have well-documented trouble remembering what they saw and integrating it into their knowledge schemata. This may also relates to the cognitive load. Cognitive load theory describes cognitive structures of information processing and learning involving long-term memory—which stores knowledge and skills on a permanent basis—and working memory, which performs tasks associated with consciousness and actively processes incoming stimuli (Harrower, 2007). MacEachren (1995) and Ware (2000) have championed a perceptual-cognitive approach to cartography and information visualization respectively, because, in part, such an approach helps to explain why map or interface designs work and not merely whether they work or not. Animated map and other forms of map presentations generate completely different cognitive loads to the users, which has been and is still an undergoing topic for researchers. In this case, it can be argued that the results show that many factors of the animated map, including speed, color scheme, and user control, might have caused the cognitive overload after a specific usage time.

5) Chart generates information of quantitative trend, and gives much better information of the overall trend comparing to animated map.

The participants who spent more time on the animated map and similar time on the other components tended to answer incorrectly. Even though the chart did not appeal to the participants compared to the map, it improved their accuracy when they fixed their eye-movements longer on the chart. The chart served as a rather statically efficient component in a multi-dimensional spatio-temporal scenario.

7.3 Other findings from these two tasks

Concerning the comparison of these two tasks, it doesn’t make sense to compare the difference of fixation duration between chart and animated map, considering that the second task was designed to test the utility of both of these two components. However, the participants pay more attention to the legend when they perform tasks. In a similar evaluation that Opach et al. (2013) conducted, it also observed that the viewing strategy influence the participants’ accuracy, where it comes to legend, repeated legend inspection during the viewing event, especially for animated map components, may considerably distract map users, potentially resulting in ineffective information acquisition. Although in this study, participants’ viewing strategy was not specifically tested, it shows that when people have tasks, and when they need to learn more statistical information from the map, they tend to view the legend much more.

8 Summary and outlook

In this thesis, the current methodologies for visualizing multi-dimensional spatio-temporal data were summarized. Among the summarized methodologies, two major forms of visualization were adopted, which are animated map and chart. The multi-dimensional aspect is achieved by effective user-interface design. The map is well designed with a base map, legend and color schemes for different weather parameters. The polygonal feature has the size of the counties. The animated map is shown as in the same area with a static map, with the possible control over the map, including zoom in/out, search, locate, etc.. The chart has two scales, which are the average of climate data in Germany and average of one county. The interactivities of the application exist in the control of the animated map and the chart.

Meanwhile, how the datasets are chosen and the procedure to proceed the dataset is described in detail, along with the description of the software, APIs, and programming languages. The success of building a pre-defined web map with pre-defined functionalities suggests that the tools, software are capable enough for such a scenario. The tools in ArcGIS Pro are efficient and practical enough for the task, especially considering the capability to combine ArcPy in Python, which proved useful. ArcGIS for Javascript 3.22 has quite a powerful visualization ability, which makes the whole procedure of building the map application, especially the animated map, easy and quick. The use of Python for data analyzing and organizing also saves a lot of time for the whole process. In comparison to other GIS software, ArcGIS Pro offer abundant and stable tools for data processing, which can also be easily accessed by programming using related APIs. This compact processing procedure is critical in the case study, owing to the huge number of datasets to process. Moreover, thanks to the consistency of the Esri products range from data processing, storing, as well as visualization, there is a notable lack of data type conversion among the procedures, which leads to less data loss than other software options. As for the aspect of cartography, ArcGIS for JavaScript API 3.22 offers standard symbols, labels, etc., while at the same time holds degree of flexibilities and possibilities of integration with other APIs. Such cartographic standards and flexibilities cannot be met at the same time in most of the other web visualization approaches, for instance, Leaflet, Google Map API.

Another important approach in this study is the evaluation of the map utility, by using the technique of eye-tracking and eye tracking analysis. Roth et al. (2015) summarized “The three U’s of interface success”, where utility, usability, and user are included. Utility describes the usefulness of an interface for completing the user’s desired set of objectives (Nielsen, 1992). The evaluation goals serve as the basis for the design of the two-phase tasks. The tasks include a 5-minute free examination task and a goal-directed task, where 15 questions that belong to three categories of information are designed. Based on area of interest analysis based on the users' accuracy to these questions, it was found that the animated map generates the spatio-temporal information regionally, while the chart renders information quantitatively. The aimated map helps the procedure of obtaining specific types of information. However, it was found that there exists a cognitive overload for viewing an animated map.

The area of interest analysis in both tasks also indicates no significant difference regarding the gender. Nevertheless, without any tasks to solve, women show more interest in animated map than men, while chart attract more interests of men than women.

The usability of the web map application was not quantitatively assessed, but it can be simply summarized from the observation of the participants' behaviors. After the instruction of the web app application, all the users could use the application without asking any questions. They also used all the functionalities quite fluently, and all the interactivities were used in most of the evaluations. Moreover, the instruction took only about 2 minutes for each user. These facts indicate that the design of user-interactivities is rather practical and efficient.

It remains a problem for cartographers to understand the relationships between map design and viewing strategy of the users. Harrower (2007) suggests that while cartographers are often very good at testing the relative effectiveness of various map designs (e.g., different color schemes, different number of data classes, different symbol sizes, different tempos of an animation), cartographers sometimes struggle to explain their results and move beyond reporting what worked best and into explaining why it worked best (from a cognitive or perceptual standpoint). There are some obstacles and shortcomings of this study in both map design and map evaluation. And the future work should focus on the aspects as follows:

- As for the design of the web map application, the feedback and the evaluation results could be taken into consideration in future work and design.
- The speed of the animated map should be better handled and controlled, and the users should also be able to change the speed.
- When the data is updated, the visualization of the climate data should also be updated, and in a more simple and automatic way. While for now, the update of the visualization means that all the procedure for the data processing has to be done from the beginning.
- There still exists a need for a better explanation of the map evaluation results, in terms of the participants viewing behavior.

9 Literature

Anderson, G., & Moreno‐Sanchez, R. (2003). Building web‐based spatial information solutions around open specifications and open source software. *Transactions in GIS, 7*(4), 447-466.

Andrienko, G., Andrienko, N., Dykes, J., Fabrikant, S. I., & Wachowicz, M. (2008). Geovisualization of Dynamics, Movement and Change: Key Issues and Developing Approaches in Visualization Research. *Information Visualization, 7*(3-4), 173-180. doi:10.1057/ivs.2008.23

Andrienko, N., Andrienko, G., & Gatalsky, P. (2003). Exploratory spatio-temporal visualization: an analytical review. *Journal of Visual Languages & Computing, 14*(6), 503-541. doi:10.1016/s1045-926x(03)00046-6

Ayres, P., Kalyuga, S., Marcus, N., & Sweller, J. (2005). *The conditions under which instructional animation may be effective.* Paper presented at the an International Workshop and Mini-conference, Open University of the Netherlands: Heerlen, The Netherlands.

Bertin, J. (1981). *Graphics and graphic information processing*: Walter de Gruyter.

Blok, C. (2000). Monitoring change: characteristics of dynamic geo-spatial phenomena for visual exploration. In *Spatial cognition II* (pp. 16-30): Springer.

Blok, C., Köbben, B., Cheng, T., & Kuterema, A. A. (1999). Visualization of relationships between spatial patterns in time by cartographic animation. *Cartography and Geographic Information Science, 26*(2), 139-151.

Bojko, A. (2006). Using eye tracking to compare web page designs: A case study. *Journal of Usability Studies, 1*(3), 112-120.

Bruggmann, A., & Fabrikant, S. I. (2016). How does GIScience support spatio-temporal information search in the humanities? *Spatial Cognition & Computation, 16*(4), 255-271. doi:10.1080/13875868.2016.1157881

Campbell, C. S., & Egbert, S. L. (1990). Animated cartography/Thirty years of scratching the surface. *Cartographica: The International Journal for Geographic Information and Geovisualization, 27*(2), 24-46.

Cliff, A. D., & Ord, J. K. (1981). *Spatial processes: models & applications*: Taylor & Francis.

Clifford, J., & Warren, D. S. (1983). Formal semantics for time in databases. *ACM Transactions on Database Systems (TODS), 8*(2), 214-254.

Çöltekin, A., Heil, B., Garlandini, S., & Fabrikant, S. I. (2009). Evaluating the effectiveness of interactive map interface designs: a case study integrating usability metrics with eye-movement analysis. *Cartography and Geographic Information Science, 36*(1), 5-17.

Couclelis, H. (1998). Worlds of information: The geographic metaphor in the visualization of complex information. *Cartography and Geographic Information Systems, 25*(4), 209-220.

Duchowski, A. T. (2002). A breadth-first survey of eye-tracking applications. *Behavior Research Methods, Instruments, & Computers, 34*(4), 455-470.

Duchowski, A. T. (2007). Eye tracking methodology. *Theory and practice, 328*.

Dunbar, B. (2015). What's the Difference Between Weather and Climate? Retrieved from https://www.nasa.gov/mission_pages/noaa-n/climate/climate_weather.html

Earthy, J. (1996). Development of the usability maturity model. *INUSE Deliverable D, 5*.

Edsall, R. M., Kraak, M.-J., MacEachren, A. M., & Peuquet, D. J. (1997). *Assessing the effectiveness of temporal legends in environmental visualization.* Paper presented at the GIS/LIS.

Fabrikant, S. I., & Goldsberry, K. (2005). *Thematic relevance and perceptual salience of dynamic geovisualization displays.* Paper presented at the Proceedings, 22th ICA/ACI International Cartographic Conference, A Coruña, Spain.

Fabrikant, S. I., Rebich-Hespanha, S., Andrienko, N., Andrienko, G., & Montello, D. R. (2013). Novel Method to Measure Inference Affordance in Static Small-Multiple Map Displays Representing Dynamic Processes. *The Cartographic Journal, 45*(3), 201-215. doi:10.1179/000870408x311396

Flanagan, D. (2006). *JavaScript: the definitive guide*: " O'Reilly Media, Inc.".

Fuchs, R., & Hauser, H. (2009). *Visualization of Multi‐Variate Scientific Data.* Paper presented at the Computer Graphics Forum.

Fuhrmann, S., & Kraak, J. (2001). Geovisualisierung. *Kartographische Nachrichten, 4*, 173-175.

Fuhrmann, S., & Pike, W. (2005). User-centered design of collaborative geovisualization tools. In *Exploring geovisualization* (pp. 591-609): Elsevier.

Gersmehl, P. J. (1990). Choosing tools: Nine metaphors of four-dimensional cartography. *Cartographic Perspectives*(05), 3-16.

GIS Dictionary: generalization. Retrieved from https://support.esri.com/en/other-resources/gis-dictionary/term/generalization

Goldberg, J. H., & Kotval, X. P. (1999). Computer interface evaluation using eye movements: methods and constructs. *International Journal of Industrial Ergonomics, 24*(6), 631-645.

Green, D. R. (1997). Cartography and the Internet. *The Cartographic Journal, 34*(1), 23-27.

Grinstein, G., Kobsa, A., Plaisant, C., Shneiderman, B., & Stasko, J. T. (2003). *Which comes first, usability or utility?* Paper presented at the Proceedings of the 14th IEEE Visualization 2003 (VIS'03).

Haber, R. N., & Hershenson, M. (1973). *The psychology of visual perception*: Holt, Rinehart & Winston.

Harrower, M. (2007). The cognitive limits of animated maps. *Cartographica: The International Journal for Geographic Information and Geovisualization, 42*(4), 349-357.

Holmqvist, K., Nyström, M., Andersson, R., Dewhurst, R., Jarodzka, H., & Van de Weijer, J. (2011). *Eye tracking: A comprehensive guide to methods and measures*: OUP Oxford.

Howard, D., & MacEachren, A. M. (1996). Interface design for geographic visualization: Tools for representing reliability. *Cartography and Geographic Information Systems, 23*(2), 59-77.

Irwin, D. E. (2004). Fixation location and fixation duration as indices of cognitive processing. *The interface of language, vision, and action: Eye movements and the visual world, 217*, 105-133.

Jenny, B., Terribilini, A., Jenny, H., Gogu, R., Hurni, L., & Dietrich, V. (2006). Modular web-based atlas information systems. *Cartographica: The International Journal for Geographic Information and Geovisualization, 41*(3), 247-256.

Kaspar, F., Müller-Westermeier, G., Penda, E., Mächel, H., Zimmermann, K., Kaiser-Weiss, A., & Deutschländer, T. (2013). Monitoring of climate change in Germany–data, products and services of Germany's National Climate Data Centre. *Advances in Science and Research, 10*(1), 99-106.

Köbben, B., & Kraak, M.-J. (1999). *Web cartography: dissemination of spatial data on the web.* Paper presented at the Proceedings of the 2nd AGILE conference on Geographic Information Science, Association of Geographic Information Laboratories in Europe, Roma.

Koua, E. L., & Kraak, M.-J. (2004). *A usability framework for the design and evaluation of an exploratory geovisualization environment.* Paper presented at the Information Visualisation, 2004. IV 2004. Proceedings. Eighth International Conference on.

Koussoulakou, A., & Kraak, M.-J. (1992). Spatia-temporal maps and cartographic communication. *The Cartographic Journal, 29*(2), 101-108.

Kraak, M.-J., & Brown, A. (2003). *Web cartography*: CRC Press.

Kucera, G. (1992). *Time in geographic information systems*: CRC Press.

Langran, G. (1993). Issues of implementing a spatiotemporal system. *International Journal of Geographical Information Science, 7*(4), 305-314.

Liao, H., & Dong, W. (2017). An Exploratory Study Investigating Gender Effects on Using 3D Maps for Spatial Orientation in Wayfinding. *ISPRS International Journal of Geo-Information, 6*(3), 60.

MacEachren, A. M., & Kraak, M.-J. (2001). Research challenges in geovisualization. *Cartography and Geographic Information Science, 28*(1), 3-12.

Maier, U., & Müller-Westermeier, G. (2010). *Verifikation klimatologischer Rasterfelder*: Selbstverl. des Dt. Wetterdienstes.

Max, N. (2005). Progress in scientific visualization. *The Visual Computer, 21*(12), 979-984.

Mitchell, T. (2005). *Web mapping illustrated: using open source GIS toolkits*: " O'Reilly Media, Inc.".

Monmonier, M. (1990). Strategies for the visualization of geographic time-series data. *Cartographica: The International Journal for Geographic Information and Geovisualization, 27*(1), 30-45.

Monmonier, M. (1992). Authoring graphic scripts: Experiences and principles. *Cartography and Geographic Information Systems, 19*(4), 247-260.

Muntz, R., Barclay, T., Dozier, J., Faloutsos, C., Maceachren, A., Martin, J., . . . Satyanarayanan, M. (2003). IT roadmap to a geospatial future, report of the committee on intersections between geospatial information and information technology. *Washington, DC: National Academy of Sciences*.

MURAKOSHI, S. (2006). Digital Map Use and Evaluation from University Students. *Map, Journal of the Japan Cartographers Association, 44*(4), 9-14.

Nielsen, J. (1992). The usability engineering life cycle. *Computer, 25*(3), 12-22.

Nielsen, J. (1994). *Usability engineering*: Elsevier.

Nielsen, J., & Pernice, K. (2009). *Eyetracking Web Usability*: New Riders Publishing.

Nivala, A.-M., Brewster, S., & Sarjakoski, T. L. (2008). Usability evaluation of web mapping sites. *The Cartographic Journal, 45*(2), 129-138.

Nivala, A.-M., Sarjakoski, L. T., & Sarjakoski, T. (2007). Usability methods' familiarity among map application developers. *International journal of human-computer studies, 65*(9), 784-795.

Nocke, T., Sterzel, T., Böttinger, M., & Wrobel, M. (2008). Visualization of climate and climate change data: An overview. *Digital earth summit on geoinformatics*, 226-232.

O'Laughlin, E. M., & Brubaker, B. S. (1998). Use of landmarks in cognitive mapping: Gender differences in self report versus performance. *Personality and Individual Differences, 24*(5), 595-601.

Opach, T., Gołębiowska, I., & Fabrikant, S. I. (2013). How Do People View Multi-Component Animated Maps? *The Cartographic Journal, 51*(4), 330-342. doi:10.1179/1743277413y.0000000049

Opach, T., Midtbø, T., & Nossum, A. (2011). A new concept of multi-scenario, multi-component animated maps for the visualization of spatio-temporal landscape evolution. *Miscellanea Geographica-Regional Studies on Development, 15*, 215-229.

Open Gaze API (2017).

Park, R. S., & Park, G. E. (1933). The center of ocular rotation in the horizontal plane. *American Journal of Physiology--Legacy Content, 104*(3), 545-552.

Parkes, D., & Thrift, N. J. (1980). *Times, spaces, and places: A chronogeographic perspective*: Wiley.

Peter, B., & Weibel, R. (1999). *Using vector and raster-based techniques in categorical map generalization.* Paper presented at the Third ICA workshop on progress in automated map generalization.

Peterson, M. P. (1995). *Interactive and animated cartography*: Prentice Hall.

Peterson, M. P. (1999). Active legends for interactive cartographic animation. *International Journal of Geographical Information Science, 13*(4), 375-383.

Peterson, T. C., & Vose, R. S. (1997). An overview of the Global Historical Climatology Network temperature database. *Bulletin of the American Meteorological Society, 78*(12), 2837-2849.

Plewe, B. (1997). *GIS online: Information retrieval, mapping, and the Internet*: OnWord Press.

Pred, A. (1984). Place as historically contingent process: Structuration and the time - geography of becoming places. *Annals of the association of american geographers, 74*(2), 279-297.

Roth, R. E. (2015). Interactivity and cartography: A contemporary perspective on user interface and user experience design from geospatial professionals. *Cartographica: The International Journal for Geographic Information and Geovisualization, 50*(2), 94-115.

Roth, R. E., Ross, K. S., & MacEachren, A. M. (2015). User-centered design for interactive maps: A case study in crime analysis. *ISPRS International Journal of Geo-Information, 4*(1), 262-301.

Schröter, D., Zebisch, M., & Grothmann, T. (2005). Climate change in Germany-vulnerability and adaptation of climate-sensitive sectors. *Klimastatusbericht des DWD, 2005*, 44-56.

Silverio, W., & Jaquet, J.-M. (2012). Multi-temporal and multi-source cartography of the glacial cover of Nevado Coropuna (Arequipa, Peru) between 1955 and 2003. *International Journal of Remote Sensing, 33*(18), 5876-5888.

Skupin, A., & Fabrikant, S. I. (2007). Spatialization. *The handbook of geographical information science*, 61-79.

Steinke, T. R. (1987). Eye movement studies in cartography and related fields. *Cartographica: The International Journal for Geographic Information and Geovisualization, 24*(2), 40-73.

Tripp Corbin, G. (2015). *Learning ArcGIS Pro*: Packt Publishing Ltd.

Van Elzakker, C. (2005). *From map use research to usability research in geo-information processing.* Paper presented at the Proceedings of the 22nd International Cartographic Conference, A Coruna, Spain.

Whitefield, A., Wilson, F., & Dowell, J. (1991). A framework for human factors evaluation. *Behaviour & Information Technology, 10*(1), 65-79.

Wolfe, J. M., & Horowitz, T. S. (2004). What attributes guide the deployment of visual attention and how do they do it? *Nature reviews neuroscience, 5*(6), 495.

Zhang, C., & Li, W. (2005). The roles of web feature and web map services in real-time geospatial data sharing for time-critical applications. *Cartography and Geographic Information Science, 32*(4), 269-283.

International Organization for Standardization. (ISO 1997) ‘Ergonomic Requirements for Office Work with Visual Display Terminals (VDTS) – Part 1: General Introduction’ (ISO 9241–1).

ISO (1999) Human-Centered Design for Interactive Systems. (ISO, 13407)

10 Appendix

The attached CD contains the major code for the whole process, which will be stated in three separate sections. The sections are data retrieving and precession, data visualization, examination results processing. The programming language of the first and the third section is Python 3.5, while it of the secondsection is Javascript. The code from HTML and CSS are not included.