Irma Kveladze


# SPACE - TIME CUBE DESIGN AND USABILITY

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Examining committee:
Prof.dr. R. Ahas, University of Tartu
Prof.dr. M.J Dijst, Utrecht University
Prof.dr.ir. M.F.A.M. van Maarseveen, University of Twente
Dr.ir. S.C van der Spek, Delft University of Technology
Prof.dr.ir. M.G. Vosselman, University of Twente

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DISSERTATION

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Irma Kveladze

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This thesis is approved by
**Prof. dr. Menno-Jan Kraak**, promoter
**Dr. Corné P.J.M. van Elzakker**, co-promoter

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# CHAPTER 1

## 1.1 Introduction

The development of spatial or geographical awareness has a long history and comes from the ancient civilization (Walford, 2002). People have used observations, measurements, and recordings to understand and investigate movement behaviours of animals, planets, stars, or other objects, to describe their locations and relations with other events. But, obviously, methods used by earliest civilization for analysing or describing different events and phenomena were different from modern technological possibilities (Andrienko*, et al.*, 2008).

We are living in a world undergoing rapid technological development (Keim*, et al.*, 2008). Over the past decades, we have witnessed increasing achievements of technology that affected the lifestyle of modern society. These developments in present days have become essential due to the active movement of people through geographical space and require navigation systems to orient in environment. In response to human demands, companies also produce a number of generations of mobile devices attracting the attention of society. They propose more and more techniques that are sophisticated and equipped with various tracking devices. Wide availability of inexpensive navigation equipment (mobile phones, digital navigation devices, GPS receivers) enables the collection of information on movements more easy than ever before. These recordings provide accurate location (latitude, longitude, altitude), time and attribute information about objects (humans, animals, vehicles, etc.) anywhere in the world and become essential of transportation systems and navigation on the ground, on the sea and in the air. Thus, such information on change in space is the study interest of experts in various research domains.

These vast amounts of data require adequate methods for proper analysis to investigate movement behaviour of various objects (Andrienko*, et al.*, 2007b). The information that is found in the data is an important and primary source to 'detect the expected and discover the unexpected' (Thomas and Cook, 2005). This requires suitable visual representations and visualization methods for exploration purposes.

Nowadays, a wide range of visual methods as well as interactive techniques, supported by computational algorithms have been developed to support the process of exploration of complex movement datasets (Gudmundsson*, et al.*, 2004; Andrienko*, et al.*, 2007b; Dodge*, et al.*, 2009; Aigner*, et al.*, 2011). They are backing these processes from a different perspective. Despite this, data exploration is essential in the way it can provide answers on where, what and when movements happened, but also on the reasons why it happened, and thus provide insight into a complex spatio-temporal dataset. At the same time, these techniques are focus of interest of usability research, and questions related to the effectiveness, efficiency and user satisfactions are critically important. Although, various evaluation studies on the usability of these visualization techniques have already been executed, usability metrics still remain critical. The major reason is the growing human demands on more exploratory and analytics tools and techniques. Consequently, the developed techniques evoke the necessity of extended usability studies.

## 1.2 Motivation and Problem Statement

Traditionally, in cartography there are three different ways of visualization of spatio-temporal data. Single maps, series of maps and animation maps that represent rapidly moving displays of series of maps (Kraak, 2003). In general, the movement of patterns can be mentally derived from two-dimensional maps, but when we have complex spatio-temporal data, there might be a need for animation. Often, animated maps are the primary choice when data include temporal information and depict changes over time for specific movements (e.g. events, individuals, or groups) (Gudmundsson, 2008). Alternatively, the Space-Time Cube (STC) has the ability to model and represent relationships between movement patterns over space and time (see Figure 1.1).

The idea of the STC originates from the concept of Time Geography (Hägerstrand, 1970) introduced at the end of the last century for studying the spatio-temporal characteristics of human activities. By that time, it was an analytical framework for the exploration of spatio-temporal interactions in people's everyday lives. Until the beginning of this century, the model was used sparsely in studies in human geography (Lenntorp, 1976; Pred, 1977; Thrift, 1977). The reason for this was the poor computational development causing tedious manual drawing and data collection. Later on, technological achievements in Geographical Information Systems (GIS) made the implementation of time geography easier. Clearly, in scientific research, space-time movements acquired significant interest of researchers, and scientists renewed their interest in time geography. Nowadays, a wide range of topics such as migration, gender studies, travel behaviour, archaeology, history, transport accessibility, etc. have accumulated complex movement datasets that require visualization in order to accommodate the extraction of knowledge. For this purpose, the STC is a widely used visual representation. However, there are some fundamental questions to be answered. In particular: why, when and how it should be used for data visualization?

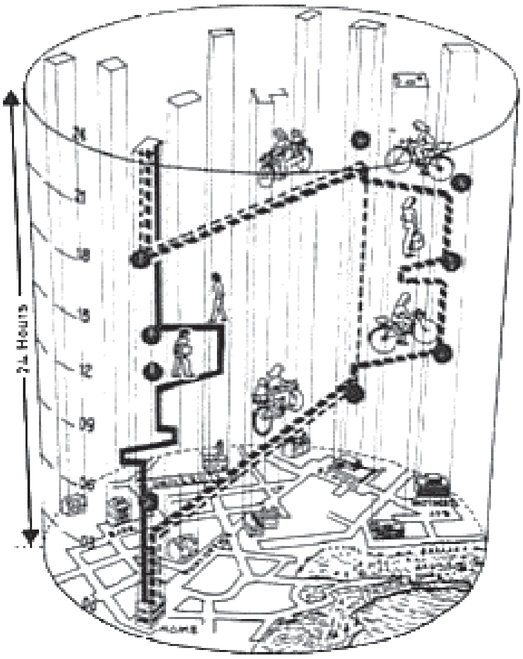



Figure 1.1 In this manually drawing STC, the horizontal axis represents time and the vertical plane at bottom represents space, the movements of people are represented as space-time path. *Source:* URL 13 and URL 14.

The STC can potentially be viewed as one of the most effective ways to deal with the visualization of spatio-temporal data related to movements in order to reveal relationships between objects and to derive meaning. But, to display many relationships simultaneously in a complex dataset leads to visualization problems. At the present time, we have the practical need to explore and analyse large datasets (Andrienko, *et al.*, 2007b), and a GeoVisual Analytics (GVA) environment should be able to support visualization to provide comprehensive information about complex patterns and their relationships (Tomaszewski, *et al.*, 2007). Such purpose is increasingly important and current techniques should satisfy these requirements.

A STC in a GVA environment can support and improve the understanding of and insight into the data represented. Interactive manipulations such as rotate, zoom, time clip, panning, highlight, filter, etc. allow users to find the best possible angle to view the cube and query its content. Additionally querying of the displayed objects, is possible (Huisman, *et al.*, 2009). The GVA environment consists of multiple linked views, dynamically linking the STC content to the views with maps, scatterplots, parallel coordinate plots, etc. representing the same or other attributes.

The general goal of this research is to develop design guidelines for the STC, which helps to understand the main principles and characteristics of the concept and 'optimize' its use. The design guidelines are suggestions on how to symbolize the data at hand based on the cartographic design theory (Bertin, 1983; MacEachren, 1995; Robinson, *et al.*, 1995; Tufte, 2006; Kraak and Ormeling, 2011). It is hypothesized that the required design is not only linked to the qualitative and quantitative nature of the data, its complexity or volume, but also to particular steps of the visualization strategies and the user task.

In 1996 Shneiderman introduced his 'Information Seeking Mantra' to improve visual analysis workflows. It is based on the steps *overview first, zoom and/or filter* and then *detail on demand.* Because of the data volume the display of data in the overview mode might need a more simple design approach then data in the detail mode. The enormous increased in data availability made Keim*, et al.* (2006) propose a change in the mantras name and steps: 'Visual Analytics Mantra': *Analyse first – Show the important – Zoom, Filter and Analyse further – Details on demand*.

To be able to understand the visualized data one has to choose correct graphical representations of the space-time paths and the stations (see section 2.2). The graphical representations have also a decisive role in aesthetic map composition. Furthermore, the visualization of large and complex datasets often leads to problems with cluttered displays, which may become incomprehensible due to human perceptual limitations. A correctly chosen visualization strategy could overcome these problems. Suggested guidelines that will incorporate the basic principles of cartographic theory, should allow the GVA environments to support, explore and analyse data.

One other important aspect of this research is related to usability. According to Slocum*, et al.* (2001), 'the most sophisticated technology will be of little use if people cannot utilize it effectively.' To be able to develop and evaluate an environment for the STC, the guidelines suggested by User-Centred Design (UCD) (ISO 13407:1999, 1999) can be applied. UCD approach focuses on the investigation of the user tasks and requirements during the early stage of the research to develop usable products. It follows well-determined methods and techniques for the analysis, design, implementation and evaluation of the product until the user is satisfied. The process starts with identification of the needs for UCD, analysis of the requirements to be met and the context of the use. The UCD is an iterative process where steps of product design, implementation and evaluation are compound from the early stage of the research.

Therefore, the success of the proposed design guidelines have to be measured according to its usability by defining how user understand the STC content based on specific tasks in the STC. According to Kraak

(2008b, pp.304), 'lots of testing has to be done, it is likely that the same graphic representation might work for some users with certain tasks in mind, while it might completely fail for others.' Therefore, the STC has to be evaluated. Some usability testing has been done before (Kristensson, *et al.*, 2009; Kjellin, *et al.*, 2010b), but still more is needed to provide clear results on efficiency, effectiveness and user satisfactions. Therefore, the research will provide a detailed and complete usability testing of the developed design guidelines, to determine the user issues and requirements.

## 1.3 Thesis Rationale

The basic rationale of this research is to understand the use of the STC for data visualization and knowledge discovery. Its observed increasing use over the last years motivates us to focus on the systematic study of the utilization of cartographic design theory and visualization strategies for the STC content through intensive usability research.

This thesis intends to contribute to the development of conceptual and methodological knowledge on how to apply cartographic design and visualization strategies for data visualization. The research should lead to the development of guidelines that will provide useful suggestions for the use of the STC for data visualization and exploration.
The next section presents the research objectives that focuses on the construction of the problem solving process. At the same time, research questions will be formulated, as such outlining the rationale of the thesis.

### 1.3.1 Research objectives and research questions

The focus of this research is on the development of effective and efficient visualization strategies and design guidelines through systematic usability studies in specially construct GVA environments to facilitate knowledge extraction from various datasets. To be able to realize this goal, the research is divided in three main objectives.

The first objective is a systematic investigation of relevant research on time geography, geovisualization and usability disciplines to highlight knowledge in theoretical and practical studies.
The second objective is to develop a conceptual framework based on objective 1's findings, by incorporating problem, solution, and evaluation perspectives resulting in the design guidelines and visualization strategies.

The third research objective concerns the evaluation. The evaluation has been split in six phases. The first phase starts from the problem perspective based on the requirement of domain experts. The second phase links to a solution perspective and is based on theoretical visualization knowledge. The third phase of the evaluation focuses of the re-evaluation of the problem and visualization strategy with domain experts to derive workflows for further usability studies. The evaluation of design guidelines and visualization strategies as core components of the conceptual framework are topic of the evaluation during the fifth and sixth phases. Where this last phase explicitly evaluates the constructed GVA environment.

During the evaluation, four test datasets in varying size and complexity based on the real world problems in close cooperation with the owners, the domain experts have been used.
The research objectives and their research questions defined for this research are following:

**Objective I Time Geography and the Space-Time Cube**

To investigate the potential of the STC in a GVA environment, where user tasks and spatio-temporal data at hand are considered as constraints.

RQ 1. What are the fundamental characteristics of the STC and on what principles is it based?
RQ 2. What kinds of applications of the STC have been developed over time? How has the cartographic design theory been applied in the developed applications?
RQ 3. What are the known limitations of the STC, and did this change over time?
RQ 4. What kind of alternative opportunities does the STC offer to represent multi-dimensional combinations of spatio–temporal data in a GVA environment, and what are the functions required?

**Objective II Design Guidelines and Visualization Strategies**

Based on the data complexity and use case scenarios, determine how the visual representation of the STC should look like to represent data effectively and efficiently for a knowledge discovery process. This should result in design guidelines and visualization strategies, which can be applied in a prototype.

RQ 5. What are the suitable visual variables for visualization of the STC content, and how does the complexity and nature of the data influence their use?
RQ 6. How to construct design guidelines based on the cartographic design theory to visualize the content of the STC?
RQ 7. How to apply the design guidelines to effectively and efficiently design the STC content depending on user task scenarios in different contexts? How can the ‘Information Seeking Mantra’ or

'Visual Analytics Mantra' be applied in the workflow of those scenarios?

RQ 8. How to create a suitable GVA environment with the STC embedded that allows the user to execute visual and analytical tasks?

**Objective III Evaluation**

To study the usability of the STC incorporated in a GVA environment with other graphic representations, based on user task scenarios.

RQ 9. What are the requirements of domain experts to visualize movement data?

RQ 10. How can the visual variables be used to represent the content of the STC resulting in design guidelines, and what is the influence of selected workflows defined be domain experts?

RQ 11. How do the domain experts judge the suggested design guidelines while executing their visualization strategy, and what additional requirement did they voice?

RQ 12. What is the opinion of geovisualization experts on the revised design guidelines in respect to the visual variables in the context of the STC environment?

RQ 13. How was the implementation of the design guidelines and visualization strategies in the STC appreciated?

RQ 14. How was the implementation of the design guideline and visualization strategies in the STC as part of a GVA environment appreciated?

## 1.4 Structure of the Thesis

The thesis is structured and organized as follows:

CHAPTER 2 reviews the basics of time geography and the STC applications developed so far for spatio-temporal data investigation purposes. Firstly, it focuses on how the basic elements of time geography have been used for the exploration of real world data. Thereafter, it will deal with the question how cartographic design theory has been applied to the basic elements of the STC space-time paths, space-time prisms and stations in order to visualize datasets of different complexity. Also, existing usability issues will be highlighted. In addition, the strengths of GVA environments will be discussed, since combinations of available visualization methods and techniques highly interactive interfaces to deal with common visualization problems of large datasets appear to be promising.

CHAPTER 3 introduces the methodology and conceptual framework that consists of three different parts. The first part focuses on user problems as indicated and presents four different use cases that are used in this research (phase 1). The second part introduces the solution space with two core components: design guidelines and visualization strategies. Besides, it will describe the conceptual approach to the analytical environment for different applications (phase 2). Finally, the methodology for of the evaluation part is presented, of which the main purpose is evaluating the usability of the proposed STC applications at different stages of the development (phase 3, 4, 5, and 6).

CHAPTER 4 presents the first results of a heuristic evaluation of phase 3 executed in close cooperation with domain experts of the use cases. This experiment helped to formulate the final workflows or sequence of steps for each use case study based on the requirements analysis. Based on the analysis of results, the guidelines for the conceptual design and construction of GVA environments were defined.

CHAPTER 5 provides the first evaluation results of phase 4 on the use of cartographic design aspects for the STC contents. In particular, it describes the research that has been done in close cooperation with experts from the geovisualization domain during a focus group evaluation. The results derived from this discussion session helped to reformulate the hypotheses on the use of the visual variables in the STC and prepared for the next step in the usability research.
CHAPTER 6 continues the research on visual variables that started in chapter 5. Based on the redefined hypotheses, this chapter will discuss the task-based evaluation sessions executed with non-expert users of the STC in phase 5. The results derived from these sessions define the most effective design combinations for each evaluated application that was used in the next stage of the usability study.

CHAPTER 7 presents the evaluation results of phase 6 of the developed STC applications in a GVA environment. Based on qualitative and quantitative usability studies their effectiveness efficiency and user satisfactions were evaluated. The test analysis provided feedback on usability metrics and required further improvements.

CHAPTER 8 discusses and summarizes the overall findings and contributions of this research. It gives some key suggestions and recommendations for the STC users by highlighting directions for future studies.

## References

Aigner, W., Miksch, S., Schumann, H. , and Tominski, C. (2011). **Visualization of Time-Oriented Data**. Springer Berlin Heidelberg, London.

Andrienko, G., Andrienko, N., and Wrobel, S. (2007). **Visual analytics tools for analysis of movement data**, 'SIGKDD Explor. Newsl.', 9, 2, pp. 38-46.

Andrienko, N., Andrienko, G., Pelekis, N., and Spaccapietra, S. (2008). 'Basic Concepts of Movement Data', in **Mobility, Data Mining and Privacy - Geographic Knowledge Discovery**, ed. by Fosca Giannotti, D. P., pp. 15-38, Springer Berlin Heidelberg, NY.

Bertin, J. (1983). **Semiology of Graphics: Diagrams, Networks, Maps**. The University of Wisconsin Press, Madison (first published in French in 1967, translated to English by Berg W.J. in 1983).

Dodge, S., Weibel, R. , and Forootan, E. (2009). **Revealing the physics of movement: Comparing the similarity of movement characteristics of different types of moving objects**, 'Computers, Environment and Urban Systems', 33, 6, pp. 419–434.

Gudmundsson, J., Kreveld, van M., and Speckmann, B. (2004). **Efficient detection of motion patterns in spatio-temporal data sets**, in Proceedings of the 12th annual ACM international workshop on Geographic information systems. Washington DC, USA, pp. 250-257.

Gudmundsson, J., Laube, P., Wolle, T. (2008). 'Movement Patterns in Spatio-Temporal Data', in **Encyclopedia of GIS**, ed. by Shekhar, S. and Xiong, H., pp. 726 - 732, Springer US, USA.

Hägerstrand, T. (1970). **What About People in Regional Science?**, 'Papers in Regional Science', 24, 1, pp. 6-21.

Hägerstrand, T. (1975). **Survival and arena: On the life-story of individuals in relation to their geographical environment**, 'The Monadnock', 49, pp. 9-29.

Huisman, O., Feliciano Santiago, I.T., Kraak, M.J., and Retsios, B. (2009). **Developing a Geovisual Analytics Environment for Investigating Archaeological Events: Extending the Space–Time Cube**, 'Cartography and geographic information science', 36, 3, pp. 225-236.

ISO 13407:1999, 1999. **Human-Centred Design Processes for Interactive Systems**.

Keim, D., Andrienko, G., Fekete, J. D., Gorg, C., Kohlhammer, J., and Melancon, G. (2008). 'Visual Analytics: Definition, Process, and Challenges', in **Information Visualization**, ed. by Kerren, A., Stasko, A. T., Fekete, J. D., and North, C., pp. 154-175, Springer Berlin Heidelberg, USA.

Keim, D., Mansmann, F., Schneidewind, J., and Ziegler, H. (2006). **Challenges in Visual Data Analysis**, in 10$^{th}$ International Conference on Information Visualization. London, UK, pp. 9-16.

Kjellin, A., Pettersson, L.W., Seipel, S., and Lind, M. (2010). **Evaluating 2D and 3D Visualizations of Spatiotemporal Information**, 'ACM Transactions on Applied Perception', 7, 3, pp. 1-23.

Kraak, M.J. (2003). **Geovisualization illustrated**, 'ISPRS Journal of Photogrammetry and Remote Sensing', 57, 5-6, pp. 390-399.

Kraak, M.J. (2008). 'Geovisualization and time : new opportunities for the space - time cube', in **Geographic visualization : concepts, tools and applications**, ed. by Dodge, M., McDerby, M., and Turner, M., pp. 293-306, Wiley & Sons, Ltd, UK.

Kraak, M.J. and Ormeling, F.J. (2011). **Cartography : visualization of spatial data**, Third edition ed.: Guilford Press, NY, London.

Kristensson, P.O., Dahlba, N., Anundi, D., Bjornstad, M., Gillberg, H., Haraldsson, J., Martensson, I., Nordvall, M., and Stahl, J. (2009). **An Evaluation of Space Time Cube Representation of Spatiotemporal Patterns**, 'IEEE Transactions on visualization and computer graphics', 15, 4, pp. 696-702.

Lenntorp, B. (1976), **Paths in Space-Time Environments: A Time Geographic Study of Movement Possibilities of individuals.** Lund Studies in Geography, The Royal University of Lund, Sweden.

MacEachren, A.M. (1995). **How Maps Work: Representation, Visualization and Design**. Guilford Press, NY.

Pred, A. (1977). **The Choreography of Existence: Comments on Hagerstrand's Time-Geography and Its Usefulness**, 'Economic Geography', 53, 2, pp. 207-221.

Robinson, A.H., Morrison, J.L., Muehrcke, P.C., Kimerling, A.J., and Guptill, S.C. (1995). **Elements of Cartography**, 6th ed.: Wiley & Sons, NY.

Shneiderman, B. (1996). **The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations**, in the 1996 IEEE Symposium on Visual Languages. BouIder, Colorado, pp. 336 - 343.

Slocum, T.A., Blok, C.A., Jiang, Bin, Koussoulakou, A., Montello, D.R., Fuhrmann, S., and Hedley, N.R. (2001). **Cognitive and usability issues in geovisualization**, 'Cartography and geographic information science', 28, 1.

Thomas, J.J. and Cook, C.A. (2005). **Illuminating the Path: The Research and Development Agenda for Visual Analytics.** IEEE Computer Society, Washington, USA.

Thrift, N. (1977). **An Introduction to Time Geography**. Geo Abstracts Ltd, University of East Anglia, Norwich.

Tomaszewski, B.M., RobinsonA.C., and MacEachren, A.M. (2007). **Geovisual Analytics and Crisis Management**, in Proceedings of the 4th International ISCRAM Conference. Delft, the Netherlands, May 13-16, pp. 173 - 179.

Tufte, E.R. (2006). **Beautiful evidence**. Graphics Press, Cheshire.

URL 13, From: http://www.itc.nl/personal/kraak/

URL 14, From: http://www.spektrum.de/lexikon/geographie/zeitgeographie/9196

Walford, N. (2002). **Geographical data : characteristics and sources**. Wiley & Sons, Chichester.

# CHAPTER 2

# TIME GEOGRAPHY AND THE SPACE - TIME CUBE

*I am looking for a way of finding conceptual coherence in the geographer's understanding of the human world all the way from home to globe and from day to lifetime.*

Torsten Hägerstrand (1975)

## 2.1 Introduction

This chapter starts with a literature review of time geography, and discusses the basic principles of the Space-Time Cube (STC) and its application over time. It also addresses the cartographic design of the STC as well as its use in a GeoVisual analytics environment to support the understanding of complex datasets. The review reveals that currently many different disciplines apply the STC to analyse their spatio-temporal data in a variety of designs and environments. This calls for attention on usability aspects of the STC designs and these environments, as scientific user research focussing on the STC is rather limited.

## 2.2 Time Geography Fundamentals

Time geography is an approach to study human activities in a space-time context and relationships between different constraints influencing people's everyday life. It was originally introduced by the Swedish geographer Torsten Hägerstrand (1970) to study movement of individuals in a spatio–temporal environment. The study of statistics on people's movement convinced Hägerstrand to consider space and time as inseparable resources and to emphasize their complex interactions. Hägerstrand (1970, pp. 10) worded this as: 'time has a critical importance when it comes to fitting people and things together for functioning in socio – economic systems.' Part of the framework he proposed was a novel method of visualization incorporating space and time in a natural visual way. According to Pred (1977, pp. 209), this novel method, the space-time cube, is 'simple in composition and ambitious in design.'

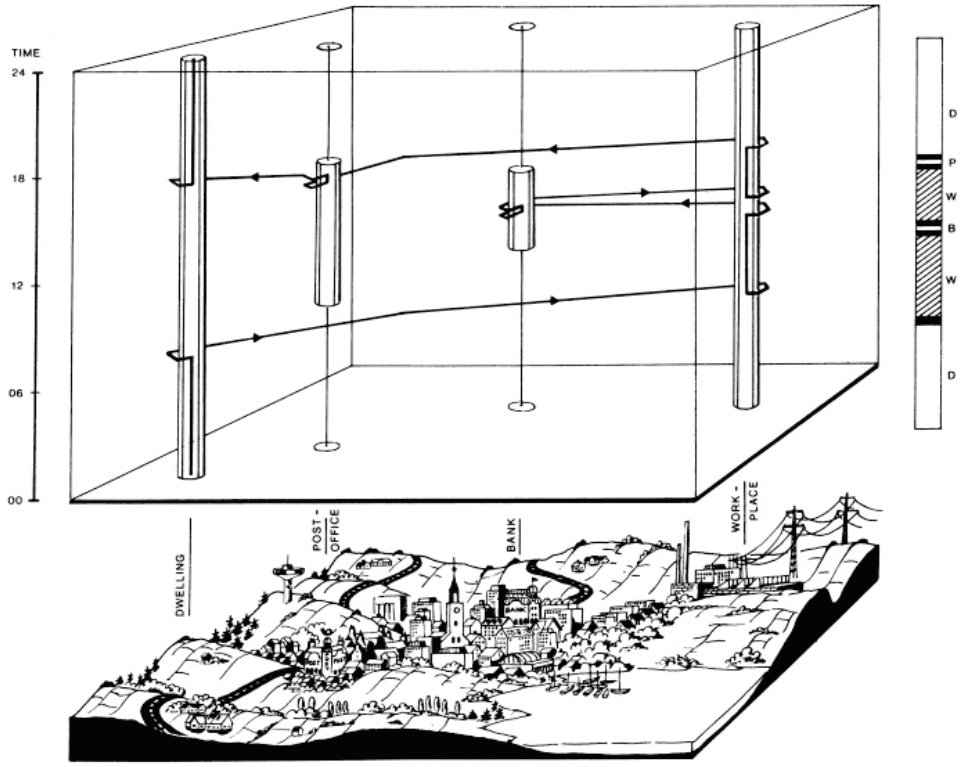



Figure 2.1 Space–time cube, simulation model of a one-day activity of an individual. *Source:* Carlstein, et al. (1978).

The concept of time geography allows one to study movements of an individual or group of individuals in a three-dimensional space. The two-dimensional horizontal plane (x, y) represents the location of an object in space and the vertical plane (t) represents its location in time (t). This representation results in the three-dimensional *Space-Time Cube* (STC) (see Figure 2.1). The concept has three fundamental elements: *Space-Time Path (st-path), Stations* and *Space-Time Prism (st-prism).*

St-path represents the movement through space-time undertaken by an individual. The 'shape' of the trajectory contains information on the nature of the movement. It can answer questions about the where (locations) and when (time), but also about 'how long' and 'how fast'. For instance, a nearly horizontal segment of a path indicates fast movement and a steep segment indicates slow movement. A vertical segment parallel to the 't' axis indicates no movement, i.e. when an individual stays at a certain location (home, workplace, etc.) for some period. These locations are called 'stations.' The reasons of existence and durations of stays at stations may vary (see Figure 2.2 – left).

Another element of time geography is *st-prism*, representing reachable space within an available time budget for an individual. In the STC, it is displayed as a space-time volume showing an individual's activity possibilities within the particular time interval determined between two vertices. An individual's st-prism is known as *Potential Path Space* (PPS) and its projection onto a plane gives an activity area of an individual known as *Potential Path Area* (PPA) (see Figure 2.2 – right).

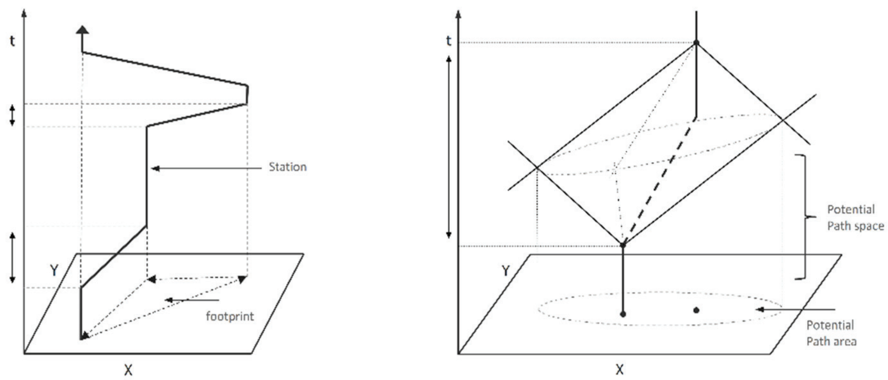



Figure 2.2 Space – time path and stations (left) and space – time prism (right).

The movements described above are influenced by constraints. Hägerstrand (1970, pp. 12-16) distinguished three major types of constraints that influence the freedom of individual activity and the sequence of events in space and time:

- *Capability constraints* are limiting the physiological necessities (eating, sleeping, personal care, etc.) and available resources (mode of transport) of individuals, based on the nature of the constrains.
- *Coupling constraints* are arising due to the temporal interaction between individuals to conduct social, sport and other activities, resulting in activity bundles at a given time and place for particular time period.
- *Authority constraints* is a simple fact that, space occupation is exclusive for every individual with limited stowage capacity of space, i.e. is a general rule or principle that determines who has access at specific time at specific place to do specific things (no individual can be at two different places at the same time and cannot cross walls).

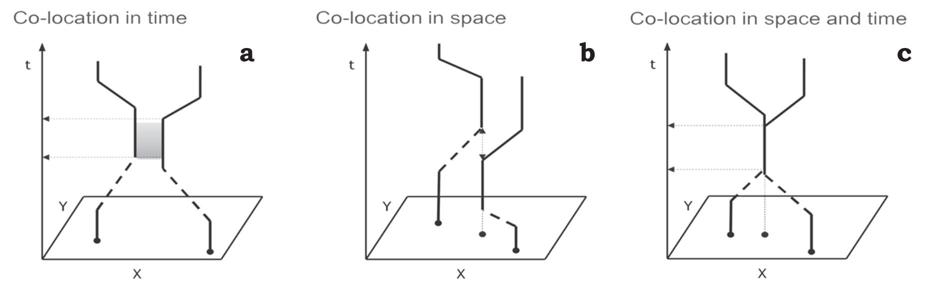



Figure 2.3 Three different models of co – existence in space and time: **a**. co – location in time, **b**. co – location in space, **c**. co – location in space and time. *Source:* Thrift (1977).

Another important notion of the time geography concept is co-existence of individuals in space and time (see Figure 2.3). It refers to the fact that individuals can visit the same location but not necessarily at the same time. Hägerstrand identifies three types of co-existence:

- *Co-location in time,* when individuals occupy the same time interval at a different location (see Figure 2.3a).
- *Co-location in space,* when individuals occupy the same space, but in a different time interval (see Figure 2.3b).
- C*o-location in space and time*, when individuals coexist and occupy the same spatial extent at the same time. When individuals co-locate in space and time they are said to form bundles (see Figure 2.3c).

The fundamental principles of time geography have now be incorporated in human geography (Lenntorp, 1976; Thrift, 1977). In this section the discussion was limited to the principles relevant for the visualization. The next section describes how these basic elements relevant for the visualization have been applied in different applications.

## 2.3 Applications of the STC

### 2.3.1 St-path

Time geography is a useful concept to analyse movement behaviour of various objects and understand ongoing dynamic processes (Miller, 2003). For researching these dynamic processes with real world data Kwan (1999; 2000b), Kraak (2003), Huisman and Forer (1998; 1999), and many others integrated the concept into GIS. Kwan applied the time geography framework to study different ethnic groups of people (see Figure 2.4). In particular, she proposed a GIS-based three-dimensional interactive geovisualization model to analyse spatio-temporal behaviour in individual activity-travel patterns. The model allows a detailed exploration of human movements via interaction and data manipulation. Kwan (2000a) and Kwan and Lee (2004) also used the st-paths to study human cyberspatial (mails, web browsing, etc.) activities based on a multi-scale 3D GIS model. The proposed method can be used to analyse active activity areas through dynamically linked views representing three different scales: local, regional and global. Kraak (2003) applied st-paths for the dynamic visualization of the famous Minard map: 'Napoleone's March on Moscow'. The map developed by Minard is considered as 'the best statistical graph ever drawn' (Tufte, 1983) From a cartographic perspective, it was an inspiration for many cartographers to produce various visualizations of Napoleon's story, but the most prominent application was created in the STC (see Figure 2.5). The trajectories of troops demonstrate the dynamic development of the event. It also shows the stationary places indicating locations of battles or stops.

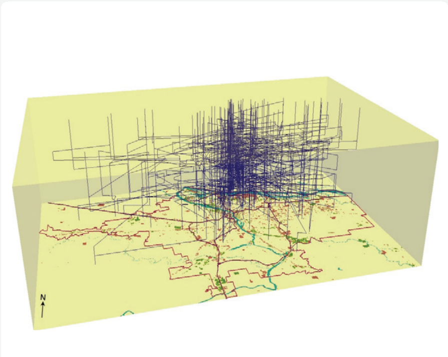


Figure 2.4 Movements of different ethnic groups of people. *Source:* Kwan (2000b).

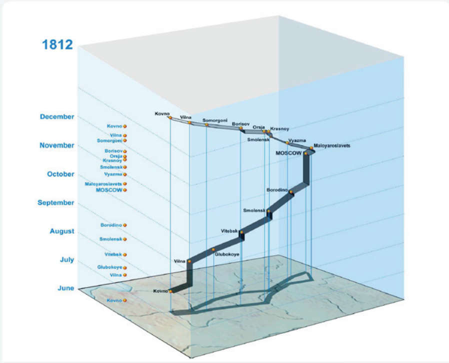



Figure 2.5 'Napoleons march on Moscow.' *Source:* Kraak (2003).

A number of researchers (Shaw and Wang, 2000; Frihida, *et al.*, 2004) analysed the spatio-temporal characteristics of human activities using GIS to explore travel activities. Kapler and Wright (2005) offered the method of visualization to represent and track spatial and temporal activities of objects through an interactive 3D view. Using the concept of time geography, they developed an annotated st-path that contains small images and icons to describe activities of moving objects (see Figure 2.6). In criminology, the method was used to reveal, track and analyse spatio-temporal relationships between suspects. Yu (2006) introduced an extension of the classical st-path as 3D GIS framework to represent human activities in physical and virtual environments. His method of dynamic segmentation can dynamically identify physical and virtual activities on st-paths for the visual exploration of different aspects of human interactions. Based on GIS tools, Shaw, *et al.* (2008) developed the method of generalized st-paths to explore large datasets. It deals with representations of spatio-temporal changes among individuals. Similar to Kapler and Wright (2005), Kraak and He (2009) proposed annotated st-paths to represent qualitative and quantitative characteristics of the data. Using annotations linked to the path, the developed application allows exploration at multiple scales of details through multiple linked views.

Figure 2.6 Annotated st-path. *Source:* Kapler, *et al.* (2008).

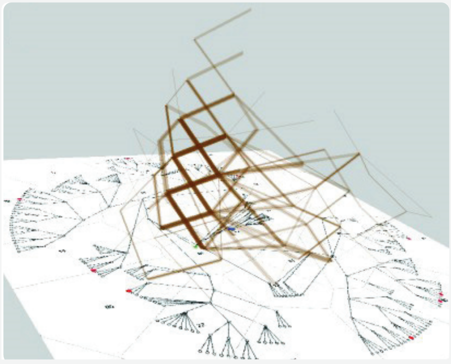


Figure 2.7 Representation of eye tracking data. *Source:* Andrienko, *et al.* (2012a).

Li, *et al.* (2010) applied st-paths to understand spatio-temporal patterns of eye movement data collected during an evaluation study. A visual analysis in the STC revealed behaviour patterns of their test persons not visible in traditional eye tracking analysis visualizations. Similarly, Popelka, *et al.* (2012) used the STC to analyse results of an eye tracking experiment related to the visual perception of map legends. The ScanPaths (GazePlots) derived from the eye movement recordings were represented in the STC to explore test participant's visual behaviours. Andrienko, *et al.* (2012a) studied various methods and tools currently used for the analysis of eye tracking data, among them the STC (see Figure 2.7). They used the STC to discover the areas of frequent sequences in eye tracking data. Based on the results, they advise to use the STC for the comparison of trajectories, general character of movements, display content or structure, etc. during the analysis of eye tracking data.

Orellana, *et al.* (2012) analysed movements of people in a natural recreational area to understand visitors' spatial behaviour with respect to the places of interest (see Figure 2.8). The research aimed to contribute to the knowledge in conservation and recreational development. Analyses show that, despite of many places of interest, only the places of cultural interest and leisure activities and places with information facilities were attracting visitors' attention. Gismondi and Huisman (2012) used st-paths in disaster management. In particular, they studied differences between people's movement behaviour during a post-earthquake period in Japan. The developed visual representation aimed to understand people's movement behaviour during evacuation and recovery processes.

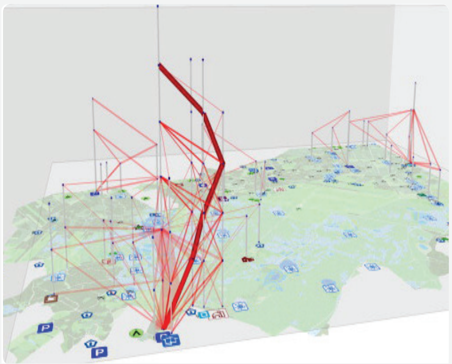


Figure 2.8 Generalized sequential patterns. *Source:* Orellana, *et al.* (2012).

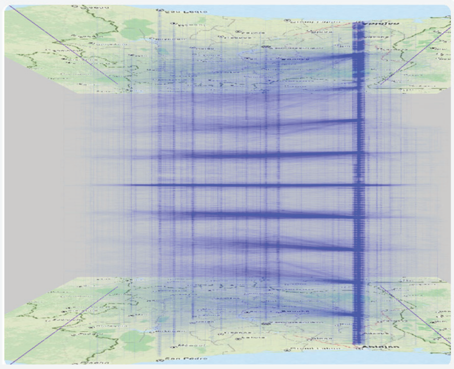


Figure 2.9 Mobile phone records over 20 weeks. *Source:* Andrienko, *et al.* (2013).

Spatio-temporal distributions of large-scale events were identified by Andrienko, *et al.* (2013) from mobile phone call records in Ivory Coast (see Figure 2.9). The analysis of call activities over 20 weeks reveals spatio-temporal locations of peak events mostly related to Islamic and Christian religious holidays. In order to contribute to movement ecology research Dodge, *et al.* (2013) also applied the STC to study the influence of environmental factors such as weather on the movement of birds.

### 2.3.2 Stations

The stations represent non-movement activities and similar to st-paths, have been applied in various domains to study spatio-temporal aspects of the data. For instance, Kwan (2000b) used the station concept to detect the highest concentration of human activity patterns with its temporal duration in Portland metropolitan area when studying gender differences. Gatalsky et al. (2004) studied earthquake events, while applying the station concept, which allowed spatio-temporal analyses of earthquake magnitudes and their distributions in the Marmara region (see Figure 2.10). Another discipline where the STC and the station concept was used is archaeology. Kraak & Koussoulakou (2005) explored the spatio-temporal distribution of excavations in Greece. They developed an application that shows different periods at different locations of old civilizations discovered during the archaeological digs (see Figure 2.11).

Tominski, *et al.* (2005) utilized the station concept to introduce a method of visualization for multiple time dependent data. They used pencil icons to visualize linear time and helix icons to display cyclic time (see Figure 2.12). Both methods are capable to represent temporal dependency and time dependent attributes. The STC was also used for the analysis of the 'Black death' epidemic in the 14th century in Europe (Kraak, 2008b). The developed application clearly demonstrated the beginning and end of the disease with its dramatic losses of people in each country (see Figure 2.13).

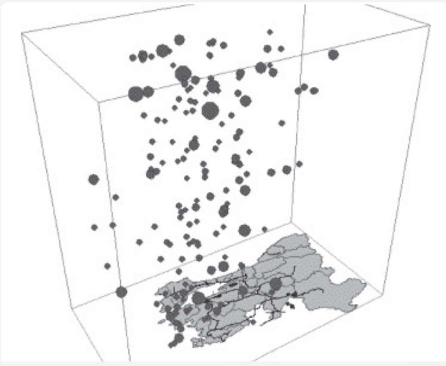


Figure 2.10 Earthquakes in Marmara, Turkey. *Source:* Gatalsky, *et al.* (2004).

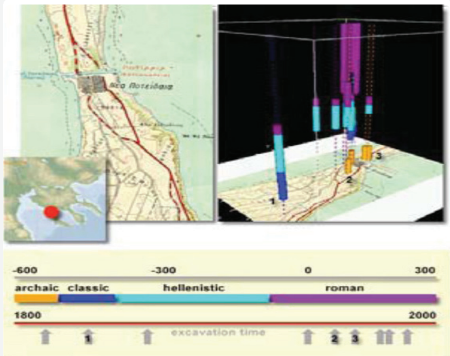



Figure 2.11 Archaeological dugs in Greece *Source:* Kraak and Koussoulakou (2005).

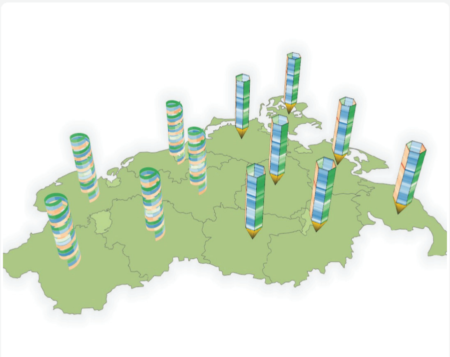


Figure 2.12 Helix & Pencil icons. Source: Tominski, et al. (2005).

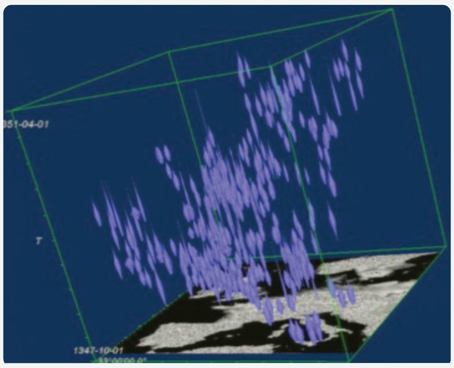


Figure 2.13 Black Death in 14th century Europe. *Source:* Kraak (2008b).

In order to discover landings of migrant boats, Andrienko (2009) presented a density-based method of clustering with interactive visual displays as the mode of visual analytics to analyse spatio-temporal data of point events and movement trajectories. In exploratory data analysis, clustering is a common option to deal with large movement datasets by combining entities with similar properties or behaviors. Similar to Kraak and Koussoulakou (2005), Huisman et al (2009) applied the STC for the analysis of archaeological excavations in Puerto Rico and integrated the STC application in to geovisual analytics environment for better exploration purposes.

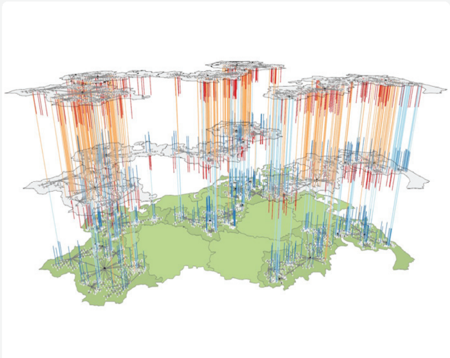


Figure 2.14 Visualization of hierarchies
*Source:* Hadlak, *et al.* (2010).

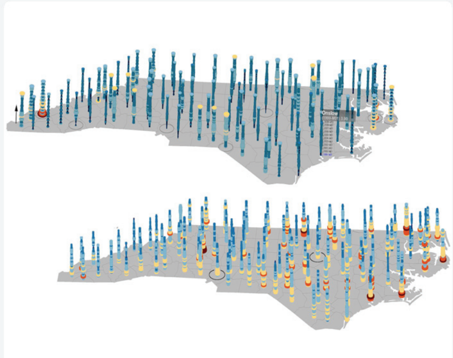


Figure 2.15 3D Glyphs.
*Source:* Thakur and Hanson (2010).

To study a complex health dataset Hadlak, *et al.* (2010) offered the application of temporal hierarchical structures by combining several concepts and techniques including stations. The developed application enables to display integrated temporal, spatial, attribute, and structural aspects of the data for multiple diseases and multiple regions during a single year (see Figure 2.14). Thakur and Hanson (2010) presented a 3D visualization method to display time-varying data (see Figure 2.15). Their proposed method incorporates the 2D 'vases' technique, developed for the visualization of profiles of multiple time-varying data into the STC. This resulted in 3D graphical representation similar to the station concept, so-called glyphs. The method allows various operations (clustering, filtering, etc.) and was developed to deal with large numbers of time-varying data. Ostermann (2010) included the STC in a study of park use patterns by the public for urban planning (see Figure 2.16). The data collected from study areas resulted in occlusion problems on a 2D static map and the STC was selected as an alternative way of visualization. However, the 3D space of the STC also suffered from overlap problems and required interactive manipulation. In order to understand ongoing processes and people's activities on the Flicker photo sharing website, Andrienko, *et al.* (2012b) reconstructed people's past activity traces using analytics tools. Through data analysis, they were able to detect peak activities in mass events taking place in Britain and Ireland over five years. For exploration purposes, several representations were used, among them the STC (see Figure 2.17).

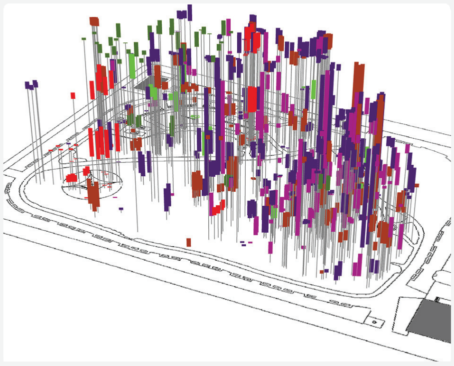


Figure 2.16 Activity types in parks. *Source:* Ostermann (2010).

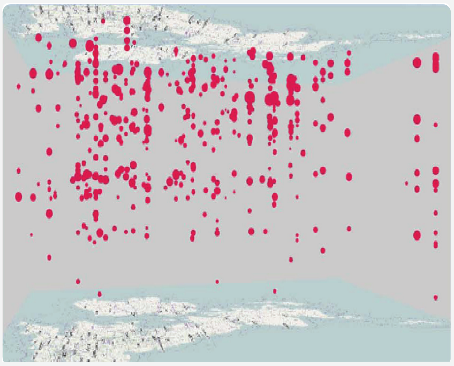


Figure 2.17 Peak activity events in Britain. *Source:* Andrienko*, et al.* (2012b).

### 2.3.3 St - prisms

The st-prism represents the potential space reachable by an individual in a budgeted time period. This concept has been used in a various domains to analyse space-time accessibilities and explore complex space-time activities (Dijst and Vidakovic, 2000; O'Sullivan*, et al.*, 2000; Hornsby and Egenhofer, 2002; Timmermans*, et al.*, 2002; Jacquez*, et al.*, 2005; Ratcliffe, 2006; Hornsby and Li, 2009; Kuijpers*, et al.*, 2011; Dijst*, et al.*, 2013). Huisman and Forer (1998; 1999) applied 'action volumes' or taxels to study accessibility (see Figure 2.18). The taxels in the figure indicate the reachable space by students during an average day in their student life. Miller (1999) applied the space-time prisms to study the accessibility of transport networks. The approach was used in transportation planning and analysis to measure accessibility on the level of an individual. Raubal *et al.* (2004) proposed the framework of an extended theory of affordance based on the ideas of classical time geography. Miller (2005) developed the analytical measurement theory for basic time geography entities and relations. Kuijpers and Othman (2009) used prisms to study object movements that are constrained by movements via roads. Besides, they presented an algorithm that can compute and display prisms for road networks with different speed limits.

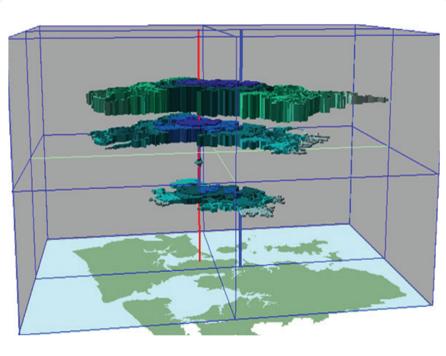


Figure 2.18 Life lines, action volumes. *Source:* Huisman and Forer (1998).

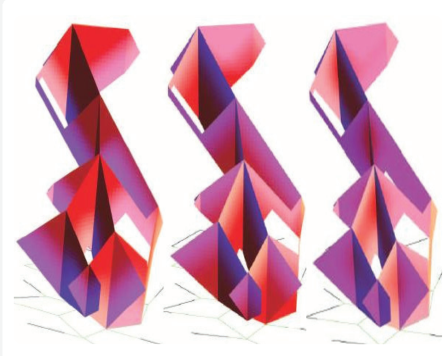


Figure 2.19 St-prism representing fractions. *Source:* Kuijpers, *et al.* (2010).

Neutens (2010) introduced a utility-theoretic model, which 'identifies and measures feasible opportunities for joint activity participation' for a group of people in a certain time period, to 'investigate the interactions between urban structure, life styles and individuals spatial choice.' Kuijpers et al (2010) presented the concept of uncertain space-time prisms or concept of generalized anchor points to anchor regions, and developed algorithms to calculate network-based st-prisms using probabilistic anchor regions (see Figure 2.19).

## 2.3.4 Non-traditional STC applications

Next to the somewhat traditional applications of the STC and its paths and stations some more alternative visualization methods using the STC have been developed as well. In order to extract features from video recordings Gareth and Chen (2003) proposed a stream-based technique or video space-time cube using a volumetric visualization method. For the exploration of human cyberspatial activities Ren and Kwan (2007) developed geovisualization approaches of hybrid 3D space-time paths. Based on the number of visited websites by particular individuals, internet speed and time duration, these authors constructed so-called 'information cubes' (see Figure 2.20). Each information cube is located in a 3D information space that individuals could access, and represents corresponding attribute parameters. Turdukulov, *et al.* (2007) applied the STC concept in meteorology to find patterns, trends and relationships in data of clouds (see Figure 2.21). To improve visual exploration by computational methods, they developed tracking and extraction algorithms to stimulate the process of visual analysis of satellite images. The developed method was intended to improve diagnoses in predicting the behavior of precipitation clouds in meteorology. Zhao, *et al.* (2008) proposed ringmaps as representation of cyclic time to investigate space-time patterns and activities (see Figure 2.22). Ringmaps represent multiple circular sectors, each divided into an equal segment of temporal granularity, and are displaying activity components of the data.

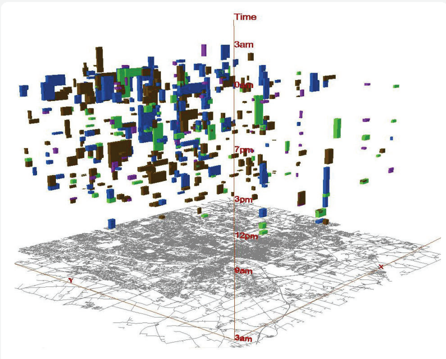


Figure 2.20 Information cubes.
*Source:* Ren and Kwan (2007).

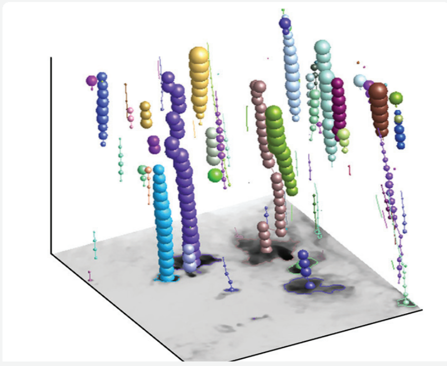


Figure 2.21 Precipitating clouds, glyphs.
*Source:* Turdukulov, *et al.* (2007).

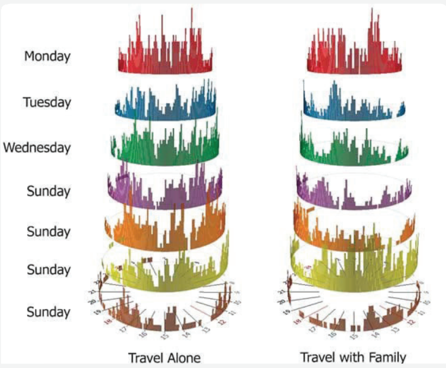



Figure 2.22 Activities, ring-maps.
*Source:* Zhao, *et al.* (2008).

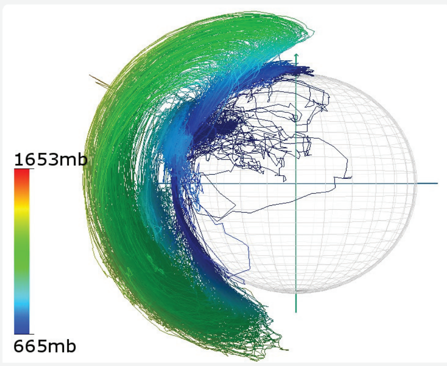



Figure 2.23 Penguin's diving behaviour.
*Source:* Grundy, *et al.* (2009).

Similar to Gareth and Chen (2003), Romero, *et al.* (2008) presented a computational approach of video abstraction of motion. The developed method of spatio-temporal abstraction was used to visualize denser data derived from video cameras in a 3D environment of the activity cube. Another interesting idea of visualization based on the STC concept was developed by Grundy, *et al.* (2009) while studding animal behaviors. In biological research, monitoring of animal behavior through accelerometers containing static and dynamic components is typical and their effective analysis is rather important for biologists. The authors proposed a multi-variety visualization, where data derived from accelerometers are attached to the sphere (see Figure 2.23). To detect geographical extent and temporal duration of patterns in crime data, Nakaya and Yano (2010) used a kernel density estimation method in the

STC. Based on the developed application, the authors could extract information by identifying clusters and analysing space-time crime events. Similarly, based on the kernel density estimation method Demšar and Virrantaus (2010) offered an algorithm of 3D space-time density. The purpose was to overcome the problem of visual clutter in large datasets. The authors applied the algorithm to vessel movement trajectories, based on real world data collected in the Gulf of Finland (see Figure 2.24). The developed method proved to be useful for revealing information regarding to the flows and routes. However, information like direction and speed was not visible.

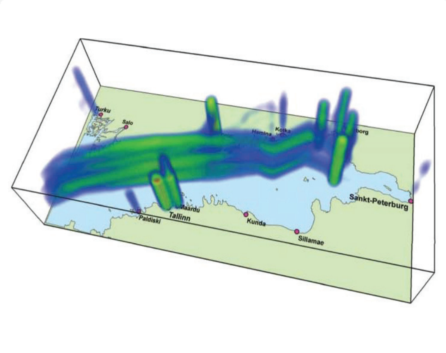



Figure 2.24 Space-time density volume.
*Source:* Demšar and Virrantaus (2010).

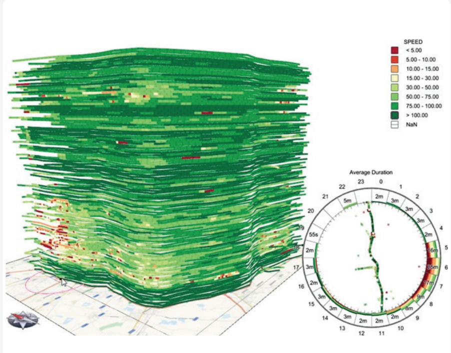


Figure 2.25 Trajectory wall.
*Source:* Andrienko, *et al.* (2014).

One other visual representation for data analysis based on the STC concept was developed by Vrotsou, *et al.* (2010). They implemented a visual representation focusing on stationary points of the st-path as activities. The sequential order of the activities in the developed 3D environment has a time location and duration but ignores geographical space and replaced it with an abstract activity space. To deal with the visualization of large datasets Tominski, *et al.* (2012) and Andrienko, *et al.* (2014) introduced a method called 'trajectory wall' (see Figure 2.25). This method is a useful way to represent spatially similar trajectories. In a case with car traffic data the method proved to be an effective way for the visualization and exploration of large datasets.

## 2.4 Cartographic Design Aspects in the STC

The power of maps is vested in their ability to visually communicate spatio-temporal patterns and relations. Human visual perception will influence how easy the map reader is able to understand the map content. The cartographic design of maps has a great influence on this process. Bertin (1983) was one of the first cartographers who focused on the study of graphical elements of the map and their perceptual properties. According to Bertin (1983), graphics can tell their story using six distinct visual variables (see section 3.4.2). He developed guidelines for their proper use. Over time Bertin's list of visual variables was extended and adapted by others (Morrison, 1984; Caivano, 1994; MacEachren, 1995; Robinson*, et al.*, 1995). These variables are successfully used in many cartographic representations, but their effect in the three-dimensional STC is less known.

The previous section has shown an increased use of the STC due to developments in information technology, and the availability of huge amounts of movement data. However, as many of the examples show this can easily lead to visual clutter in the STC. This is partly caused by the fact that trajectories are identified in three-dimensional space (x, y, t) and are mapped in a two-dimensional view, but also because basic design guidelines are not followed.

Part of this study is focusing on the application of a proper cartographic design to improve legibility. This can be realized by considering the correct use of the visual variables. In addition, due to the three-dimensional nature of the STC one has also to consider the use of depth cues. One can distinguish between depth cues like shading and perspective which can be applied to the graphic content of the cube, and those depth cues which affect the three-dimensional environment of the STC simulated by rotation and even stereo views (Ware, 2008; Goldstein, 2010). Alternatively, one can also think of other visual representations such as density volumes, which aggregate the many paths and stations and reduce the visual clutter. But also here the correct application of the cartographic design rules remains necessary.

The examples in section 2.3 revealed that only a few of the graphic variables have been applied for visualization of STC content. These are color hue (see Figures 2.6, 2.11, 2.12, 2.16, 2.21, 2.22), size (see Figures 2.7, 2.8, 2.10, 2.13, 2.17), color saturation (see Figures 2.14, 2.15, 2.23, 2.24, 2.25) and depth cue transparency (see Figures 2.7, 2.9) and shading (2.5, 2.16, 2.20). Not surprisingly, color is used most. It is one of the most powerful graphical variables due to its perceptual properties (Robinson, 1952; Brewer, 1994; Olson and Brewer, 1997). However, the other graphical variables have useful perceptual properties as well. Bertin (1983) identified four perceptual properties, and by following these studies, this research will evaluate perceptual properties of visual variables for designing the STC content.

Figure 2.26 Movement of different gender groups in Downtown Portland. *Source:* Kwan and Lee (2004).

Another important aspect to consider in designing the cube, is related to the fact that the third dimension is not used for heights as in most three dimensional graphic representations but for time. However, some applications even used both height and time along the same 'z' axis (Kwan and Lee, 2004). For instance, Figure 2.26 represents 3D GIS based STC model to understand movements of different gender groups in Downtown Portland. To supply the reader with detail information on the Downtown area, the base map located on bottom of the STC application represents 3D model of buildings. The cube's vertical axis represents building heights. However, next to these 3D buildings, movement trajectories of individuals are also shown, and now the vertical axis represents time. Although representation looks pleasant, the problem is that double use of the third dimension might confuses the reader. Even though most software that can create a STC is interactive and allows one to rotate the cube, which strengthens the three dimensional impression, it might also lead to some confusion because the user can lose orientation. Thus, a good cartographic design is required to create an informative and attractive STC to allow the user to retrieve information intuitively.

Even without much attention to a systematic design of the STC that considers both cartographic design and 3D depth cues some usability research on the STC has been done. These aspects are discussed in the next section.

## 2.5 Limitations and Usability Issues

The first usability evaluation of an STC was executed by Kristensson, *et al.* (2009). They compared an interactive 2D map with an interactive STC (see Figure 2.27). The experiment focused on how visual representations can provide 'users with an overall understanding of the spatio-temporal patterns in the dataset.' The dataset used consisted of several walking tracks and a campus map. Thirty participants, divided in two groups, were asked a set of questions at different levels of complexity. Most of them could understand the STC better than the 2D map. Despite this, the STC gave more errors for simple and direct queries, but observation time on complex patterns was lower than when using the 2D representation. However, one could argue whether the design of both map and cube were of the same 'quality' for a fair comparison.

Another evaluation was published by Demissie (2010). He compared an animation, STC, single static map, and multiple static maps while searching for the most suitable visual representation of movement features like speed change, return to the same location, stops and returns along the same path. Totally sixteen participants were selected and placed in four groups, one for each visualization method. The results of the tasks execution show a better performance of the animation in almost all aspects, except in visualizing stops and returns to the same path. Here the STC did better.

Kjellin, *et al.* (2010b) compared the 3D STC with an animation and 2D visualization (see Figure 2.28). Test persons had to predict the meeting place of moving objects based on history, and decide in what order the moving objects would arrive at specific locations. The first experiment proved that the 3D STC and animation were less effective than 2D. After this test, the STC content was redesigned and re-evaluated against the same 2D visualization. Despite the STC improvements, the traditional 2D still performed better, but cube did better too. Willems, *et al.* (2011) evaluated the performance of a dot animation, density maps and the STC in their capability to represent maritime movement features: busy lanes, stops and fast movements (see Figure 2.29). Based on the correctness of the answers and their response time it was proved that the STC did not perform as well as they expected. However, the STC was successful in identifying lanes tasks for movement features.

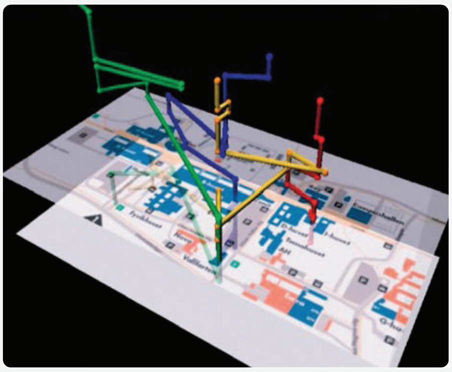


Figure 2.27 Evaluation of the STC & 2D map. *Source:* Kristensson, et al. (2009).

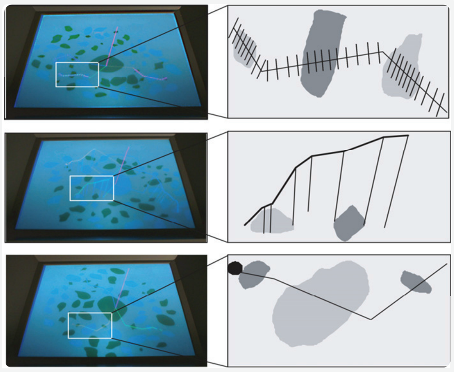


Figure 2.28 Evaluation of the STC, 2D & animation. *Source:* Kjellin*, et al.* (2010b).

In a different experiment Kjellin*, et al.* (2010a) evaluated two versions of a STC, 3D stereoscopic and 3D monocular visualization, with special attention for depth perception (see Figure 2.30). The experiment examined two research questions: first, how suitable is the STC to represent discrete spatio-temporal data, and, second, does the use of only relative size and interposition have the same effect on monocular stereo as it has with binocular. The usability research involved thirty-two test persons. Based on response time and correctness of the answers the experiment proved that in both cases the STC was indeed effective.

Morgan (2010) applied a user centred design approach by involving crime mapping experts and practitioners in an experiment were he tested the usefulness of prisms for the exploration of crime events. Via questions related to crime scenarios he tried to understand how 'the tools of time geography based on the visual representation of the map' worked. Totally, 19 participants were interviewed in an experiment and the results show that prisms were perceived well by the crime mapping experts, but not by practitioners.

In order to study the activities of individuals and to identify temporal patterns in their behaviour, Vrotsou*, et al.* (2010) developed and then evaluated an abstract space based 3D activity-time cube following the STC paradigm. The main purpose of evaluation was to detect whether users are able to identify areas in space with similar characteristics. In the experiment, the test person looked at the cube from three different angles: front, 2D side view, and rotation along a single axis 3D view. Based on typical exploratory tasks, the results show that performance in 3D worked comparatively better than in 2D. Besides, 3D performance can be used for the analysis of complex tasks containing more sequences, while 2D can result in memory overload when task complexity increases.

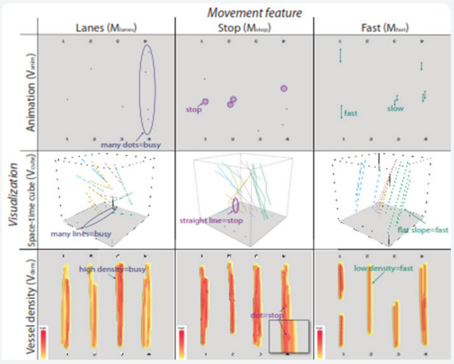



Figure 2.29 Evaluation of the STC, animation & density map. *Source:* Willems, *et al.* (2011).

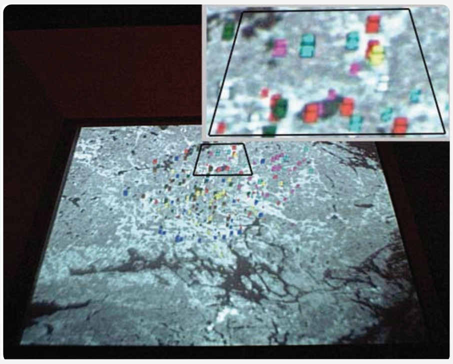


Figure 2.30 Evaluation of the depth cues in the STC. *Source:* Kjellin, *et al.* (2010a).

Despite the increasing popularity of the STC, brought about by hardware and software developments and the data rich environment, usability research still remains limited. Based on the above literature review, what has been done so far is summarized in Table 2.1. In most of these researches, the STC is compared with other graphic representations. The table also lists the user tasks given and the evaluation methods applied.

The studies described mainly focus on the effectiveness of the task performance, but questions related to the cartographic design and its effect on the operational environment are still missing. Only Kjellin's experiments showed that design is also important for effective visualization outcomes (Kjellin, *et al.*, 2010b). In an earlier experiment they discussed aspects of 3D depth cues as well (Kjellin, *et al.*, 2010a). However, they did not consider the cartographic design of the STC content, whereas it is our hypothesis that this will have an impact on the efficiency and effectiveness of the use of the STC. This thesis will look at the usability of the STC from this and from a user-centred design perspective, working with domain experts and real data. Having the domain experts work with their own data in the STC should help to define a workflow and improve the visualization options for the STC. These options need to be evaluated and should lead to recommendations on how to visualize movement data in the STC depending on context and circumstances.

In addition, in this research the STC is not considered as a stand-alone visual representation but as an integrated part of a GeoVisual Analytics (GVA) environment. In order to deal with inherent spatial and temporal components of the data, visualization is closely related to the field of GVA. GVA techniques have the ability to provide exploratory data analysis to detect expected and discover unknown knowledge (Thomas and Cook, 2005; Andrienko, *et al.*, 2007a). This approach has been used for the STC, and the next section focuses on this development.

Table 2.1 Usability research of the STC in existing literature

| Evaluation research | | Kristensson, *et al.* (2009) | Demissie (2010) | Kjellin et al. (2010 a) | Kjellin et al. (2010 b) | Morgan (2010) | Willems et al. (2011) |
|---|---|---|---|---|---|---|---|
| Comparison of STC with: | 2D map | ● | | ● | | | |
| | Single static and multiple static maps | | ● | | | | |
| | Animation | | ● | ● | | | ● |
| | STC 3D stereoscopic | | | | ● | | |
| | STC 3D monocular static | | | | ● | | |
| | Density map | | | | | | ● |
| Tasks applied for evaluation | Simple ‘when’ and simple ‘what + where’ | ● | | | | | |
| | Simple ‘when’ and general ‘what + where’ | ● | | | | | |
| | General ‘when’ and simple ‘what + where’ | ● | | | | | |
| | General ‘when’ and general ‘what + where’ | ● | | | | | |
| | Stops | | ● | | | | ● |
| | Returns | | ● | | | | |
| | Speed change | | ● | | | | |
| | Fast | | | | | | ● |
| | Depicting path | | ● | | | | |
| | Lanes | | | | | | ● |
| | Predict place to meet | | | ● | | | |
| | Estimate order of arrival at place | | | ● | | | |
| | Distinguish spreading of patterns using: interposition and perspective effect | | | | ● | | |
| | Compare and identify patterns using: relative size | | | | ● | | |
| | Search strategy, by locating in space and time | | | | | ● | |
| Evaluation method | User profiling | | | ● | ● | | |
| | User interview | ● | | | | ● | ● |
| | Looking at the results of the task execution | ● | ● | ● | ● | ● | ● |

## 2.6 Towards GeoVisual Analytics

GeoVisual Analytics (GVA) is an interdisciplinary field, integrating Visual Analytics (Thomas and Cook, 2005) and Geographic Visualization (GVis) (MacEachren and Kraak, 2001; Kraak, 2003; MacEachren, *et al.*, 2004; Dykes, *et al.*, 2005). More specifically, it incorporates information and scientific visualization with geographic information science and introduces new techniques for knowledge discovery. GVA was suggested for spatial decision support and defined as the science of analytical reasoning and decision-making on geospatial information, to support situation awareness, representation and computational methods for a visual environment which integrates multiple data sources (Andrienko, *et al.*, 2007a). It facilitates collaboration with different disciplines to progress interactive knowledge construction and management strategies. According to Andrienko*, et al.* (2007a) 'GVA methods and tools must be scalable with respect to the amount of data.' The specific focus of 'spatial decision support' on space and time helps to solve generic research problems (Tomaszewski*, et al.*, 2007).

GVA provides a number of analytical tools to support the exploration of large time dependent information, multivariate attributes and spatial dimensions simultaneously through Multiple Coordinated Views (MCV) (North and Shneiderman, 1997). MCV is a powerful user-interface technique for data exploration where each view focuses on one type of information. By combining the strength of visualization methods with analytical capabilities, the MCV approach can enhance ways of exploration, gain insight into phenomena and operate all in one interface (North and Shneiderman, 2000). According to Andrienko and Andrienko (2007a), the need of MCV's is significant when it comes to investigate large and complex datasets. They offer improved user performance, discovery of unforeseen relationships and unification of desktop (North and Shneiderman, 1997). For instance, Andrienko and Andrienko (2004) offered the software system CommonGIS that can incorporate a two-dimensional map, a STC and various graphs with analytical capabilities in a single interactive environment to support processes of knowledge discovery and to enhance performance (see Figure 2.31). Kapler*, et al.* (2008) demonstrated a prototype GeoTime that integrates dynamically linked diagrams for exploring the workflow of annotated st-paths in the STC (see Figure 2.32). Next to the STC view, non-temporal diagrams are generated, supporting geo-temporal analysis when representing internal relationships in multi-dimensional sets of events. Such a highly interactive environment allows the user to find correlations between objects by selection and highlighting functions. Huisman*, et al.* (2009) introduced a GVA environment and its functions for the STC application to complement the analytical capabilities of this application. The purpose was to integrate space, time, and attribute components of data in a single interactive environment through different visual representations. It could allow users to uncover, for example, spatio-temporal relationships between archaeological artefacts of different periods.

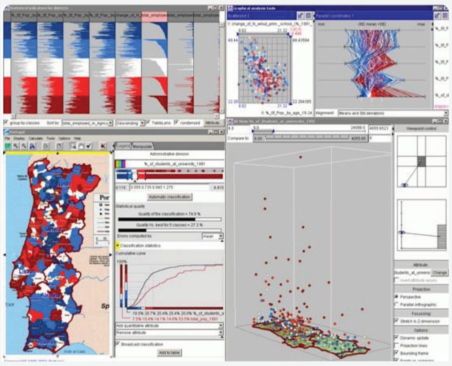


Figure 2.31, Analytical environment in CommonGIS. *Source:* Andrienko and Andrienko (2004).

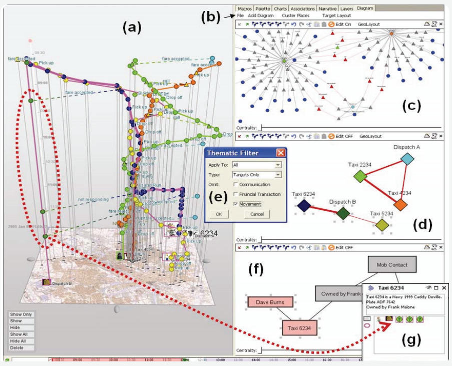



Figure 2.32 Analytical environment in GeoTime. *Source:* Kapler, *et al.* (2008).

The potential of available analytical techniques gives flexibility for interactive visual analysis (Dykes, *et al.*, 2005). However, simultaneous representation of temporal, spatial and thematic aspects of the data still is a challenge even with MCV, and requires a careful selection and usability studies. In the opinion of Andrienko, *et al.* (2007a), the analysis of a large dataset is not yet well supported by existing MCV systems. High interactivity between different dimensions of data in a GVA environment is a significant but complex process. Eventually, the core focus during the implementation should be the involvement of the user. An intensive involvement of the user can ensure to avoid unnecessary mistakes such as ineffective combinations of visualization methods for problem solving, location and quantity of MCV's in developed visual environments and also an overload of human memory and visual system. However, as mentioned before, these assumptions require systematic empirical studies to design and develop highly interactive analytical environments for the STC applications.

Cartographic literature does offer guidelines with explicit suggestions on how to construct MCV's to meet current demands (North and Shneiderman, 1997; Baldonado, *et al.*, 2000; Roberts, 2005b; Andrienko and Andrienko, 2007a). These guidelines are capable to design interactive environments to allow users direct interaction with their data. For instance, Baldonado, *et al.* (2000) indicated the importance of design aspects during the implementation and presented a model for the construction of a multiple view system with three components: selection views, presentation view and interaction among views. To design the coordination between visualization and computations, Shneiderman (1996) proposed the paradigm 'Overview, zoom & filter, details-on-demand.' But, due to the scalability problem Keim, *et al.* (2006) replaced it with 'Analyze First - Show the Important - Zoom, Filter and Analyze Further - Details on Demand' (see section 3.4.1). First comes the necessity of the operations and computations (analyze first) before the visualization of the data (show the important), and then interaction with visualization by zooming and filtering data until the details on demand. However, it is critically important in this process to design computational data analysis methods to consolidate visualizations and make computations more intelligent via human-computer interaction studies.

Human-Computer Interaction (HCI) is a multidisciplinary field that focuses on the improvement of interaction processes between humans and computing systems (Sarmento, 2005). It investigates impacts of computer systems and user interfaces on peoples everyday activities, which helps to design effective interactive systems (Coutaz, 1995; Brown, 1997; Helander*, et al.*, 1997). By deep understanding and gaining knowledge of user problems and requirements, developers are able to produce usable products. Accordingly, Nyerges (1995) distinguishes between the problem domain and tool domain knowledge, i.e. 'those experiences related to spatial problems to be solved and those experiences related to tools read about and/or used.' In problem domain, two types of spatial knowledge can be identified: conventional spatial knowledge that comes from daily experiences, and professional spatial knowledge that comes from educational (discipline) skills. Tool domain knowledge also consists of two types: conventional tool knowledge and professional tool knowledge. The first can be obtained by learning a basic system to operate elements (mouse, keyboard, etc.), while the second one stresses knowledge of communication, such as map control and operation (pan, zoom in/out, etc.) (Nyerges, 1995). The knowledge and experiences derived from users are important for visualization to build useful interactive visual environments.

The field of information visualization is dramatically growing but to create well-designed visualizations is still a challenge to specialists (Helander*, et al.*, 1997; Rogers*, et al.*, 2002). Cartographic literature suggests a range of tools and techniques to design effective interactive visual environments, but the development of comprehensive interactive information visualization must be based on systematic usability studies. The initial starting point of usability research for effective product development is problem determination, while the second step considers the establishment of user requirements and needs through use and user research. These steps are essential in a way that knowledge derived from users can evolve into clear goals to develop applications and continuous cooperation with end users will help to build even more effective interactive visual environments and meet their requirements. These considerations were taken into account carefully when developing the different phases of the conceptual framework that will be described in chapter 3.

## 2.7 Discussion

This chapter sketched the context of the thesis. First, it outlined classical Time Geography as a valuable concept to understand and explore temporal and spatial behavior of movement patterns and introduced a wide range of developed applications. Until the beginning of this century, the STC was only limitedly used, but due to technological developments its popularity has changed. This was illustrated by an extensive overview of applications using the STC, based on its characteristic elements: the st-path, station and st-prism. Despite the fact that st-prism and stations are important concepts of the STC, this research will particularly focus on the use of the st-path.

The importance of a cartographic design applied to the STC content was recommended, including the need to pay attention to the depth cues to improve the three-dimensional perception of the STC. Both will be treated in more depth in chapter 3. Despite its increased popularity, very limited research has been done into the usability of the STC. The research found in literature did not really approach the evaluation from a user centred design perspective. Such an approach is seen as a requirement of this type of research. In addition, the STC should also be seen in the context of a GVA environment, because the cube on its own will not solve most problems addressed by domain experts.

## References

Andrienko, G. and Andrienko, N. (2004). **Research on visual analysis of spatio-temporal data at Fraunhofer AIS: an overview of history and functionality of CommonGIS**, in Proceedings of the Knowledge-Based Services for the Public Services Symposium, Workshop III: Knowledge Discovery for Environmental Managment. pp. 26-31.

Andrienko, G. and Andrienko, N. (2007). **Coordinated Multiple Views: a Critical View**, in Coordinated and Multiple Views in Exploratory Visualization, 2007. CMV '07. Fifth International Conference on. pp. 72-74.

Andrienko, G. and Andrienko, N. (2009). **Interactive spatio-temporal cluster analysis of VAST challenge 2008 datasets**, in Proceedings of the ACM SIGKDD Workshop on Visual Analytics and Knowledge Discovery: Integrating Automated Analysis with Interactive Exploration. Paris, France, pp. 5-11.

Andrienko, G., Andrienko, N., Burch, M., and Weiskopf, D. (2012a). **Visual Analytics Methodology for Eye Movement Studies**, 'Ieee Transactions on Visualization and Computer Graphics', 18, 12, pp. 2889-2898.

Andrienko, G., Andrienko, N., and Fuchs, G. (2013). **Multi-perspective analysis of D4D fine resolution data**, in NetMob 2013, Special session on the D4D challenge. Cambridge, MA, pp. 383-396.

Andrienko, G., Andrienko, N., Jankowski, P., Keim, D., Kraak, M.J., MacEachren, A., and Wrobel, S. (2007). **Geovisual analytics for spatial decision support:**

**setting the research agenda**, 'International journal of geographical information science', 21, 8, pp. 839 - 857.

Andrienko, G., Andrienko, N., Mladenov, M., Mock, M., and Pölitz, C. (2012b). **Identifying Place Histories from Activity Traces with an Eye to Parameter Impact**, 'IEEE Transactions on Visualization and Computer Graphics', 18, 5, pp. 675-688.

Andrienko, G., Andrienko, N., Schumann, H., and Tominski, C. (2014). 'Visualization of Trajectory Attributes in Space–Time Cube and Trajectory Wall', in **Cartography from Pole to Pole**, ed. by Buchroithner, M., Prechtel, N., and Burghardt, D., pp. 157-163, Springer Berlin Heidelberg, USA.

Baldonado, M.Q.W., Woodruff, A., and Kuchinsky, A. (2000). **Guidelines for using multiple views in information visualization**, in Proceedings of the working conference on Advanced visual interfaces. Palermo, Italy, pp. 110-119.

Bertin, J. (1983). **Semiology of Graphics: Diagrams, Networks, Maps**. The University of Wisconsin Press, Madison (first published in French in 1967, translated to English by Berg W.J. in 1983).

Brewer, C. (1994). 'Color use guidelines for mapping and visualization', in **Visualization in Modern Cartography**, ed. by MacEachren, A. M. and Taylor, D. R. F., pp. 123-147, Pergamon, Oxford, UK.

Brown, J. (1997). **Exploring Human-Computer Interaction and Software Engineering Methodologies for the Creation of Interactive Software**, 'SIGCHI Bulletin', 29, 1, pp. 32-35.

Caivano, J.L. (1994). **Towards An Order System For Visual Texture**, 'Languages of Design', 2, 1, pp. 59-84.

Carlstein, T., Parkes, D., and Thrift, N.J. (1978). **Human Activity and Time Geography**. Vol 2, Arnold, London.

Coutaz, J. (1995). 'Evaluation techniques: Exploring the intersection of HCI and software engineering', in **Software Engineering and Human-Computer Interaction**, ed. by Taylor, R. N. and Coutaz, J., pp. 35-48, Springer Berlin Heidelberg, USA.

Demissie, B. (2010). **Geo-Visualization of Movements: Moving Objects in Static Maps, Animation and The Space-Time Cube**. VDM Verlag Dr. Müller, Germany.

Demšar, U. and Virrantaus, K. (2010). **Space-time density of trajectories: exploring spatio-temporal patterns in movement data**, 'International Journal of Geographical Information Science', 24, 10, pp. 1527 - 1542.

Dijst, M. and Vidakovic, V. (2000). **Travel time ratio: the key factor of spatial reach**, 'Transportation', 27, 2, pp. 179-199.

Dijst, M.J., Rietveld, P. , and Steg, L. (2013). 'Individual needs, opportunities and travel behaviour: a multidisciplinary perspective based on psychology, economics and geography', in **The transport system and transport policies**, ed. by Van Wee, B., Annema, J. A., and Banister, D., Edward Elgar, Cheltenham, UK.

Dodge, S., Bohrer, G., Weinzierl, R., Davidson, S., Kays, R., Douglas, D., Cruz, S., Han, J., Brandes, D., and Wikelski, M. (2013). **The environmental-data automated**

**track annotation (Env-DATA) system: linking animal tracks with environmental data**, 'Movement Ecology', 1, 1, pp. 3.

Dykes, J., MacEachren, A., and Kraak, M.J. (2005). **Exploring geovisualization.** Elsevier on behalf of the International Cartographic Association (ICA), Amsterdam.

Frihida, A., Marceau, D.J., and Thériault, M. (2004). **Development of a Temporal Extension to Query Travel Behavior Time Paths Using an Object-Oriented GIS**, 'GeoInformatica', 8, 3, pp. 211-235.

Gareth, D. and Chen, M. (2003). **Video Visualization**, in Proceedings of the 14th IEEE Visualization 2003 (VIS'03). pp. 54.

Gatalsky, P., Andrienko, N., and Andrienko, G. (2004). **Interactive Analysis of Event Data Using Space - Time Cube**, in the 8th international conference on information visualisation. pp. 145-152.

Gismondi, M. and Huisman, O. (2012). **Spatio-temporal behaviour after an earthquake: a case study of Kawaguchi town, Japan**, 'Disaster Prevention and Management', 21, 3, pp. 370-385.

Goldstein, E.B. (2010). **Sensation and perception**. Brooks Cole Publishing, NY.

Grundy, E., Jones, M.W., Laramee, R.S., Wilson, R.P., and Shepard, E.L.C. (2009). **Visualisation of Sensor Data from Animal Movement**, 'Computer Graphics Forum', 28, 3, pp. 815-822.

Hadlak, S., Tominski, C., Schulz, H.J., and Schumann, H. (2010). **Visualization of attributed hierarchical structures in a spatiotemporal context**, 'International Journal of Geographical Information Science', 24, 10, pp. 1497-1513.

Hägerstrand, T. (1970). **What About People in Regional Science?**, 'Papers in Regional Science', 24, 1, pp. 6-21.

Hägerstrand, T. (1975). **Survival and arena: On the life-story of individuals in relation to their geographical environment**, 'The Monadnock', 49, pp. 9-29.

Helander, G., Landauer, T.K., and Prabhu, P.V. (1997). **Handbook of Human-Computer Interaction**. Elsevier Science, NY.

Hornsby, K.S. and Egenhofer, M.J. (2002). **Modeling Moving Objects over Multiple Granularities**, 'Annals of Mathematics and Artificial Intelligence', 36, 1, pp. 177-194.

Hornsby, K.S. and Li, N. (2009). 'Modeling Spatiotemporal Paths for Single Moving Objects', in **Research Trends in Geographic Information Science**, ed. by Navratil, G., pp. 151-167, Springer Berlin Heidelberg, USA.

Huisman, O., Feliciano Santiago, I.T., Kraak, M.J., and Retsios, B. (2009). **Developing a Geovisual Analytics Environment for Investigating Archaeological Events: Extending the Space–Time Cube**, 'Cartography and geographic information science', 36, 3, pp. 225-236.

Huisman, O. and Forer, P. (1998). **Computational agents and urban life spaces: a preliminary realisation of the time-geography of student lifestyles**, 3rd International Conference on GeoComputation, University of Bristol. From: http://www.geocomputation.org/1998/68/gc_68a.htm

Huisman, O. and Forer, P. (1999). **Student Access and Campus Geographies: Operationalising Time-Geography for the Study of University Student Life**, in 20th New Zealand Geographical Society Conference. Palmerston North New Zealand, Hamilton, pp. 153-158

Jacquez, G.M., Greiling, D.A., and Kaufmann, A.M. (2005). **Design and implementation of a Space-Time Intelligence System for disease surveillance**, 'Journal of Geographical Systems', 7, 1, pp. 7-23.

Kapler, T., Eccles, R., Harper, R., and Wright, W. (2008). **Configurable Spaces: Temporal analysis in diagrammatic contexts**, in IEEE Symposium on Visual Analytics Science and Technology, 2008. VAST '08. Columbus, OH, pp. 43-50.

Kapler, T. and Wright, W. (2005). **Geo time information visualization**, 'Information Visualization', 4, 2, pp. 136-146.

Keim, D., Mansmann, F., Schneidewind, J., and Ziegler, H. (2006). **Challenges in Visual Data Analysis**, in 10th International Conference on Information Visualization. London, UK, pp. 9-16.

Kjellin, A., Pettersson, L.W., Seipel, S., and Lind, M. (2010a). **Different Levels of 3D: An Evaluation of Visualized Discrete Spatiotemporal Data in Space-Time Cubes**, 'Information Visualization', 9, 2, pp. 152 -164.

Kjellin, A., Pettersson, L.W., Seipel, S., and Lind, M. (2010b). **Evaluating 2D and 3D Visualizations of Spatiotemporal Information**, 'ACM Transactions on Applied Perception', 7, 3, pp. 1-23.

Kraak, M.J. (2003). **Geovisualization illustrated**, 'ISPRS Journal of Photogrammetry and Remote Sensing', 57, 5-6, pp. 390-399.

Kraak, M.J. (2008). 'Geovisualization and time : new opportunities for the space - time cube', in **Geographic visualization : concepts, tools and applications**, ed. by Dodge, M., McDerby, M., and Turner, M., pp. 293-306, Wiley & Sons, Ltd, UK.

Kraak, M.J. and He, N. (2009). **Organizing the neo - geography collections with annotated space - time paths**, in ICC 2009 : Proceedings of the 24th international cartographic conference ICC : The world's geo - spatial solutions, International Cartographic Association (ICA). Santiago, Chile, pp. 7.

Kraak, M.J. and Koussoulakou, A. (2005). **A Visualization Environment for the Space-Time-Cube**, 'Developments in Spatial Data Handling 11th Intrenational Symposium on Spatial Data Handling'pp. 189-200.

Kristensson, P.O., Dahlba, N., Anundi, D., Bjornstad, M., Gillberg, H., Haraldsson, J., Martensson, I., Nordvall, M., and Stahl, J. (2009). **An Evaluation of Space Time Cube Representation of Spatiotemporal Patterns**, 'IEEE Transactions on visualization and computer graphics', 15, 4, pp. 696-702.

Kuijpers, B., Grimson, R., and Othman, W. (2011). **An analytic solution to the alibi query in the space–time prisms model for moving object data**, 'International Journal of Geographical Information Science', 25, 2, pp. 293 - 322.

Kuijpers, B., Miller, H.J., Neutens, T., and Othman, W. (2010). **Anchor uncertainty and space-time prisms on road networks**, 'International Journal of Geographical Information Science', 24, 8, pp. 1223 - 1248.

Kuijpers, B. and Othman, W. (2009). **Modeling uncertainty of moving objects on road networks via space–time prisms**, 'International Journal of Geographical Information Science', 23, 9, pp. 1095 - 1117.

Kwan, M.P. (1999). **Gender, the Home-Work Link, and Space-Time Patterns of Nonemployment Activities**, 'Economic Geography', 75, 4, pp. 370-394.

Kwan, M.P. (2000a). 'Human Extensibility and Individual Hybrid-accessibility in Space-time: A Multi-scale Representation Using GIS', in **Information, Place, and Cyberspace, Springer Berlin Heidelberg**, ed. by Donald, G. J. and David, C. H., pp. 241-256, Springer Berlin Heidelberg, USA.

Kwan, M.P. (2000b). **Interactive geovisualization of activity-travel patterns using three-dimensional geographical information systems: a methodological exploration with a large data set**, 'Transportation Research Part C: Emerging Technologies', 8, 1-6, pp. 185-203.

Kwan, M.P. and Lee, J. (2004). 'Geovisualization of Human Activity Patterns Using 3D GIS: A Time-Geographic Approach', in **Spatially Integrated Social Science: Examples in Best Practice**, ed. by Goodchild, F. and Janelle, D. G., pp. 48-66, Oxford University Press, Oxford.

Lenntorp, B. (1976), **Paths in Space-Time Environments: A Time Geographic Study of Movement Possibilities of individuals.** Lund Studies in Geography, The Royal University of Lund, Sweden.

Li, X., Çöltekin, A., and Kraak, M.J. (2010). 'Visual Exploration of Eye Movement Data Using the Space-Time-Cube', in **Geographic Information Science**, ed. by Fabrikant, S., Reichenbacher, T., van Kreveld, M., and Schlieder, C., pp. 295-309, Springer Berlin Heidelberg, USA.

MacEachren, A.M. (1995). **How Maps Work: Representation, Visualization and Design**. Guilford Press, NY.

MacEachren, A.M., Gahegan, M., Pike, W., Brewer, I., Cai, G., Lengerich, E., and Hardisty, F. (2004). **Geovisualization for Knowledge Construction and Decision Support**, 'IEEE Comput. Graph. Appl.', 24, 1, pp. 13-17.

MacEachren, A.M. and Kraak, M.J. (2001). **Research challenges in geovisualization**, 'Cartography and geographic information science', 28, 1, pp. 3-12.

Miller, H.J. (1999). **Potential contributions of spatial analysis to geographic information systems for transportation (GIS-T)**, 'Geographical Analysis', 31, pp. 373-99.

Miller, H.J. (2003). **What about people in geographic information science?**, 'Computers, Environment and Urban Systems', 27, 5, pp. 447-453.

Miller, H.J. (2005). **A Measurement Theory for Time Geography**, 'Geographical Analysis', 37, 1, pp. 17-45.

Morgan, D.J. (2010), **A Visual Time-Geographic Approach to the Crime Mapping**. Florida state university, Florida.

Morrison, J.L. (1984). **Applied Cartographic Communication: Map Symbolization For Atlases**, 'Cartographica: The International Journal for Geographic Information and Geovisualization', 21, 1, pp. 44-84.

Nakaya, T. and Yano, k. (2010). **Visualising Crime Clusters in a Space-time Cube: An Exploratory Data-analysis Approach Using Space-time Kernel Density Estimation and Scan Statistics**, 'Transactions in GIS', 14, 3, pp. 223-239.

Neutens, T. (2010). **Space, time and accessibility: analyzing human activities and travel possibilities from a time-geographic perspective**. Ghent University. Faculty of Sciences, Ghent, Belgium.

North, C. and Shneiderman, B., 1997. **A Taxonomy of Multiple Window Coordinations**. University of Maryland: Accessed December 1997.

North, C. and Shneiderman, B. (2000). **Snap-together visualization: a user interface for coordinating visualizations via relational schemata**, in Proceedings of the working conference on Advanced visual interfaces. Palermo, Italy, pp. 128-135.

Nyerges, T.L. (1995). **Cognitive aspects of human - computer interaction for geographic information systems**. Springer, Netherlands.

O'Sullivan, D., Morrison, A., and Shearer, J. (2000). **Using desktop GIS for the investigation of accessibility by public transport: an isochrone approach**, 'International Journal of Geographical Information Science', 14, 1, pp. 85 - 104.

Olson, J.M. and Brewer, C. (1997). **An Evaluation of Color Selections to Accommodate Map Users with Color-Vision Impairments**, 'Annals of the Association of American Geographers', 87, 1, pp. 103-134.

Orellana, D., Bregt, A.K., Ligtenberg, A., and Wachowicz, M. (2012). **Exploring Visitor Movement Patterns in Natural Recreational Areas**, 'Tourism Management', 33, 3, pp. 672-682.

Ostermann, F.O. (2010). **Digital representation of park use and visual analysis of visitor activities**, 'Computers, Environment and Urban Systems', 34, 6, pp. 452-464.

Popelka, P., Brychtova, A., and Brus, J. (2012). 'Advanced Map Optimalization Based on Eye-Tracking', in **Cartography - A Tool for Spatial Analysis** ed. by Bateira, C., pp. 18, InTech, Portugal.

Pred, A. (1977). **The Choreography of Existence: Comments on Hagerstrand's Time-Geography and Its Usefulness**, 'Economic Geography', 53, 2, pp. 207-221.

Ratcliffe, J.H. (2006). **A temporal constraint theory to explain opportunity-based spatial offending patterns**, 'Journal of Research in Crime and Delinquency', 43, pp. 261-291.

Raubal, Martin, Miller, Harvey J., and Bridwell, Scott (2004). **User-Centred Time Geography for Location-Based Services**, 'Geografiska Annaler: Series B, Human Geography', 86, 4, pp. 245-265.

Ren, F. and Kwan, M.P. (2007). **Geovisualization of Human Hybrid Activity-Travel Patterns**, 'Blackwell Publishing Ltd', 11, (5), pp. 721–744.

Roberts, J.C. (2005). 'Exploratory Visualization with Multiple Linked Views', in **Exploring geovisualization**, ed. by Dykes, J., MacEachren, A. M., and Kraak, M. J., pp. 159-180, Elsevier, Amsterdam.

Robinson, A.H. (1952). **The look of maps: an examination of cartographic design**. University of Wisconsin Press, Madison.

Robinson, A.H., Morrison, J.L., Muehrcke, P.C., Kimerling, A.J., and Guptill, S.C. (1995). **Elements of Cartography**, 6th ed.: Wiley & Sons, NY.

Rogers, Y., Sharp, H., and Preece, J. (2002). **Interaction Design: beyond human-computer interaction**, 3rd ed.: Wiley & Sons, NY.

Romero, M., Summet, J., Stasko, J., and Abowd, G. (2008). **Viz-A-Vis: Toward Visualizing Video through Computer Vision**, 'IEEE Transactions on visualization and computer graphics', 14, 6, pp. 1261-1268.

Sarmento, A. (2005). **Issues of Human Computer Interaction**. Idea Group Inc, IGI Global, USA.

Shaw, S.L. and Wang, D. (2000). **Handling Disaggregate Spatiotemporal Travel Data in GIS**, 'GeoInformatica', 4, 2, pp. 161-178.

Shaw, S.L., Yu, H., and Bombom, L. (2008). **A Space-Time (GIS) Approach to Exploring Large Individual-based Spatiotemporal Datasets**, 'Transactions in GIS', 12, 4, pp. 425-441.

Shneiderman, B. (1996). **The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations**, in the 1996 IEEE Symposium on Visual Languages. BouIder, Colorado, pp. 336 - 343.

Thakur, S. and Hanson, A.J. (2010). **A 3D Visualization of Multiple Time Series on Maps**, in Information Visualisation (IV), 2010 14th International Conference. pp. 336-343.

Thomas, J.J. and Cook, C.A. (2005). **Illuminating the Path: The Research and Development Agenda for Visual Analytics.** IEEE Computer Society, Washington, USA.

Thrift, N. (1977). **An Introduction to Time Geography**. Geo Abstracts Ltd, University of East Anglia, Norwich.

Timmermans, H., Arentze, T.T., and Joh, C.H. (2002). **Analysing space-time behaviour: new approaches to old problems**, 'Progress in human geography', 26, pp. 175-190.

Tomaszewski, B.M., RobinsonA.C., and MacEachren, A.M. (2007). **Geovisual Analytics and Crisis Management**, in Proceedings of the 4th International ISCRAM Conference. Delft, the Netherlands, May 13-16, pp. 173 - 179.

Tominski, C., Schulze-Wollgast, P., and Schumann, H. (2005). **3D Information Visualization for Time Dependent Data on Maps**, in Proceedings of the 9th International Conference on Information Visualisation. pp. 175-181.

Tominski, C., Schumann, H., Andrienko, G., and Andrienko, N. (2012). **Stacking-Based Visualization of Trajectory Attribute Data**, 'Visualization and Computer Graphics, IEEE Transactions on', 18, 12, pp. 2565-2574.

Tufte, E.R. (1983). **visual display of quantitative information**. Graphic Press, Cheshire.

Turdukulov, U.D., Kraak, M.J., and Blok, C.A. (2007). **Designing a visual environment for exploration of time series of remote sensing data: In search for convective clouds**, 'Computers & Graphics', 31, 3, pp. 370-379.

Vrotsou, K., Forsell, C., and Cooper, M. (2010). **2D and 3D representations for feature recognition in time geographical diary data**, 'Information Visualization', 9, 4, pp. 263-276.

Ware, C. (2008). **Visual Thinking: for Design**. Morgan Kaufmann, USA.

Willems, N., van de Wetering, H., and van Wijk, J.J. (2011). **Evaluation of the Visibility of Vessel Movement Features in Trajectory Visualizations**, 'Computer Graphics Forum', 30, 3, pp. 801-810.

Yu, H. (2006). **Spatial-temporal GIS design for exploring interactions of human activities**, 'Cartography and Geographic Information Science', 33, pp. 3-19.

Zhao, J., Forer, P., and Harvey, A.S. (2008). **Activities, ringmaps and geovisualization of large human movement fields**, 'Information Visualization', 7, 3, pp. 198-209.

# CHAPTER 3

# CONCEPTUAL FRAMEWORK AND METHODOLOGY

## 3.1 Introduction

The previous chapter described the basics of time geography, zooming in on the Space-Time Cube and its applications with an emphasis on visualization and its analytical potential. Since the purpose of this research is to judge the usability of the STC in different situations this chapter will describe the conceptual framework of a user-centred design approach.

The framework consists of three main parts: problem, solution, and evaluation stage as shown in Figure 3.1.

*The problem* identification or requirement analysis is the first part of a user-centred approach. Based on four use cases with problems defined by domain experts, the user requirements are outlined. The four cases differ in data complexity and data quantity. For each of these cases, experts have formulated questions to be answered, which were translated into defined user tasks to be solved in the proposed solution part.

*The solution* stage describes the environment in which the STC operates. Here, two parts, visualization strategies and design guidelines, which are influencing each other, are emphasized. The visualization strategies offer a methodological approach on how information could be explored to support the task execution. This workflow follows the overview ↔ detail principle (Shneiderman, 1996). The design guidelines suggest 'how to show' the STC content based on the cartographic design theory (Bertin, 1983; MacEachren, 1995). Since the STC is a three dimensional representation, the design should also consider 3D depth perception. This perception can be evoked by a variety of depth cues.

*The evaluation* stage describes the setup of the usability testing of the STC. It consists of six sequential phases. In the first phase, several alternative workflows for each of the four use cases were established in very close cooperation with domain experts. The workflows are composed of steps derived from the visualization strategies.

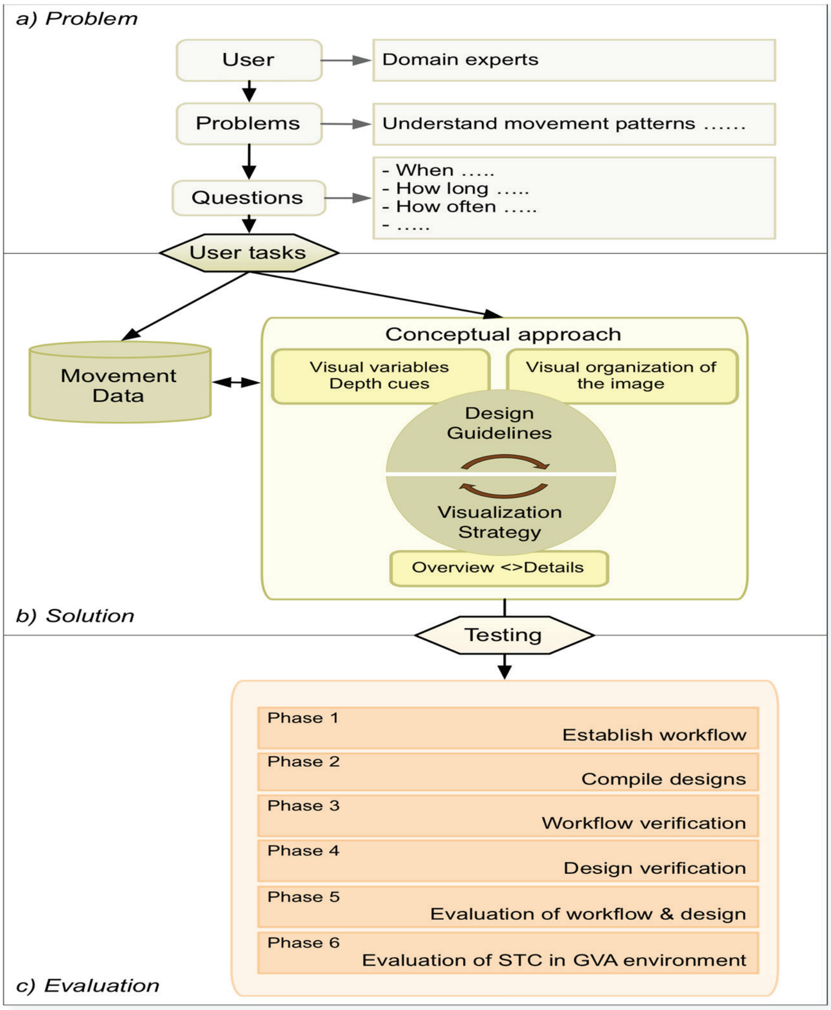



Figure 3.1 Research framework: (a) problem stage, a description of case studies and user defined questions to be answered; (b) solution stage, conceptual framework suggesting visualization strategies and design guidelines; (c) evaluation stage, describing the steps of the evaluation process.

During the second phase, design guidelines are applied to the data. In the third phase, domain experts are revisited to get feedback on the actions of phase 1. Phase 4 involves cartographers and scientists, who are experienced with the STC, to evaluate the designed use case studies from a cartographic and analytical perspective. These persons expressed ideas and remarks about the validity of the cartographic design and implementation in the STC. Phase 5 is a task based session and evaluates verified designs adapted to the workflows with non-expert users. Finally, phase 6 is a usability test with a large group of test persons, representing the end users. The STC will be evaluated in a GVA environment. Here results should lead to clarity about the effectiveness, efficiency and satisfaction of the use of the STC in different circumstances.

## 3.2 User - Centred Design Methodology

### 3.2.1 Fundamentals of a user - centred design approach

According to Norman (1988, pp.188) User-Center Design (UCD) is ‘a philosophy based on the needs and interests of the user, with an emphasis on making products usable and understandable.’ Nielsen (1993) defined usability as a combination of multiple components associated with learnability, efficiency, memorability, errors and satisfaction. ISO 13407:1999 (1999) determines it as ‘an approach to interactive system development that focuses specifically on making systems usable…. the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use.’ From the above definitions, the one proposed by ISO 13407:1999 (1999) has become a main reference that intends to support users in achieving goals through several measurement aspects. See Table 3.1.

According to Bevan (1995), UCD incorporates user characteristics, tasks, workflows and environment in the design process, and follows well-defined usability methods to analyse and evaluate the final product. He defined the quality of use of a product by its effectiveness, efficiency and user satisfaction. These metrics were determined through the context of use that incorporates users, tasks, and environment, i.e. quality of use itself is a result of interaction between user and system while the user is accomplishing a particular task in a technical, physical, or social and organizational environment. Guidance for the UCD process was proposed by Gould and Lewis (1985). They were the first to suggest three principal phases supporting each other in the system design process. It consists of early and continual focus on the user and their tasks, empirical measurement of design products by representative users, and an iterative design of the system until the user is satisfied. Later, this approach was further developed by Nielsen (1993, pp.71) as ‘usability engineering lifecycle.’ According to him, ‘usability cannot be seen in isolation from the broader corporate product development context where one-short projects are fairly rare.’ This is an extended process, which applies to the development of the entire product and consists of twelve different steps (see Figure 3.2).

Table 3.1 Definition of usability metrics, *source*: ISO 13407:1999 (1999) and ISO 9241-11:1998 (1998)

| **Usability measurement type** | **Definition** |
|---|---|
| Effectiveness | The accuracy and completeness with which users achieve specified goals |
| Efficiency | The resources expended in relation to the accuracy and completeness with which users achieve goals |
| Satisfaction | Freedom from discomfort, and positive attitude to the use of the product |
| Context of use | Characteristics of the users, tasks and the organizational and physical environments |
| Goal | Intended outcome |
| Task | Activities required to achieve a goal |

Other guidance for the UCD process was offered by ISO 13407:1999 (1999) (see Figure 3.3). It is based on the four principles of human-centred design processes for interactive systems, as defined by ISO:

⇒ Active involvement of users and a clear understanding of user task requirements. The key point is here an end-user with knowledge of the context where the developed system will be used.

⇒ Appropriate allocation of functions between users and systems. Highlights to determine user demands regarding the tasks. In particular, distinguish between tasks completed by the user and tasks completed by the system.

⇒ Iteration of design solutions. Based on an end user's attempt to complete 'real world' tasks while the system is still in the design process can result in useful feedback to develop it further.

⇒ Multi-disciplinary design. It is important to involve in the process various experts who have insight and knowledge to share about the product. Such teams can include end-users, usability specialists, graphic and interaction designers, task experts, etc.

The model of human-centred design activities developed by ISO 13407:1999 (1999) discusses the process of product development of UCD iteratively until the objectives in terms of the usability metrics will be achieved (see Figure 3.3).

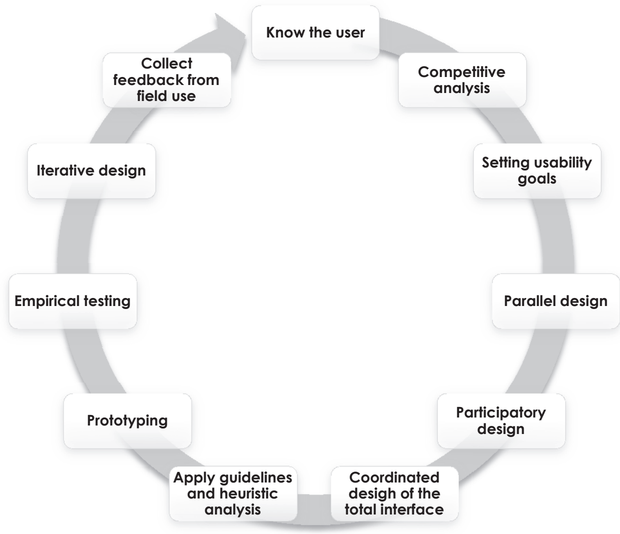



Figure 3.2 Steps of the usability lifecycle. *Source:* Nielsen (1993).

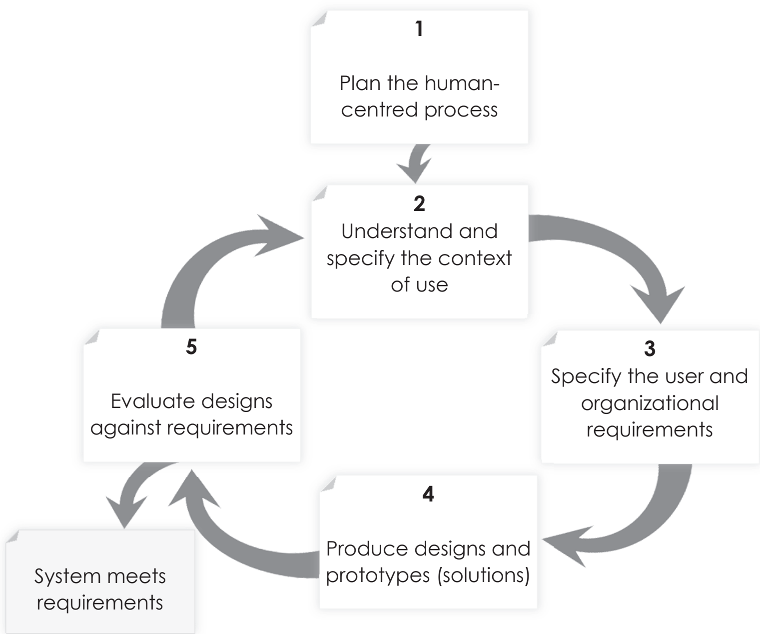



Figure 3.3 Key principles of human-centred design activities, as defined by ISO 13407:1999 (1999).

The iterative lifecycle consists of five substantial steps incorporating UCD activities. The first step considers the integration of different activities of the UCD lifecycle. The second step addresses aspects related to the potential user, their tasks and environment where the product will be used, and the third step specifies user and organizational requirements related to the previous step (context of use). The results of the second and third steps are explicit design solutions (fourth step) that will be evaluated later against requirements (fifth step). The fifth evaluation stage is an essential part of this lifecycle and defines whether the developed product met the requirements initially set. There is a variety of applicable usability evaluation methods, which will be discussed in section 3.2.3.

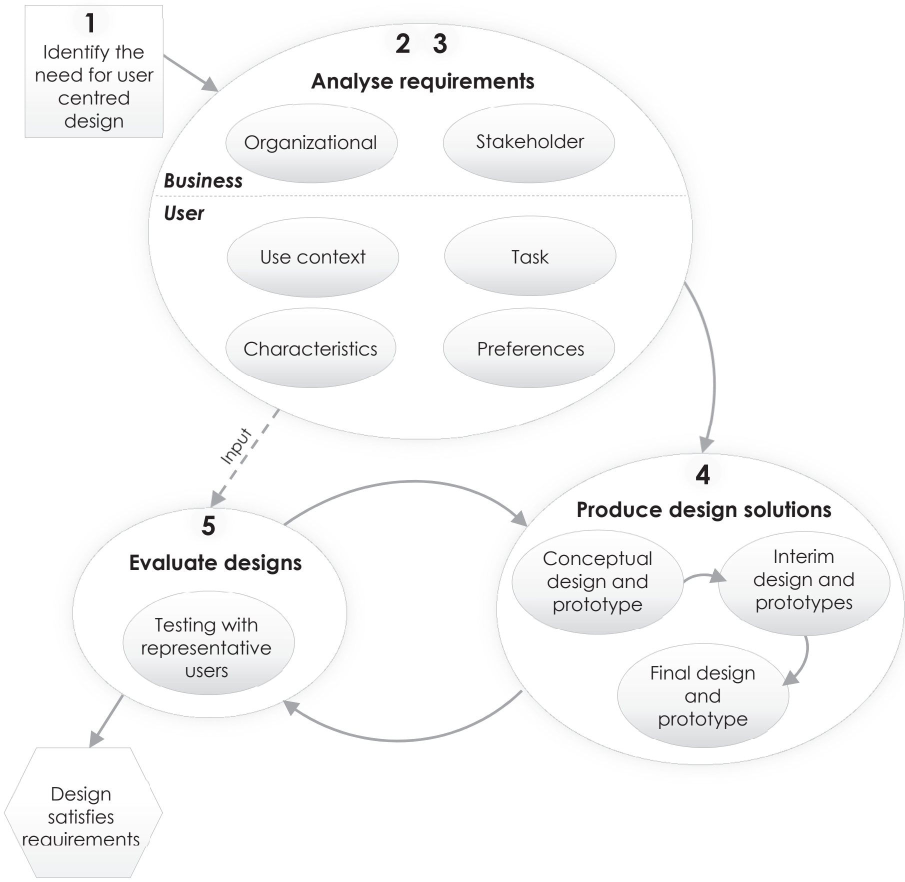



Figure 3.4 UCD process, the bold numbers in the figure refer to the steps in Figure 3.3. *Source:* van Elzakker and Wealands (2007).

As stated by Maguire and Bevan (2002), user requirement analysis is a complex process that analysts are facing with. In accordance to their statement, they proposed a suitable method to generate and validate user requirement analysis through four stages: information gathering of user background, user needs identification from collected data, envisioning and evaluation of developed prototype to validate requirements, and requirements specification.

The UCD lifecycle incorporates a set of activities taking place during the process of product development. Similar to ISO 13407:1999 (1999), van Elzakker and Wealands (2007) also emphasize the significance of requirements in the UCD lifecycle in the context of use, user and organizational demands (see Figure 3.4). However, it differs from the ISO 13407:1999 (1999) approach because it merges the context of use (step 2) and the requirements (step 3) into one 'analyse requirements' stage. When the prototype is designed, it can be iteratively evaluated until it meets the user needs initially identified.

In compliance with the literature described above, it is critically important to understand user needs to achieve a desirable result in user satisfaction, an increase in quality of work and productivity and less training costs. In the context of product development, standards exist to meet technical and functional requirements. Again, it is essential to focus on the needs and interests of potential users. In this regard Norman (1988) further extended the UCD concept by focusing on usability of the design and offering four principles to develop products which help the user to orient in 'what to do' and 'what is going on'. The four principles required in the process of usable designing are:

⇒ Make it easy to determine what actions are possible at any moment.

⇒ Make things visible, including the conceptual model of the system, the alternative actions, and the action results.

⇒ Make it easy to evaluate the current state of the system.

⇒ Follow natural mappings between intentions and the required actions; between actions and the resulting effect; and between the information that is visible and the interpretation of the system state.

Obviously, these principles position the user in the center of the design, while the designer's task is to propose to the user a product that takes little effort to learn how to use it. However, only telling designers that the product proposed to the users should be easy to use and intuitive is not enough. Therefore, Norman (1988, pp.188) came up with other principles for the designers. In particular, these principles are essential to facilitate the designer's task and to guide the process of usable design, as described above. The seven basic principles for designers to go about the task are:

⇒ Use both knowledge in the world and knowledge in the head, based on conceptual models *(design, user, system image)* and instruction manuals.

⇒ Simplify the structure of tasks. This refers to less memory overload by restructuring complex tasks into simple ones, so that the user could keep them under control.

⇒ Make things visible: bridge the gulfs of execution and evaluation. The user should understand the use of an object by seeing the proper buttons or devices required for operations.

⇒ Get the mappings right. To help users understand and determine relationships in an easy way, it is best to use graphics or pictures.

⇒ Exploit the power of constraints, both natural and artificial. To give the user the feeling that there is only one possible thing to do and that is the right thing.

⇒ Design for error. Plan for the errors made by users and think of user actions to step in the right direction. Observe the dialog between user and system and support the user's responses while recovering from errors.

⇒ When everything else fails, standardize. Standardize the actions, systems, problems, outcomes, display, etc. in order to avoid arbitrary mappings. It does not matter how arbitrary the standardized mechanism (calendar, keyboards, etc.) is, because the user only has to learn it once to effectively use it.

UCD is a valuable approach and plays a prominent role in the development of effective and efficient applications. Thus, the above overview of the literature is fundamental for developing our conceptual framework. The key characteristics described are the research focus to build relationships between the different phases of the experiments. By following models of the usability lifecycle as proposed by van Elzakker and Wealands (2007), a set of activities in the process of product development will be realized to achieve usability of the newly presented applications. Thus, the conceptual framework to be developed will consist of six different chronologically ordered phases. The first phase will specify the requirements in terms of contexts of use as shown in the 2$^{nd}$ and 3$^{rd}$ stage of Figure 3.4 (see section 3.3 too). The second phase, as outcome of the previous phase, will provide conceptualized design solutions as visualization strategies and design guidelines to apply to applications to be developed (4$^{th}$ stage of Figure 3.4, see also section 3.4). The third phase aims at evaluating the developed application, to derive further instructions for improvement (5$^{th}$ stage of Figure 3.4, see also chapter 4). The outcome of phase three is the starting point for the next three phases of the research. In particular, the phase four (chapter 5) and phase five (chapter 6) will evaluate the influence of the cartographic design on the STC data content (4$^{th}$ stage of Figure 3.4). While phase six intends to realise further development of the applications and re-evaluate to meet the user requirements (5$^{th}$ stage of Figure 3.4, see also chapter 7). The details of the phases three, four, five, and six are also described in section

3.5. To realize the usability study at different phases it will focus on the evaluation of actual tasks derived from realistic problems identified by the users.

## 3.2.2 Task development

One of the important aspect of UCD process is development of actual tasks for product evaluation. In cartographic literature a wide range of task taxonomies exist that are important for the development of cartographic representation (Casner, 1989; Wehrend, 1990; Casner, 1991; Zhou and Feiner, 1998; Amar, *et al.*, 2005; Roth, 2012). For instance, Wehrend and Lewis (1990) introduce a classification matrix formed by objects and operations for visualization problems and their corresponding techniques. Knapp (1995) offers a task analysis methodology to produce user-oriented visualization software requirements with intuitive designs. The task model he developed consists of six different steps (see Figure 3.5).


Figure 3.5 Six different steps in the task model developed by Knapp (1995).

In another research, based on the activity theory, Gotz and Zhou (2009) 'characterize a user's visual analytic behaviour at multiple levels of granularity based on the semantic richness of user activity.' Their model describes a characterization of user analytic activity and consists of four main steps (see Figure 3.6).

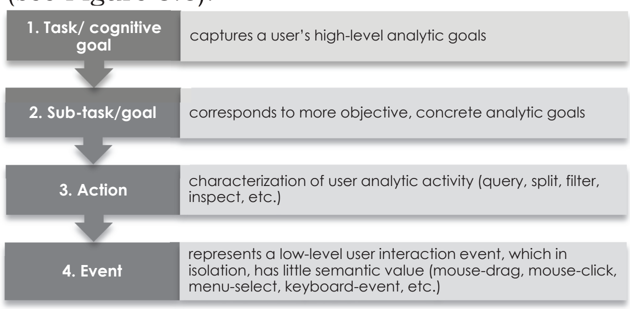



Figure 3.6 Four different steps in the task model developed by Gotz and Zhou (2009).

In this model, the first two levels are considered as high-level logically ordered analytic processes, while the fourth level is considered as a low-level interaction event. The third action level is an executable step that represents user actions performed through visualization tools and domains. Based on the approach of Gotz and Zhou (2009), the focus of this research is to understand the user's analytic behaviour while achieving their particular goal, through sub-tasks and action activity. A different graphic representation will deal with different research questions and their usability metrics will depend on the successful execution of the tasks completed by the user. Consequently, various analytical tasks have to be executed in the developed visual environments to meet the objective of the usability experiments. The task-based experiments will consist of completing analytic / action activities (identify, locate, compare, distinguish, etc.) by the user in the developed visual environment of the STC.

### 3.2.3 Applied methods of user research

To achieve desirable results for product development, one has to consider applying particular methods in the different phases of the usability research. Based on the standards defined by ISO 13407:1999 (1999) (see Figure 3.3), Maguire (2001) suggested a set of user research methods to support the four different UCD phases described above (context of use, requirements, design, and evaluation for product development (see Table 3.2). The same techniques can be used in different stages of the UCD process (e.g. interviews, questionnaires, observations, etc.).

Table 3.2 Methods used in UCD, *Source:* Maguire (2001)

| **Context of use** | **Requirements** | **Design** | **Evaluation** |
|---|---|---|---|
| Identify stakeholders | Stakeholder analysis | Brain storming | Participatory evaluation |
| Context of use analysis | User cost-benefit analysis | Parallel design | Assisted evaluation |
| Survey of existing users | User requirements interview | Design guidelines standards | Heuristic or expert evaluation |
| Field study/user observation | Focus groups | Storyboarding | Controlled user testing |
| Diary keeping | Scenarios of use | Affinity diagram | Satisfaction questionnaires |
| Task analysis | Personas | Card sorting | Assessing cognitive workload |
| | Existing system/ competitor analysis | Paper prototyping | Critical incidents |
| | Task/function mapping | Software prototyping | Post-experience interviews |
| | Allocation of function | Wizard of Oz prototyping | |
| | User, usability and organizational requirements | Organizational prototyping | |

Although other authors also conceived categorizations of user research methods (Holtzblatt and Beyer, 1993; Nielsen, 1993; Butler, 1996; Mayhew, 1999; Maguire, 2001; Wealands, 2007). In conducting user research, generally two approaches can be followed: qualitative and quantitative research. Both methods can be characterized as different by the data collection and analysis techniques they employ. The sub-sections below provide a comparison of these two approaches and present the techniques used in this research.

#### Qualitative research

Qualitative research allows one to examine people's experiences, actions, behaviour, etc. in detail since it provides complex descriptions of experiences gain during the experiment. It focuses on processes that are behind people's behaviour and includes opinions, feelings and emotions to draw a detailed picture of particular reasons or motivations. In-depth qualitative research results help to define why (understand issues), how (describe process or behaviour) or what are the influences, processes or context of users' experiences (Hennink, *et al.*, 2010). The resulting data type as an outcome of qualitative research are often (but not always) transcription documents gathered via oral discussions, interviews, etc. with users and they require interpretative strategies of analysis.

The use of the qualitative research has become common in the field of cartography and geovisualization (van Elzakker, 2004; Lloyd, 2009). The approach is exploratory and is useful to study new products and their issues from different perspectives. Here the combination of qualitative methods of video/audio/screen recordings, think aloud, observation and post experience interviews have been used for phase four (see chapter 4), phase five (see chapter 6) and six (see chapter 7). The focus group discussion allows to identify range of issues, opinions and other information during discussion (see chapter 5). Table 3.3 provides the qualitative methods used in this research project with their objectives, advantages and disadvantages.

Table 3.3 Qualitative research methods used in this research and their objectives, advantages and disadvantages (*source:* Hennink, et al. (2010)

| *Method* | *Objective* | *Advantage* | *Disadvantage* |
|---|---|---|---|
| Focus group | To identify a range of opinions on specific issues or seek community norms | • Group interaction provides a range of issues, opinions and information quickly<br>• Discussion provides detail, justification and clarification<br>• High emancipatory effect | • Less depth of information and less suitable for personal experiences<br>• Managing group dynamics<br>• Hard to analyse |
| Post-experience Interview | To identify an individual's perception, feelings, opinion and experiences | • Gain in-depth information<br>• Identify context and personal experiences<br>• Useful for sensitive issues<br>• Possible to conduct in many situations | • No interaction or feedback from others<br>• Individual perceptions only<br>• Multiple interviews needed to identify a range of issues |
| Think aloud | To understand the mental processes in which users are engaged | • In-depth understanding of cognitive processes<br>• Provides rich qualitative data<br>• User thoughts are immediately voiced and memorized | • Cognitive load of problem solving and speaking may be difficult for some users<br>• Time consuming and difficult to verbalize |
| Observation | To observe how users act and interact in certain situations | • Much contextual and supportive information<br>• Identifies user's actual behaviour<br>• Possible to conduct in many situations | • Interpretation of observations may be subjective<br>• Time consuming and difficult to verbalize |
| Video recording | To memorize users' facial impressions | • Captures user's emotional behaviour during evaluation to obtain more information<br>• Possible to conduct in many situations | • Interpretation of facial impressions without sound may be subjective<br>• Time consuming and difficult to verbalize |
| Audio recording | To memorize sessions for detailed analysis | • Allows to extract more contextual information from captured sessions<br>• Possible to conduct in many situations | • Interpretation of user's voice without facial impression may be subjective<br>• Time consuming and difficult to verbalize |
| Screen recording | To memorize user's manipulation on the screen | • Allows to study and analyse in detail what users did on the screen when interacting with a product<br>• Possible to conduct in many situations | • To understand the reason of particular behaviour on the screen will require user's facial and voice impression<br>• Time consuming and hard to analyse |

**Quantitative research**

Quantitative research intends to measure, quantify and count research issues identified during a usability study. Such results can report user performance and allow to uncover problems in design. Quantitative research relies on statistical analysis and consists in answering questions like: How much? How often? What proportion? Therefore, based on the numbers derived from statistical evidences, it will help to reveal specific usability problems. The nature of quantitative research consists of comparison of performances and usability metrics to measure the users' overall experience. For conducting quantitative user research various methods exist, and Table 3.4 shows those methods that are used in this research. The combination use of task analysis, eye tracking, and pre-selection questionnaire will lead to the efficiency metrics to draw more conclusions in phase five (see chapters 6) and six (see chapters 7).

Table 3.4 Quantitative research methods used in this research and their objectives, advantages and disadvantages (*source:* Nielsen (1993)

| *Method* | *Objective* | *Advantage* | *Disadvantage* |
|---|---|---|---|
| Task analysis | To understand how users perform given tasks to achieve their goals | • Provides rich quantitative data while gathering and organizing information<br>• Focuses on crucial aspects<br>• Obtains knowledge of the tasks that the user wishes to perform<br>• Helps to detect and analyse errors | • Very detailed investigation of complex problems might be time consuming<br>• Requires to develop an approach to measure the results of analysis |
| Questionnaire (pre-selection) | To generate user's background profile | • Obtains user's professional knowledge and experience regarding the object of evaluation<br>• Easy to process | • Less depth of information |
| Eye tracking | To understand how and where users interact with the visual environment | • Provides rich, accurate and quick quantitative data<br>• No training is required | • Eye movements of users with contact lenses, long eye lashes, or narrow eyes have gaze recording problems<br>• Users are limited to move or change their position when eye calibration has been done; abrupt movement will result in data loss<br>• Eye calibration requires time |

**Combination of user research methods**

The evaluation of a product is a complex task and utilization of a single or few methods may not allow to derive reliable results. Thus, combination of several qualitative and quantitative methods will provide comprehensive and meaningful results (Nielsen, 1993). Moreover, the different methods have different potentials and limitations. They will lead to different information about product use and user, but together offer proper information to judge the product. The exact combination of methods depends on the project characteristic. This commonly used approach in UCD enables simultaneous collection of qualitative and quantitative data (van Elzakker, 2004; Wealands, 2007; Delikostidis, 2011). Nowadays, various tools and programs exists that offer multi sensor data capture (URL 6; URL 7) through video, audio and screen recording methods and the eye tracking method (URL 8). These tools have the ability to capture and identify requirements and the context of use of a product while the user is completing a task. For example, according to Benel, *et al.* (1991) an eye tracker can collect data to study on what parts of the screen users are looking at, how long they are looking, what they miss or how their focus is moving from one point to another. Alternatively, applying it in combination with think aloud techniques it can lead to a better understanding of the cognitive process of individual users when completing a particular task. Knowledge derived from such experiments on characteristics and limitations can lead to new scientific hypotheses, which undoubtedly will require usability evaluation for validation. In this research the categorization proposed by Maguire (2001) has been used as the basis for the selection of user research methods, extended with think aloud, eye tracking, screen/video recording methods that are important to study qualitative and quantitative aspects (feelings, confusions, usability problems, etc.) in usability research.

## 3.3 Phase One – Problem Identification with Domain Experts

The problem identification phase focuses on getting a first understanding of the context of use and user requirements. With the help of domain experts problems have been identified in four use cases. Semi-structured qualitative interviews were conducted at the beginning of the project with domain experts of the use cases I, III and IV (see sections 3.3.2, 3.3.4, 3.3.5). The problem for use case II has been identified from existing textbooks. All of the domain experts such as human geographers, urban planners, and researchers on field trips 'struggled' with their movement data. They were aware of the STC and familiar with time geography concepts, but did not have STC tools available, and as such were not experienced with their use.

The domain experts as the owners of the data have formulated research questions that have to be answered. Interviews with the experts were to understand and identify how they intended to analyse their spatio-temporal data. The one-hour interviews sessions at the working location of the experts were the starting-point for developing visualization strategies, with the purpose to get insight into the data, and formulate alternative scenarios for answering the research questions (see Figure 3.7). The scenario itself includes a workflow on 'how to go about' and is linked to the steps of the information seeking mantra (Shneiderman, 1996).

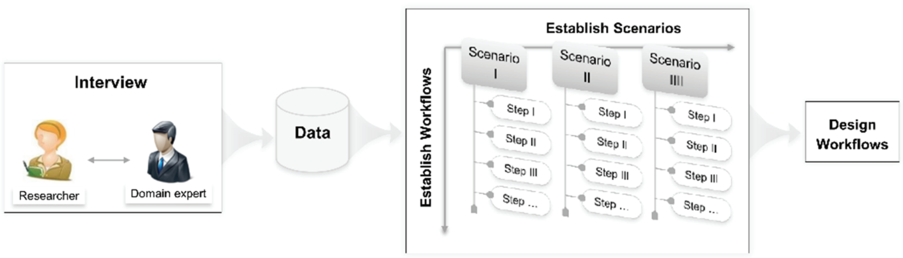



Figure 3.7 Phase one: establishing workflows and scenarios for visualization strategies.

The interview sessions had an introductory character and were aimed at getting familiar with the research activities of the domain experts in their working environment. Main discussions were related to data characteristics, the research problems that experts were facing and the visual representations to support them in solving their problems. Another objective of these discussion sessions was to define time related research questions. The details of these sessions are reported below.

The sessions were not video/audio recorded. The important remarks were noted down and additional documents were collected as well. For each of their research questions, experts were asked to formulate a workflow on 'how to go about data.' In other words, what are the data characteristics that can best answer the defined research questions end extract useful information. They provide relevant attribute characteristics but indicated that the logical workflow of the data needs to be tested in the STC, and if necessary reformulated.

## 3.3.1 Establishing workflows

In this research, a workflow is defined as a set of logically connected consecutive steps or sub-tasks executed by researchers during the exploration of their data. The objective of establishing a workflow is to understand how the researchers approach their problems, and to verify whether the STC's working environment has the necessary functionality. The workflows established for the different use cases are 'calibrated' by the 'Information Seeking Mantra' (Shneiderman, 1996).

In this way, the workflow is an essential component of a visualization strategy that tells how to go about data, and intends to be a helpful guidance for the user to extract information. For each of the use cases a workflow to solve the domain expert's research questions was established in close cooperation with those domain experts. These domain experts were a traveller for the use case 'Estonia,' human geographers for the use case 'Tallinn' and an urban planner for the use case 'Delft.' The experts were visited in their own working environment. As for the use case 'Napoleons march to Moscow,' the research questions and problems were derived from existing literature reported by the researchers of this historical event.

## 3.3.2 Use case I Estonia

#### Data characteristics

The dataset contains an annotated movement trajectory of an individual, collected by a GPS device during a conference visit in Estonia (see Figure 3.8). The given path is characterized by various activities undertaken during the trip, including the use of multiple transport modes. The collected large number of annotations such as pictures, videos, documents and Web information has been linked to the path. The traveler who is interested in analysing the trip while back home is considered as 'domain expert'. In the past, this user worked with Google Maps or some other Web GIS source with particular focus on spatial distribution and statistical analysis of information, such as number of annotations, altitude, etc. for the analysis of his travel log data.

#### Specification of the problem and user requirements

The domain expert identified for this use case study is a researcher in the Faculty of Geo-Information Science and Earth Observation of the University of Twente. He is a frequent traveller who is visiting different countries with scientific objectives such as attending conferences, workshops, lectures, etc. The objective of this user is to understand the spatio-temporal distribution and diversity of his trips based on mode of transport (plane, bus, etc.) and other activities. During the discussion a potential workflow including all data characteristics was set up.

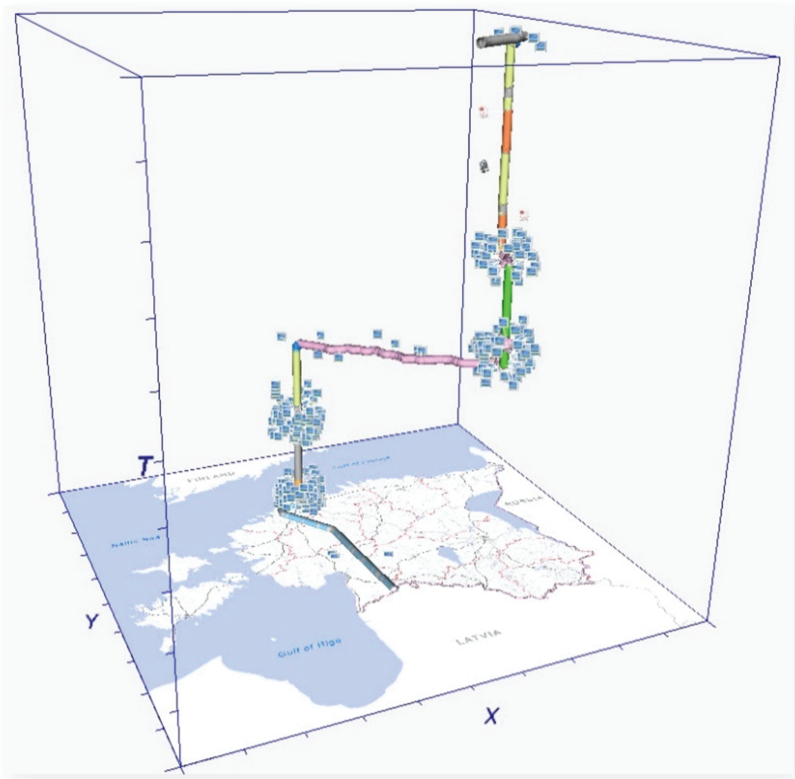



Figure 3.8 Travel log data: Path in Estonia. The colors of the st-path refer to different modes of transport, annotations refer to pictures, videos, and other documents collected during the trip. This STC was created in the uDig software environment.

Potentially, a case like this has many users, since nowadays many people record and annotate their movements, and feel the need to analyse their travel experiences later. These users could be, for example, tourists or scientists collecting data during fieldwork.

## 3.3.3 Use case II Napoleon

**Data characteristics**

These data represent the paths followed by 15 different corps of Napoleon's Grand Army in 1812. Each corps within the Grand Army had its own itinerary to reach its destination (see Figure 3.9 and 3.10). Source for the paths were three different books describing the details of the campaign (Labaume, 2002; Smith, 2002; Zamoyski, 2005). From them information such as routes, time, populated areas, temperature, places of battles, and the number of soldiers for each corps were collected. The data collected can be considered as an extended version of the data Minard used for his famous map (URL 1; Kraak, 2014).

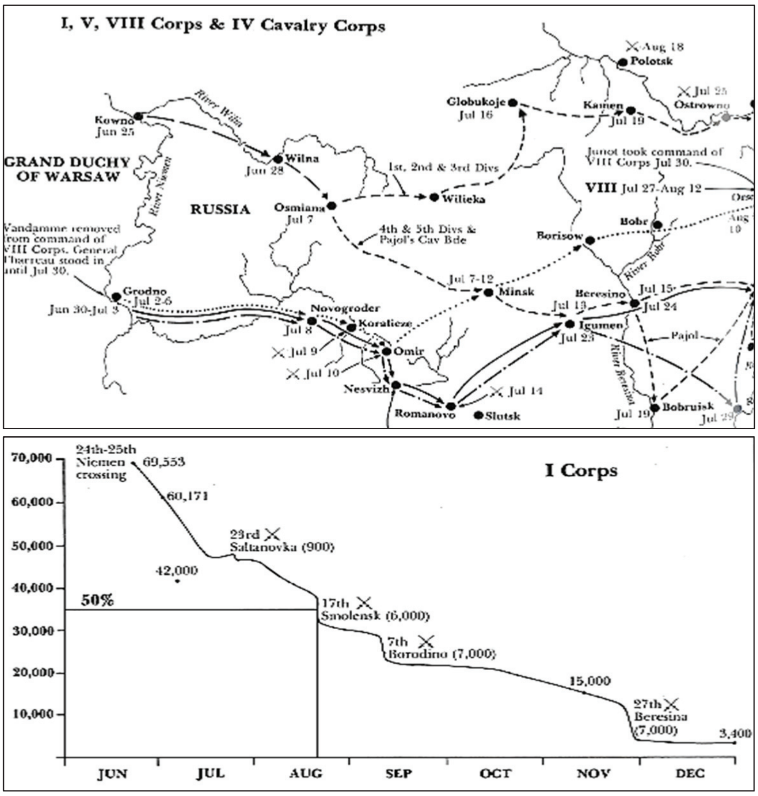



Figure 3.9 The example of original materials, maps and graphs derived from historical sources. *Source:* Smith (2002).

**Specification of the problem and user requirements**

Domain experts are historians interested in the fate of the army. Their objective is to understand the whereabouts of the different corps over time to get insight in the narrative of the campaign. They also want to comprehend the influence of factors such as temperature and battles on the number of soldiers in the different corpses. According to historical sources, the largest influencing factor on the death of the soldiers in the Grand Army was epidemic diseases such as dysentery and typhus. Unfortunately, these sources do not provide any number on the amount of victims caused by diseases. To explore the available data there is a need to develop a visual environment of the scenario to understand this historical event.

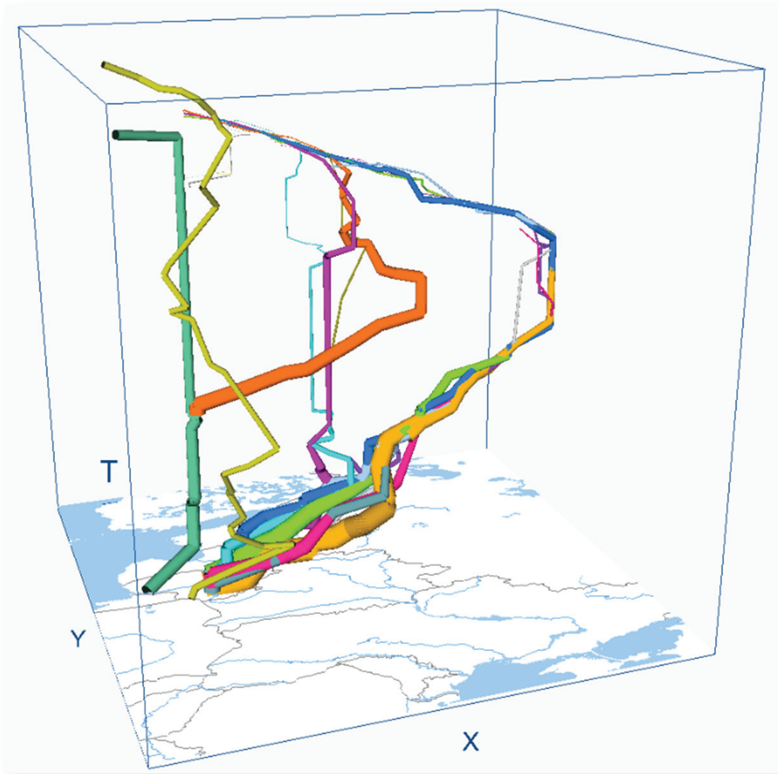



Figure 3.10 Historical event: Napoleon's Russian Campaign. The colored trajectories each represent different corps. The number of soldiers for each corps is indicated by the path width. The STC in this figure was created in the Ilwis software environment.

### 3.3.4 Use case III Tallinn

**Data characteristics**

This complex movement dataset represents 203 trajectories of suburban commuters representing their daily life style (see Figure 3.11). The data were collected over eight days, and include the position of the mobile phones of commuters in the Tallinn district (Estonia). The passive mobile positioning data are automatically stored in the log files of mobile operators, based on the user's phone activity (outgoing/incoming calls, text messages). The commuters had given permission to determine their locations to mobile operators. In a separate online questionnaire, background characteristics of the commuters were collected and linked to their movements. More details can be found at (URL 5; Ahas, *et al.*, 2007a; Ahas, *et al.*, 2007b).

The use case dataset contains information on phone positions between 5th and 12th of April 2006. It also includes positioning time of phones, intervals, and user characteristics (user ID, location, data/time, resident municipality, workplace municipality, number of household members, language, marital status, income, gender, age, education, nationality, occupation). In total, 60,000 points were collected for 277 users positioned within 15 minutes frequency from 06:00AM to 00:00PM, and with 2 hours interval from 00:00PM to 06:00AM. The collected data represent a chronological sequence of people's movements through Tallinn district. Based on the geographical extent of the study area (Tallinn) and the requirements of domain experts, finally 203 movement trajectories were selected for the experiment.

**Specification of the problem and user requirements**

The domain experts are human geographers. Their objective is to understand the spatio-temporal behaviour of different types of suburban commuters during the week. In their optional workflow, the experts considered the background characteristics of suburban commuters as described above but also their places of living and places of working, as derived from the dataset.

Domain experts would prefer to investigate their dataset in an interactive visual environment that allows spatio-temporal analysis. This resulted in their research questions that were defined as follows:

- Which land use patterns are normally separated in urban studies: historical center, central business district, industrial area, shopping center, etc.?
- Which land use patterns can be distinguished with diurnal activities, with weekly data, or with socio-demographic data?

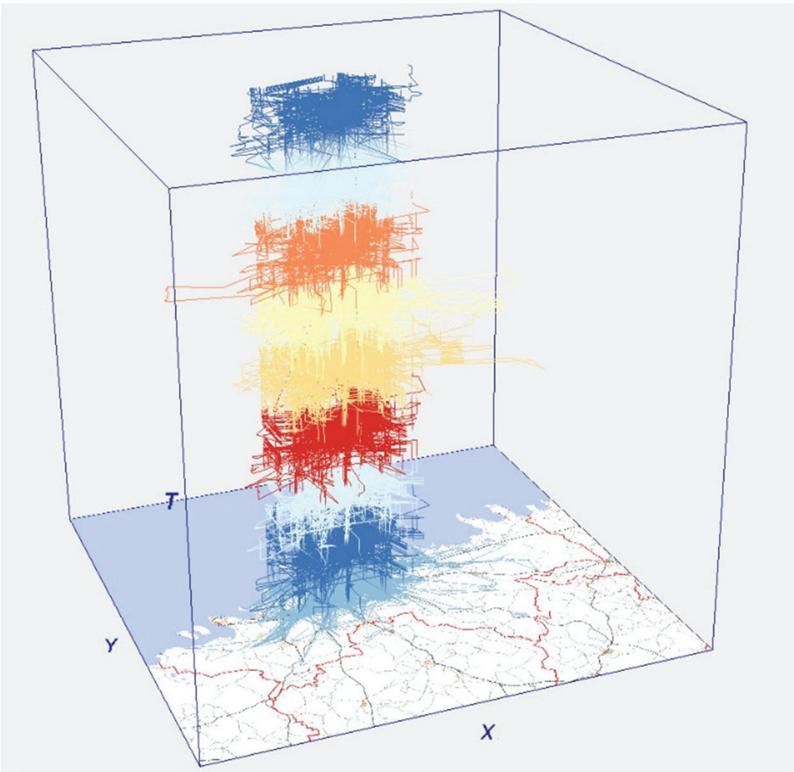



Figure 3.11 Passive mobile phone positioning data of commuters in Tallinn district. The different colors in the STC represent different days. The STC in this figure was created in the Ilwis software environment.

### 3.3.5 Use vase IV Delft

**Data characteristics**

The data represent movement trajectories of people within the city center of Delft, collected with GPS devices. The data were collected to get insight in the shopping and leisure activities of visitors of the city center of Delft. These included neighbourhood residents and tourists. The data were collected within the framework of the 'spatial metro' project of the Faculty of Architecture at Delft University of Technology (TU Delft). The aim was to improve the city center for pedestrians by observing the use of public space. To realise the idea, representatives of TU Delft developed two different methods. The first method was the observation of visitor movements based on GPS tracks. And in a second study pedestrian experiences were collected by using interviews.
Starting point for the data collection were two parking facilities: Zuidpoort and Phoenix. The Zuidpoort garage is located in the very south of the city center (capacity 900 cars) and the Phoenix garage is located on the west

side of the city (capacity 210 cars). The researchers had GPS devices prepared which were handed out to pedestrians willing to participate in the project. They carried the GPS receivers during their walks in the city. After completing the business in the city, they returned to the garage with the GPS receiver and were interviewed. This interview aimed to obtain background information such as gender, age, visit purpose, marital status, etc. Both garages were used simultaneously during one week. The collected data cover four days for 300 pedestrians, between 18th and 21st of November 2009, approximately from 10:00AM to 17:00PM. Highly detailed data on location, time, and movement directions were collected for each participant. Studies of the data have been described by (van der Spek, 2009; van der Spek*, et al.*, 2009; van der Spek*, et al.*, 2013).

**Specification of the problem and user requirements**

The domain expert was an urban planner who was interested in the peoples' movement activities undertaken during these four different days (see Figure 3.12). The objective was to understand the pedestrians spatio-temporal behaviour regarding shopping and leisure activities within the historical city center of Delft. An optional workflow included personal (age, origin, familiarity, etc.), spatial and temporal aspects. This resulted in the following research questions:

- Which routes are used, which destinations are visited and are these results logical compared to the urban analysis: the offered network and set of destinations?
- Why these routes, these destinations? Is this depending on personal aspects, i.e. age, origin, familiarity, or on spatial aspects?
- What is the influence of spatial aspects to the route choice and visiting behaviour? What is the influence of the temporal aspect on these issues?

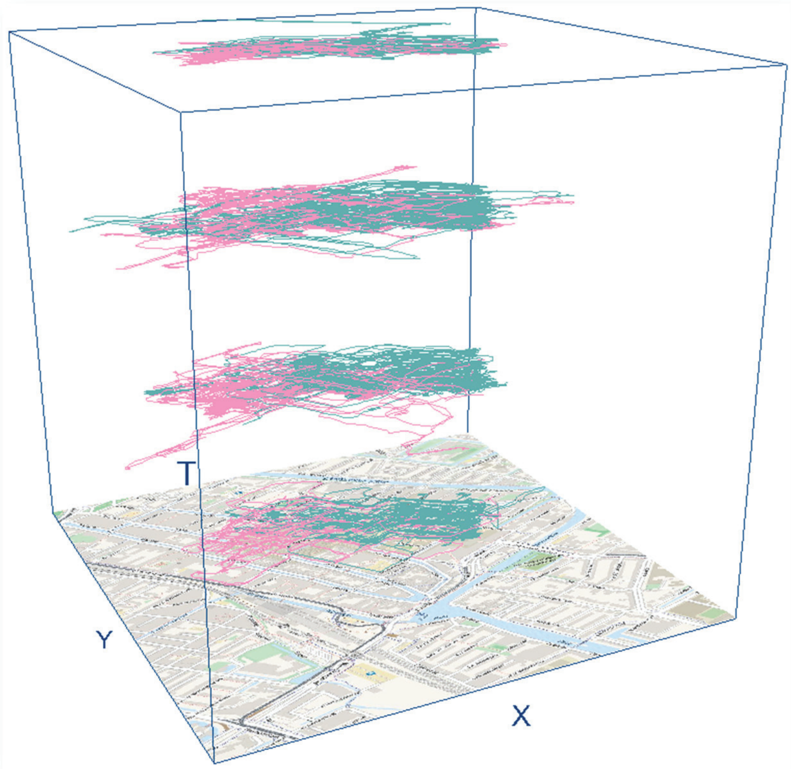



Figure 3.12 Pedestrian movements in Delft city centre. The paths in pink represent pedestrians from Phoenix garage and those in green pedestrians form Zuidpoort garage. The STC in this figure was created in the Ilwis software environment.

## 3.4 Phase Two – Solution Strategy and Design

Once the research questions had been decided and agreed upon with domain experts, an appropriate symbolization for data had to be selected. To do so, a visual solution strategy incorporating two essential aspects, visualization strategy and design guidelines, was proposed (see Figure 3.13).

The visualization strategies are based on the information seeking mantra of Shneiderman (1996) and on the visual analytics mantra by Keim*, et al.* (2006). The utilization of this strategy depends on the data that have to be represented, and on the tasks that have to be executed (Buja*, et al.*, 1996; Hinneburg*, et al.*, 1999; Keim, 2002). Each step of the strategy is supplemented by design guidelines, which are based on the cartographic design theory and suggest how the data should look like for optimal visual representation. The resulting map images will display the complex relationships, and allow for insight in the nature of movement patterns. A smooth interactive transition between the different phases of the detail exploration process is required.

The design guidelines are based on Bertin's (1967; 1983) theoretical framework. Because of the nature of the content of the STC, it focuses on line (paths) and point (stations) symbolizations in three-dimensional space. Over time, Bertin's typology of visual variables was commented upon and extended (Morrison, 1984; Caivano, 1994; MacEachren, 1995; Robinson et al., 1995). The visualization of the st-paths and stations will depend on their qualitative or quantitative characteristics, and the constraints set by the cartographic design theory in relation to the data complexity.

The link between the visualization strategy and design guidelines is seamless as shown in Figure 3.13. Accordingly, a user is able to make a desirable selection and (re-)symbolization at each step of the information seeking mantra. The visual variables are the key in representing data characteristics, but in the three-dimensional environment of the cube depth perception has to be taken into account too. As will be described in more detail in section 3.4.2 below, the correct application of depth cues can strengthen the visualization, especially in situations where the data are likely to be cluttered. Some depth cues can be applied directly on the symbology for the paths and stations. Examples are various combinations of perspective effects, transparency, shading, etc. While others like motion parallax can be part of the viewing environment. However, in all situations a logical and reasonable organization of the displayed information in regard to data complexity is required.

The overall hypothesis with respect to the visual solution space is that each step of the visualization strategy might require a different design, depending on the data complexity. For instance, compare a simple dataset like 'Napoleon's campaign' with complex data like 'pedestrian movements in Delft.' In particular, at overview level, a small dataset would already allow more advanced design related to the paths or stations, whereas complex data representation requires simple graphics to avoid exaggeration of visual clutter. However, the detailed design might work for both simple and complex data in later steps of the exploration. This approach of adaptive design for each step of the visualization strategy, while considering the data volume and complexity, should support users to get insight into the data (Kraak, 2011).

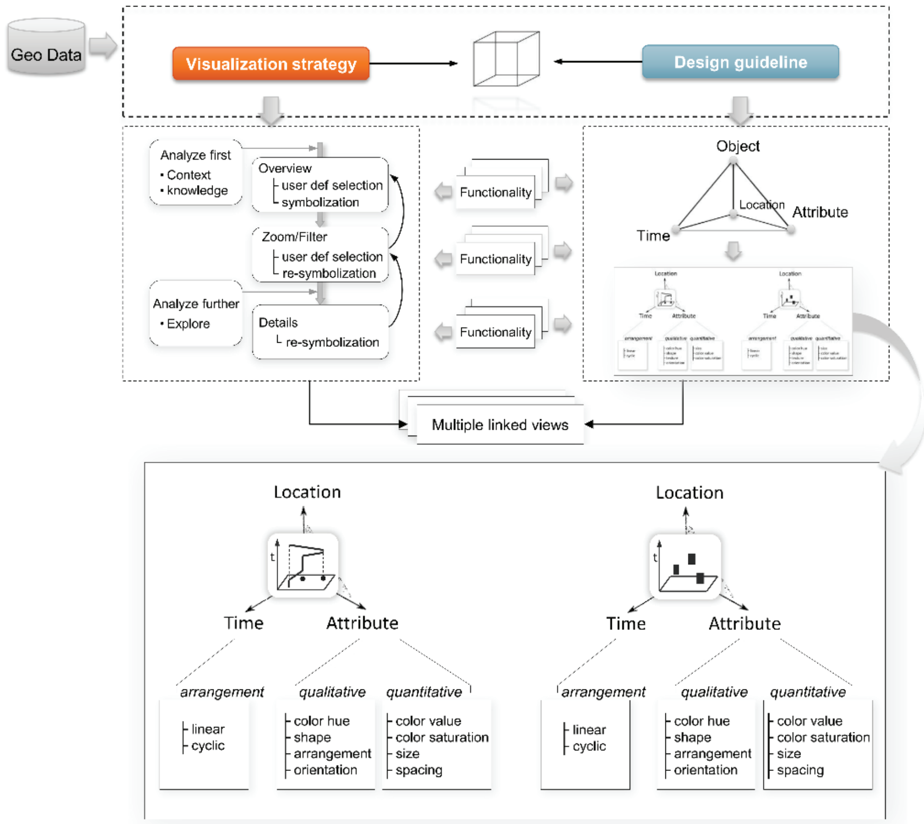



Figure 3.13 Visual Solution Space incorporating visualization strategies and design guidelines. Visualization strategies are based on the principles suggested by Shneiderman (1996) and Keim, *et al.* (2006). The design guidelines are based on the triad model developed by Peuquet (2002) and on cartographic design theory *(or cartographic theoretical frameworks)* (Bertin, 1983; MacEachren, 1995; Robinson, *et al.*, 1995).

The STC need not be a stand-alone graphic representation. It may also be part of a multiple linked view environment in which other graphic representations are interactively linked to the cube. This allows brushing, classifying, and manipulating visualization parameters. Such an environment will also be part of the evaluation study in this research. Further detailed descriptions of the components of the visual solution space are described in the sections below.

## 3.4.1 Visualization strategy

A visualization strategy should help the user to execute a sequence of logically organized steps to get an answer to their research questions and as such assist the user to gain insight into the dataset while extracting knowledge.

**Information seeking mantra and visual analytics mantra**

According to Shneiderman's (1996) 'Information Seeking Mantra' (ISM), visual data exploration includes three major steps: 'overview first, zoom/filter and details on demand.' In this guideline, *Overview first* offers the general context of the dataset and shows all components and their relationships with the aim to identify the patterns of interest. *Zoom and Filter* allows the selection of data subsets detected in the global view. *Zooming* in space and time can overcome limitations of display overload and facilitate the process of information extraction. *Filtering* of attributes removes unnecessary information and allows concentrating on interesting subsets of the data. Then, to further analyse the selected samples, one applies *details on demand* (Craft and Cairns, 2005). This approach represents a suggestion on how information should be displayed.

Due to increased data complexity Keim *et al.* (2006) proposed to extend the 'Information Seeking Mantra' into a 'Visual Analytics Mantra' (VAM) by including some analytical steps: 'Analyse first – Show the important – Zoom, Filter and Analyse further – Details on demand.' This guideline for a typical data exploration process suggests to *analyse data first* by launching computational queries. When data of interest are extracted and the problem is uncovered, it can be inspected through visualization to *show the important*. Further, a range of interactive toolkits (zoom, filter and analyse further) can be used for data examination. And whenever the user requires, the *details* it will be accessible to present. The main idea of the new mantra is to reduce the size and complexity of the data through computational analysis before the visual representation.

VAM is based on an intertwined process between visual and algorithmic analysis and when dealing with complex datasets it is a valid approach to apply. In the visual solution space, the approaches of Shneiderman (1996) and Keim *et al.* (2006) were embraced to support user tasks. In this way, the user is able to define the level of data complexity and to decide which approach to follow, applying algorithmic tools with a combination of visualization or visual analysis. For instance, to analyse the historical movement data of Napoleon's invasion, a historian does not need algorithmic tools (see Figure 3.10). However, the passive mobile phone data of Tallinn district area require to first analyse the data and then show the important (see Figure 3.11).

**Overview detail approach for data complexity**

The above strategies for data exploration as proposed by Shneiderman (1996) and by Keim *et al.* (2006) have been widely adopted. For instance, Chen et al (2008) applied VAM to understand a multivariate dataset with the help of different methods for data analysis, such as clustering, synthesis, searching, etc. Their 'Visual Inquiry Toolkit' showed the effectiveness of the approach of using visual analytics technics.

Andrienko and Andrienko (2007c) proposed to use VAM to support the analysis of massive collections of movement data and visual exploration. To do so, they developed a special toolkit. In another research, Andrienko and Andrienko (2007b) applied VAM to link coordinated multiple views and used their ability to support the representation of heterogeneous data. Zeqian*, et al.* (2012) followed VAM to design a system for an efficient visual analysis of a large web session dataset.

In this research, the proposed visualization strategy to execute the user tasks is based on a workflow that follows the steps of ISM (*overview ↔ detail*) and VAM (*query ↔ visualization ↔ exploration*). The idea is to suggest the user 'how to go about data.' In other words: which steps to follow, or what data context to study for each step of the workflow. Whereby each step of the visual exploration might require a specific approach depending on the data characteristics and the task. The visualization strategy offers a smooth transition between steps of the workflow. Depending on data complexity, it offers two approaches of an iterative data investigation process, *overview ↔ detail* and *query ↔ visualization ↔ exploration*, until the user is satisfied with the results achieved. For example, an initial stage of study through *'overview first'* or '*overview ↔ detail*' is related to a use case like 'Napoleon's march to Russia,' while *'analyse first'* or '*query ↔ visualization ↔ exploration*' via *context* or *knowledge* is applied to a complex dataset like 'Tallinn suburban commuters.'

In both cases, it is the intention to use varying levels of cartographic design in each step of the workflow. In particular, visualization is linked with graphic representations of the st-path and stations. When data are complex, the visual clutter of trajectories can be controlled via re-symbolization of represented data in every step of the exploration. Thus, complex data require simple graphics design, while sparse data most likely require elaborate (complex) graphics design. In both cases, cartographic design can facilitate reading and visual perception of the information in the 3D visual environment of the STC.

In this design process, the character of the data plays an important role. A systematic approach using the three components of spatio-temporal data was distinguished by Peuquet (1994; 2002). In the model she developed, three main questions were formulated to describe phenomena: attribute *characteristics* for objects (*what*), location space (*where*) and time (*when*). These components are used to structure three different types of questions on spatio-temporal data:

- *When + where → what*
- *What + when → where*
- *Where + what → when*

In this way, by considering task and data complexity, the visual solution space in the proposed framework intends to support different workflows through various tools and techniques.

**Functionality and multiple coordinated views**

To be able to work with the data the analytical environment needs a proper functionality. According to Keim*, et al.* (2005) this depends on three criteria: data type to be visualized, visualization technique, and interaction technique (see Figure 3.14). Similar to this approach, Andrienko and Andrienko (2005) developed 'a methodological framework for the design, selection, and application of visualization techniques and tools for the exploratory analysis of spatially referenced data.' There is no single graphic representation that can deal with all these requirements and also the STC is unable to answer all questions on its own. Therefore, it often functions in a coordinated multiple view environment. Each of the individual views can give a different graphical representation of the data. In our research environment, next to the STC, a two dimensional map and some diagrams are available, each giving an alternative view of the data. In such an environment, selecting an object in one view will automatically highlight that object in the other views as well.

Multiple Coordinated Views (MCVs, see section 2.6) offer a variety of benefits to compare information displayed via different representations (Norman*, et al.*, 1986; Chimera and Shneiderman, 1994). However, they represent a challenge for developers. The designer should consider which visual representation to select (Roberts, 2007), and where to locate each view (Baldonado*, et al.*, 2000). The multiple views can also be used to display the different stages of the information seeking mantra (Convertino*, et al.*, 2003; Seeling and Becks, 2004; Suvanaphen and Roberts, 2004). Different authors have discussed the use of interactive techniques for MCVs, to uncover complex relationships within a dataset (Roberts, 2005a). Earlier, Buja*, et al.* (1991) emphasized two principles of interactive visualization, focusing and linking. Interactive focusing, or brushing, aims to identify subsets of data through selection, while interactive linking aims to highlight them in other views.

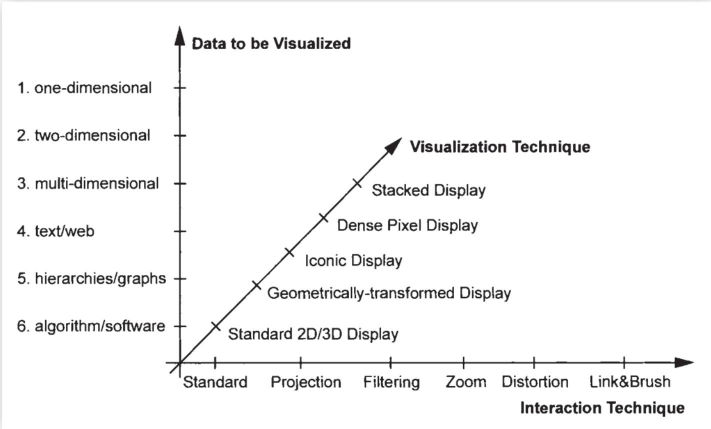



Figure 3.14 Information visualization techniques, *Source:* Keim*, et al.* (2005).

By utilizing the knowledge described above, this research aims to develop an interactive visual environment that will improve user performance through coordinated views displaying different attribute characteristics. For instance, the use case 'Napoleons march to Moscow' contains different attribute characteristics (see section 3.3.3) that can be represented in a single visual environment for better interactive visual analysis. In particular, multidimensional data can be displayed by utilizing the STC, a 2D map, time wave, time graph, or other suitable technique to cover relevant aspects for effective exploration. Thus, the user will be able to select interesting samples of data in one view and then observe them in adjacent windows to explore relationships between characteristics. However, to coordinate the visualizations in an effective way, one has to consider characteristics of data and the tasks that have to be accomplished. Such an approach can support overview and provide context of data while identifying interesting subsets. For instance, the filter function will work with attribute space based on the question which and what, and the zoom function is possible within temporal and location space. Finally, details on demand will focus on a selected sample to display information related to various components of spatio-temporal data.

The coordination in the visual solution space highly depends on the functionality developed. It should support a smooth and consistent transition between components when the user makes changes for visualization and exploration purposes.

### 3.4.2 Design guidelines

The design guidelines are a helpful recommendation that should lead to well-designed aesthetical maps (symbology, color, text, etc.). Today's cartographic guidelines originate from traditional cartographic theory extended with possibilities offered by computer technology. Still, the map creation and its design remain a combination of a mental and physical process of human creativity.

**Bertin's visual variables as basis for information visualization**

Current cartographic design principles are based on the work of the French cartographer Bertin (1983). In his book 'Semiology of Graphics,' originally published in 1967, Bertin identified six fundamental visual variables for three types of phenomena (point, line, area). The utilization of each is based on the characteristics of the data to be represented. Each variable has perceptual properties that should visually express the so-called measurement level, i.e. qualitative, ordered, or quantitative nature of the data (or better: nominal, ordinal, interval and ratio). These perceptual properties can be associative, selective, ordered and quantitative (see Figure 3.15).

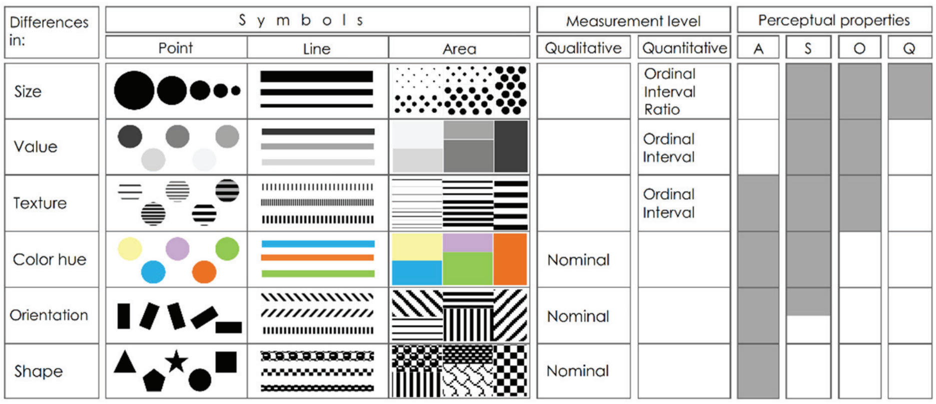



Figure 3.15 Visual variables and their perceptual properties linked to the measurement levels of the data. Perceptual properties: A – associative, S – selective, O – ordered, and Q – quantitative. *Source:* Bertin (1983).

*Associative* visual variables allow the perceptual grouping of similar categories of particular variations of a symbol's shape, orientation, color and texture. They can be used to distinguish between groups of different nature or characteristic. The visual variables size and value are considered to be dissociative.

*Selective* visual variables enable to distinguish all elements/symbols of one particular category among the other elements. Therefore, selective perception can be immediate, as far as it forms a group of similar symbols. According to Bertin, the visual variable shape is not selective but, size, value, texture, and color are selective. Orientation can be selective only for point and line symbols.

*Ordered* visual variables enable to distinguish a ranking among two or more objects. One can perceive warm versus cold or high versus low. The visual variables texture, value and size can be used to realize this but shape, orientation and color are not suitable.

*Quantitative* perception enables to see amounts, i.e. the perception of the numeric ratio between symbols which has an immediate effect on the reader. According to Bertin, only size has a quantitative perceptual characteristic.

**Extended theoretical knowledge of cartographic design**

Over time, cartographers have criticized and extended Bertin's list of visual variables. Morrison (1974; 1976; 1984) was among the cartographers who suggested some supplements and proposed a framework for a symbol syntactics, where color (saturation) and pattern (arrangement) were decomposed, leading to additional visual variables. Bertin (1983) did not distinguish between color hue and saturation, and integrated them in a single category of 'color', while Morison recognized color intensity (saturation) as an independent variable and linked it to the ordering measurement scale. According to McCleary (1983), 'having only six variables might appear to make for an extremely restricted vocabulary, the fact is that the permutations and combinations of these visual variables create an almost limitless vocabulary for creating maps, graphs, charts, and diagrams.' MacEachren (1992) also argued that Bertin's system of graphic variables requires a further extension for the visualization of uncertainty and he proposed *focus* as a variable to deal with *sharpness, resolution and transparency* mainly for screen maps. Later MacEachren (1995), refined his idea and proposed the alternative term *clarity,* and its subdivisions *crispness, resolution* and *transparency*. *Crispness* adjusts details of a map that have no clear boundary, *resolution* allows change in spatial precision, and *transparency* deals with the overlapping problem between objects.

Caivano (1990; 1994) elaborated on the visual variables and took the approach of Jannello (1963) as starting-point. Janello stated that texture may vary in *directionality, size* and *density*. However, he did not specify details for their use. Caivano (1990; 1994) classified texture by depth as two-dimensional and three-dimensional, and by level of complexity as simple and complex texture. By redefining the aspects of Jannello's approach (*directionality, size and density*), he brings forward visual texture as a sign and considers it as a semiotic system. However, despite such research, texture may still considered as a weak visual variable for data representation.

A distinction between primary and secondary visual variables for representing the qualitative and quantitative nature of phenomena can be found in Robinson*, et al.* (1995). The primary visual variables such as shape, size, orientation, color hue, color value, and chroma / color scheme have the ability to distinguish information. Whereas secondary visual variables such as pattern arrangement, texture and orientation have the ability to enhance information. The primary visual variables value, size, and chroma are known as ordered variables, while color hue, orientation and shape are differentiating variables according to Robinson, *et al.* (1995). Contrary to primary variables, secondary variables are used for graphic effects. For example, the use of texture can create an effect of order, while arrangement and orientation can evoke an effect of differentiation.

Visual variables have the possibility to represent multiple attributes within the same symbol by their combination (Bertin, 1983, p.184). For instance, by incorporating the visual variables color hue, shape and pattern orientation we can simply accomplish the simultaneous representation of several attributes of phenomena in one symbol. However, with such complex visualizations one cannot guarantee that the representation will be well readable. In order to represent multivariate information within one type of symbol, we have to consider the geometric nature of phenomena (point, linear, areal) as well as the perceptual property of each visual variable. If the nature of a feature is point or area then a representation of several attributes within one symbol is rather simple. However, the same approach will be difficult to consider for linear phenomena (Kimerling, *et al.*, 2011) and will, for example, impact the representation of a simple st-path.

Table 3.5 Visual variables in different cartographic textbooks

| ***Author*** | ***Visual variables*** | | | | | | | | | | | | | ***Total*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | color hue | color value | shape | size | orientation | texture, spacing | arrangement | color saturation | perspective height | focus | chrispness | resolution | transparency | |
| Bertin (1983) | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | 6 |
| Morrison (1974; 1984) | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | 8 |
| MacEachren (1995) | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | ■ | ■ | ■ | 12 |
| Robinson, *et al.* (1995) | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | 8 |
| Monmonier (1996) | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | 6 |
| Slocum (2009) | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | 9 |
| Dent, *et al.* (2009) | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | | | | 9 |
| Tyner (2010) | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | 8 |
| Kraak and Ormeling (2011) | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | 6 |
| Kimerling, *et al.* (2011) | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | | | | | | 7 |

Table 3.5 gives an overview of how the visual variables have been extended based on Bertin's originals. Based on these studies, cartographic literature offers a wide range of textbooks where different authors are proposing an extension of visual variables with their corresponding rules of use. The table shows how ten different textbooks deal with the list of visual variables. It is obvious that the visual variables identified by Bertin (1983) are untouched, and the other most distinguished additional variables are arrangement and color saturation.

Based on Table 3.5, this research will focus on the application of the eight most used visual variables (see Table 3.6) as applied on st-paths.

**Perceptual properties of visual variables**

As discussed before, visual variables have particular perceptual properties to represent objects which allows them to represent information in an effective way (Bertin, 1983). These properties were also discussed intensively by MacEachren (1995, p. 36, 82). According to him, Bertin (1967; 1983) did not investigate the perception of visual variables experimentally and based his conclusions on his own experiences, i.e. considered his own theories as facts. Besides, Bertin (1983) did not provide any references to other experiments as supporting empirical evidence. However, other researchers from the field of physiology have done some experimental research with some of the variables. For instance, Julesz (1965; 1975) investigated different colours and shapes of texture arrangement as well as depth perception to help in the design of machines generating automated contour maps. Within this experiment, he found that similar patterns resulted in clusters that could attract visual attention and lead to segregation, i.e. a selective effect. Olson and Attneave (1970) investigated the effectiveness of textural variables by considering similarity grouping. Contrary to Bertin's view, their results showed that orientation as a visual variable has a selective perceptual property with areal symbols. Another experiment on arrangement was conducted by Nothdurft (1992). Like Olson and Attneave (1970) he also proved that pattern arrangement has a selective perceptual property.

On the other hand, findings of cartographers who studied the perceptual properties of visual variables support Bertin's conclusions. Garlandini and Fabrikant (2009) investigated the effectiveness and efficiency of color hue, color value, size and arrangement. Their results reveal that the visual variable size is the most effective and efficient to detect change, while texture is less effective and efficient. Also, they found that with the visual variable orientation, test participants needed more time to detect change. Therefore, they conclude that 'with orientation (in areas) it is hard to isolate an area of change, as the variable emphasizes similarity' and has a more homogeneous appearance.

It is indisputable that Bertin (1967; 1983) was the first cartographer who formulated systematic guidelines and defined syntactic rules to match visual variables with data characteristics. For this research, we followed the approach of Bertin (1983) and also combined it with some findings from the literature as summarized in Table 3.6.

Table 3.6 Visual variables and their perceptual properties

| Perceptual properties | Qualitative visual variables | | | | Quantitative visual variables | | | |
|---|---|---|---|---|---|---|---|---|
| | color | shape | arrange ment | orientation | saturation | value | size | texture |
| Associative | | | | | | | | |
| Selective | | | | | | | | |
| Ordered | | | | | | | | |
| Quantitative | | | | | | | | |

**Depth perception and depth cues**

For the three-dimensional STC it is also important to incorporate the notion of *depth cues.* Depth cues help the human visual system in perceiving three-dimensional objects and their relationships. The human visual system has a striking ability to specify the depth, distance, and shape of any object in the three-dimensional surroundings of the real world (Goldstein, 2010). Knowledge of the human vision system and interpretation of reality is important for cartographers because they often simulate the 3D environment on 2D displays (Marr, 1982; Marr, 2010). To understand the complex aspects of human visual perception and the visualization process, depth cues were the study interest of some cartographers (Kraak, 1988; Goldstein, 2010).

Kraak (1988) introduced a taxonomy for depth cues in cartography. He distinguishes between *physiological* and *psychological (pictorial)* depth perception. Physiological depth cues *(accommodation, convergence, retinal disparity and monocular movement parallax)* are related to the physical processes of the visual system due to the reaction on a three-dimensional environment. While pictorial depth cues *(overlap, shading, perspective and color)* are related to the object structure or resulting image and enhance the three-dimensional impression of the human vision system. In many cases, physiological depth cues are used in combination to provide a better 3D impression. However, it is not a guarantee for improved visualization and can result in optical illusions. On the other hand, to improve 3D perception a carefully and properly selected combination of psychological and physiological depth cues can result in a good design and strengthen depth perception of 3D visualization.

Goldstein (2010) distinguishes between *cue theory* and *ecological cue*. Cue theory detects information through a retina image and identifies the depth of the actual environment, while ecological cue implies the observer and her/his interaction with the environment. In addition, Goldstein differentiates between *binocular* and *monocular (pictorial, motion-produced, oculomotor)* depth cues (see Table 3.7). Binocular depth cues work via two different partly overlapping images merged in the brain to perceive a three dimensional view. Monocular depth cues allow information to be perceived from a single image.

Table 3.7 Visual depth cues used in uDig and Ilwis software

| Depth cues | Description |
|---|---|
| **Binocular** | |
| ➢ *retinal disparity / binocular parallax / Stereopsis* | differences in image that are transformed by each eye on far away and closer distances |
| ➢ *convergence* | rotation of the eyes inward when focusing on a single object |
| **Monocular** | |
| **pictorial/static** | |
| ➢ perspective | |
| – linear perspective | depth perception of parallel lines evolved by convergence towards the horizon |
| – relative size / size gradient | the objects appear closer or farther away depending on the depth perception of the distance cues, especially when the size of a feature is known |
| – texture gradient | high density texture appears more detailed and means being closer to an object; low density texture appears smooth and means farther away from an object |
| ➢ interposition/overlap/occlusion | this depth cue gives a sensation that objects that partially overlap others are near and overlapped objects are farther away |
| ➢ light and shadow distribution / shading | depth cues facilitate perception of features in 3D space through the location of the light source and see casting shadows |
| ➢ color | objects of color appear at different depth according to their wavelength (*chromostereopsis*) |
| – atmospheric (aerial) perspective / transparency | the ability to see through the layer in front of a layer or behind it |
| **motion-produced/dynamic** | |
| ➢ motion parallax | when the observer moves, far objects appear to move slower than closer objects |
| ➢ kinetic depth effect | a wireframe cube is drawn that, when rotated, provides the necessary information for perception of the third dimension |
| **accommodation** | is the ability of the human eye lens to alter the optical power or focal length of the lens, while holding the objects at a different distance into focus |

In the domain of information visualization Ware (2008) had a similar approach and differentiated between *pictorial* and *non-pictorial* depth cues. A pictorial depth cue *(occlusion, perspective, shading, depth of focus, etc.)* is reproduced from a photograph or painting. Non-pictorial cues are *stereopsis, structure from motion and convergence* (see Table 3.7). He also suggests to consider what we are trying to accomplish when selecting particular depth cues for design purposes.

The understanding of depth in 2D displays with various depth cues to enhance 3D perception has been the study interest of many researchers, and resulted in a number of scientific publications (Sollenberger and Milgram, 1993; Ware and Franck, 1996; Clarke*, et al.*, 1999; Munzner*, et al.*, 1999; Wills, 1999; Ware and Mitchell, 2008). Table 3.7 summarizes the depth cues used in existing uDig (URL 2) and Ilwis (URL 10) software that later will be used in experiments in phase three, four, five and six, however, the table 3.8 refers four depth cues intended to use in evaluation studies in this research.

So far, very limited research has been done from a usability perspective with depth cues and their effects on human visual perception in relation to the STC. Only Kjellin, *et al.* (2010a) have reported results of experiments (see section 2.5). However, from the discussion above it is clear that depth cues are essential for a better perception in the 3D visual environment of the STC. They should be part of the design process to allow observers a better sense of information content.

### 3.4.3 Integration of design guidelines with visualization strategy

In Table 3.8 the depth cues and visual variables are combined, and are the basis for a set of detailed hypotheses, as presented in chapter 6, section 6.3.1.

Table 3.8 Multiple design options for the STC content

| Visualization strategy / Design guideline | | Overview | | Zoom | | Filter | | Details |
|---|---|---|---|---|---|---|---|---|
| | | Complex data | Simple data | Complex data | Simple data | Complex data | Simple data | Simple data |
| **Qualitative visual variables** | | Depth cues | | | | | | |
| | | A | B | C | D | E | F | G |
| Color hue | 1 | Simple graphics | • Shading | Simple graphics | • Shading | Simple graphics | • Shading | • Shading |
| | 2 | | • Transparency<br>• Shading | | • Transparency<br>• Shading | | • Transparency<br>• Shading | • Transparency<br>• Shading |
| | 3 | | • Relative size<br>• Shading | | • Relative size<br>• Shading | | • Relative size<br>• Shading | • Relative size<br>• Shading |
| Shape | 4 | Simple graphics | • Shading | Simple graphics | • Shading | Simple graphics | • Shading | • Shading |
| | 5 | | • Transparency<br>• Shading | | • Transparency<br>• Shading | | • Transparency<br>• Shading | • Transparency<br>• Shading |
| | 6 | | • Relative size<br>• Shading | | • Relative size<br>• Shading | | • Relative size<br>• Shading | • Relative size<br>• Shading |
| Arrangement | 7 | | • Shading | | • Shading | | • Shading | • Shading |
| | 8 | | • Transparency<br>• Shading | | • Transparency<br>• Shading | | • Transparency<br>• Shading | • Transparency<br>• Shading |
| Orientation | 9 | | • Shading | | • Shading | | • Shading | • Shading |
| | 10 | | • Linear perspective<br>• Shading | | • Linear perspective<br>• Shading | | • Linear perspective<br>• Shading | • Linear perspective<br>• Shading |
| **Quantitative visual variables** | | | | | | | | |
| Color value | 11 | Simple graphics | • Shading | Simple graphics | • Shading | Simple graphics | • Shading | • Shading |
| | 12 | | • Transparency<br>• Shading | | • Transparency<br>• Shading | | • Transparency<br>• Shading | • Transparency<br>• Shading |
| | 13 | | • Relative size<br>• Shading | | • Relative size<br>• Shading | | • Relative size<br>• Shading | • Relative size<br>• Shading |
| Color Saturation | 14 | Simple graphics | • Shading | Simple graphics | • Shading | Simple graphics | • Shading | • Shading |
| | 15 | | • Transparency<br>• Shading | | • Transparency<br>• Shading | | • Transparency<br>• Shading | • Transparency<br>• Shading |
| | 16 | | • Relative size<br>• Shading | | • Relative size<br>• Shading | | • Relative size<br>• Shading | • Relative size<br>• Shading |
| Size | 17 | Simple graphics | • Shading | Simple graphics | • Shading | Simple graphics | • Shading | • Shading |
| | 18 | | • Transparency<br>• Shading | | • Transparency<br>• Shading | | • Transparency<br>• Shading | • Transparency<br>• Shading |
| Spacing | 19 | | • Shading | | • Shading | | • Shading | • Shading |
| | 20 | | • Linear perspective<br>• Shading | | • Linear perspective<br>• Shading | | • Linear perspective<br>• Shading | • Linear perspective<br>• Shading |

Table 3.8 also brings together two concepts discussed before, visualization strategy (horizontal), and design guidelines (vertical) as indicated in the header of the table. The presented combination of visual

variables and depth cues is unlimited. This table shows that depth cues are not used for complex datasets, while in simple datasets a variety of them can be used. The experiments were designed to test this hypothesis based on the options in Table 3.8. The results are reported in chapters 5 and 6.

One element in this research is the distinction between simple – complex and small – large datasets. This approach was important for the use of the design options defined in Table 3.8. According to the Oxford dictionary (URL 9), 'complex' is group of things that are linked in a complicated way, containing many different connected parts and hard to understand or analyse. In the same dictionary, 'large' is defined as 'considerable or relatively great size, extent, capacity or a significant scale.' By considering both definitions, this research distinguishes between:

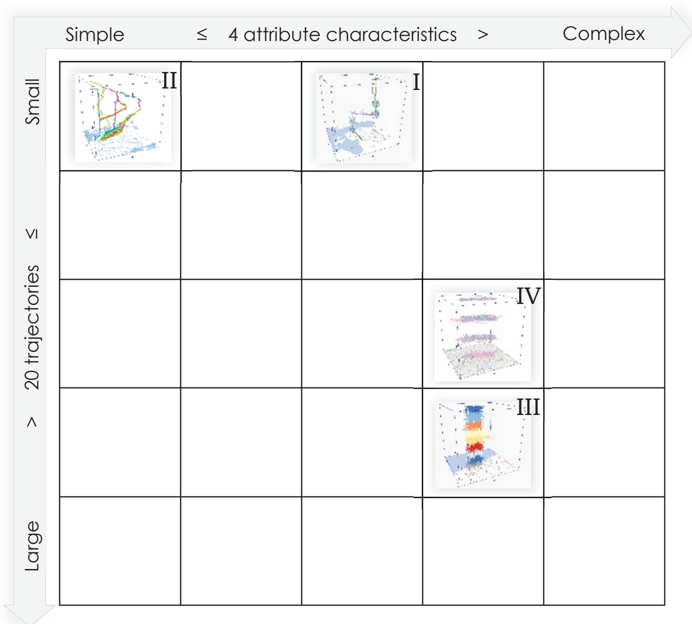



Figure 3.16 Location of the use cases on large-small and simple-complex scales for visual understanding as used in this research.

- Simple-small data, i.e. twenty or less trajectories with four or less attribute characteristics that allow a simple exploration process, such as use case II 'Napoleon.'
- Small-complex data, i.e. twenty or less trajectories with more than four attribute characteristics that make the exploration process complicated or intricate. Use case I 'Estonia' is considered to be in this category

- Large-complex, i.e. more than twenty trajectories with more than four attribute characteristics that make the exploration process complicated: use cases III 'Tallinn' and IV 'Delft' belong to this category.

The division is based on the schematic drawing in Figure 3.16, and shows how each use case fits the above classification.

## 3.5 Phase Three, Four, Five and Six - Evaluation Studies

The basic setup of the usability research, following user centred design principles, has already been described in sections 3.3 (phase 1) and 3.4 (phase 2). Here, the details of phase three, four, five, and six are described:

### 3.5.1 Phase three – verification of the workflow

In phase three domain experts were revisited to confirm the workflows developed in the first phase (section 3.3) and implemented in phase two (section 3.4). The aim was to let the experts work with the developed scenarios in the STC to solve the problems defined in phase one. See Figure 3.17.

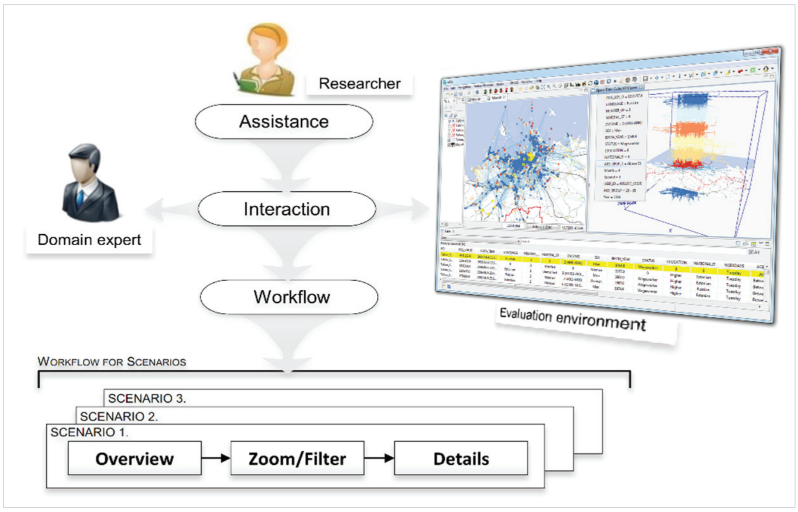



Figure 3.17 Phase three: confirm workflows and visualization strategies.

In this evaluation session, combinations of different qualitative usability research methods were applied, such as screen logging, audio recording, think aloud and interviews.

The target was to achieve sophisticated visualization strategies and to define necessary tools and techniques for effective exploration of the spatio-temporal data. For this purpose, a testing environment was created, consisting of three linked views: a 2D map view, STC view and attribute table view. Feedback received during this phase was used to prepare phases 5 and 6, the actual evaluation phases. These experiments are described in chapter 4.

### 3.5.2 Phase four – evaluation of the design

Phase four evaluates the design summarized in Table 3.8 via a focus group session with geovisualization experts (see Figure 3.18). In the focus group session, experts judged the effectiveness of the design options, as defined in phase two. This was done in a spatial decision room equipped with interactive touch tables with the Tallinn use case (see Figure 3.11). The session was video and audio recorded for analysis. It brought some clarity on the use of the design for the different steps of the visualization strategies and data complexity. It led to a refinement of the options presented in Table 3.8 and resulted in more realistic hypotheses to be tested through individual laboratory test sessions. In summary, the domain experts in phase three verified the workflow established in phase one, and the design experts in phase four verified the design established in phase two. Comments received from geovisualization experts were used to prepare actual evaluation sessions with non-expert users in phase 5. The result of focus group evaluation is reported in chapter 5.

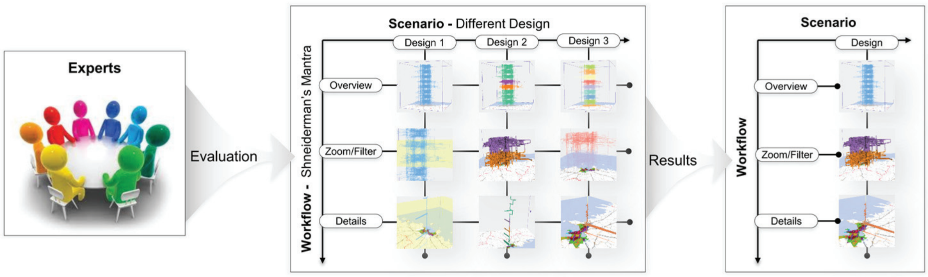



Figure 3.18 Phase four: experts in cartography and evaluation of the design guidelines.

### 3.5.3 Phase five – evaluation of the design

In phase five, non-expert participants are involved in an individual laboratory test for three use cases of Estonia (see Figure 3.8), Napoleon (see Figure 3.10) and Delft (see Figure 3.12). These non-experts consisted of people not familiar with the data nor with the STC, but had knowledge of different GIScience domains. See Figure 3.19. They have been recruited from the student population of the Faculty of Geo-Information Science and Earth Observation (ITC) of the University of Twente. The design options and hypotheses formulated in the previous phase were objective of the test. Several evaluation methods were applied: pre-selection questionnaire, desktop screen logging, video/audio recording, eye tracking, task performance, interview, and think aloud. The results of this test helped to understand how to apply visual variables and depth cues in relation to the steps of the visualization strategies. Based on the collected qualitative and quantitative usability measures the most effective designs were defined and tested in phase six. The results of these evaluation sessions are reported in chapter 6.

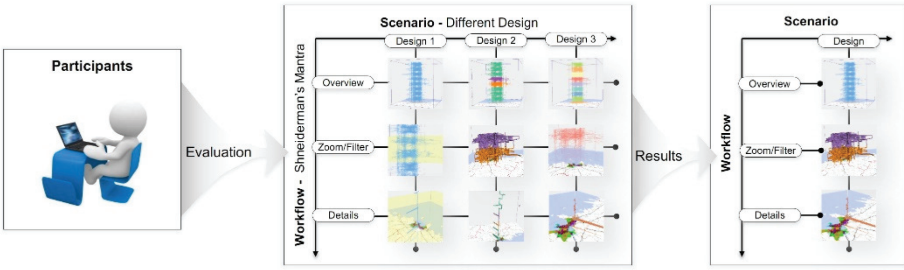



Figure 3.19 Phase five: non-experts and evaluation of the design guidelines.

### 3.5.4 Phase six – evaluation of the application in a GVA environment

Phase six is built on the results of the previous experiments and differs by evaluation content (see Figure 3.20). The goal was to define how the STC performs in the context of a geovisual exploration environment (GVA), where it is combined with several other graphic visualizations (time wave, parallel coordinate plots, graphs, and maps). This environment allows an interaction with the locational, attribute and time components of the data.

This final experiment addressed several hypotheses and, based on task completion, error rates and user satisfaction, conclusions were drawn regarding the usability of the STC in the GVA environment. Combinations of several qualitative and quantitative evaluation methods with two different groups of test participants were completed. The first test group was composed of domain experts from phase one and three, while the second group was composed of non-experts who were not familiar with the use-case context nor with the STC.

Based on the analysis of the movement data, several questions were designed with a specific focus on the type of information, i.e. location, attribute and time. Test participants had to execute different categories of tasks (comparison, attribute-based, etc.) while following the workflows in the GVA environment. The collected information will be analysed and summarized, and the results of the two groups will be compared. This will allow us to judge the efficiency, effectiveness, and satisfaction of our approach. The results of these experiments are reported in chapter 7.

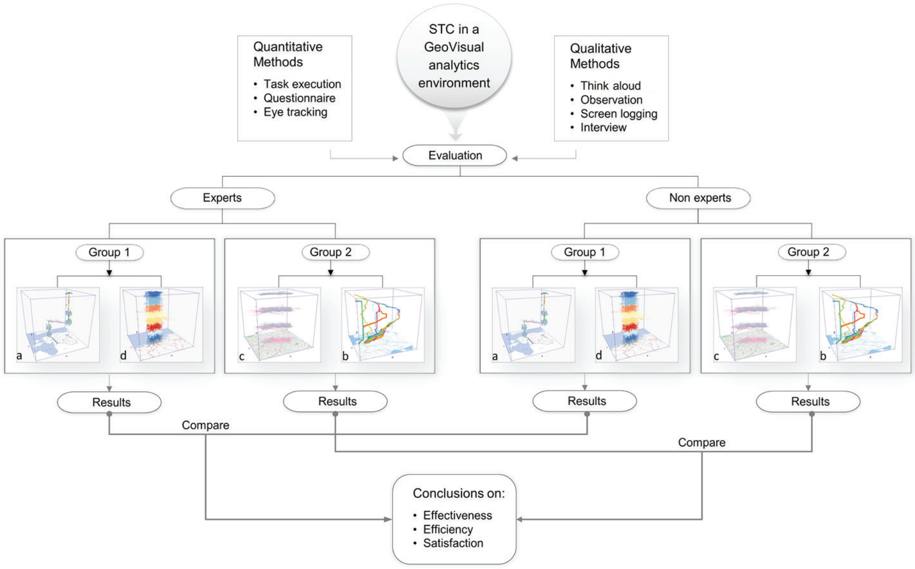



Figure 3.20 Phase six: evaluation of the solution block with experts and non-experts.

## 3.6 Discussion

The conceptual framework introduced in this chapter consists of three main parts and outlines the details of the steps undertaken in this research. Each step focused on a particular phase of the study and tried to reveal valuable results and inputs for next stage. The first phase focuses on the problem identification with domain experts and reports research questions identified during a discussion session. The second phase is about visual solutions for different use cases and consists of two parts: visualization strategy and design guidelines. The visualization strategy intends to support the user in the process of knowledge extraction and follows three basic steps that is a methodological suggestion on how information should be represented. The visualization environment also considers interactive techniques to support steps of the visualization strategy depending on the task and data complexity. Another part of the visual solution space are the design guidelines based on the cartographic design theory. The last part described the setup of the usability studies applied to evaluate the suggested designs (phases three, four, five and six).

# References


Ahas, R., Aasa, A. , Silm, S. , Aunap, R. , Kalle, H. , and Mark, U. (2007a). **Mobile positioning in space--time behaviour studies: social positioning method experiments in Estonia**, 'Cartography and Geographic Information Science', 34, 4, pp. 259-273.

Ahas, R., Laineste, J., Aasa, A., and Mark, Ü. (2007b). 'The Spatial Accuracy of Mobile Positioning: Some experiences with Geographical Studies in Estonia', in **Location Based Services and TeleCartography**, ed. by Gartner, G., Cartwright, W., and Peterson, M. P., pp. 445-460, Springer Berlin Heidelberg, NY.

Amar, R., Eagan, J., and Stasko, J. (2005). **Low-level components of analytic activity in information visualization**, in IEEE Symposium on Information Visualization. Baltimore, Maryland, pp. 111-117.

Andrienko, G. and Andrienko, N. (2007a). **Coordinated Multiple Views: a Critical View**, in 5th International Conference on Coordinated and Multiple Views in Exploratory Visualization, 2007. CMV '07. Zurich, pp. 72-74.

Andrienko, N. and Andrienko, G. (2005). **Exploratory Analysis of Spatial and Temporal Data: a Systematic Approach**. Springer-Verlag Berlin Heidelberg, Germany.

Andrienko, N. and Andrienko, G. (2007b). **Designing Visual Analytics Methods for Massive Collections of Movement Data**, 'Cartographica: The International Journal for Geographic Information and Geovisualization', 42, 2, pp. 117-138.

Baldonado, M.Q.W., Woodruff, A., and Kuchinsky, A. (2000). **Guidelines for using multiple views in information visualization**, in Proceedings of the working conference on Advanced visual interfaces. Palermo, Italy, pp. 110-119.

Benel, D.C.R., Ottens, D., and Horst, R. (1991). **Use of an eye tracking system in the usability laboratory**, in Proceedings of the Human Factors and Ergonomics Society Annual Meeting September 1991. Santa Monica, pp. 461-465.

Bertin, J. (1967). **Semiologie Graphique: Les Diagrammes, Les Réseaux, Les Cartes**. Mouton , Gauthier-Villars, Paris etc.

Bertin, J. (1983). **Semiology of Graphics: Diagrams, Networks, Maps**. The University of Wisconsin Press, Madison (first published in French in 1967, translated to English by Berg W.J. in 1983).

Bevan, N. (1995). **Measuring usability as quality of use**, 'Software Quality Journal', 4, 2, pp. 115-130.

Buja, A., Cook, D., and Swayne, D.F. (1996). **Interactive High-Dimensional Data Visualization**, 'Computational and Graphical Statistics', 5, 1, pp. 78-99.

Buja, A., McDonald, J.A., Michalak, J., and Stuetzle, W. (1991). **Interactive data visualization using focusing and linking**, in Proceedings of the 2nd conference on Visualization '91. San Diego, USA, pp. 156-163.

Butler, K.A. (1996). **Usability engineering turns 10**, 'interactions', 3, 1, pp. 58-75.

Caivano, J.L. (1990). **Visual texture as a semiotic system**, 'Semiotica', 80, 3-4, pp. 239-252.

Caivano, J.L. (1994). **Towards An Order System For Visual Texture**, 'Languages of Design', 2, 1, pp. 59-84.

Casner, S.M. (1989). **A Task-Analytic Approach to the Automated Design of Information Graphics**, 'Carnegie Mellon University Technical Report AIP - 82, 42 pages'.

Casner, S.M. (1991). **A Task-Analytic Approach to the Automated Design of Graphic Presentations**, 'ACM Transactions on Graphics', 10, 2, pp. 111-151.

Chen, J., MacEachren, A., and Guo, D. (2008). **Supporting the Process of Exploring and Interpreting Space-Time, Multivariate Patterns: The Visual Inquiry Toolkit**, 'Cartography and geographic information science', 35, 1, pp. 33-50.

Chimera, R. and Shneiderman, B. (1994). **An exploratory evaluation of three interfaces for browsing large hierarchical tables of contents**, 'ACM Trans. Inf. Syst.', 12, 4, pp. 383-406.

Clarke, K.C., Teague, P.D., and Smith, H.G. (1999). **Virtual Depth-based Representation of Cartographic Uncertainty**, in International Symposium on Spatial Data Quality 99. Hong Kong, pp. 253-259.

Convertino, G., Chen, J., Yost, B., Ryu, Y.S., and North, C. (2003). **Exploring context switching and cognition in dual-view coordinated visualizations**, in CMV '03: Proceedings of the conference on Coordinated and Multiple Views In Exploratory Visualization. Washington, DC, USA, pp. 55-62.

Craft, B. and Cairns, P. (2005). **Beyond guidelines: what can we learn from the visual information seeking mantra?**, in Proceedings of the 9th International Conference on Information Visualisation, 2005. Washington DC, USA, pp. 110-118.

Delikostidis, I. (2011), **Improving the usability of pedestrian navigation systems**. ITC Dissertation, University of Twente Faculty of Geo-Information and Earth Observation ITC, Enschede.

Dent, B.D., Torguson, J.S., and Hodler, T.W. (2009). **Cartography : thematic map design**, Sixth edition ed.: McGraw - Hill, NY.

Garlandini, S. and Fabrikant, S. (2009). 'Evaluating the Effectiveness and Efficiency of Visual Variables for Geographic Information Visualization', in **Spatial Information Theory**, ed. by Hornsby, K., Claramunt, C., Denis, M., and Ligozat, G., pp. 195-211, Springer Berlin Heidelberg, NY.

Goldstein, E.B. (2010). **Sensation and perception**. Brooks Cole Publishing, NY.

Gotz, D. and Zhou, M.X. (2009). **Characterizing users' visual analytic activity for insight provenance**, 'Information Visualization', 8, 1, pp. 42-55.

Gould, J.D. and Lewis, C. (1985). **Designing for usability: key principles and what designers think**, 'Commun. ACM', 28, 3, pp. 300-311.

Hennink, M., Hutter, I., and Bailey, A. (2010). **Qualitative Research Methods**. SAGE Publications Ltd, London.

Hinneburg, A., Keim, D.A., and Wawryniuk, M. (1999). **HD-Eye: visual mining of high-dimensional data**, 'Computer Graphics and Applications IEEE', 19, 5, pp. 22-31.

Holtzblatt, K. and Beyer, H. (1993). **Making customer-centered design work for teams**, 'Communications of the ACM', 36, 10, pp. 92-103.

ISO 9241-11:1998, 1998. **Ergonomic requirements for office work with visual display terminals (VDTs) - Part 11: Guidance on usability**.

ISO 13407:1999, 1999. **Human-Centred Design Processes for Interactive Systems**.

Jannello, C. (1963). **Texture as a visual phenomena**, 'Architectural Design', 33, pp. 394-396.

Julesz, B. (1965). **Texture and visual perception**, 'Scientific American', 22, 2, pp. 38-48.

Julesz, B. (1975). **Experiments in the visual perception of texture**, 'Scientific American', 232, 4, pp. 34–43.

Keim, D. (2002). **Information Visualization and Visual Data Mining**, 'Transactions on Visualization and Computer Graphics IEEE', 8, 1, pp. 1-8.

Keim, D., Mansmann, F., Schneidewind, J., and Ziegler, H. (2006). **Challenges in Visual Data Analysis**, in 10th International Conference on Information Visualization. London, UK, pp. 9-16.

Keim, D., Panse, C., and Sips, M. (2005). 'Information Visualization: Scope, Techniques and Opportunities for Geovisualization Exploring Geovisualization', in **Exploring Geovisualization**, ed. by Dykes, J., MacEachren, A., and Kraak, M.-J., pp. 1-17, Elsevier, Oxford.

Kimerling, A.J., Buckley, A.R., Muehrcke, P.C., and Muehrcke, J.O (2011). **Map Use: Reading Analysis Interpretation (Seventh eddition)**. ESRI Press Academic, California, USA.

Kjellin, A., Pettersson, L.W., Seipel, S., and Lind, M. (2010). **Different Levels of 3D: An Evaluation of Visualized Discrete Spatiotemporal Data in Space-Time Cubes**, 'Information Visualization', 9, 2, pp. 152 -164.

Knapp, L. (1995). 'A task analysis approach to the visualization of geographic data', in **Cognitive aspects of human-computer interaction for geographic information systems**, ed. by Nygers, T. L., Mark, D. M., Laurini, R., and Egenhofer, M. J., pp. 355 - 371, Kluwer Academic Publishers, The Netehrlands.

Kraak, M.J. (1988), **Computer-assisted cartographical three-dimensional imaging techniques**. Delft University Press, Delft.

Kraak, M.J. (2011). **Is There a Need for Neo-Cartography?**, 'Cartography and geographic information science', 38, 2, pp. 73-78.

Kraak, M.J. (2014). **Mapping time : illustrated by Minard's map of Napoleon's Russian campaign of 1812**. ESRI Press, Redlands.

Kraak, M.J. and Ormeling, F.J. (2011). **Cartography : visualization of spatial data**, Third edition ed.: Guilford Press, NY, London.

Labaume, E. (2002). **1812 Through Fire and Ice with Napoleon: A French Officer's Memoir of the campaign in Russia**. Helion and Company, England.

Lloyd, D. (2009), **Evaluating human-centered approaches for geovisualization**. City University London, London.

MacEachren, A.M. (1992). **Visualizing uncertain information**, 'Cartographic Perspectives', 13, pp. 10-19.

MacEachren, A.M. (1995). **How Maps Work: Representation, Visualization and Design**. Guilford Press, NY.

Maguire, M. (2001). **Methods to support human-centred design**, 'International Journal of Human-Computer Studies', 55, 4, pp. 587-634.

Maguire, M. and Bevan, N. (2002). **User requirements analysis**, in Proceedings of IFIP 17th World Computer Congress. Montreal, Canada, pp. 133-148.

Marr, D. (1982). **Vision: A Computational Investigation into the Human Representation and Processing of Visual Information**. W.H. Freeman and Company, San Francisco.

Marr, D. (2010). **Vision: A Computational Investigation into the Human Representation and Processing of Visual Information**. MIT Press, Cambridge, Mass.

Mayhew, D.J. (1999). **The Usability Engineering Lifecycle: A Practioner's Handbook for User Interface Design**. Morgan Kaufmann Publishers, San Francisco.

McCleary, G.F. (1983). **An Effective Graphic "Vocabulary"**, 'Computer Graphics and Applications, IEEE', 3, 2, pp. 46-53.

Monmonier, M. (1996). **How to lie with maps**, 2nd ed.: The University of Chicago Press, Chicago etc.

Morrison, J.L. (1974). **A theoretical framework for cartographic generalization with the emphasis on the process of symbolization**, 'International Yearbook of Cartography', 14, pp. 115-127.

Morrison, J.L. (1976). **The science of cartography and its essential processes**, 'International Yearbook of Cartography', 16, pp. 84-97.

Morrison, J.L. (1984). **Applied Cartographic Communication: Map Symbolization For Atlases**, 'Cartographica: The International Journal for Geographic Information and Geovisualization', 21, 1, pp. 44-84.

Munzner, T., Guimbretiere, F., and Robertson, G. (1999). **Constellation: A Visualization Tool for Linguistic Queries from MindNet**, in Proceedings of the 1999 IEEE Symposium on Information Visualization. San Francisco, CA, pp. 132.

Nielsen, J. (1993). **Usability Engineering.** Morgan Kaufmann Publishers Inc., Boston.

Norman, D.A. (1988). **The Design of Everyday Things**. Doubleday, NY.

Norman, K.L., Weldon, L.J., and Shneiderman, B. (1986). **Cognitive layouts of windows and multiple screens for user interfaces**, 'Int. J. Man-Mach. Stud.', 25, 2, pp. 229-248.

Nothdurft, H.C. (1992). **Feature analysis and the role of similarity in preattentive vision**, 'Perception & Psychophysics', 52, 4, pp. 355-375.

Olson, R.K. and Attneave, F. (1970). **What Variables Produce Similarity Grouping?**, 'The American Journal of Psychology', 83, 1, pp. 1-21.

Peuquet, D.J. (1994). **It's about time : a conceptual framework for the representation of temporal dynamics in geographic information systems**, 'In: Annals of the Association of American Geographers', 84, 3, pp. 441-461.

Peuquet, D.J. (2002). **Representations of space and time.** The Guilford Press, NY.

Roberts, J.C. (2005). 'Chapter 8 - Exploratory Visualization with Multiple Linked Views', in **Exploring Geovisualization**, ed. by Dykes, J., MacEachren, A. M., and Kraak, M. J., pp. 159-180, Elsevier, Oxford.

Roberts, J.C. (2007). **State of the Art: Coordinated & Multiple Views in Exploratory Visualization**, in 5th International Conference on Coordinated and Multiple Views in Exploratory Visualization, 2007. CMV '07. Zurich, pp. 61-71.

Robinson, A.H., Morrison, J.L., Muehrcke, P.C., Kimerling, A.J., and Guptill, S.C. (1995). **Elements of Cartography**, 6th ed.: Wiley & Sons, NY.

Roth, R.E. (2012). **Cartographic Interaction Primitives: Framework and Synthesis**, 'Cartographic Journal, The', 49, 4, pp. 376-395.

Seeling, C. and Becks, A. (2004). **Analysing associations of textual and relational data with a multiple views system**, in Proceedings of the 2nd International Conference on Coordinated & Multiple Views in Exploratory Visualization (CMV'04). Washington, DC, USA, pp. 61-70.

Shneiderman, B. (1996). **The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations**, in the 1996 IEEE Symposium on Visual Languages. Boulder, Colorado, pp. 336 - 343.

Slocum, T.A. (2009). **Thematic Cartography and Geographic Visualization**. Pearson Prentice Hall, USA.

Smith, D.G. (2002). **Armies of 1812: the Grand Armeé and the armies of Austria, Prussia, Russia and Turkey**. Staplehurst, Spellmount.

Sollenberger, l.R. and Milgram, P. (1993). **Effects of Stereoscopic and Rotational Displays in a Three-Dimensional Path- Tracing Task**, 'Human Factors: The Journal of the Human Factors and Ergonomics Society', 35, 3, pp. 483-99.

Suvanaphen, E. and Roberts, J.C. (2004). **Textual difference visualization of multiple search results utilizing detail in context**, in Theory and Practice of Computer Graphics, 2004. Bournemouth, England, pp. 2-8.

Tyner, J.A. (2010). **Principles of Map Design**. Guilford Press, NY.

URL 1, From: http://www.edwardtufte.com/tufte/minard

URL 2, From: http://udig.refractions.net/

URL 5, From: www.positium.com

URL 6, From: http://www.techsmith.com/snagit.html

URL 7, From: http://www.techsmith.com/camtasia.html

URL 8, From: http://www.tobii.com/

URL 9, From: http://www.oxforddictionaries.com/

URL 10, From: http://52north.org/communities/ilwis

van der Spek, S.C. (2009). 'Mapping Pedestrian Movement: Using Tracking Technologies in Koblenz', in **Location Based Services and TeleCartography II**, ed. by Gartner, G. and Rehrl, K., pp. 95-118, Springer, Heidelberg, Berlin.

van der Spek, S.C., van Langelaar, C.M., and Kickert, C.C. (2013). **Evidence-based design: satellite positioning studies of city centre user groups**, in Proceedings of the ICE - Urban Design and Planning. 166, pp. 206-216.

van der Spek, S.C., van Schaick, J., De Bois, P., and De Haan, R. (2009). **Sensing Human Activity: GPS Tracking**, 'Sensors', 9, 4, pp. 3033-3055.

van Elzakker, C.P.J.M (2004), **The use of maps in the exploration of geographic data**. Institute for Geo-Information Science and Earth Observation, Enschede, The Netherlands.

van Elzakker, C.P.J.M. and Wealands, K. (2007). 'Use and Users of Multimedia Cartography', in **Multimedia cartography**, ed. by Cartwright, W., Peterson, M., and Gartner, G., pp. 487-504, Springer Berlin Heidelberg, NY.

Ware, C. (2008). **Visual Thinking: for Design**. Morgan Kaufmann, USA.

Ware, C. and Franck, G. (1996). **Evaluating Stereo and Motion Cues for Visualizing Information Nets in Three Dimensions**, 'ACM Transactions on Graphics', 15, 2, pp. 121-139.

Ware, C. and Mitchell, P. (2008). **Visualizing graphs in three dimensions**, 'ACM Transactions on Applied Perception', 5, 1, pp. 1-15.

Wealands, K. (2007), **Cartographic user interface design models for mobile Location-Based Services applications** RMIT Univeristy, Melbourne, Australia.

Wehrend, S. and Lewis, C. (1990). **A problem-oriented classification of visualization techniques**, in Proceedings of the 1st IEEE Conference on Visualization, 1990. Visualization '90'. San Francisco, CA, pp. 139-143-469.

Wehrend, S.C. (1990). **A Categorization of Scientific Visualization Techniques**. University of Colorado, USA.

Wills, G.J. (1999). **NicheWorks: Interactive Visualization of very large graphs**, 'Journal of computational and Graphical Statistics', 8, 2, pp. 190-212.

Zamoyski, A. (2005). **Moscow 1812: Napoleon's Fatal March**. Harper Collins Publishers, NY.

Zeqian, S., Jishang, W., Sundaresan, N., and Kwan-Liu, M. (2012). **Visual analysis of massive web session data**, in IEEE Symposium on Large Data Analysis and Visualization (LDAV), 2012. Seattle, USA, pp. 65-72.

Zhou, M.X. and Feiner, S.K. (1998). **Visual task characterization for automated visual discourse synthesis**, in Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. LA, USA, pp. 392-399.

# CHAPTER 4

## VERIFICATION OF THE WORKFLOW

### 4.1 Introduction

In this research, the role of experts was quite important. They provided case study data, the problems to be solved and the questions to be answered. In addition, they offered first feedback to the proposed solutions.

This chapter describes phase 3 when the domain experts were revisited to review their requirements, with the purpose to see whether the workflows developed in phase one had to be changed based on the experiences with the 'new' STC environment. This was done in sessions in which the experts were allowed to 'play' with their own data in the STC's visual environment and to solve the problems they defined before. Thus, they tried to confirm or redefine workflows and to comment on the usefulness of the STC.

These empirical evaluation sessions applied user research methods such as interviews, think aloud, screen logging and audio recording. In these studies, the domain experts of the Tallinn and Delft use case studies participated. The experiments took place at their home universities. The following sections discuss of the outcomes of these two sessions.

### 4.2 Verification Purpose

The purpose of this phase was to involve domain experts again in their scenario development process to confirm or redefine their own original workflows. Additionally, it was expected that these sessions could identify possible usability problems regarding the use of the software. Therefore, measuring the success of user activities and user satisfaction was an essential element that provided additional feedback on the required tools, design, interface, etc.

We consider the conducted usability testing as part of the UCD process in the working environment of the domain experts, as a proper way to define the real contexts of use of the STC. Domain experts could experience and experiment with the interactive environment while studying their own data in the STC and identifying scenarios for real usage. It resulted in more accurate workflows than those defined before in phase one. Interviews with the experts revealed some ideas on the necessity of additional tools for analytical purposes. These studies clearly provided useful feedback including the domain experts' attitudes and satisfaction.

Before the test sessions, the experts were informed about the objectives of the verification study, on the methods to be used during the sessions and on the user research ethics. It was pointed out to them that the purpose of this evaluation study was to measure the visual and analytical capabilities of the proposed visual environment, and not their abilities to explore the data.

## 4.3 Use Case III Tallinn

This use case is an exploratory study of the movements of suburban commuters in the Tallinn district area. The movement data of 203 commuters have been collected over eight days based on positioning data of their mobile phones.

The domain experts had reported about these data before. They found evidence of temporal rhythms in commuter movement behaviour (Ahas, *et al.*, 2010) (see Figure 4.1). However, some questions related to the temporal distribution of different groups remained unanswered. It was expected that the STC could assist them to find these answers.

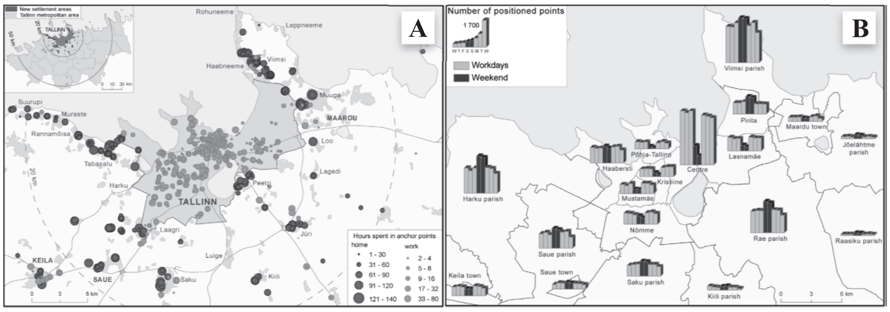



Figure 4.1 Tallinn district area, **A**. The home (dark dots) and work location (grey dots) of commuters, **B**. The distribution of suburban commuters over eight days, weekdays (grey) and weekends (black). *Source:* Ahas, *et al.* (2010).

### 4.3.1 Domain Experts

The usability evaluation of the STC representing the Tallinn commuter dataset was organized in the working environment of the domain experts at the Department of Geography, University of Tartu. Two domain experts, one female and one male, were involved in the experiment. They had no previous experience with data analysis in the STC's interactive environment. However, they both were aware of the STC concept and its analytical potential.

## 4.3.2 Design of the Experiment

The main purpose of this qualitative evaluation was the verification of the workflow/visualization strategy that was set up before, based on the earlier discussions with the experts. In addition, it intended to measure user satisfaction with respect to the cube's performance and existing functionality. In order to get feedback from the experts, an environment consisting of three multiple linked views, a 2D map, the 3D STC, and an attribute information view was prepared (see Figure 4.2).

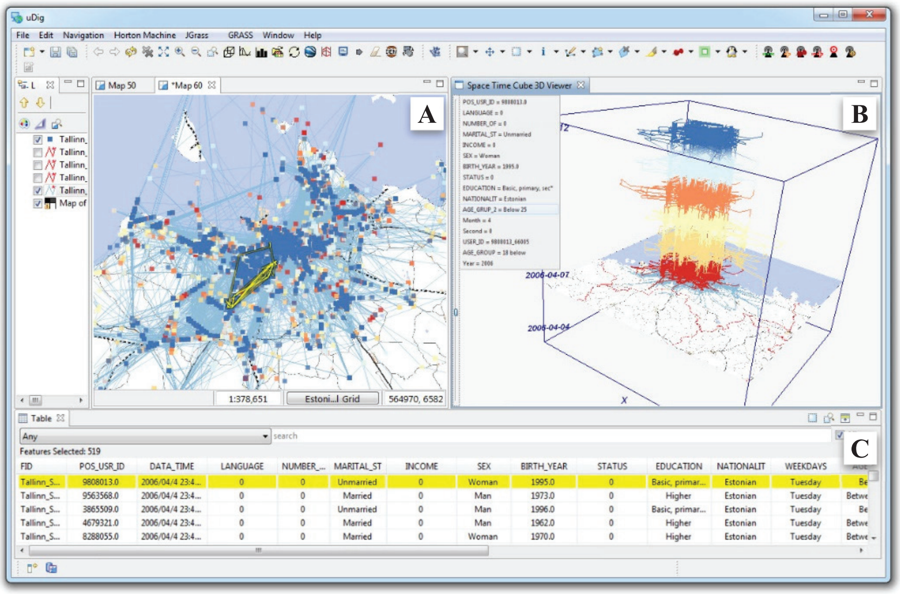



Figure 4.2 Visual environment of the use case study in the uDig program environment during the discussion. **A**. 2D map view, **B**. 3D STC view, **C**. Attribute table view.

Both the 2D map and the 3D STC displayed the same movement information, but from a different perspective. The cube's supporting base map was identical to the 2D map and contained information about administrative boundaries, main roads, railways, water areas, populated areas, and land use. For the domain experts, land use information was an important factor during their exploration of these data (see Figure 4.3). During this activity, they could change the content of the base map and attribute information as well, to help in formulating their workflows. The STC environment allowed the users to work following Shneiderman's 'information seeking mantra'.

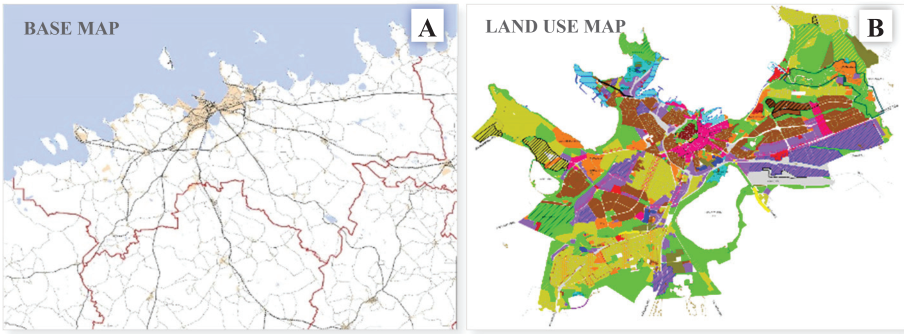



Figure 4.3 Base map options for the STC: **A**. administrative data and infrastructure; **B**. land use map.

The whole experiment was based on the two research questions defined during the first visit to the experts in Tartu in phase one (see section 3.3.4). The idea was to let domain experts find the answers themselves. They had to pick up a question related to the attribute information, for each step in Shneiderman's mantra. This information had to be ordered in a consecutive way to follow the overview - zoom steps. This could help to understand how the STC could / should be used for problem solving purposes. Usability metrics such as effectiveness (task accuracy) and efficiency (response time) were not as critically important as user satisfaction in this phase of the evaluation.

For the experiment, we used one laptop running a Windows workstation with a screen of 15 inch at a 1920 by 1080 pixel resolution, and a mouse for a more flexible manipulation of the program environment. The STC was introduced in a uDig open source GIS (URL 2) environment with a JAVA based plugin. During the experiment, user activities and cursor manipulations on the screen were recorded. The sessions were audio recorded, capturing the think aloud actions of the experts and the interviews with them. For these screen and audio recordings Snagit 10 software was used.

Thus, experts were asked to indicate step by step how they tackled the defined research question. What was the information that they would use to study at overview level, and how would they go about the zoom / filter steps? From which perspective (location, attribute or time) would they like to study the defined research question in the overview - detail modes?

### 4.3.3 Procedure

The domain experts involved in the experiment were presented a prepared PowerPoint presentation explaining the purpose of the verification study, the test procedure and user research ethics (confidentiality). They were reminded about the research questions and tasks set up during the meeting in phase one (section 3.3.4). This was followed by a demonstration of the working environment of the application, (see Figure 4.2), and the usability methods applied for this experiment. In addition, the experts were given instructions on different functions and tools to familiarize themselves with and manipulate the visual environment. They were also allowed to experiment with this functionality of the STC before the test session started. During the evaluation, experts could ask for the assistance of the test moderator. More importantly, when answering their own questions in the STC, experts particularly were asked to think aloud and express their opinions.

The session was planned to last one hour in a separate room, but the experts were not limited in time. When the session started, they were asked to interact with the visual environment and to complete their research questions.

### 4.3.4 Analysis and results

In this experiment have participated two domain experts, with whom previously in phase one were discussed research questions and requirements. The expert 1 made various remarks in relation to the 'new' view on their data. This expert became enthusiastic about the STC view on her data. She expected it to be a complete and full-fledged geo-analytical environment, starting even to complain about missing functions.

The first expert observed data in the STC's environment and decided to use the assistance of the test moderator. First, she started to ask questions related to the functional capabilities, in order to compare the movement behaviour of different nationalities and their space-time use.

> *"I would like to compare the space-time use for different groups, for Estonians and for Russians…..can you do two different cubes next to each other, in one Estonians and in another Russians?"*

It was obvious that the research question provided in the first phase suddenly started to change. The interest of the domain expert totally focused now on the study of different nationalities. A new idea and question appeared when the expert 1 saw the data from a different perspective and decided to tackle her problem differently, because the methods and visual representations she had used before did not allow what was possible in the STC. However, the software did not offer the requested functionality, and only one STC view could be shown at a time. During this discussion, she also highlighted the difficulties that research is facing when analysing attribute information. In particular, she pointed at the necessity of the comparison of different dimensions of the data (nationalities, gender, age, etc.) simultaneously, and she complained' that a single map or graph did not offer such possibility.

> *"It is too many dimensions to put in one map or graph"*

From this discussion, it also became clear that our expert needed a well-structured analytical environment with multiple linked views, which would offer possibilities of comparison of various attribute data. Besides, she made remarks regarding the need to analyse the temporal dimensions of the data for different levels of details. The traditional ways do not satisfy her requirements, but still there is a need to extract time-related knowledge from the data.

> *"This is a question for me also, how to see this time scale of these regions, and also the nationalities."*

After she observed the movement behaviour of ethnic groups, she started to focus on the most dominant groups, which were Estonians and Russians. And in the next step of the exploration she studied movement differences for weekends and weekdays. These differences were obvious in the STC view and could not stay without the expert's attention. To understand it better, she decided to compare a weekday - Wednesday with a weekend day - Saturday. The requirement here was to switch off the other information to keep focused on the selected time-periods and places of interest. However, the software could not offer such convenient manipulation and therefore, in order to keep the exploration and workflow development process going on, the selected days were represented in the STC view with a single additional file. The expert could follow the movement of the 2D base map along the time axis and she could identify any time-period or spatial location of trajectories she was interested in.

> *"In these different days we can see differences between Estonians and Russians….I think if I want to compare Estonians and Russians, it is better to do it separately. For example, now this is Saturday only Estonians and to look on all these movements, and then only Russians"*

Expert 1 indicated that she wanted to divide the data and study them separately. The main reason for this were the dominant trajectories of Estonians.

> *"Because now I can see only these blue trajectories (Estonians) and some very segmented red trajectories (Russians). I cannot understand where Russians go from this view."*

She also indicated that such data might need clustering to understand what is going on. She stressed the point densities in the 2D map view and the complex trajectories in the STC view. The software provided a link between the 3D STC and the 2D map. Expert 1 could see the movement of the selected trajectory not only from a temporal perspective but also from a spatial perspective. Despite this, she found the interaction not enough and suggested more interactivity between the 2D and 3D STC views. In particular, when the base map is moving along the T axis, the points related to that particular time moment at that particular place should be reflected by the 2D map as a selection to show the areas of distribution in space.

In order to sum up the exploration efforts and link them to Shneiderman's mantra, expert 1 was asked to repeat once again the steps that had been taken until this moment in the session.

> *"From the beginning we selected different nationalities. Then we filter out information based on the different days, in particular we focus on weekends. During these weekdays, I would like to understand movement behaviour in space, in what directions people are moving. Then again, filter out this information by different nationalities and study them separately. To know the difference between Estonians and Russians who have been in the city center, and then again for different days."*

The idea was to select and study trajectories of people going into and out of the city center of Tallinn, on overview level, and compare these movements over several days to see potential repetitions and differences in movement. To do so, it was first needed to focus on a spatio-temporal zoom for one day, and then observe and study these aspects for the other days.

> *"To compare who lives for example in Pirita and who lives in Nomme. In northern part and southern part, is there a difference in movements in the city center?"*

Besides, she was also interested in whether these people could meet each other at a particular time and at the same location, and whether this is happening once or every time.

> *"I just want to know if they in same time and same place can meet each other, the people who are leaving in Pirita and in Nomme. If they go to city center, are they bought in the same time or only Estonians go for some week days in the mornings and Russians on Friday nights and they cannot meet…"*

Based on previous studies, the expert knew that these two nationalities have divided activities in the city center. However, they still would like to understand whether there are any possibilities of space-time intersections, and, if so, what are their personal characteristics (age, gender, etc.).

In the discussion, the domain expert mentioned that they derived some general answers from previous studies but that in the STC, this question can be answered in a more convenient and precise way.

> *"…we did analyse exactly to know why these co-presences and we found three hours period and then look at all this people who did call activities….but it is more exact in this visual representation* (pointing to the STC)*, with the same logic, to find at the same place and same time, and then know what is age, gender, nationalities, etc..."*

During this discussion, the expert also showed interest in creating space-time density maps for particular analyses in the STC. Such density maps should reveal the number of trajectories for some particular place and particular time. Also, the use of a Parallel Coordinate Plot (PCP) data analysis was suggested, for instance to study visitors by nationality and in relation to different districts of the city center.

> *"...that time period is on this level and number of people in different days…and to select, for example this region and then the time and then to take these people and then to look where this people been in different times. For example if the question is, who is on Friday nights in the city center of Tallinn, and have they been in the city center in other days also, or they have been only on Friday nights there. Look where these people comes from, where their usual space activities are, or where they move for different activities…"*

At the end of the test session, the workflow as shown in Table 4.1 was defined for the research question: How to compare the space-time use of two different ethnic groups, Estonians and Russians? At the end of the test session, domain expert 1 was interviewed to get her overall impressions. The results of this interview session is presented in Table 4.2.

Table 4.1 The workflow structure defined by expert 1

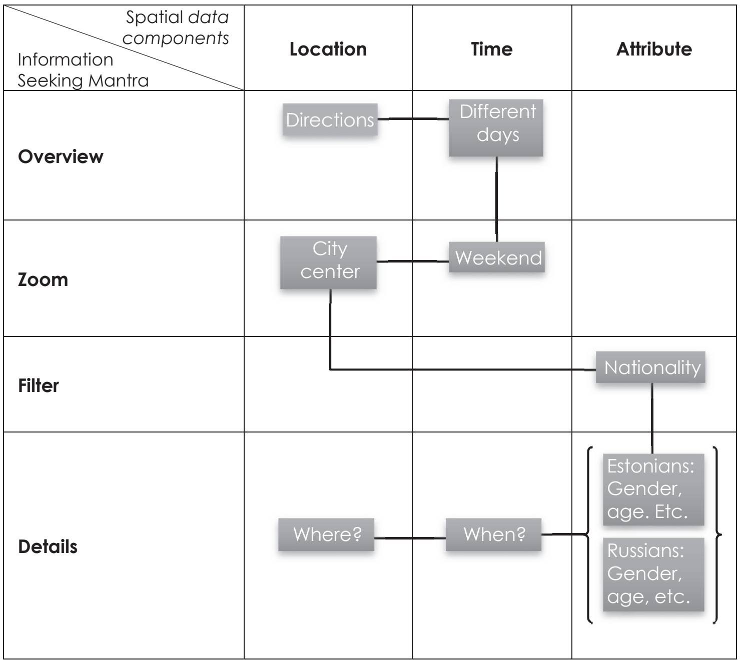



Table 4.2 Interview with expert 1

| Question | Answer |
|---|---|
| What are the visual representations that you normally use for analysis of this type of data? | Graphs and 2D maps, for example for week days I usually use choreme graphs and maps. It can show for example the weekday differences for different regions. Also for nationality, same graphs and maps and then I can compare differences, but they are all two-dimensional. |
| What are the advantages of those visual representations? | I think the cube can show different dimensions more, and it is more useful, I'm not satisfied with these maps that I'm using usually. They can show only 2D space, although it is easy to make. |
| What are the disadvantages of those visual representations? | My maps do not provide always all answers on the questions. I have regions, time scales and social characteristics and all this information is too much to put on the 2D map to get answers. I think the cube will handle it, If I can select and then do things as I want. |
| What do you expect from the STC? | STC can help in early stage of a research to get some particular hints on the data. It can show information from different dimensions and its interactive environment is more useful, it can handle all necessary information to get answers on the questions. |

The expert 2 expressed a desire to manipulate the visual environment himself, which he found easy. After a short training, he was ready to start the session. At the beginning, he explored the dataset in the STC's visual environment by moving the 2D base map along the time axis and observed the trajectories for different days.

> *"To study land use, I would like to have persons with higher education in business areas"*

For this requirement, the STC showed the trajectories colored based on the highest level of education of each person: basic-primary-secondary, vocational and higher. In a next step, the domain expert filtered the data, by displaying only trajectories of people with higher education. Expert 2 was observing data in the STC's view for several minutes without comments and then asked if there is possibility to select a particular time period.

> *"Ok, and we want to separate land use, so can we take night time out of these data? From 22:00 of evening."*

Unfortunately, such specific function was not available. Only moving the 2D base map along the time axis allowed time selection. In order to help him to distinguish day and night activities visually in the STC, he was shown so-called space-time windows representing very distinctive movements of people over a course of 24 hours. After that, expert 2 asked to identify the Friday out of these data. The shown principle was clear to him. He could easily distinguish daytime from night. After some time of observation, he asked whether we can have information about school children in the STC view:

> *"So, if we want to have school children, how we can see it here?"*

In response, the population statistics including the age group of school children were displayed. The dataset contained only a few trajectories of school children. The expert selected those and compared them in the 2D map view. He could now clearly see how far school children travelled to school and their paths show that children moved in different directions, which means that they are studying in different schools. After these studies, the expert was ready to provide the structure of his workflow. But first, he summarized his opinion about the working environment, mentioning that the environment is limited in its options to manipulate selected information. In particular, it is impossible to hide unnecessary information when studying selected data.

> *"Ok, now I know what kind of functionality you have here, and what kind of possibilities exist. For me it is a little bit complicated because you can just select and everything else is still on the screen, it is actually disturbing me. For me it is easier to see if I want young people or old people and then everything else is invisible. Now here is 200 persons, but if we will have 10 000 persons, then it is a lots of noise. Actually, it is better if you can select some persons and make the rest invisible."*

A second remark was made regarding the temporal selection or zooming in to the data while the expert was looking at the work status of the suburban commuters in the STC.

> *"Here is evening and normally from 4 o'clock to 7 o'clock is rush time. So, it is not mid-day actually, and for me it is complicated to follow, because I cannot see time…"*

Next to the temporal zoom, the importance of both spatial zoom and selection and filtering of different attribute information was stressed. Expert 2 similar to expert 1 also stressed the importance of the land use profile (land use map) that can facilitate the exploration process in the STC.

> *"For land use I have great use to see its profile. I can go for instance, on Monday mid night and see….I need some selector to see what is on that particular land use. I need, Monday mid night and then I will go further on Tuesday morning….Actually I can select these suburbs, office spaces and consumer places if I find this from 6 o'clock to 7 o'clock. For land use I can use it quite well, so I can see here sleeping city, working city and it is easy for me to see the reflection of this profile…Actually, STC can be used for land use. For finding all basic distinction between sleeping city, working city and consumer city."*

During this discussion, the domain expert concluded that the STC is useful for a land use study. It can even help to understand the functioning of a completely unknown city from a land use perspective. He provided the scenario for a workflow on how to use the land use profile to find the required answers on the research questions given above.

> *"If we have land use profile here from mobile operator for example, I can use cube and tell something about interesting spots. For instance central business district in some particular time-period…I can see profile, time, select for example old women patterns and select only area what to see."*

During this stage of discussion, the domain expert was asked to formulate the scenario of exploration of the research question shown in the beginning of the session. So far, the actions of the expert were intended to experience and understand the principles and functioning of the STC. He suggested that the starting-point for the exploration of the research question has to be age groups, then status and finally education and gender.

> *"I think the age group is most important first, second is status (working, student, school, etc.), then education is important and after is gender."*

The expert also mentioned that it is not necessary to follow the exact order of the described workflow. One is flexible to change the order of the given attribute data, because the user still will end up with the same answer and same result. The order suggested is the traditional approach of the human geographer:

> *"We still get same results….I think there is no big difference if we start from education and then age and gender…it is traditionally if you will look in population geography, first age groups, after you have occupation, education, gender and income."*

Important is that the domain expert did not find useful and interesting the idea of implementing different scenarios on the mentioned attribute data to answer the research question.

> *"If it is visualization approach, I go to the city I know or city I do not know, I probably use different strategies. Maybe, I take only male pensioners I look what is happening with this data, then I take also young people and I will look on Friday night and then I look on business stay in mid-day. So, I select different approach, it is kind of learning and studying…It is not fixed frame of questions but it is more like observation….the first result of studying land use is observation."*

In further discussions, the expert described qualitative and quantitative ways of using the STC for research. For qualitative research, they can observe and detect patterns of interest in space and time and develop hypotheses and strategies to answer questions in mind for further investigation. As a result of such a study, experts will continue with an investigation in the field by collecting statistical and photo materials. This seems to be a common strategy in human geography to investigate unexplored surroundings. As for the quantitative analysis of data, they will use statistical questionnaires to gather information for investigations. Further, they will derive statistical data and use these for a quantitative study to make various comparisons between different attribute characteristics.

> *"First approach is that I used it as observation, I study city I learned, and maybe I make plan for field works or I get good understanding how the city is functioning, where is center, etc. The second step is that I stop planning of going somewhere, making pictures, questionnaires or whatever and I want to do statistics out of it."*

According to the discussion, at the end of the test session the workflow in Table 4.3 was defined based on the research question: Which land use patterns can be distinguished with diurnal activities, with weekly data, or with socio-demo data? At the end of the session, domain expert 2 was interviewed to get his overall impressions. The results of interview session is shown in Table 4.4.

Table 4.3 The workflow structure defined by expert 2

| Spatial *data components* / Information seeking Mantra | **Location** | **Time** | **Attribute** |
|---|---|---|---|
| **Overview** | City area | | |
| **Zoom** | Particular land use | Monday<br>Tuesday | |
| **Filter** | | Midday<br>Midday | |
| **Details** | | | Age, gender, occupation, education, income |

Table 4.4 Interview with expert 2

| *Question* | *Answer* |
|---|---|
| What are the visual representations that you normally use for analysis of this type of data? | Normally if this information is collected from land use, you know where it is and you make succession if there is a shopping center, restaurant or school, you have assumptions on what is happening in these places. Normally, if we study land use of cities we are designing land use map as functional zones like shopping areas, railway stations, business district, etc. on the 2D maps. In some studies, we are using street maps, because we want to know more. |
| What are the advantages of those visual representations? | Easy to make 2D maps. |
| What are the disadvantages of those visual representations? | Bad is to make whole map of the city, it is related to the human and financial resources, for observation of all streets and blocks. Also, in small and compact cities it is problem to make very good land use maps because everything is mixed, but in big cities it is very easy to distinguish. |
| What do you expect from the STC? | In the STC is easy to observe information, because it has many statistics to interact, like age group, education, etc. If you do street observation, we can get more information about activities what we are doing, drinking, partying, working, shopping or whatever. You can put also information about young women or old women. Street observation is giving you sense of what is happening there, but you do not have actually this attribute information here. |

### 4.3.5 Summary

It was very interesting to note that while working with the visual environment (see Figure 4.2), the domain experts started to redefine the research questions they formulated in phase one (see section 3.3.4) and made them more realistic. Thus, two main questions regarding to the use case were identified as following:

- How to compare the space-time use of two different ethnic groups, Estonians and Russians?
- Which land use patterns can be distinguished with diurnal activities, with weekly data, or with socio-demo data?

As it appeared, domain experts had no difficulties to manipulate the STC view and orient themselves to study the data. They seemed to feel comfortable and started debating what additional GVA functionality they would like to see available. In this discussion, they referred to familiar GIS software and their own research to express their needs. They for instance indicated that visual solutions incorporated in the interactive visual environment should allow for comparison and simultaneous analysis of multiple attribute characteristics. As a result, small multiple views of the STC and a Parallel Coordinate Plot were added to the final GVA environment as will be reported on in chapter 7.

## 4.4 Use Case IV – Delft

Increasing use of tracking technologies in various domains caused an information accumulation that offers new opportunities for researchers to evaluate their data from alternative perspectives, and this might lead to new insights.

As has been described in section 3.3.5, the focus of this use case is to investigate people's movements within the city centre of Delft. Based on the data collected of the pedestrian movement behaviour through GPS devices, it is now possible to analyse the use of the road network, visited locations, actual activities, length of stays, etc. The GPS tracking technology as an instrument to collect data on movement in public spaces is considered to be a valuable method by urban planners (van der Spek, 2009). It has been applied for the analysis of the actual use of public space in the cities of Koblenz, Rouen and Norwich (van Schaick and van der Spek, 2008; van der Spek, *et al.*, 2009) within the 'Spatial Metro Project,' and later for the city of Delft.

An extensive study of pedestrian movement behaviour in the city center of Delft was carried out by (van der Spek, 2009; van der Spek, *et al.*, 2009). Examples can be found in Figure 4.4. In their analysis, they looked at the movement behaviour of three different groups of pedestrians. These are tourists/visitors from out of town, residents of the suburbs, and city center inhabitants. They investigated similarities and differences of the use of the city center by the above groups. Also, they identified the most visited areas in the center, destinations, transport mode, etc.

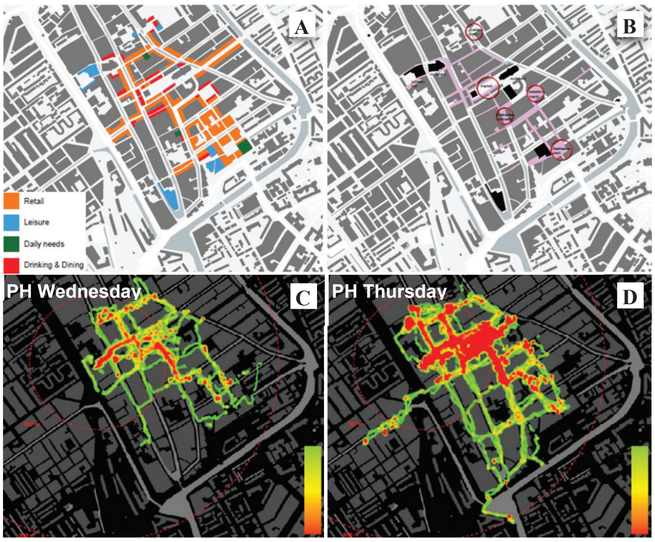



Figure 4.4 Delft city center: **A**. Leisure activities and **B**. Places of interest. **C**. Pedestrian density on a Wednesday and **D**. Pedestrian density on a Thursday. *Source:* images by S. C. van der Spek, 2009 (Kveladze*, et al.*, 2012).

The domain expert who participated in this research, was familiar with different visualization methods used for the investigation of the spatial distribution of pedestrians in Delft. Despite this, questions related to the temporal aspects of the patterns still remained to be partly unanswered.

## 4.4.1 Test participant

In this experiment, the test person was an expert in Urban Design and Planning at the Faculty of Architecture and the Built Environment of Delft Technical University. The evaluation took place at his work location to discuss a scenario-based workflow for the Delft use case study. Because of his involvement in different movement data related projects, he was well aware of the data, their problems and the research questions the data were collected for.

## 4.4.2 Design of the Experiment

The proposed visual environment consisted of a 2D map view and a 3D STC and attribute table view (see Figure 4.5 and 4.6). The used background data for the 2D map and the base map of the STC were water area, road network and a kernel density map showing the most visited places in the Delft city over a period of four days. Both views (2D and 3D) were showing the same information, but from a different perspective. The 2D map view represented the spatial distribution of people's movements and the 3D STC showed their spatio-temporal distribution over a period of four days. The data were divided in two different sets, one with persons starting at the 'Phoenix' garage and the other with persons starting from the 'Southport' garage.

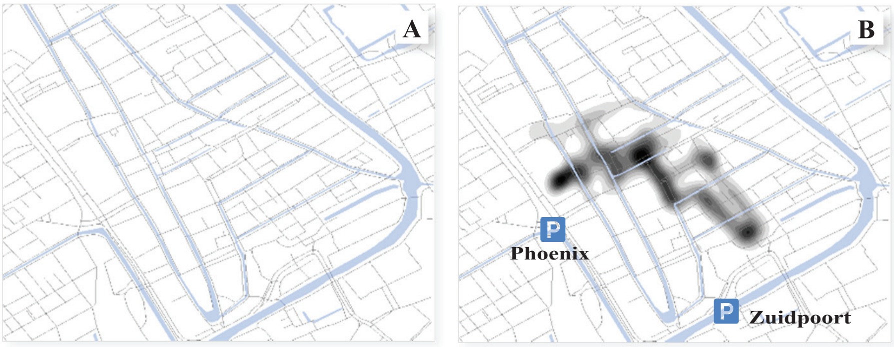



Figure 4.5 Materials used for the Delft use case verification session, **A**. Basic background information: water areas and roads network, **B**. Basic background information and kernel density.

Similar to the previous experiment, the working environment was constructed in uDig open source GIS (URL 2), with a JAVA based STC plugin. This experiment was also designed on a DELL XPS 15 laptop running Windows 7 with a 1920 by 1080 pixel resolution. During the experiment, the domain expert could use the mouse to manipulate the working environment. The test session was audio recorded and screen recorded through Snagit 10 software.

### 4.4.3 Procedure

The evaluation session took place at TU Delft. Similar to the test sessions for the Tallinn use case study, the experimenter visited the domain expert in his working environment to define the workflow. In an introductory PowerPoint presentation the expert was reminded about the research questions identified during phase one (see section 3.3.5). This was followed by a demonstration of the working environment consisting of three multiple linked views and used background information. The domain expert was informed about the user research methods to be applied during the session: think aloud, screen recording, audio recording and interview. Also, he was able to switch on/off layers during the experiment to explore the dataset and (re)formulate the workflow. He could ask for assistance of the researcher during the exploration process.

The session duration was planned for one hour, however he was not limited in time. Accordingly, the discussion session with domain expert took 2 hour and 30 min. The expert was asked to think aloud and interact with the visual environment during the experiment. Before the actual test session, he was able to familiarize himself with the functionality and manipulation options of the visual environment.

The purpose of the session was the verification of the final workflow for the visualization strategy. Therefore, the domain expert was asked to find answers to his own research questions in the developed visual environment. At the start of the session, the visual environment was showing movement trajectories of different gender groups from both garages over a period of four days (see Figure 4.6).

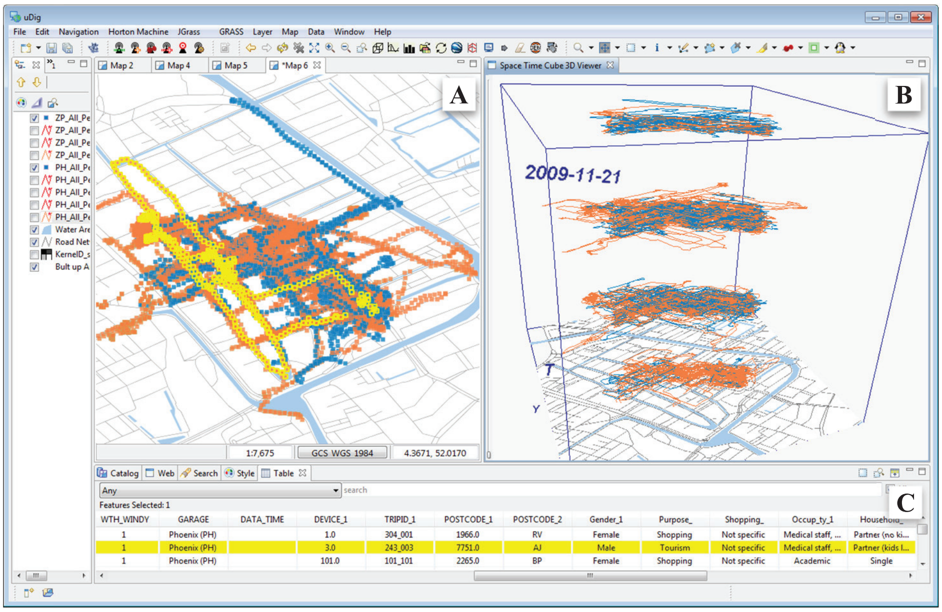



Figure 4.6 Visual environment of the Delft use case study in the uDig program environment during the verification session. **A**. 2D map view, **B**. 3D STC view, **C**. Attribute table view.

Thereafter, the domain expert was asked to start the exploration of the data and to think aloud continuously while formulating the workflow. At the end of the test session, he was interviewed. The interview questions would have to help to understand the previous experiences of the domain expert with data exploration and his current expectations of the STC.

## 4.4.4 Analysis and results

At the beginning of the test session the expert decided to observe the data in the STC view. He mainly looked at the trajectories for each day on the base map. The base map was convenient and easy to move along the time axis to identify more details with respect to the movements of pedestrians on different streets. However, later on he decided to continue working in the 2D map view. He started to switch on/off supporting information, and soon it became clear that different streets have different loads of use in the city center. After that, he decided to look at randomly selected individual trajectories to understand the logic of the movement behaviours. For this, he again observed the movements along several trajectories from the beginning until the end. Then he identified all streets that pedestrians cross; based on the resulting bunch of points he could understand the places visited and was able to guess the pedestrians intentions.

> *"So, this is fine, because this is market, market represented by this road, but this is strange because he can walk everywhere....then went to the "Vermeer" museum here and then followed another street, and they went to the shop here. There is a supermarket on this side, so, I am not sure, or they walk to the other side. Then back, this is Choorstraat, which is very nice shopping street, but they did not shop anywhere. They continue walking even, they stop here and there, there are some nice cafe or only does he/she here, no window-shopping. This is remarkable, because a lot of arts studios there* (means Choorstraat), *so this will be the one of the thing to look at."*

During the discussion, the expert started to formulate questions on the relation between an individual's speed and the city's land use. For him it was very interesting to look at the different streets and see how pedestrians are using them.

> *"Not only which roads are used, but how streets are used. Are people stopping on the streets, is that low speed street like the shopping street…whether are unlike shops. I mean, it is not hema or blocker, it is about specialty shops like Danish design shops."*

The expected pedestrian behaviour in these shopping areas was characterized by a slow speed and if the behaviour was not actual shopping than at least window-shopping.

> *"It is just amazing to see that people are just walking through these streets"*

Considering the type of pedestrians, different behaviours were spotted. People from Delft city itself seem to have a clear purpose and move from point A to point B. Tourists wandered around more and did some (window) shopping. Besides, there is some difference between female and male movement patterns. Females might would stop for shopping, or at least do window-shopping. Domain expert explained these differences:

> *"Yes, it might depend on the group and time, if I'm doing effective shopping I would not go there on Saturday after 11:00. That is time, I try to skip,*

> *because you cannot move. You can walk slowing down and you cannot bring your bike…so that's the time I do not want to be there, but I'm surprised by the patterns looking the people go that they use the streets, but maybe this is because of the other things where they stopped…actually it is very strange…"*

After these discussions, we moved to the STC view. The expert appreciated seeing the same trajectories from a temporal perspective. He could clearly understand not only movements in 2D space, but also their time distributions and the durations of stops that pedestrians made in different places. In order to identify the location of trajectories (or st-paths) for different time-periods he again was suggested to move the cube's base map along the time axis. Having a particular purpose in mind, the domain expert was able to easily manipulate the environment and to find the required information. In the STC view, the base map also represented the footprint of the trajectories, which was found distracting by the expert. The main interest of the exploration of the st-paths at this stage was to identify where pedestrians stopped for a while. The question was what was located at those places or perhaps some other related contextual information. The expert was also asked about the design of the base map and how detailed it should be to extract information on movements and to identify places.

> *"I'm looking for that. I am missing the squares that actually we are using in public domain. Now I see the only road network….I am missing either building blocks that you can recognize space, or you miss the information…let me speak about squares, we would like to see the public domain"*

With this discussion, it became clear that the domain expert needed a detailed base map that would help him to identify very detailed land use information. In particular, he wanted to extract information about each building in Delft. As an option to get more details, he was proposed to use OpenStreetMap in the STC view. In order to study the tracks, it is important that the base map shows the places where pedestrians have been.

> *"We can walk through the grasses, like park area…If it is about public space, it should show the public space itself."*

In this discussion it was decided to use OpenStreetMap as the base map focusing on the context of the buildings in Delft city center. However, the domain expert clearly stressed the most important mission of the STC in this study.

> *"I would say the only thing which is important, is where people really stop. So, if you can connected like, ok people stop here in this building then you can show what is the building, very clear then it is this building where people went in."*

The discussion ended up with the idea that such contextual information definitely should be represented in the 2D map. However, the STC view should be able to provide even more information:

> *"I think the 3D STC should show something else than only this information… If you have results there…if you have STC you can find out retrieve the locations where peoples stop and then you can connect to what's there either public space or by buildings, land use."*

As the expert mentioned, he had an opportunity before to see the information visualized in the STC but never had the chance to use and manipulate it. From his observation, he considered it to be very interesting to see where the represented trajectories are going in time and what comes out of it. Besides, the STC could show some results with respect to the movement directions that were not visible before on the 2D maps.

> *"In time line I can see directions, time they spent, and if we can get that out, that would be great. But also, on the detailed level, people do not stop on this Choorstraat, but they wait a bit in the beginning, and either they visited building, we have to decide and that can be seen from the data. They waited at end, and did they wait or did they go to the shops in the corner. That could be interesting. If they visited shops in the corner but not in the street then that is something, which is very strange. Does it happened once or multiple times."*

According to the domain expert, there is need to look at the details and to find out who are the people going there and what is the purpose to visit these places. Thus, it requires to explore movement behaviours on individual level, which is not yet done. Besides, to ensure that these individuals can be representative, the idea is to study similar patterns and to detect space-time activities. In this case, research could contribute to the total picture and describe pedestrian activities in the city center.

> *"I want to know how much time people spent at specific places, but also how much time people spent to walk from this side of the street to the end of the street. Because that could give information about the speed…"*

At this stage of the discussion, it became clear that the interest of the domain expert was to see the length profiles of the streets, i.e. from the beginning until the end over the period of four days. His idea was to focus on, and narrow down to two streets and compare their character. Thus, he indicated the necessity of an additional graph that can show street profiles from a time perspective. In other words, to compare the profiles of different streets and to find out more about visitors' movement speeds. In the graph, the steeper the trajectories the longer the visitors stay on the street and the more gentle the trajectories the shorter the visitors stay on the street and pass through it faster. An interesting remark was made about a pedestrian who might enter the same street several times during day. This type of movement behaviour was found very interesting for the expert. Accordingly, a comparison through street profiles makes it easy to identify similarities and to say more about pedestrian movement behaviour.

> *"Then look for similarities, so are people all walking through the street without stopping, and if you compare it with map, with the land use you will recognize that there are a lot of shops and people are hardly stopping there. That is the issue…I would like to know more about use of the streets…I mean people walk there and that is great, liveability. But, if people walk just through all the time it is lovely street, but it does not contribute anything to the shops…"*

In the exploration process, important aspects such as the people's social characteristics have to be considered as well. For instance, are they suburban families that do not often spend money in speciality shops or people who are coming for effective shopping? Generally, in shopping activities the domain expert identified three types: window shopping or walking in shops, effective shopping – visit of particular shops for a particular reason, non-shopping – pass by the street without stopping.

The comparison between streets will help to find out differences in the use of these streets. Is this difference due to the location of the shops that attract the attention of pedestrians, and what are those shops: specialty brand shops or shops that are everywhere in Europe (Hema, Blokker, etc.)? Therefore, the research question is about the use of the specific streets where we want to distinguish patterns of use by comparing them. We narrowed down our attention to two streets located in different parts of the city. The first street was the Choorstraat, which is in an old shopping area with specialty shops, and which is located in the northern part of Delft. The second street is Paradijspoort with new developments and which is located in the southern part of the city. The central market area is located in the city center and it is possible to reach it from and then return to the southern garage through the Paradijspoort. But in order to approach the market from the northern part, pedestrians do not necessarily have to pass by the Choorstraat. This street has interesting brand shops, but a visit of pedestrians depends on the shopping purpose.

> *"I think it is going deeper because it is peaking about roots of the destinations, but we are going to look at two specific types of streets, almost same size, and they have different position in a network, and specifically they have different retail, different shops. But of course, this one here (Paradijspoort) have people entrance and going there and here it is bit difficult (Choorstraat), because this one is further away in the all system…"*

In both cases, the main destination of pedestrians is the central market area. However, the question is whether pedestrians use these streets for reaching the market area or to do some shopping too. If they do shopping, then what type of shopping is it? Is it effective shopping, less effective shopping or just window-shopping? Based on the street profiles it will be possible to answer these questions. The expert found it to be very important for his research to link the spatial patterns with the background characteristics of pedestrians as provided in the data.

> *"We have tracks selected, and we know something about the characteristics of these people. Can we also say something about those characteristics…to split in people living in Delft and not living in Delft is not significant anymore… from the attributes you can select people, but how about to use spatial pattern to say something, to get know what the background is, and then try to recognize if there is patterns…"*

The expert discussed and specified some factors that are influencing people's shopping activities. In particular: shops in Delft are open until 6 o'clock in the evening, in November it is getting dark at 5:30 and people are rushing home at that time. An important point was made as well on how two streets can be selected for comparison. As mentioned, people have to go specifically to the Choorstraat, while Paradijspoort has to be passed anyway to reach the open market and then return to the garage. However, it was argued to be part of the research context. Significant was the discussion on the number of tracks identified for each street from the whole dataset. The main question was whether, based on the identified trajectories, we could judge the behaviour of pedestrians in general and say something sensible about the use of these streets. According to the statistical information that the domain expert was holding, the number of trajectories for each street was fair for a comparison, but also necessary for the contribution to local urban development.

At the end of the discussion, the domain expert was asked to formulate a workflow for newly formulated research questions. For the workflow, first he proposed to look at the spatial distribution of the data to know where people come from. Then look at the social status of visitors such as visiting the city with a partner, with kids, alone, etc. The age group was not considered to be an important factor in this stage of the research, but it could be interesting in the further investigation process. Other research related background information is the origin of pedestrians and the frequency of their visits.

> *"People are alone, with kids or partners. So if you have kids then you might have different than others, so I think this we should keep in mind….if there is differences, yes or now…Origin where they come from, is it Delft, national or international. First visit is interesting, if people are first time it might be a different, how good they know the city. The household not important, occupation not important…. How many times do they visit the city is important, the frequency….we have to see if there are differences for the parts that they are looking at… The time difference might be based on type of group…if you have a group visiting with kids then it is school related…"*

In addition to the above characteristics, we have also discussed weather as influential factor on visit behaviours. But the domain expert was not sure about how much it could be a reason for visits. Therefore, it was considered as additional attribute information, having the potential to reveal some interesting patterns.

Table 4.5 The workflow structure defined by the domain expert

| Spatial *data components* / Information seeking Mantra | **Location** | **Time** | **Attribute** |
|---|---|---|---|
| **Overview** | Spatial Distribution | | |
| **Zoom** | | One day | |
| **Filter** | | | Social status<br>Origin<br>Visit frequency |
| **Details** | Visited shops | Time difference | |

As a result of this evaluation session, the workflow as shown in Table 4.5 was defined for the research questions: How are the Choorstraat and Paradijspoort characterized by the different movement speeds of the pedestrians? How long did people stay in the most frequently visited shops, and what kind of shops are those? After test session, domain expert was interviewed to get his overall impressions. The results of the interview session is presented in Table 4.6.

Table 4.6 Interview with domain expert

| *Question* | *Answer* |
|---|---|
| What are the visual representations that you normally use for analysis of this type of data? | Before, we just study slices of time by using videos, and showing the past two, or past four hours and play with color variations and transparency, so the transparent shift point every 10 minutes. And trip gets vague in the past. And further we did it in the STC and we could recognize patterns that went out in the certain directions. |
| What are the advantages of those visual representations? | We did kernel density maps and people liked it. It is easy and then you can compare it to other maps, different density maps. You see the location of garages, the main tracks and so on. |
| What are the disadvantages of those visual representations? | The question is, if we can use density maps, partly we can, but the problem with kernel density is that it changes the legend. Legend never the same. If we use same on another level then distribution of the points are different, so there are always difference in a number of points. Somehow I do not trust this anymore. |
| What do you expect from the STC? | For us time is very interesting, I want to know how much time people spent at specific places, how much time people spent to walk from this side of the street from the end of the street. Because that could give information about the speed and it is possible in the STC. |

## 4.4.5 Summary

The outcomes of this experiment helped to redefine the research questions identified in phase one as following:

- How are the Choorstraat and Paradijspoort characterized by the different movement speeds of the pedestrians?
- How long did people stay in the most frequently visited shops, and what kind of shops are those? How to characterize their shopping behaviour:
    - Window shopping – walking in shops to admire goods but not intending to buy them
    - Efficient shopping – visit a shop to buy the product they want
    - Pass by/no shopping – moving along the street to go to another street

The domain expert showed a high interest into the STC. Similar to the previous experiment, there was a need for a detailed analysis of the spatio-temporal aspects of the data. By observing and studying the trajectories in the STC, the domain expert narrowed down his interest to the use of the streets during daytime. In particular, the domain expert came up with the idea to compare frequency of the visits and shopping activities between old and newly developed streets.

The discussion during the experiment also included research findings related to previous use case studies. However, the approach proposed within this experiment differed because of the new exploratory view on the data.

The domain expert was familiar with the concept of the STC and found it easy to manipulate its visual environment. He did not express a need for the development of new functionalities or graphical representations to further explore data. However, it was suggested to develop a new graph that would allow the comparison of the street profiles over course of a day.

A street profile graph that allows interactive manipulation of the represented data by measuring distance and time to derive the speed of movements was developed. This graph gives indications of the most visited streets, shops, how long people stay there, etc. The implementation and evaluation results of this experiment are discussed in chapter 7.

## 4.5 Discussion

This chapter contains reports on the results of experiments executed for workflow confirmation. The main principle indicated by experts during the sessions was the importance of the time component in data. For example, human geographers first prefer to identify time and then characterize various principles regarding to the background characteristics of represented trajectories. While the urban planner first preferred to identify a particular location and then explore various temporal aspects in human movements. As a final result of these experiments, research questions were re-formulated. For Tallinn see section 4.3.5 and for Delft see section 4.4.5. For each of them workflows were defined on how to go about the data (see tables 4.1, 4.3, 4.5).

These evaluation sessions also showed that each domain expert preferred to set up one scenario of visualization for each workflow. According to them, there is no big difference in workflow order between selected variables for different steps of the mantra. For instance, the human geographer mentioned that:

> *"The answer will be same user will start exploration from education, age group, or gender. This set up of the workflow is a traditional way to study human movements".*

Therefore, one workflow will suffice to represent various background characteristics of the participants trajectories in multiple ways. Based on the workflows defined by the experts, schematic transcripts have been defined as shown in Tables 4.1, 4.3, 4.5. The individual steps of these workflows or scenarios to answer the questions were linked to the phases of the Shneiderman's (1996) 'Information Seeking Mantra'. This resulted in different visualization strategies for each use case. The determined research questions and workflows, obtained through domain experts for different use cases, can be a useful guideline for the use of the STC.

## References


Ahas, R., Aasa, A., Silm, S., and Tiru, M. (2010). **Daily rhythms of suburban commuters' movements in the Tallinn metropolitan area: Case study with mobile positioning data**, 'Transportation Research Part C: Emerging Technologies', 18, 1, pp. 45-54.

Kveladze, I., van der Spek, S.C., and Kraak, M.J. (2012). **Recognition of temporal patterns in pedestrian behaviour using visual exploration tools : extended abstract**, in In: Proceedings of GIScience 2012 : 7th international conference on Geographic Information Science. Columbus, Ohio, pp. 6.

Shneiderman, B. (1996). **The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations**, in the 1996 IEEE Symposium on Visual Languages. BouIder, Colorado, pp. 336 - 343.

URL 2, From: http://udig.refractions.net/

van der Spek, S.C. (2009). 'Mapping Pedestrian Movement: Using Tracking Technologies in Koblenz', in **Location Based Services and TeleCartography II**, ed. by Gartner, G. and Rehrl, K., pp. 95-118, Springer, Heidelberg, Berlin.

van der Spek, S.C., van Schaick, J., De Bois, P., and De Haan, R. (2009). **Sensing Human Activity: GPS Tracking**, 'Sensors', 9, 4, pp. 3033-3055.

van Schaick, J. and van der Spek, S.C. (2008). **Urbanism on track: application of tracking technologies in urbanism**. Delft University Press, Delft.

# CHAPTER 5

## EVALUATION OF THE DESIGN

### 5.1 Introduction

This chapter reports on the outcomes of the evaluation study of the design options for the STC data content, as hypothesized in Table 3.8 in section 3.4.3. The purpose of the experiment was to gain insight into the cognitive aspects (Carroll, 1987) of the use of the visual variables (Bertin, 1983; Morrison, 1984; MacEachren, 1995; Robinson*, et al.*, 1995) and depth cues (Marr, 1982; Kraak, 1988; Ware, 2006; Goldstein, 2010) in the STC.

Expert users from the geovisualization domain participating in the workshop *Analysis and visualization of movement data* (URL 11), were invited to discuss the visual variables during a focus group discussion. They were introduced to six different design alternatives. Based on the research questions identified in phase three with the use case study domain experts (section 4.3), the questions were developed to stimulate discussion between participants. They judged the introduced design options for the complex datasets of the Tallinn case study, which was presented on touch screen tables for optimal group interaction. Accordingly, they described the most useful combinations of visual variables and depth cues for this use case. The session was video/audio recorded. Analysing the expert's discussions revealed argumentations regarding the type of the data and usable design options.

### 5.2 Evaluation Purpose and Execution

The usability study in this fourth phase of the research project, aimed at understanding the application of the cartographic design theory on the STC data content. The design alternatives proposed intend to represent data effectively and efficiently to allow users to detect patterns and other interesting information. Thus, cartographic design for 3D visual representations should provide options for sufficient distinction of information to connect reality to its abstract graphic representation.

In order to obtain suitable design options, a usability study was conducted that involved experts from the geovisualization domain, i.e. experts who have experience in working with STC applications and cartography. The experiment aimed at discussing the issues regarding the performance of the STC with a large and complex dataset in a wide context. The discussion during a focus group session was stimulated by the use case of the ''Tallinn suburban commuters' (see Figure 3.11). The main objective was to evaluate the hypotheses developed in Table 3.8. The experts had to answer questions related to several design options.

The primary focus was to establish a link between cartographic design and visualization strategy. A relation that is affecting the visualization and exploration process in the STC. This focus group usability study was conducted in a special decision room to stimulate test participants to discuss all related aspects. Based on the discussions, conclusions and remarks on the use of the design options were made.

## 5.3 Designing STC's Visual Environment

The previous phases of this research project were executed in the uDig GIS open source program environment (URL 2). However, its visual environment proved to be insufficient to allow flexible manipulation of data. In order to avoid further inconvenient software problems, the STC plugin was re-implemented in the Ilwis program environment. Originally, the open source Ilwis GIS was developed at the Faculty of Geo-Information Science and Earth Observation (ITC) as a tool for studying land use planning and watershed management. It was raster and vector GIS/remote sensing software capable for various visual and statistical analyses. Later, its exploration capabilities were extended by implementing different visual representations and analytical tools (see chapter 7) as an additional option for the analysis of spatio-temporal data (for more information, see URL 10).

From a cartographic design perspective, this software provides a wide range of options to design every element in the 3D visual environment of the STC. For instance, for the visualization of the st-paths or stations, the user is able to apply design options through selection of different visual variables (color, size, orientation, etc.) and depth cues (shading, transparency, etc.) depending on the nature of the phenomena and data complexity. The software also allows to influence the design of the STC itself and its labels along the spatial (longitude – latitude) and temporal axes. Accordingly, all elements in the interactive visual environment to be developed can be designed upon the user's choice and decisions. In this phase, attention is directed towards the effectiveness, efficiency, and user satisfaction of design alternatives to represent data content in the STC's visual environment.

## 5.4 Phase Four – Design Verification

In order to gather valuable information, a focus group discussion was organized. A focus group is an informal technique for interactive discussion with users, and known as an efficient qualitative method for design improvement and development (Nielsen, 1993; Kitzinger, 1994;

Krueger, 1994). This method of evaluation involves the use of group interviews where participants are selected purposefully based on specific criteria. In particular, they should have certain characteristics in common that relate to a product and would have something to say on the topic that has to be discussed (Krueger, 1994). The recommended number of participants according to Nielsen (1993, pp. 214) is 6 to 9 persons and the average duration of a session is 60 to 90 minutes. This special type of group in terms of size, composition, and procedure is different from individual interviews and can provide deep discussions on the use of design options. Focus group interviews encourage debates on ideas and opinions that individuals would like to express regarding to the particular issues. During a session, the test moderator can observe spontaneous reactions, behaviours, feelings, and attitude of the users, as well as the ways of exchanging ideas, or group dynamics. Thus, in a relatively short time period it can generate a large amount of information on the discussed topic.

Focus group interviews have been used intensively in cartography by a number of researchers (Monmonier and Gluck, 1994; Harrower, *et al.*, 2000; Suchan and Brewer, 2000; Robinson, *et al.*, 2005). In this research, attention is given to the identification of design problems based on the reactions, behaviour and ideas of the focus group participants. Thus, in the context of the questions given, it should help to define 'why', 'how' and 'when' to use particular visual variables in the STC.

## 5.4 1 Focus group participants

The test persons involved were selected from the participants of a workshop on the analysis and visualization of movement data using the STC (URL 11; Kveladze and Kraak, 2012). The objective of the workshop was to discuss positive and negative aspects of this visual representation. Participants made presentations and discussed their experiences on visualization of their movement data in the STC.

For the focus group discussion nine participants, two female and seven male experts were selected based on their long expertise with the STC. From the selected participants, four were PhD student and five senior researchers from different research groups in different countries. The participants were of different age groups and had no color-blind deficiency.

## 5.4.2 Design of the experiment

#### Materials

The objective of this focus group discussion session was to get insight into the effectiveness and efficiency of proposed design options. The suburban commuter movements in the Tallinn district area, as one of the large and complex datasets used in this research, was the object of study. With the case study's research questions defined in phase three in mind (section 4.3.5), different design options as proposed in Table 3.8 were applied and shown to the test participants. In total, six different design options to represent the qualitative and quantitative nature of the data were used (see Figure 5.1 and 5.2). For the first scenario different ethnic groups of Tallinn suburban commuters where represented, and for the second scenario different income groups. In both cases, the first task was to judge the map on overview level followed by zoom level.

For the representation of the qualitative data (ethnic groups), the following designs were used:

- Color hue (simple st-path)
- Color hue & depth cue shading
- Arrangement & depth cue shading

To show quantitative data (income) the designs below were used:

- Color value (simple st-path)
- Color value & depth cue shading
- Size & depth cue shading

For each design in the overview and zoom mode hypotheses were formulated as in Table 5.1:

Table 5.1 Hypotheses on the effectiveness of the design options

| Data complexity / Design combination | | Large complex dataset | | Figure | | The questions for discussion, section 5.4.4 |
|---|---|---|---|---|---|---|
| | | Overview | Zoom | Overview | Zoom | |
| Qualitative | Color hue | | | 5.1 – 1a | 5.1 - 1b | Q 1.1 |
| | Color hue & shading | | | 5.1 – 2a | 5.1 - 2b | Q 1.2 |
| | Arrangement & shading | | | 5.1 – 3a | 5.1 - 3b | Q 1.3 |
| Quantitative | Color value | | | 5.2 – 4a | 5.2 - 4b | Q 2.1 |
| | Color value & shading | | | 5.2 – 5a | 5.2 - 5b | Q 2.2 |
| | Size & shading | | | 5.2 – 6a | 5.2 - 6b | Q 2.3 |

– Most effective
– Effective
– Less effective
– Poor effect

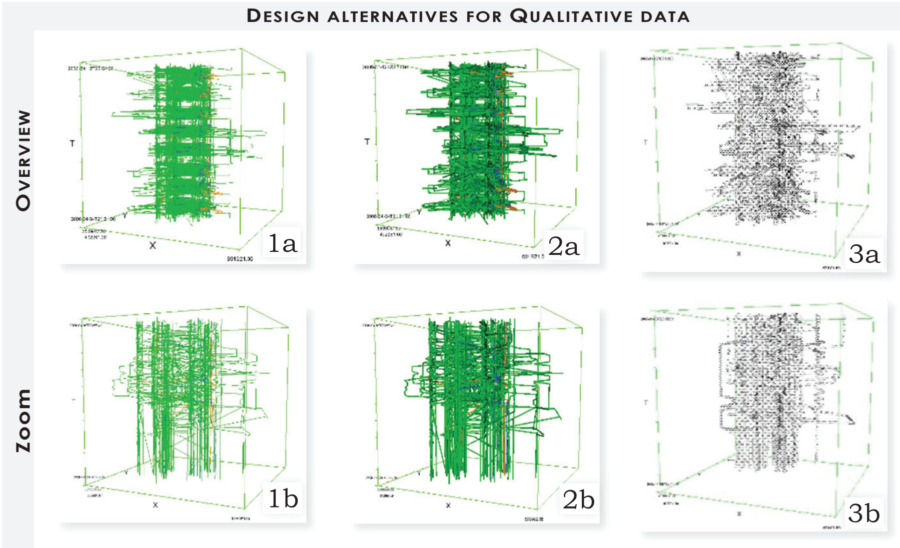



Figure 5.1 The qualitative designs 1a – 1b Color hue; 2a – 2b Color hue & shading; 3a – 3b Arrangement & shading.

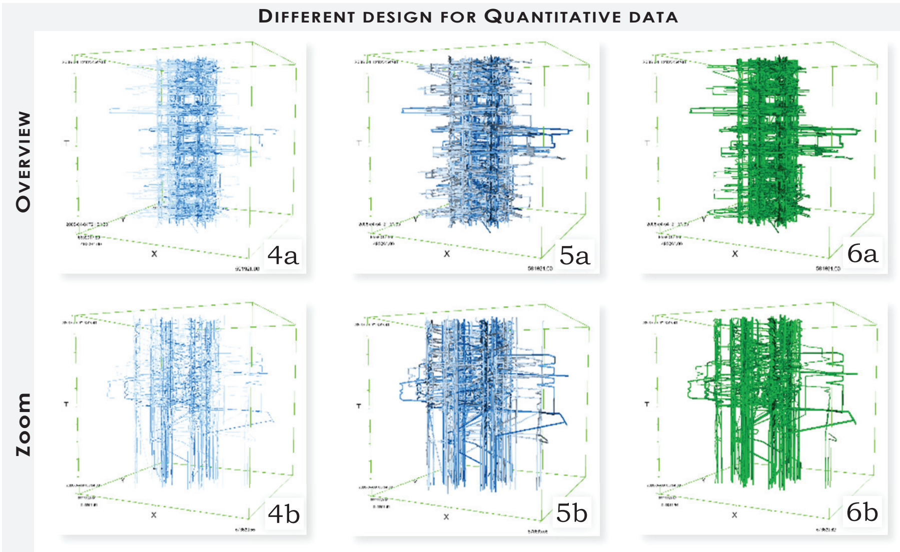



Figure 5.2 The quantitative designs 4a – 4b Color value; 5a – 5b Color value & shading; 6a – 6b Size & shading.

The hypotheses assumed that each step of the workflow requires its own design. For instance, for the overview of a larger dataset, simple graphics are needed, while after zooming in on details more complex and sophisticated visualizations are possible. In other words, the use of color hue with simple thin st-paths for this particular dataset might be effective for both situations. While, the same color hue in combination with depth cues could lead to visual overload on the overview level, but be effective after zooming in. In Table 5.1 the options are qualified as most effective, effective, less effective and poor effect.

Interesting observations were made regarding to the visual variable arrangement. The STC applications using this visual variable are unknown. Therefore, the purpose of the focus group discussion was to find out why this visual variable has not been used before. The hypotheses are based on the experimenter's own practical experiences. Arrangement in combination with depth cues is supposed to have a poor effect for both steps of the mantra. For visualization of quantitative data, color value with simple thin st-paths was indicated as effective design option for both steps of the mantra. However, the same color value with depth cues was marked as a poor design for overview, and less effective for the zoom step. The visual variable size was considered to be less effective for the overview step, but effective for the zoom step. To keep participants focused on the cartographic design of the STC, only the cubes were shown without context information through a 2D base map.

The 12 different design options for overview and zoom steps (Figures 5.1 and 5.2) were made available in the interactive Ilwis environment (URL 10), but also as high-resolution on-screen static (images) maps.

**Set-up**

The experiment was executed in a dedicated group decision room, at the Faculty of Geo-Information Science and Earth Observation (ITC) of the University of Twente. The decision room is equipped with interactive touch screen tables and an interactive whiteboard. During the discussion, two touch screen tables of 32 and 42 inch respectively were used, both with a 1024 by 768 screen resolution. The whiteboard and touch screen tables were linked to different 24-inch desktop screens to show the information in all parts of the room (see Figure 5.3). The whiteboard was used to introduce the experiment (see Appendix 1), and the touch screen tables to show the qualitative and quantitative visual variables for discussion (see Figure 5.1 and 5.2).

During the experiment, the desktop monitors were used with the touchscreen tables in parallel. This option was proposed to participants when it was discovered that Ilwis (URL 10) software was not capable of rotating the image on the display surface of the touch screen table. Thus, participants allocated around the touch screen table could see the visual environment in the right position from one side, but others from the top or the side. However, on touch screen table participants could interactively manipulate the cube using rotation, zooming in/out and panning options. Doing so, the software rotation problem was not even noticed and participants stayed focused on the STC's visual environment. The interaction process allowed users to change the cube's perspective view by rotation when it was necessary. In addition, a standard mouse and keyboard were also available. A camcorder was prepared to record the whole test session on video (including an audio recording of the focus group discussion).

Figure 5.3 Decision making room, test environment for the focus group interview.

### 5.4.3 Procedure

The experiment started by welcoming the focus group participants and informing them about usability ethics and respondent confidentiality. Via a PowerPoint presentation on the whiteboard they were informed about the objectives of the experiment, followed by a detailed description of the case study scenarios used, instructions for the test procedure, the test environment and the usability methods applied (see Appendix 1).

After this presentation, participants were encouraged and invited around the first touch table to discuss the first scenario of the 'Tallinn suburban commuters' and the use of qualitative visual variables. The participants were explained the working principle of the touch screen table. Besides, they were particularly asked not only to look at the display and judge design options, but also to interact with the visual environment by zooming in/out and rotating the STC. All participants already got some exposure to the Ilwis STC environment during the previous days of the workshop they participated in (URL 11). In addition, the test moderator, once again, briefly reminded them of the purpose of the focus group discussion and started the test session.

The one-hour session was divided into two parts. During the first part, the participants, assembled around the large touch table, were presented the Tallinn case study data. The discussion was stimulated by the questions for qualitative visual variables. First, the participants were shown the design option of '*color hue with simple st-path'* in the overview level (see Figure 5.1–1a). They were asked to judge the effectiveness of color hue to represent the qualitative information. When the discussion was completed, the test moderator zoomed-in on Sunday through the temporal zoom option, and asked participants to judge whether this design option is also suitable to represent data effectively at this zoom level (see Figure 5.1–1b). The same procedure was repeated for the other two design options (see Figure 5.1 – 2a-b *color hue & shading*, and 3a-b *arrangement & shading*). In total, the discussion took 30 minutes for the qualitative visual variables, i.e. 10 minutes for each design option including both the overview and zoom steps.

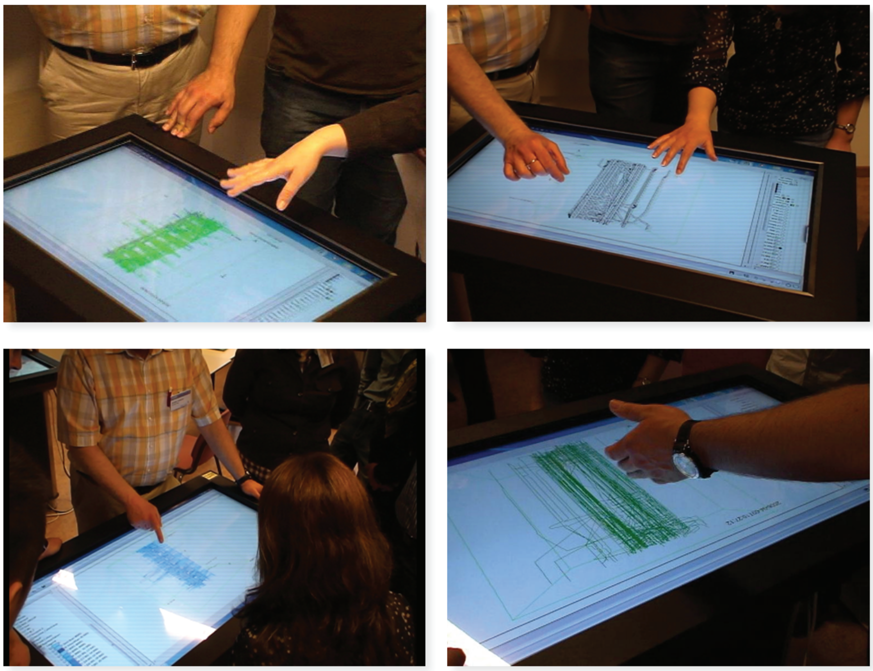


Figure 5.4 Focus group interview discussion on visual variables.

After completing the first session, the participants were invited to the second touch table, which showed a quantitative dataset. Similar to the procedure described above, the discussion was stimulated by the questions for quantitative visual variables. Discussions started from representing information through '*color value with simple st-path'* for the overview level (see Figure 5.2 – 4a). The participants were again asked to judge the effectiveness of the shown visual variable for quantitative information. After completing the discussion on this topic, the test moderator again zoomed-in on Sunday via the temporal zoom, and asked participants to judge if color value with simple st-path is a proper option to represent data effectively on the selected zoom level as well (see Figure 5.2 – 4b). Similarly, they discussed the two other design options (see Figure 5.2 – 5a-b *color value & shading*, and 6a-b *size & shading*). This session also took 30 minutes.

### 5.4.4 Analysis and results

The focus groups session was audio / video taped and a transcript was created. A summary of important remarks and observations made during the session is described in this section.

***Q 1.*** *What are the qualitative visual variables that can effectively visualize different nationalities on overview level, considering the data complexity? And on zoom level?*

This question was the lead for the first part of the discussion on qualitative visual variables. The participants examined the different visualization options one by one. Having discussed them, they attempted to give a clear judgment on the effective use of these visual variables in the STC. There was inevitably some overlap between their opinions and our hypothesis, but there were also some differences. The review below discusses each option offered for evaluation, following Table 5.1.

***Q 1.1.*** *How effective is color hue to display the different nationalities?*

The first visual variable for discussion was color hue with simple st-paths (see Figure 5.1 – 1a-1b). As predicted, the experiment proved that at overview level a simple design would provide sufficient support for the data exploration process. Color allowed participants to answer the questions about ethnicity easily, without any need for interaction. To describe the data content, one glance at the screen was enough for the participants. Despite this, the experts spent some time to discuss the potential problems that might arise when the amount of tracks would increase considerably. However, they concluded that this simple design would work well, even considering the potential data clutter.

Similar comments were made for the zoom level. As they mentioned, there is not much difference between these two steps from a data complexity perspective, because a temporal zoom does not change the amount of trajectories. Therefore, the hypothesis in Table 5.1 for Q1.1 on color hue was confirmed.

***Q 1.2.*** *What is the effect if we add depth cues to the representation on overview level? At the zoom level?*

The second map shown was the same as the first, but now with shading applied to improve the three - dimensional experience in the visual environment of the STC. The purpose was to find out how much 3D design would be possible or needed for this dataset on both overview and zoom level (see Figure 5.2 – 2a-2b). To apply the depth cues, the widths of the paths had to be increased, which also increased the visual clutter in the image. The reaction of participants on the cluttered view was not unexpected. They used negative terms to express their opinion about this design option. They commented that with such complex data the use of depth cues is limited and result in occlusion. Thus, with a dataset like this, depth cues are not useful and made things worse. Also for the zoom level, the use of the depth cues was not advised. Answering the ethnicity questions would be difficult because of this design. According to the discussion, the application of depth cues does not get any approval from experts, not for overview nor for zoom levels. Their opinion coincided with the hypotheses in Table 5.1 for Q1.2 for the overview level.

***Q 1.3.*** *What do you think about arrangement in the STC? Can we use it for data representation with depth cues? Does it make sense on overview or on zoom level?*

As an alternative but uncommon visual variable arrangement was applied on the shaded st-paths (see Figure 5.2 – 3a-3b). In the existing literature there is no evidence that arrangement has ever been used for data visualization in the STC. This attempt here is to understand whether this design option can be used for data representation in the STC.

The initial reaction of all participants was strongly negative. Despite this, they made comments and suggestions on possible design improvement in case of its use. It was first advised to use arrangement for encoding some categorical attributes with a low overlap problem. Further, the unsophisticated and clumsy design offered by the Ilwis software was mentioned. In particular, if arrangements were to be used, they should stick to the path so that they could follow the rotation of the cube. In this way, this might change the perception of this visual variable. Participants also came with the idea to use line tags instead, giving volume to st-paths in order to make more space for overlapping information. But it was immediately argued that trajectories in the STC are constantly changing directions and at such moments dashes might get lost. Besides, dashed lines might be confused with broken or interrupted trajectories, although at the overview level arrangement might provide a general impression on data content of the STC. Despite this discussion, the experts remained very critical towards arrangement in the STC context. Answering the ethnicity questions would be virtually impossible and the results were again in line with the hypothesis in Table 5.1 – Q1.3 for the overview step.

This disapproving attitude did not change after zooming-in. All participants agreed that even at zoom level arrangement poorly represents the data. Arrangement sometimes increases the confusion because they made it difficult to distinguish places of intersection. Introducing dynamics by rotation and zooming in/out functions was slightly helpful, but did not solve the problem.

Interesting was that the participants also made some positive remarks. For instance, arrangement does not cause a clash with colors, although it is not recommend for interruptive trajectories. Despite this, experts advised to use the visual variable orientation with balanced striped lines and color for visualization instead of arrangement. Finally, it was concluded that the use of arrangement in the STC depends on the sophistication of the graphic design. Nevertheless, participants did not recommend the visual variable arrangement for use in the STC. This result coincided with the hypothesis in Table 5.1 – Q1.3 for the zoom step.

***Q 2.*** *What are the quantitative visual variables that can effectively visualise different income groups on overview level consider the data complexity? And on zoom level?*

The second part of the discussion was about the use of quantitative visual variables. The map on the touch screen represented four income classes via color value ordered from light blue to dark.

***Q 2.1.*** *How effective is color value to display the different income groups?*

Discussions again began with emphasizing that data complexity is the major factor influencing the success of the use of any visual variables (see Figure 5.2 – 4a-b). In case of value, the overlap between trajectories complicated a proper perception of the four classes represented by color value. There proved to be insufficient difference between color values and because of this the participants found it difficult to distinguish the income groups visually. Moreover, color value was considered to be a less effective visual variable even for the zoom level. Overall, participants were not satisfied with color value and suggested to use color saturation. For instance, use light red, red, light blue and dark blue and distinguish between the poorest and the richest groups. Such use of color was considered much easier for perception than value differences within a single color. The outcome of this discussion was different from the hypothesis identified in Table 5.1 for Q2.1.

***Q 2.2.*** *What is the effect if we add depth cues to the representation on overview level? At the zoom level?*

Concern over visual clutter was expressed continuously and seen as a barrier for using depth cues in the STC's visual environment. The used depth cue shading was even increasing visual clutter rather than improving the view. Participants had the same reaction as when they were confronted with the application of shading as depth cues before: an increased visual clutter (see Figure 5.2 – 5a-b). They advised not to use this depth cue under the current circumstances, neither on overview nor on zoom level. The income related questions could not be answered, and the hypothesis in Table 5.1 for Q2.2 was partly rejected.

***Q 2.3.*** *What do you think about size as visual variable in the STC? Can we use it for representation with depth cues? Does it make sense on overview level? At the zoom level?*

The last visual variable discussed was the visual variable size with the depth cue shading (see Figure 5.2 – 6a-b). It was representing the same income group categories as discussed before with color value. The participants commented that the differentiation in size or thickness among the individual paths was not big enough to judge. In order to deal with individual objects and to make them more distinctive it was advised to use transparency. Besides, for effective visualization of quantitative information they suggested to use color saturation instead of size. However, the size visual variable can be effective in combination with a qualitative color hue.

The participants did not have a different opinion for the zoom level. Experts did not see much difference between overview and zoom steps from data complexity perspective. As was described above, the zoom level was reducing the number of days, but not the quantity of trajectories. Therefore, the use of size as single visual variable in this case was not recommended. The question regarding the income groups was difficult to answer, and the hypothesis in Table 5.1 for Q2.3 was rejected.

### 5.4.5 Summary of results for focus group discussion

The hypotheses on the use of the visual variables in the STC have been formulated based on the cartographic design theory. In addition, special attention was given to the depth cues. In practice, the use of visual variables was somehow limited by what the STC could represent with this amount of data for st-paths. The hypotheses formulated for each level of the visualization strategies also required different designs. The main question here was how STC content influenced the design when working at different levels of Shneiderman's mantra considering the data complexity.

The focus group interview concentrated on the design of the STC content. The hypotheses have been evaluated and compared with the conclusions made by the experts. The discussions revealed some interesting facts that were not considered before.

The combination of visual variables with depth cues was not recommended for such a complex dataset on 'overview' nor on 'zoom' steps. The Table 5.2 represents results on effectiveness of evaluated design options identified during the discussion with experts from geovisualization domain. Experts argued that the human visual system is limited in dealing with such complex datasets even with simple st-paths. The inclusion of depth cues did not have a positive effect. An interesting contradictory opinion was detected when discussing the use of color value and size. The use of color value in terms of simple lines was considered as an effective design option. However, experts rejected this hypothesis. As for size, they rejected it both for overview and for zoom step too. Instead, they suggested to use color saturation to represent quantitative aspects of the data for both steps. As a consequence of the discussion, it can be concluded that when representing such complex data in the STC for 'overview' and 'zoom' steps color differentiation is most effective for data with both a qualitative and a quantitative nature.

Table 5.2 Test results on effectiveness of the design options

| Design combination \ Data complexity | | Large complex dataset | | Figure | |
|---|---|---|---|---|---|
| | | Overview | Zoom | Overview | Zoom |
| Qualitative | Color hue | Most effective | Most effective | 5.1 – 1a | 5.1 - 1b |
| | Color hue & shading | Less effective | Poor effect | 5.1 – 2a | 5.1 - 2b |
| | Arrangement & shading | Less effective | Less effective | 5.1 – 3a | 5.1 - 3b |
| Quantitative | Color value | Effective | Effective | 5.2 – 4a | 5.2 - 4b |
| | Color value & shading | Less effective | Less effective | 5.2 – 5a | 5.2 - 5b |
| | Size & shading | Less effective | Less effective | 5.2 – 6a | 5.2 - 6b |

– Most effective – Less effective

– Effective – Poor effect

The overall conclusions of this experiment are perhaps not surprising. Many times the limitations of the STC in relation to large datasets was mentioned. But from this discussion it also became clear that this limitation is related to the content design as well. Besides the focus on visual variables, it was difficult to avoid comments on interaction and functionalities of the prototype. All participants agreed that design is just one aspect of the exploration process, and for a deeper investigation, more interactive and analytical functions have to be provided.

Obviously, experts considered the Tallinn use case as large and complex for the STC. Also, the utilization of just Shneiderman's Information Seeking Mantra (1996) to execute the tasks was seen as limited. The mantra guides how to represent information so that it is effective for the user. Thus, the author observed that with lots of efforts the experts could summarize and draw conclusions about some essential elements in the movement data when accomplishing tasks at overview and zoom levels. However, as mentioned above, it was not considered to be enough for an effective exploration and visualization due to the complexity of the data and the large number of trajectories. Accordingly, to support and speed up the process of task execution with such a complex dataset, it was recommended to apply more analytical functions and tools to analyse first and then show the important as described by Keim et al. (2006) in Visual Analytics Mantra.

## 5.5 Discussion

This chapter reported on the results of the usability experiment of phase four. The objective was to verify the design guidelines developed during phase two with experts who have experiences in working with the STC. Starting point for the design guidelines was a typology of visual variables with a focus on line symbolization. In the case of the STC, it was extended to the three-dimensional st-path. Accordingly, in the 3D cube, depth perception is an important aspect and its correct usage can help in data exploration. But when there are situations in which the data are likely to be over-cluttered, the depth cue will only increase the visual perception problems.

The visualization of the st-path depends on its qualitative or quantitative character and constraints set by the cartographic design theory and data complexity. The results of the experiment clearly revealed the influence of data complexity on the use of design options by emphasizing the limitations of the Information Seeking Mantra and the need for Visual Analytics Mantra, i.e. it is required to analyse first instead of getting an overview first. The domain experts did not confirm all hypotheses on the effectiveness of the introduced design alternatives for the different steps of the Information Seeking Mantra. Besides, the experiment showed that not all introduced design alternatives could be a solution for the visualization of complex datasets in the STC. The only exception was color hue that proved to be the best option for displaying qualitative information, while other options appeared to be ineffective. A useful finding was the suggestion to use color saturation for an effective visualization of quantitative information. Thus, the outcomes of this experiment revealed color as preferred visual variable for both qualitative and quantitative aspects of the data. In addition, the experts from geovisualization domain stressed the combination of analytical functionality with the design solutions to answer questions in the STC.

## References

Bertin, J. (1983). **Semiology of Graphics: Diagrams, Networks, Maps**. The University of Wisconsin Press, Madison (first published in French in 1967, translated to English by Berg W.J. in 1983).

Carroll, J.M. (1987). **Interfacing thought: Cognitive aspects of human-computer interaction**. The MIT Press, Cambridge, MA.

Goldstein, E.B. (2010). **Sensation and perception**. Brooks Cole Publishing, NY.

Harrower, M., MacEachren, A.M., and Griffin, A.L. (2000). **Developing a Geographic Visualization Tool to Support Earth Science Learning**, 'Cartography and geographic information science', 27, 4, pp. 279-293.

Keim, D., Mansmann, F., Schneidewind, J., and Ziegler, H. (2006). **Challenges in Visual Data Analysis**, in 10th International Conference on Information Visualization. London, UK, pp. 9-16.

Kitzinger, J. (1994). **The methodology of Focus Groups: the importance of interaction between research participants**, 'Sociology of Health & Illness', 16, 1, pp. 103-121.

Kraak, M.J. (1988), **Computer-assisted cartographical three-dimensional imaging techniques**. Delft University Press, Delft.

Krueger, R.A. (1994). **Focus groups: a practical guide for applied research**. Thousand Oaks, Sage Publications, CA.

Kveladze, I. and Kraak, M.J. (2012). **What do we know about the space - time cube from cartographic and usability perspective?**, in Proceedings of AutoCarto 2012: the international symposium on Automated Cartography. Columbus, Ohio, USA, pp. 16-18.

MacEachren, A.M. (1995). **How Maps Work: Representation, Visualization and Design**. Guilford Press, NY.

Marr, D. (1982). **Vision: A Computational Investigation into the Human Representation and Processing of Visual Information**. W.H. Freeman and Company, San Francisco.

Monmonier, M. and Gluck, M. (1994). **Focus Groups for Design Improvement in Dynamic Cartography**, 'Cartography and geographic information science', 21, 1, pp. 37-47.

Morrison, J.L. (1984). **Applied Cartographic Communication: Map Symbolization For Atlases**, 'Cartographica: The International Journal for Geographic Information and Geovisualization', 21, 1, pp. 44-84.

Nielsen, J. (1993). **Usability Engineering.** Morgan Kaufmann Publishers Inc., Boston.

Robinson, A., Chen, J., Lengerich, E., Meyer, H., and MacEachren, A.M. (2005). **Combining Usability Techniques to Design Geovisualization Tools for Epidemiology**, in Proceedings, AutoCarto 2005. Las Vegas, USA, pp. 18-23.

Robinson, A.H., Morrison, J.L., Muehrcke, P.C., Kimerling, A.J., and Guptill, S.C. (1995). **Elements of Cartography**, 6th ed.: Wiley & Sons, NY.

Shneiderman, B. (1996). **The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations**, in the 1996 IEEE Symposium on Visual Languages. Boulder, Colorado, pp. 336 - 343.

Suchan, T.A. and Brewer, C.A. (2000). **Qualitative Methods for Research on Mapmaking and Map Use**, 'The Professional Geographer', 52, 1, pp. 145-154.

URL 2, From: http://udig.refractions.net/

URL 10, From: http://52north.org/communities/ilwis

URL 11, From: http://www.itc.nl/personal/kraak/move/

Ware, C. (2006). **3D Contour Perception for Flow Visualization**, in the 3rd symposium on Applied perception in graphics and visualization. Boston, Massachusetts, pp. 101-106.

# CHAPTER 6

## DESIGN VERIFICATION

### 6.1 Introduction

The previous chapter reported on the results of the focus group discussion as starting point for the evaluation of the use of visual variables and depth cues in the STC. It also assessed the influence of data complexity on the use of cartographic design in a 3D visual environment. As a result, the hypotheses on the effectiveness of visual variables and depth cues regarding to the data complexity have been revised (see Table 5.1). As a follow-up to the previous chapter, this chapter reports on the results of an empirical evaluation with the aim to define usability metrics of visual variables and depth cues in depicting STC content. Twenty-two volunteered participants joined task-based experiments to judge the effectiveness and efficiency of design alternatives for three use case studies, of a simple dataset, complex dataset, and complex annotations respectively. Totally 13 different design alternatives were applied to get an understanding of the cognitive aspects of the use of visual variables for the STC data content. Each use case was evaluated in two sessions for qualitative and quantitative data. Based on the usability methods of think aloud, video/audio/screen/eye recordings, task execution and user interviews usability metrics were derived. The user tests were executed based on real world problems with particular attention for the visualization strategy and data complexity (see Chapter 3). The test data collected through Tobii Studio (URL 8) were processed and resulted in effectiveness, efficiency, and user satisfaction metrics. As a result, this experiment lead to better understand the cognitive aspects of the use of visual variables in the STC, and also revealed that color visual variables are the most efficient and effective to represent data of various complexity in the STC.

### 6.2 Evaluation Purpose and Execution

The empirical study conducted within phase five of this research project aims to answer usability questions regarding to the use of the visual variables in representing the STC content. It tries to find answers to questions like: do the users easily understand the meaning of the STC content? Do visual variables have any influence on task execution? What are the most effective and efficient visual variables for the STC? Does a link exist between cartographic design and a particular visualization strategy?

To answer these questions, an experiment was designed that aimed to evaluate pre-defined hypotheses through a task-based usability study with non-cartographic users. The participants selected were scientists from the geo-domain, experienced with maps, but not with the STC. It was assumed that through such novel users it would be possible to identify existing usability problems with respect to the performance of the design options. Besides, it may provide possible solutions that are difficult to comprehend for the author and other experienced STC users. The experiment was designed in Ilwis and uDig GIS environments, and carried out in a well-equipped usability laboratory. Both qualitative (video/audio/screen recordings, user interviews and think aloud) and quantitative (questionnaire, eye movement recordings and task execution) evaluation methods were used for comprehensive data collection. It was assumed that the study could provide sufficient feedback on design options by identifying problems during the experiment that are key for designing the STC data content. By measuring time spent to complete tasks, error rates, as well as analysing video/audio/screen/eye movement recordings and think aloud protocols, the effectiveness, efficiency, and user satisfaction for different design options will be defined.

## 6.3 Design Options for Evaluation

The main purpose of this experiment was to find the relationship between data complexity and visual variables, as well as their perceptual properties (see section 3.4.2) for the overview and zoom steps described by Shneiderman (1996) for the three use cases already described in Chapter 3, which differ in data complexity and thematic contents (see Figure 6.1 and Table 3.8).

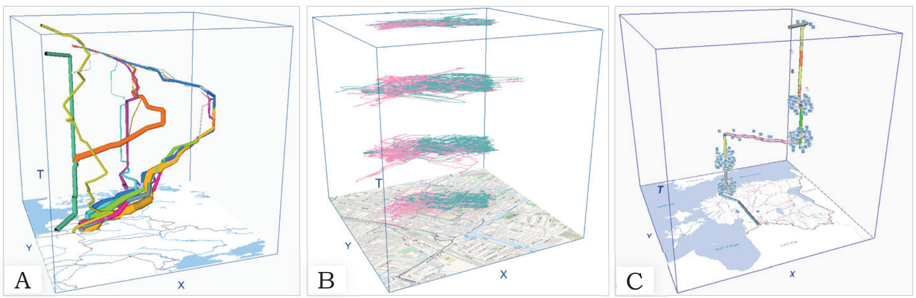



Figure 6.1 Three cases studies used for the experiment, A. simple dataset: 'Napoleons march to Moscow'. B. complex dataset: Pedestrian movements in city center of Delft. C. complex annotations: Travel log data of Estonia.

According to the hypotheses formulated in section 3.4.3, the use of design alternatives greatly depends on data complexity and on the tasks that users have to accomplish. Thus, this experiment focused on the design alternatives that were suitable for the visualization to answer the research questions identified earlier with domain experts in phase 1 and 3 and the focus group discussion with geovisualization experts (section 3.3 and chapter 4). Besides, the case study data guaranteed a realistic context of use of design options considering the different steps of the workflows (see Table 4,1, 4.3 and 4.5). The combination of different evaluation methods assisted with the inference of cognitive processes and reactions of the users.

In total, six visual variables have been employed in the design alternatives that were put to the test in this experiment: color hue, color value, color saturation, size, orientation, and shape. This in combination with the depth cues shading and transparency. For the case study 'travel log data of Estonia,' also icons were used. The test results derived from focus group discussion with the experts from geovisualization domain (phase four, see Table 5.2), resulted in the adaption of the hypothesis formulated before (see Table 3.8). Similar to phase four, for each use case study eight different design alternative for qualitative and quantitative data were selected. For the complex annotations only four options with qualitative visual variables were selected. The new hypotheses (see Table 6.1), defined on the effectiveness and efficiency of design alternatives were evaluated through twelve different designs. The experiment assessed the usability of these design alternatives through task based evaluation studies.

### 6.3.1 Generating hypotheses

The hypotheses in Table 6.1 are related to the expected capabilities of the visual variables and depth cues to represent the STC content effectively and efficiently. An efficient design will allow users to *faster* detect information, and an effective design will result in *correct* answers to the questions asked. Important factors are the perceptual properties of the visual variables to communicate the represented information. In addition, the use of transparency may improve the clarity of representation in the visual environment and facilitate reading of overlapped information. Accordingly, visual variables can be selective (color hue, color value, color saturation, size), associative (color hue, orientation), ordered (size, color value, color saturation) or quantitative (size) (Bertin, 1983; Green, 1998) (see Table 3.6). The hypotheses for each design option regarding to the data complexity at the overview and zoom steps are shown in Table 6.1.

Table 6.1 Hypotheses on the effectiveness and efficiency of the design options

| Design combination \ Data complexity | | Simple dataset | | Complex dataset | | Complex annotations | |
|---|---|---|---|---|---|---|---|
| | | Overview | Zoom | Overview | Zoom | Overview | Zoom |
| Qualitative | Color hue | | | | | | |
| | Color hue & thick st-path | | | | | × | × |
| | Color hue & shading | | | | | × | × |
| | Color hue & shape | × | × | × | × | | |
| | Color hue & shape & shading | × | × | × | × | | |
| | Orientation & shading | | | | | × | × |
| | Icons | × | × | × | × | | |
| Quantitative | Color saturation | × | × | | | × | × |
| | Color saturation & shading | × | × | | | × | × |
| | Color value | | | | | × | × |
| | Color value & thick st-path | | | × | × | × | × |
| | Color value & shading | | | | | × | × |
| | Size & shading | | | × | × | × | × |

– Most efficient and effective
– Efficient and effective
– Less efficient and effective
– Poor effect
× – Not evaluated

In this table, three different use cases are referred as simple datasets, complex datasets and complex annotations (see Figure 6.1) based on the distinctions made in section 3.4.3 (see Figure 3.16). Not all possible combinations offered by Table 6.1 were incorporated in the evaluation because these were impossible or irrelevant. The more detailed descriptions of the selected design alternatives are given below.

#### Color hue

Overview: Qualitative information represented by *'color hue & thin st-path,'* is less effective and efficient at the *'overview level'* for simple datasets than for complex datasets (see Figure 6.2). In simple datasets the user will have difficulties to detect thin trajectories in the 3D visual environment of the STC, while for complex datasets it will facilitate the visual differentiation of overlapped trajectories in a most effective and efficient way. However, for complex annotations this option will be less efficient and effective. Here, overlapping annotations will accumulate color patterns and users will have difficulties to differentiate between similar types of information.

Zoom: Color hue can be effective and efficient for simple datasets to distinguish between trajectories (*how many*). However, it will have a poor effect to answer questions like *who, what, where, etc*. Whereas for complex datasets *'color hue'* becomes efficient and effective to discern information. Thus, the user will be able to see overall movement patterns. As for the annotated st-path, *'color hue'* will have poor effects due to the aggregated color spots (see Figure 6.2).

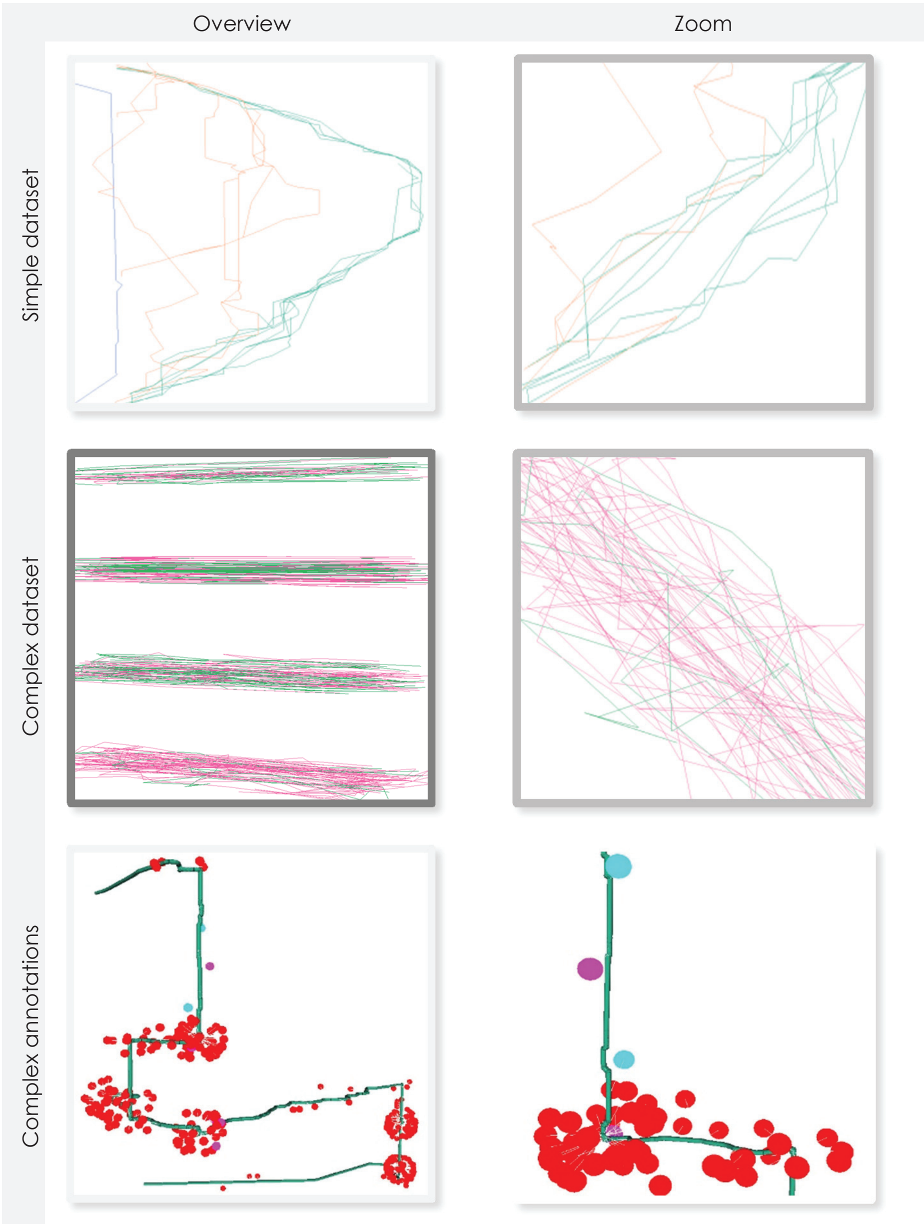



Figure 6.2 Design options for qualitative information. Color hue applied to the thin st-paths. The gray values of the figure frames refer to the hypotheses on most efficient and effective (dark gray), efficient and effective (gray), less efficient and effective (light gray), and poor effect (white) in Table 6.1.

**Color hue & thick st-path**

Overview: *'Color hue & thick st-path'* refers to a different line size (thickness) of the trajectories that makes the design distinct in the 3D visual environment of the STC. For simple datasets, this design alternative will be effective and efficient. The same is expected for complex datasets, despite data overlap issues, because color patterns could be effective for the user to distinguish similar information (see Figure 6.3).

Zoom: In both simple datasets and complex datasets, the user can identify similar information, but where tracks overlap each other it will be difficult to differentiate between them. Despite of this problem, this option might be considered as useful to detect similar patterns on the detail step of exploration (see Figure 6.3).

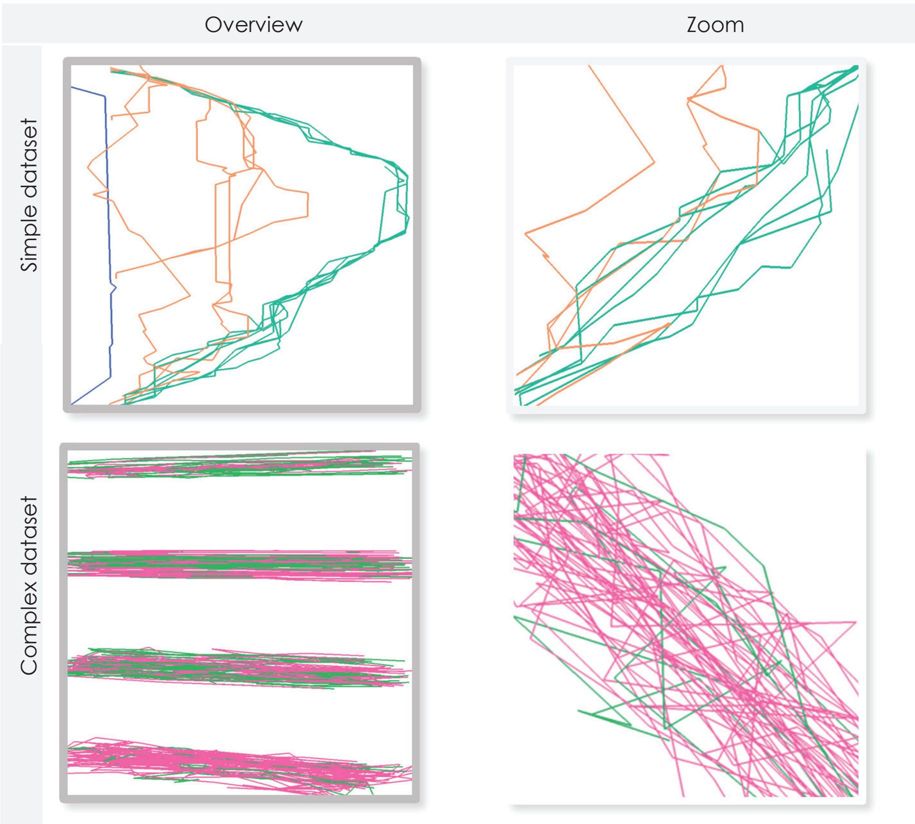



Figure 6.3 Design option for qualitative information: color hue attached to thick st-paths. The gray value of the figure frames refer to the hypotheses on efficient and effective (gray), less efficient and effective (light gray) and poor effect (white) in Table 6.1.

**Color hue & shading**

Overview: By adding shading the trajectories become tubes, and the space in between them is reduced. For small datasets, this will work efficiently and effectively (see Figure 6.4). However, for complex datasets the image might become cluttered, but still allows overall patterns to be seen.

Zoom: Visual perception of information will be improved for simple datasets and, as such, his design will be efficient and effective. For complex datasets, this design alternative will be informative too, but with a chance of visual clutter (see Figure 6.4).

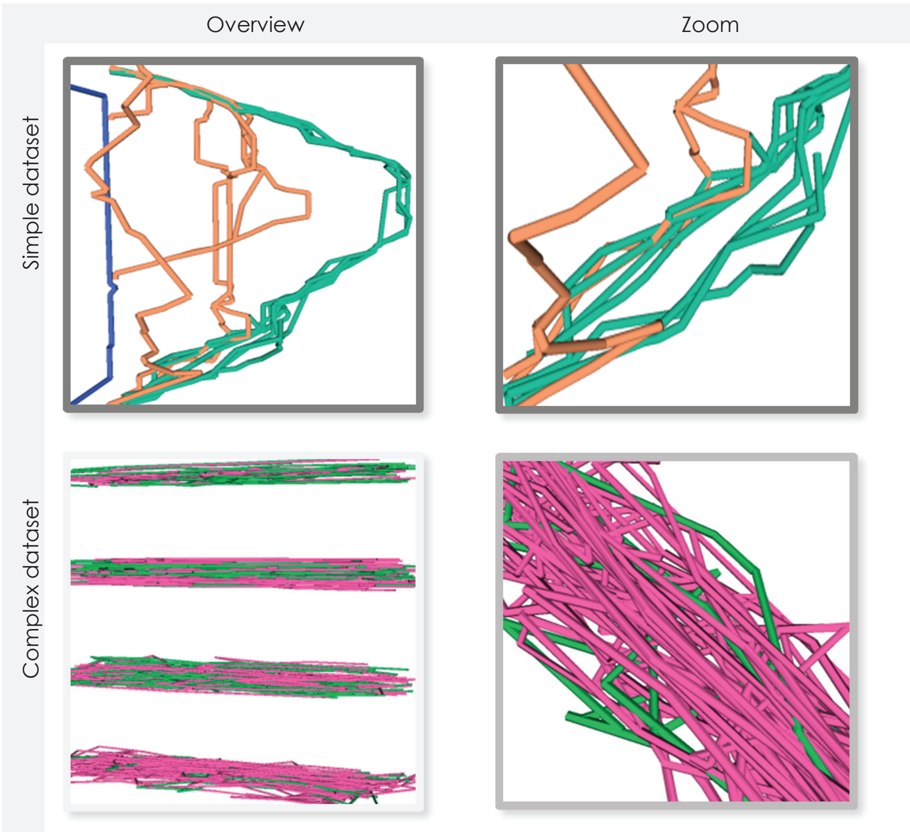



Figure 6.4 Design option for qualitative information: color hue & shading. The gray value of the figure frames refer to the hypotheses on most efficient and effective (dark gray), efficient and effective (gray), less efficient and effective (light gray) in Table 6.1.

**Color hue & shape**

Overview: This design alternative is used for annotated st-paths. According to the hypothesis in Table 6.1, *'color hue & shape'* will be efficient and effective to discern between different types of annotations but ineffective for similar types of information (see Figure 6.5).

Zoom: This option will be less efficient and effective for data exploration at zoom level. Differentiation between different types of information via color and shape of symbols will be possible but more difficult between similar types of annotations (see Figure 6.5).

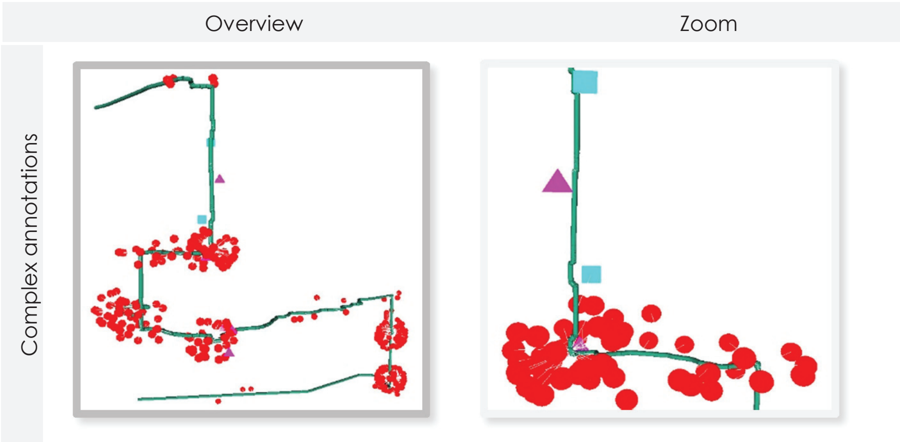



Figure 6.5 Design option for annotated st-paths: color hue & shape. The gray value of the figure frames refer to the hypotheses on efficient and effective (gray), less efficient and effective (light gray) in Table 6.1.

**Color hue & shape & shading**

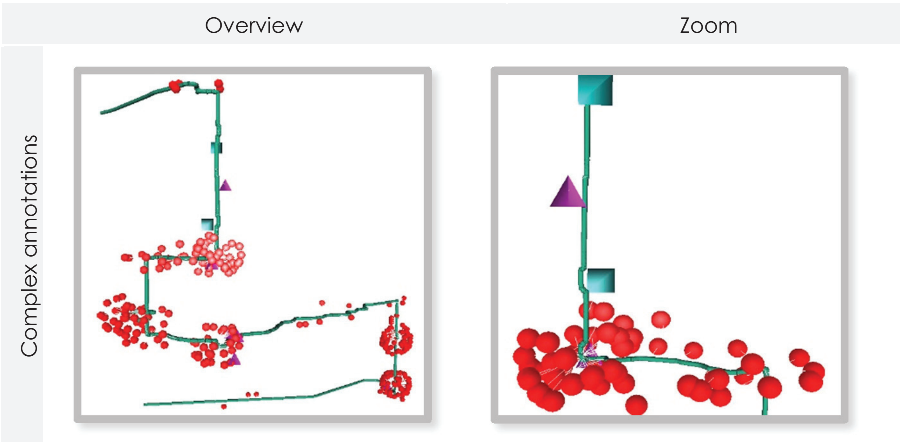



Figure 6.6 Design option for annotated st-paths: color hue & shape & shading. The gray value of the figure frames refer to the hypotheses on efficient and effective (gray) in Table 6.1.

Overview: The combination of *'color hue & shape & shading'* is considered as a most efficient and effective way to visualize annotated st-paths. The use of the depth cue will improve performance in the 3D visual environment of the STC and facilitate the perception of similar types of information (see Figure 6.6).

Zoom: This design option will be most effective and effective for data exploration at zoom level too. Distinction between the same types of information, even at overlapped places, will be much easier for the user due to the shading depth cue (see Figure 6.6).

**Orientation & shading**

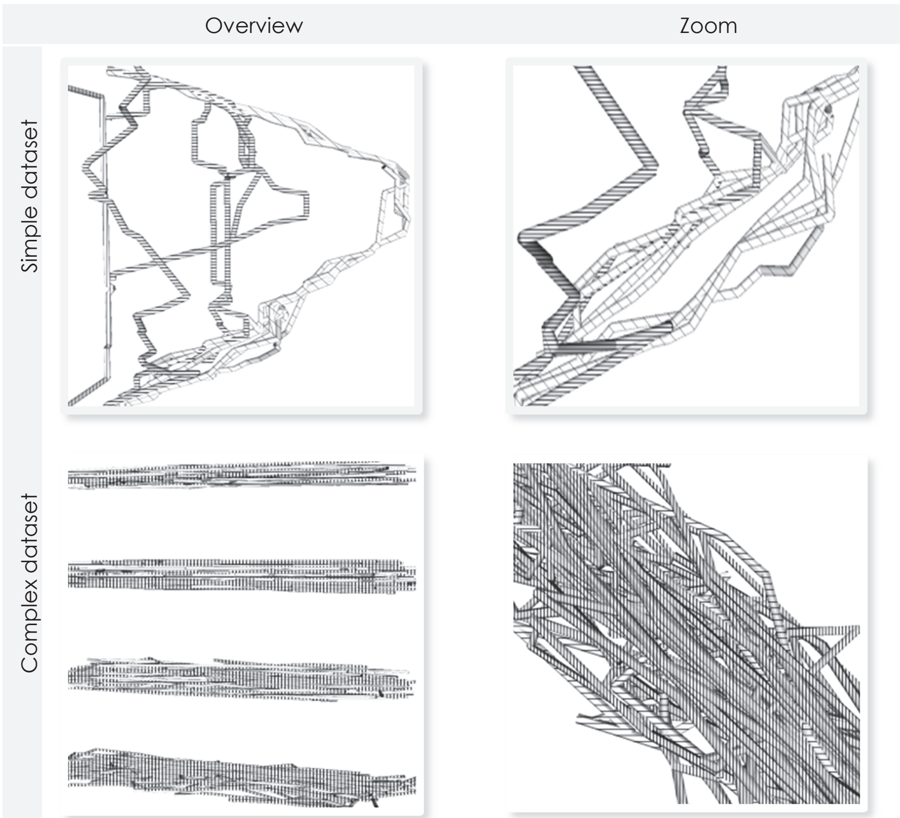



Figure 6.7 Design option for qualitative information: orientation & shading. The gray value of the figure frames refer to the hypotheses on less efficient and effective (light gray) and poor effect (white) in Table 6.1.

Overview: The design option of '*orientation & shading*' was developed for qualitative information as advised during the focus group discussion (see chapter 5). With simple datasets, this option will have the ability to give general information on a limited number of classes and will be less effective and efficient. As for complex datasets, it will have a poor effect (see Figure 6.7).

Zoom: For simple datasets, this option will provide information, but will be difficult for the user to memorize its content. In case of complex datasets, it might allow the user to distinguish between different information, but will be less effective (see Figure 6.7).

**Icons**

Overview: *'Icons'* are commonly accepted in cartography to annotate various types of information on the maps. They affect human visual memory and the way in which individuals *perceive information. By c*onsidering this factor, icons will be the most efficient and effective option to represent annotated information in the STC (see Figure 6.8).

Zoom: Icons will be the most efficient and effective option to represent annotated information for the zoom step too.

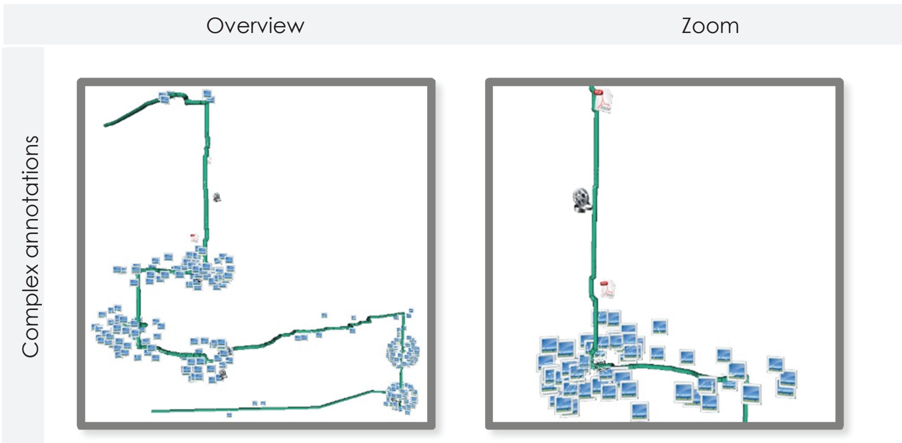



Figure 6.8 Icons as design option for the visualization of annotated st-paths. The gray value of the figure frames refer to the hypotheses on most efficient and effective (dark gray) in Table 6.1.

**Color saturation**

Overview: *'Color saturation'* will help the user to discern information in overlapping trajectories and will be the most efficient and effective to represent quantitative information in complex datasets (see Figure 6.9).

Zoom: Here, *'color saturation'* might result in st-paths scattered in the 3D visual environment of the STC because of the thin trajectories and will be an efficient and effective option (see Figure 6.9).

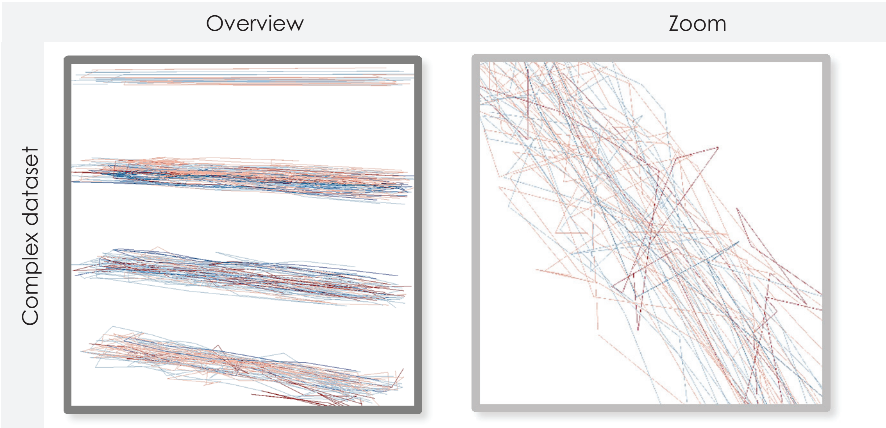



Figure 6.9 Design option for quantitative information: color saturation with thin st- paths. The gray value of the figure frames refer to the hypotheses on most efficient and effective (dark gray), efficient and effective (gray) in Table 6.1.

**Color saturation & shading**

Overview: The combination of '*color saturation & shading*' will increase trajectories in volume and will likely exaggerate the clutter problem by reducing the space between trajectories. Despite this, depth cues in the 3D visual environment are important and help the user to detect samples with similar color patterns. This design option for complex datasets will be efficient and effective (see Figure 6.10)

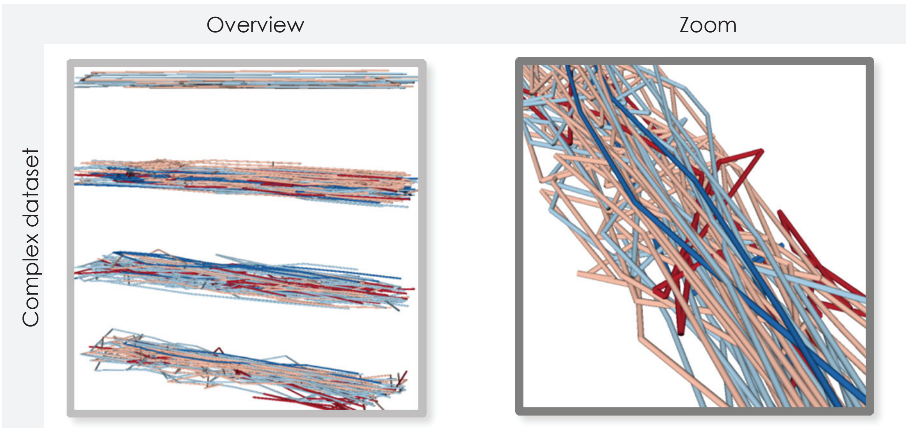



Figure 6.10 Design option for quantitative information: color saturation & shading. The gray value of the figure frames refer to the hypotheses on most efficient and effective (dark gray), efficient and effective (gray) in Table 6.1.

Zoom: Different from the overview level, the cluttering is less of a problem because of the expanded space between trajectories. Therefore, this option will be most efficient and effective for complex datasets (see Figure 6.10).

**Color value**

Overview: For the visualization of quantitative information, '*color value'* will be less efficient and effective for both simple and complex datasets, with the worst result for simple datasets. This is because it will evoke visibility problems due to the thin trajectories in the 3D visual environment of the STC, and also because of the gradually changing single color. For complex datasets color value might make the overlapping trajectories better distinguishable, however, differentiation between color gradations might be an issue here too (see Figure 6.11).

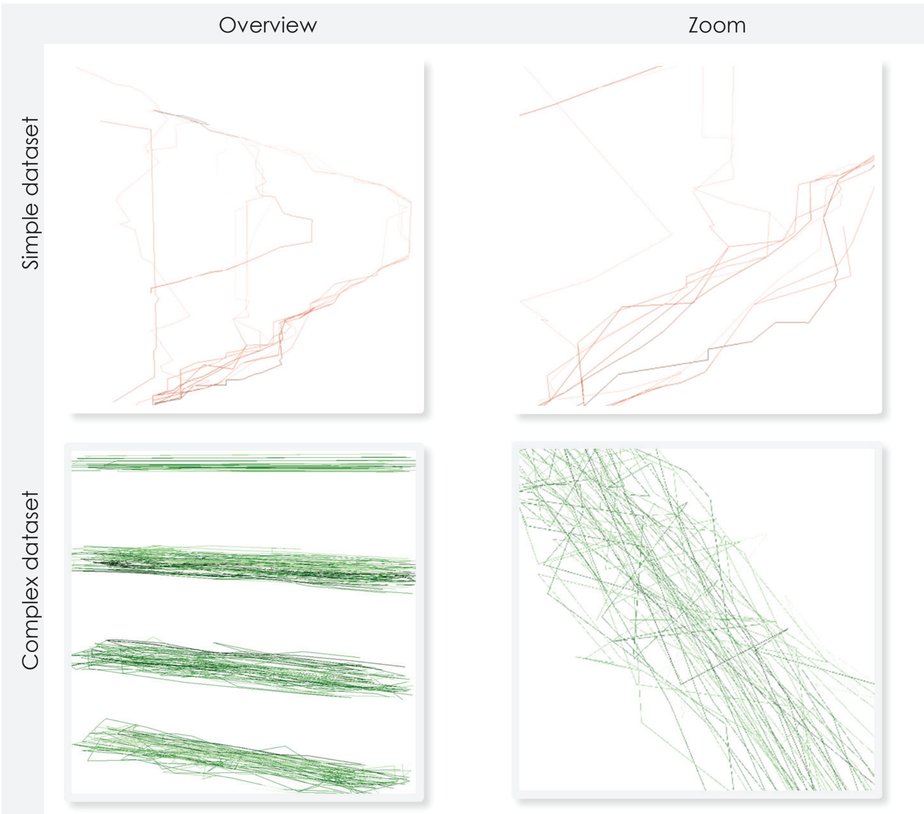



Figure 6.11 Design option for quantitative information: color value with thin st-paths. The gray value of the figure frames refer to the hypotheses on less efficient and effective (light gray) and poor effect (white) in Table 6.1.

Zoom: This design option will have a very poor effect for small datasets. When enlarging the representation, the distance between trajectories becomes larger, e.g. thin lines are scattered in the 3D space of the STC, and to detect color values becomes hard. Compared to simple datasets, elements of complex datasets will be better detectable. When trajectories overlap, the gradually ordered color patterns might be visible (see Figure 6.11), but will still be less efficient and effective.

#### Color value & thick st-path

Overview: *'Color value & thick st-path'* should improve the appearance of information for simple datasets when compared to the previous option. The visibility of color gradation becomes more distinguishable and allows one to notice change in color value. This design option for simple datasets will be effective (see Figure 6.12). Complex datasets were not considered because of the very high cluttering.

Zoom: For simple datasets *'color value & thick st-path'* will be efficient and effective to represent information. It will accumulate color patterns in places and help to detect information of similar value. However, it will be difficult to differentiate directions of the st-paths when trajectories are tangled (see Figure 6.12).

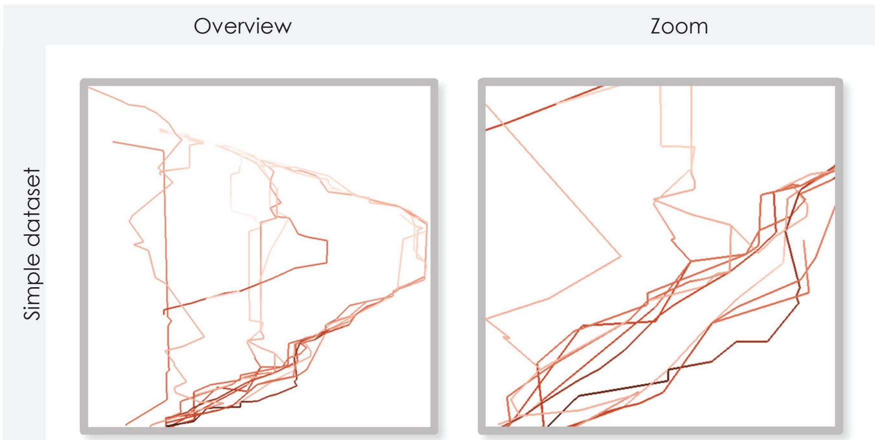



Figure 6.12 Design option for quantitative information: color value with thick st-paths. The gray value of the figure frames refer to the hypotheses on efficient and effective (gray) in Table 6.1.

#### Color value & shading

Overview: *'Color value & shading'* will be efficient and effective for the visualization of simple datasets. Depth cues will emphasize a gradual change in color value that will allow the user to detect amounts without trouble. For complex datasets, this design option will result in an increased overlapping problem, because it cannot represent *differences* in amount in a distinct way. Thus, for complex datasets this option will be less effective and efficient (see Figure 6.13).

Zoom: This option will be efficient and effective to represent amounts within trajectories in simple datasets as well as differences between trajectories in complex datasets. At the zoom step, differentiation between color gradations will be easier for human eyes than for the overview level.

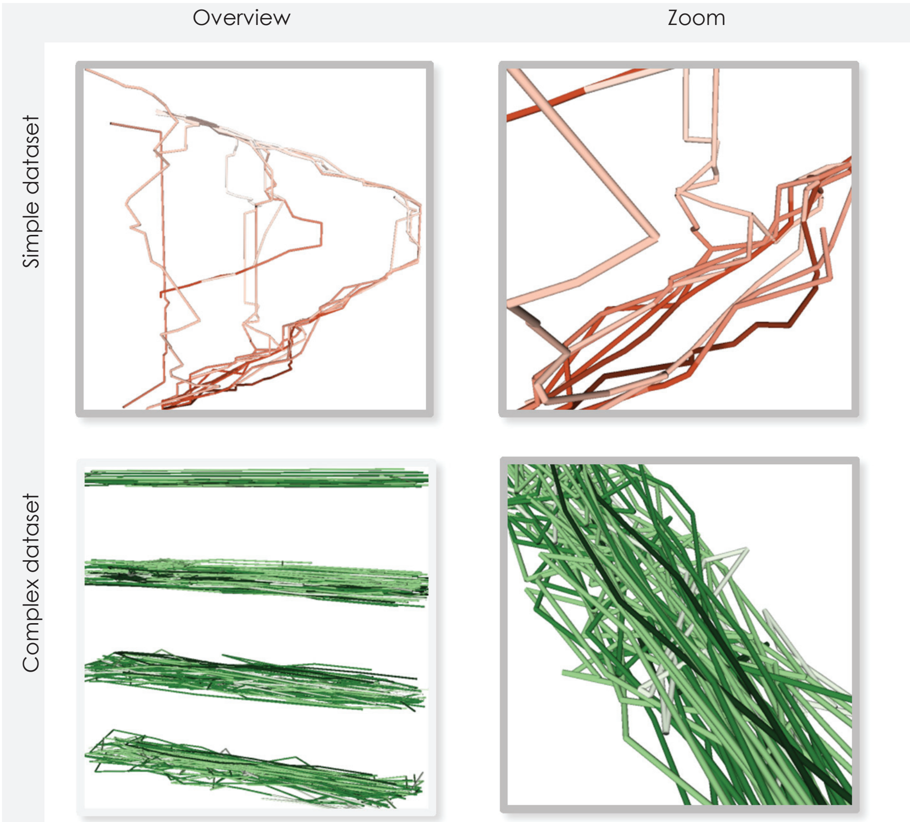



Figure 6.13 Design option for quantitative information: color value & shading. The gray value of the figure frames refer to the hypotheses on efficient and effective (gray) and less efficient and effective (light gray) in Table 6.1.

**Size & shading**

Overview: With the '*size & shading*' option, the representation of amounts in small datasets will be the most efficient and effective way to detect differences (see Figure 6.14). Experts disapproved the use of this design option for large datasets (see chapter 5).

Zoom: The '*Size & shading*' option will be the most efficient and effective way for human vision to detect change in amounts for simple datasets.

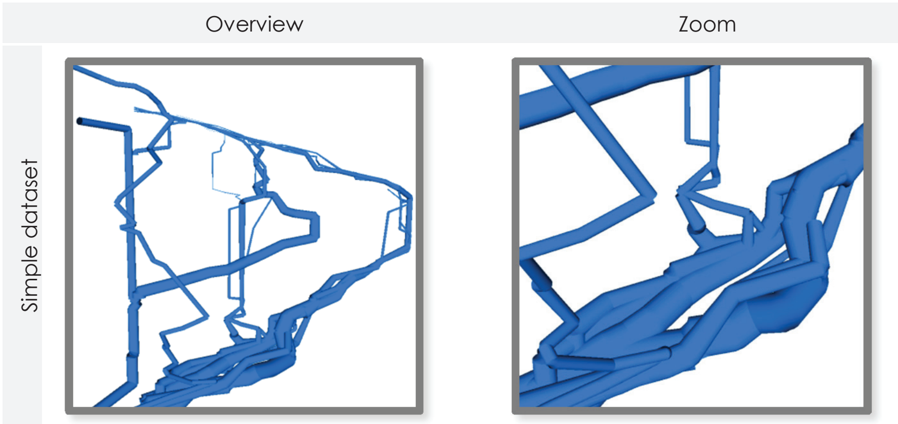



Figure 6.14 Design option for quantitative information: size & shading. The gray value of the figure frames refer to the hypotheses on most efficient and effective (dark gray) in Table 6.1.

In addition to all options presented above, as supporting depth cue in the exploration process transparency was embedded into the visual environment of the STC, as additional option to improve the visibility of information. It adds to the hypothesis that the use of transparency with all design options will improve visibility of cluttered situations.

## 6.3.2 Task execution scenarios

During the test sessions described below, users had to interact with the STC's visual environment to execute tasks (see Appendix 2). These interaction scenarios are important to understand why particular design options work better. Thus, based on the comparison of task performances, the usability of each design alternative will be measured. The questions with corresponding map use tasks were defined, and hypothesized as expected task execution scenarios identified in section 3.3 and chapter 4. The results collected will allow to comprehend the aspects of the use of the design options regarding to the tasks and data complexity. The task execution scenarios for each use case study were defined as follows:

**Simple dataset of 'Napoleon's march to Moscow'**

| | |
|---|---|
| QUESTION 1 | The displayed views are representing information about the leaders of the troops / corps. Please look at the representations and estimate visually: How many corps arrived in Moscow, and who was their leader? |
| EXPECTED TASK EXECUTION | By overviewing the data content in the STC, participants should *locate* both Moscow and trajectories arriving there. Then they have to use the proper tool (zoom in) to *estimate* visually the quantity of trajectories. Then again, they will have to use the proper tool (zoom |

| | |
|---|---|
| | out) to *distinguish* between colours and name the leader of the corps at the point of intersection. |
| QUESTION 2 | The newly displayed views are representing the number of soldiers in the troops/corps. Please look at the representations and estimate visually: When did the corps have their highest strength / number of soldiers? |
| EXPECTED TASK EXECUTION | Participants should have a quick overview (pan, rotate) of the information to *locate* cursor at the beginning of the campaign and *estimate* the strength visually. |

**Complex datasets of 'Pedestrian movement in city center of Delft'**

| | |
|---|---|
| QUESTION 1 | On your screen, four different views are representing information on gender. Please look at the representations and estimate visually: Are there any differences between female and male trajectories / movements over four days? |
| EXPECTED TASK EXECUTION | Participants are expected to *distinguish* male and female trajectories visually over four days, and *locate* the day with distinctively more female trajectories. |
| QUESTION 2 | The newly displayed views are representing pedestrians by age groups. Please look at the representations and estimate visually: Do you see differences in the composition of age groups on different days? |
| EXPECTED TASK EXECUTION | Participants should *compare* the distribution of different age groups over four days, and *locate* the day with a clear underrepresentation of certain age groups. |

**Complex annotations of 'Travel log data of Estonia'**

| | |
|---|---|
| QUESTION 1 | Please look at the annotations in the views and write down how many types of information are represented by these annotations. |
| EXPECTED TASK EXECUTION | Participants are expected to *identify* different attribute information and *estimate* the amount of annotation types. |
| QUESTION 2 | Please list the contents of the information represented by the annotations. |
| EXPECTED TASK EXECUTION | Participant should name the represented types of annotation by *locating* them on the st-paths. |

### 6.3.3 Selecting and scheduling non-expert test participants

A group of 22 students of the Faculty ITC of the University of Twente participated in the experiment. Through an online questionnaire their user profile was established (see Appendix 3). Among them, there were 13 female and 9 male participants. The participants, of different nationalities and age groups were mainly PhD candidates in the geographical domain (see Table 6.2).

Table 6.2 General background characteristics of TPs. The colors in the table refer to the case studies in which the TP's participated. Blue–simple (Figure 6.1A); pink – complex (Figure 6.1B); green – annotations (Figure 6.1C)

| Test day | TP № | Country of origin | Gender | Age group | Educational degree | Degree obtained in | Occupation |
|---|---|---|---|---|---|---|---|
| Day I – Simple datasets | TP 1 | India | Male | 41 – 50 | Master's degree | Agriculture | PhD candidate |
| | TP 2 | Spain | Female | 31 – 35 | Master's degree | Physics & Thermal Remote Sensing | PhD candidate |
| | TP 3 | China | Male | 26 – 30 | Master's degree | Remote Sensing | PhD candidate |
| | TP 4 | China | Female | 20 – 25 | Master's degree | Geo-Information Science | PhD candidate |
| | TP 5 | China | Male | 31 – 35 | Master's degree | Atmosphere Science | PhD candidate |
| | TP 14 | New Zealand | Female | 26 – 30 | Master's degree | Environmental Science | PhD candidate |
| | TP 15 | China | Male | 31 – 35 | Master's degree | Ecology | PhD candidate |
| Day II – Complex datasets | TP 6 | China | Female | 20 – 25 | Master's degree | Urban planning and management | PhD candidate |
| | TP 7 | Italy | Male | 26 – 30 | Master's degree | Environmental sciences | PhD candidate |
| | TP 8 | China | Male | 31 – 35 | PhD degree | Information and communication engineering | College teacher |
| | TP 9 | Nepal | Male | 26 – 30 | Master's degree | Water Resources | PhD candidate |
| | TP 10 | South Africa | Female | 36 – 40 | Master's degree | Earth observation and Geo-Information | PhD candidate |
| | TP 11 | Egypt | Male | 26 – 30 | Master's degree | Geo-Information Science | PhD candidate |
| | TP 12 | China | Female | 20 – 25 | Master's degree | natural resources | PhD candidate |
| | TP 13 | China | Male | 26 – 30 | Bachelor's degree | Atmosphere Science | Student |
| Day III – Complex annotations | TP 16 | China | Female | 26 – 30 | Master's degree | Cartography & Geographic Information System | PhD candidate |
| | TP 17 | Malaysia | Male | 26 – 30 | Master's degree | Geo-Informatics | Tutor |
| | TP 18 | Colombia | Female | 31 – 35 | Master's degree | Forest and Nature Conservation, GIS | PhD candidate |
| | TP 19 | Iran | Female | 26 – 30 | Master's degree | Natural resources | PhD candidate |
| | TP 20 | Iran | Female | 26 – 30 | Master's degree | Natural resource | PhD candidate |
| | TP 21 | Kenya | Female | 31 – 35 | Master's degree | Earth observation, natural resources | PhD candidate |
| | TP 22 | China | Female | 26 – 30 | Master's degree | Land administration | PhD candidate |

The selection of participants was based on their background characteristics derived via the questionnaire. These characteristics were significant for the experiment, but among them the highest attention was given to map use experience and color blindness. Thus, none of the selected participants was color blind or had a poor map use experience. Test subjects also were asked about the use of glasses or contact lenses because of the eye tracking method used for the evaluation study. As it turned out, 12 participants out of the 22 were wearing glasses or contact lenses. In addition, all of the 22 TPs were experienced map users of which 4 appeared to be passive users, and 6 indicated that they rarely used interactive maps (once in a month or less (see Table 6.3, Figure 6.15-A, B).

Table 6.3 Individual characteristics of TPs related to map use. The colors in the table refer to the case studies in which the TP's participated. Blue–simple (Figure 6.1A); pink – complex (Figure 6.1B); green – annotations (Figure 6.1C)

| Test day | TP № | How often do you use maps in your daily life? | Do you know what visual variables are? | Have you ever designed a map yourself? | How often do you use interactive (computerized) maps? | Are you familiar with the STC? | If your answer was 'Yes' on the previous question, have you ever used the STC in an interactive environment? |
|---|---|---|---|---|---|---|---|
| **Day I – Simple datasets** | TP 1 | Once in a day | Yes | 6 | Once in a day | No | |
| | TP 2 | Once in a week | No | 3 | Once in in a week | No | |
| | TP 3 | 2 – 3 times in a week | Yes | 10 very often | Never | No | |
| | TP 4 | Once in a week | Yes | 8 | Once in a week | No | |
| | TP 5 | 2 – 3 times in a year | No | 2 | 2 – 3 times in a year | No | |
| | TP 14 | Once in a day | Yes | 2 | Once in a day | No | |
| | TP 15 | Once in a month | No | 5 | Once in a month | Yes | 1 never |
| **Day II – Complex datasets** | TP 6 | 2 – 3 times in a week | No | 9 | 2 – 3 times in a week | Yes | 2 |
| | TP 7 | 2 – 3 times in a week | No | 7 | Once in a week | No | |
| | TP 8 | Once in a week | Yes | 1 never | 2 – 3 times in a year | Yes | 1 never |
| | TP 9 | Once in a month | No | 6 | Once in a week | No | |
| | TP 10 | 2 – 3 times in a week | Yes | 5 | 2 – 3 times in a week | No | |
| | TP 11 | Once in a day | Yes | 5 | Once in a day | Yes | 8 |
| | TP 12 | Once in a day | Yes | 4 | Once in a day | No | |
| | TP 13 | Once in a day | No | 1 never | Once in a day | No | |
| **Day III – Complex annotations** | TP 16 | 2 – 3 times in a week | Yes | 5 | 2 – 3 times in a week | Yes | 1 never |
| | TP 17 | Once in a day | Yes | 5 | 2 – 3 times in a week | Yes | 1 never |
| | TP 18 | Once in a week | No | 5 | Once in a week | No | |
| | TP 19 | Once in a month | No | 7 | Once in a month | No | |
| | TP 20 | Once in a week | Yes | 10 very often | Once in a week | No | |
| | TP 21 | 2 – 3 times in a week | Yes | 10 very often | 2 – 3 times in a week | No | |
| | TP 22 | Once in a week | No | 2 | Never | No | |

According to the individual characteristics, only 12 of the TPs were familiar with visual variables (see Figure 6.15-C). However, all claimed to be successful in using maps in their daily life, which means that they are able to read information represented through visual variables. In addition, all but two of the participants have no experience in designing maps themselves (see Figure 6.15-D).

Only 6 of the test participants were familiar with the STC. Among them, one was well experienced working with the STC's interactive environment (TP11, see Table 6.3). While others were less experienced (1) or never interacted with the STC before (4) (see Figure 6.15-E, F).

After identifying their background characteristics, they were divided into three similar groups, one for each use case study. The participants were able to select their own time slot for the evaluation session.

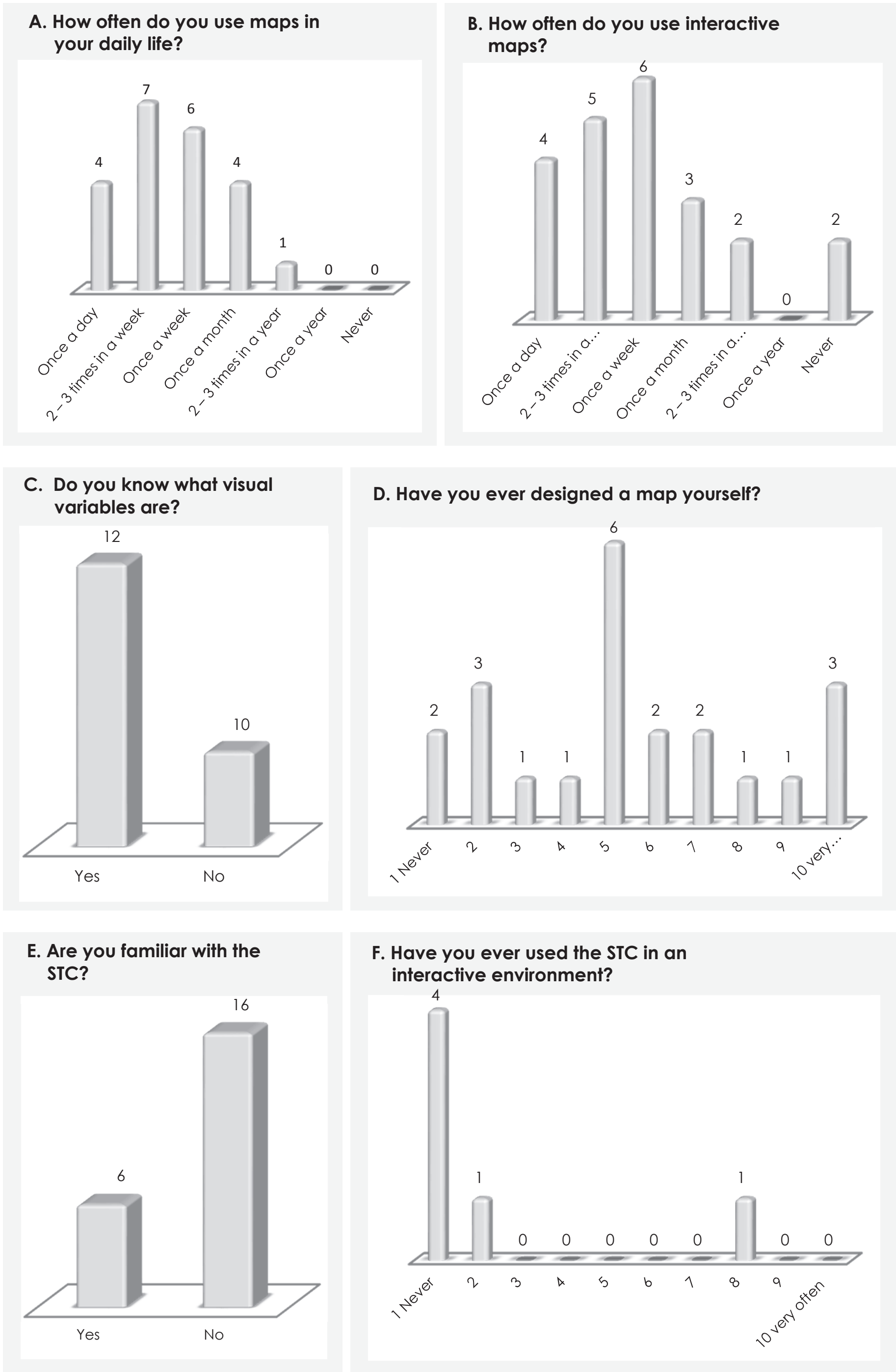



Figure 6.15 Background characteristics of the test participants.

## 6.3.4 Design of the experiment

**Materials**

For each use case, the evaluation was divided into two sessions. And each of these two sessions was again separated in the task executions and an interview part (see Figure 6.16). For the task session different designs were prepared (see section 6.3.1 above), each with a legend and a slider to vary transparency to see through occluded objects. The task sessions were intended to measure the effectiveness and efficiency, while the interview sessions were meant to identify the user satisfaction about the introduced design options. For both sessions a mix of usability research methods was applied, as shown in Figure 6.16.

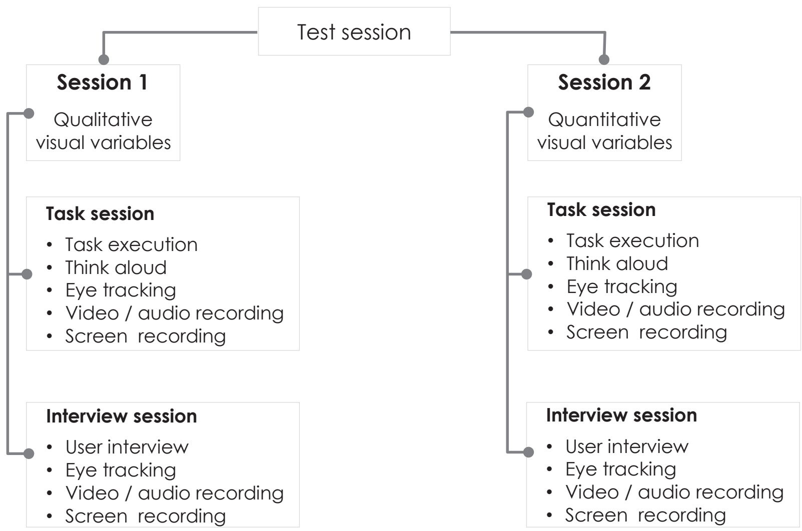



Figure 6.16 Schematic view of the test session structure for each TP.

During the test sessions, the participants were presented four design options with qualitative visual variables and four design options with quantitative visual variables for simple and complex case. These options were introduced and described in section 6.3.1. Figure 6.17 shows the design options as introduced in the visual environment during the first session with the simple datasets. The complex dataset was presented similarly. Figure 6.18 shows the details of designs for the case study with the simple dataset, and Figure 6.19 does so for the case study with the complex dataset. Both Figures 6.18 and 6.19 are created based on the figures introduced in section 6.3.1.

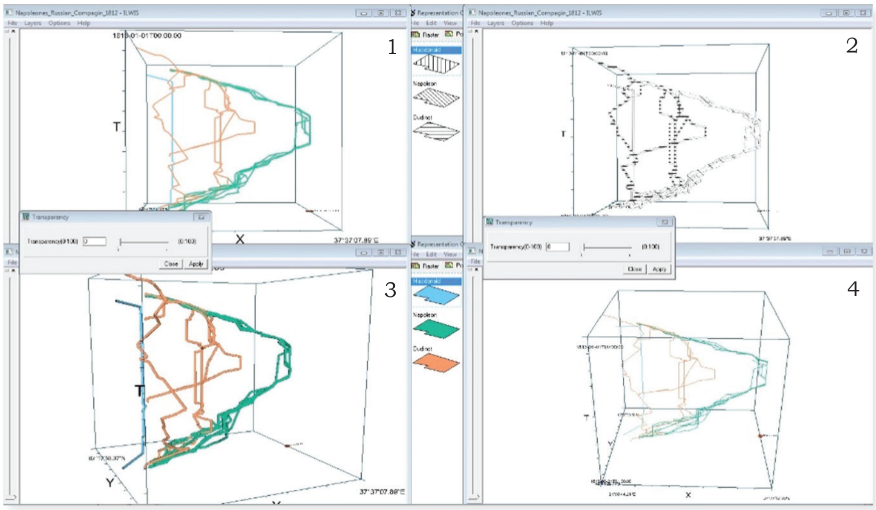



Figure 6.17 Visual environment and design options for qualitative visual variables of the simple dataset. The numbers in the views correspond to the design options in Figure 6.18, session 1 qualitative visual variables.

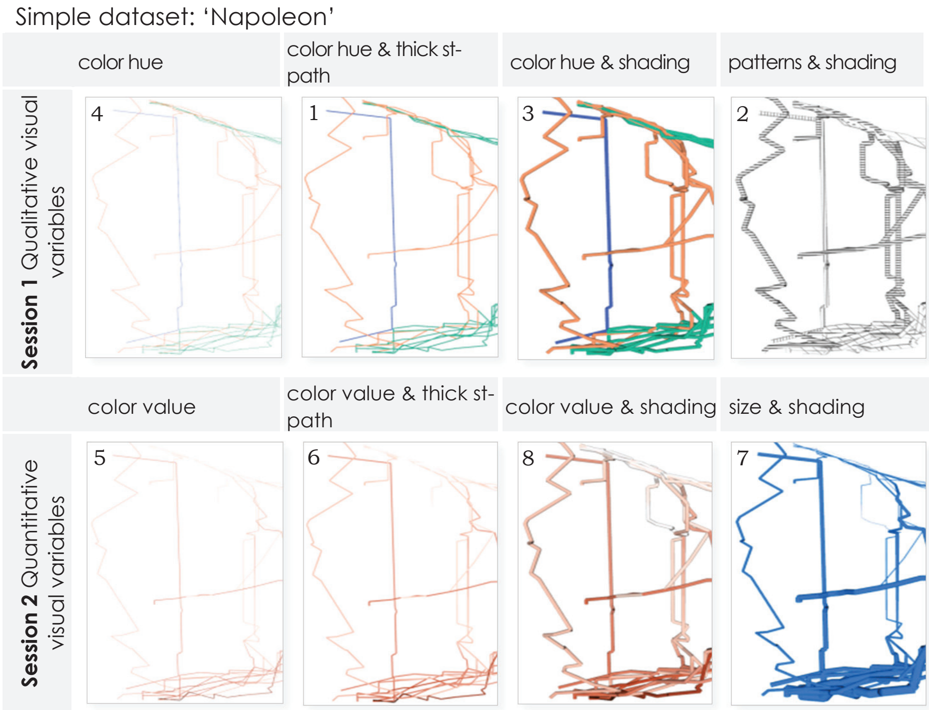



Figure 6.18 Details of the design options for the simple dataset: 'Napoleons march to Moscow'. The numbers in the pictures correspond to views on the display during the experiment, such as in Figure 6.17.

Similar to the focus group experiment, the contextual information of the base map was ignored to keep the users focused on the design alternatives. In the next phase of the research project (see chapter 7), this context will be added. Besides, test participants were provided with a document with the use case related questions and a table to rate the preferred design options (see Appendix 2).

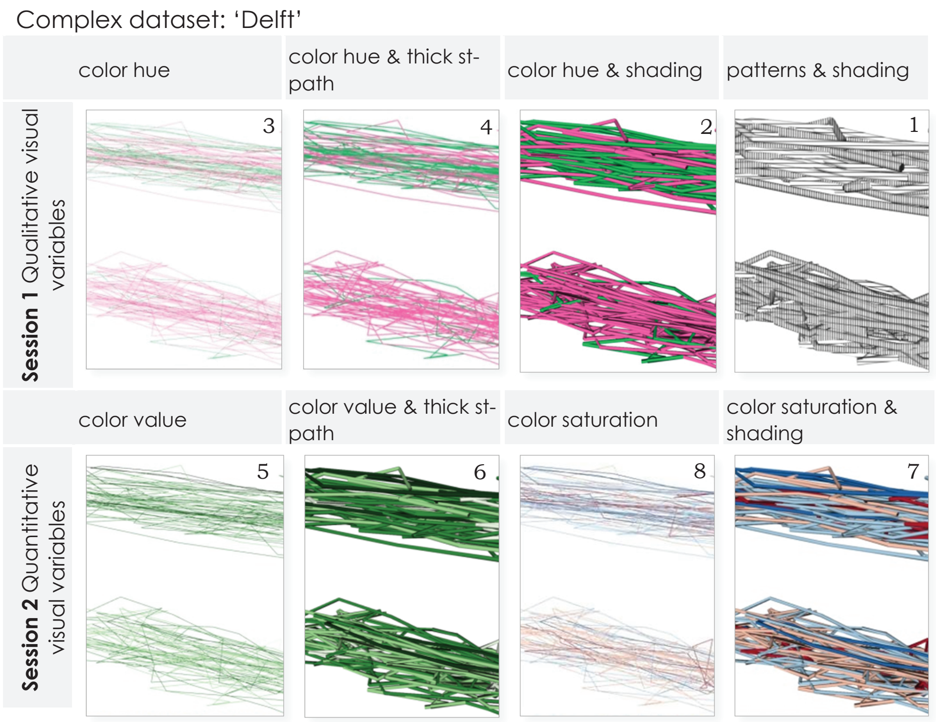



Figure 6.19 Details of the design options for the complex dataset: 'Pedestrian movements in the city center of Delft.' The numbers in the pictures correspond to views on the display during the experiment.

The usability experiment for complex annotations slightly differed from that for the simple and complex datasets. During this experiment, the participants were introduced to four design options for qualitative visual variables (see Figure 6.20) but with some additional tasks related to the qualitative and quantitative characteristics of the data.

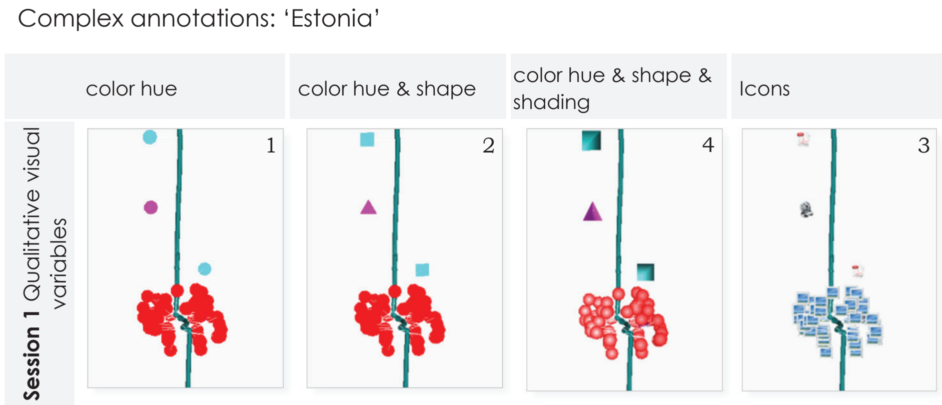



Figure 6.20 Design options for the complex annotations: 'Travel log data of Estonia.' The numbers in the pictures correspond to views on the display during the experiment.

**Setup**

The experiments were designed and performed on a Windows 7 workstation running Tobii Studio 3.2 software. The STC's were shown on a 24" LCD flat panel display (1680 x 1050 screen resolution). The users could interact with the visual environment and manipulate the STC using a standard mouse and keyboard. A Tobii X 60 Eye Tracker with a 60Hz resolution captured the eye movements and screen activities and video and audio recordings were captured synchronously for all test subjects. Ilwis software was used to display the design alternatives for the simple datasets and complex datasets. For the display of the complex annotations the uDig program environment was applied

## 6.3.5 Procedure

The experiment took place in the usability laboratory of the Department of Geo-Information Processing of the University of Twente (see Figure 6.21). At the beginning of the test session, the participants were welcomed into the usability-lab, and asked to sit in front of the computer showing the design options prepared for the first session (see Figure 6.17). They were given a printed document with test instructions explaining the purpose of the experiment, the evaluation methods used and the rules applied during the session (see Appendix 4). During the task session, participants were free to decide which of the four design options to use for execution. However, they were also required to interact with all views via zooming in/out, panning, rotating and using the transparency slider to gather experiences and an opinion on the design alternatives. On the other hand, test subjects were not allowed to move or minimize/maximize windows, to switch on/off the legend window or move it into the visual environment. These rules were important for the final analysis of the eye tracking data. Furthermore, they were asked to think aloud during the task session and to formulate their opinions on whether design alternatives were appropriate for the given tasks, but also to explain the reasons of their particular behaviour.

After familiarization with the instructions, they were demonstrated the visual environment and the required functionality. Thereafter, the participants were given 10 minutes to practice with the demonstrated functionality in order to get familiar with the visual environment. After the practice session ended, the test subjects were briefly explained how the eye recorder works and the eye tracker was calibrated. After the calibration procedure, participants were given the task document and the session started (see Appendix 2). The eye movement recording, video, audio and screen recordings started simultaneously through Tobii Studio 3.2.

Figure 6.21 Test environment in the usability laboratory.

After completing the first task session, TPs had to rate the evaluated design options in the table given right below the task on the task document (see Appendix 2). Through this ranking, they indicated their preferred design options, but they were also interviewed to share gathered experience and opinions. The interview session took about 10 minutes and helped to clarify some additional information on effectiveness, efficiency and user satisfaction of the design options (see Appendix 5).

The first interview session was followed by a second task session for the quantitative visual variables, displaying the design options prepared in advance. Similar to the first session, participants first completed the tasks, then rated their preferred design options and were interviewed thereafter. During the transitions between the first and second sessions, the recordings were not stopped, but unnecessary materials were deleted later during the analysis.

## 6.4 Analysis of the Results

The starting point for the analysis of the collected materials was a video segmentation of the recordings in Tobii studio, based on the task execution, rating, discussion, and user interview sessions (see Figure 6.22). Later, these segments were integrated into corresponding segment groups (task, interview, discussion & rating) for further qualitative and quantitative analysis.

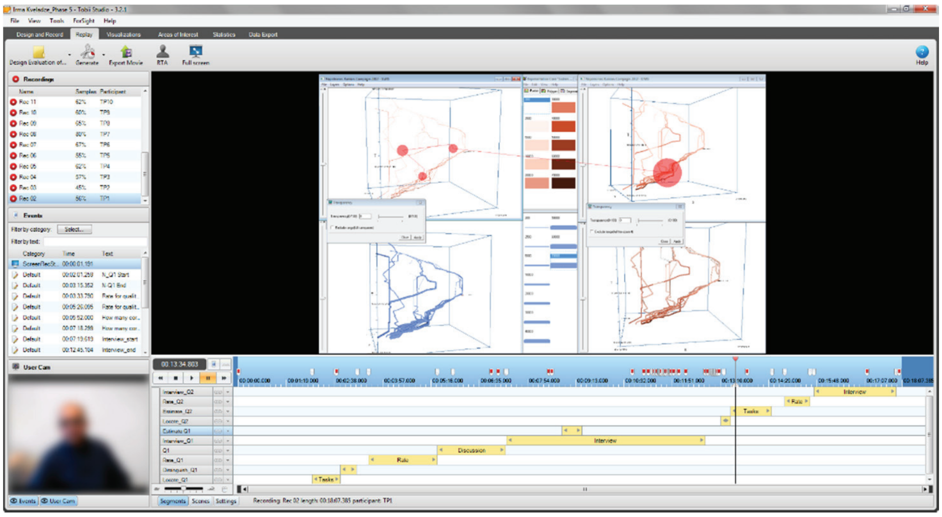


Figure 6.22 Visual environment of Tobii studio in the process of recording segmentation.

The combination of qualitative and quantitative user research methods was applied to understand the usability and utility of design options in the STC. Such a mix of methods helps to produce insightful results because they complement each other. For quantitative analysis, the employed task execution and eye recordings helped to extract effectiveness and efficiency metrics on test subject's task performance. These metrics were used to examine TPs eye movement behaviour for design alternatives. For each design option, Areas of Interest (AOI's) were identified to calculate eye tracking metrics (see Figure 6.23). Descriptive statistic information on the time spent looking at design alternatives and on error rates was obtained. The time to first fixation is a typical metric used in usability research to identify how long participants took to first fixate an area of certain interest (Goldberg and Kotval, 1999; Strandvall, 2009). In addition, the intention of this research was to understand the use of the displayed design alternatives during the whole task execution period. For this reason, efficiency metrics on the 'total time spent' were employed to identify the total time each design option was viewed while executing the task. These metrics should reveal the task performance speed in AOIs. The results were later integrated with the qualitative analysis for understanding the ongoing cognitive processes during task exploration and the participant's attitude.

The statistics collected in Tobii Studio, were exported as a text file into Microsoft Excel and processed for statistical analysis. During data processing, missing values were discovered indicating incomplete eye movement recordings. The reason was the movement of TPs towards the screen to see design options from nearby. As a result, the eye tracker lost its signal and further recordings were collected sporadically. Such incomplete recordings were found only in the first (TP2-14%) and second sessions (TP3-14%, TP4-14%) of the simple dataset. In order to avoid bias, the eye recordings having such deficiencies were excluded from the data analysis. The processed data resulted in box plots that allowed a profound quantitative analysis of the experiment. Besides, these graphs are supplemented with Heat Maps to represent the distribution of the users visual attention over 'the displayed design alternatives during the task execution (Bojko, 2009). Attention Heat Maps generated through Tobii Studio show the absolute duration of the total number of fixations in views.

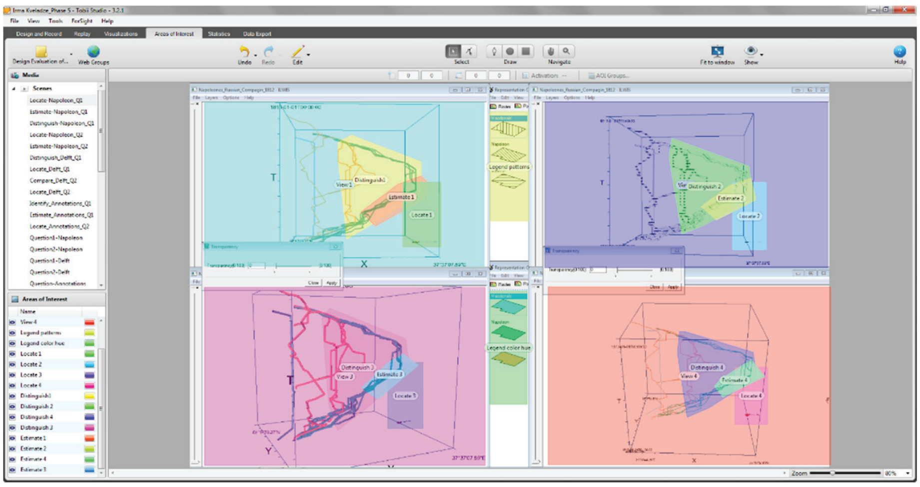


Figure 6.23 Areas of Interest (AOI) identified for the first task session with the simple dataset in Tobii Studio.

For the qualitative analysis a combination of think aloud, eye tracking, screen action, video/audio recordings, and user interview methods were used as research materials. The videos derived from Tobii Studio, were integrated for verbatim transcript in a program environment of the qualitative research software "ATLAS.ti" (URL 3). As a result, a detailed document containing the descriptive analysis of the test sessions was made (see Appendix 6). In order to analyse the produced transcripts effectively, a list of important activities (identify, locate, compare, etc.) undertaken by the TPs was defined (see Table 6.4).

Table 6.4 The coding structure for the analysis of the transcript document

| Evaluation | Task/activity | Action | View |
|---|---|---|---|
| Confusion | Compare | Pan | View 1 |
| Eye movement not recorded | Distinguish | Rotate | View 2 |
| Help | Identify | Zoom | View 3 |
| Negative sense | Estimate | 2D base map | View 4 |
| Positive sense | Locate | | Legend |
| Observation | | | Transparency |
| Remark | | | |
| Session start | | | |
| Session end | | | |
| Usability problem | | | |

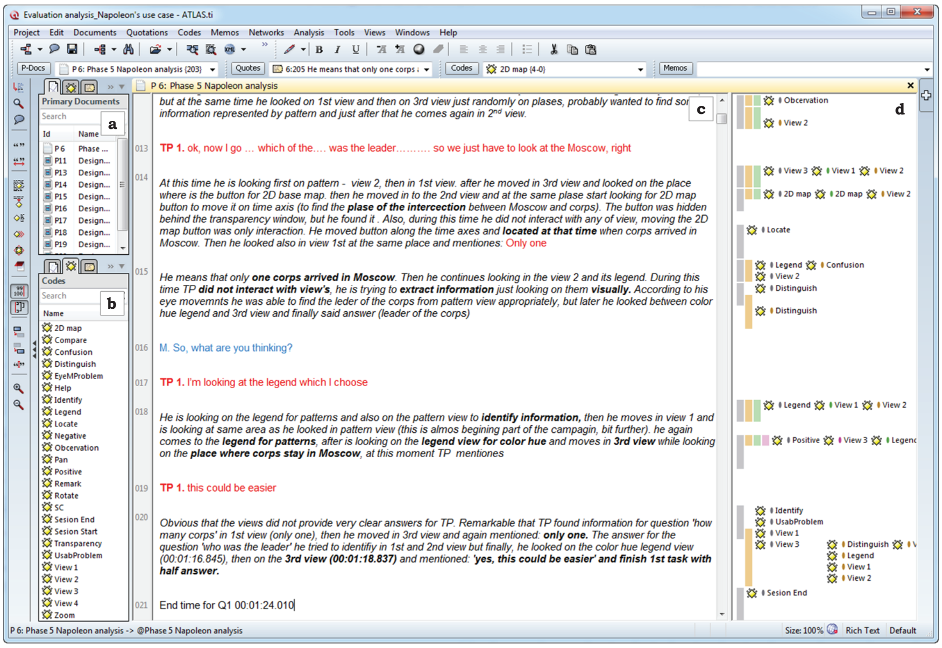



Figure 6.24 View of a transcript document in the environment of the qualitative data analysis software ATLAS.ti, **a**. Recordings derived from Tobii studio, **b**. Single coded words identified for the transcript document (see also Table 6.4), **c**. Transcript text document, **d**. Single coded words linked to the particular text segments to describe the exploration activities. See also appendix 6.

The video/audio/screen/eye recordings and think aloud were used to find out about the task performance of the participants, their confusion, usability problems, remarks, positive and negative senses, etc. through their thoughts, reactions, and opinions. Thus, these single coded words referring to particular actions of the participant were linked to the particular text segments in the document to describe the exploration activities. By analysing the document through single coded words, it is relatively easy for the test moderator to retrieve information related to the experiment. In total, in this experiment 25 codes were identified that are integrated under the family codes of evaluation, task/activity, action, and view (see Table 6.4). The resulting encoded document was used to understand the usability aspects of the proposed design options. The use of these codes in 'ATLAS.ti,' is shown in Figure 6.24. It represents an example of a transcript text document as developed for this experiment.

## 6.4.1 Simple dataset – Napoleons march to Moscow

In this experiment, test subjects completed five analytical tasks (see Table 6.4). During the first test session, participants performed tasks such as *locate, estimate* and *distinguish* with the option to interact via zoom in/out, pan and rotate. During the second evaluation session, they completed tasks like *compare* and *estimate* with the same interaction options. The results derived from the recordings revealed that, in most cases, the starting point for task execution was a quick visual observation of the design options followed by studying the corresponding legend views. Doing so, test subjects could understand the differences between design alternatives, and link them to the tasks afterwards. The analysis also revealed that the training session before the task execution was enough for some test subjects to remember the differences between the design alternatives and make quick decisions about their use during the actual test session.

#### Analysis of task execution with qualitative visual variables

The results show that during the first evaluation session the tasks *locate* and *distinguish* were performed more effectively and efficiently than the task *estimate*. Figure 6.25 represents the effectiveness and efficiency of the executed tasks for each TP, whereas Figure 6.26 shows the average task efficiency. Regarding the task effectiveness, two participant (TP5, TP15) out of seven were not able to *estimate* the number of trajectories from the qualitative visual variables, and ignore it by arguing that 'answer for given question is not visible in representations.' The other participants could complete the task on average in 125.5s. In addition, the task execution sessions revealed the participants exploration behaviour for the task *estimate*. For instance, to identify the number of corps, TP2, TP3 and TP5 expected a pop-up window at the point of intersection. While TP1 and TP4 pointed at the inconvenience of counting tangled trajectories without proper analytical tools. Despite this, the majority (5) of the TPs could estimate the number of corps visually. However, the reason for inefficiency in executing the task *estimate* was a missing analytical tool.

The execution of the tasks *locate* and *distinguish* was performed in a relatively short time. All participants were able to complete the task *locate* on average in 46s, while the task *distinguish* yielded the shortest response time - on average 24.5s (see Figure 26).

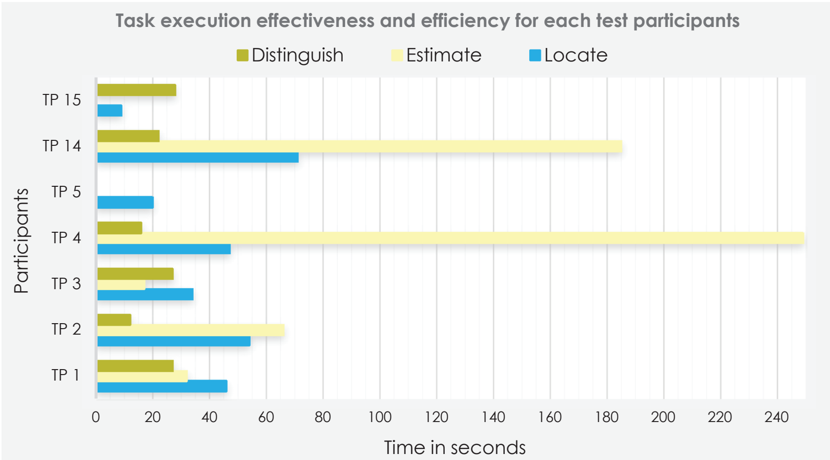



Figure 6.25 Time spent by participants to accomplish the tasks using quantitative visual variables. The colors in graph represent the different tasks. If the task is done, it is considered effective.

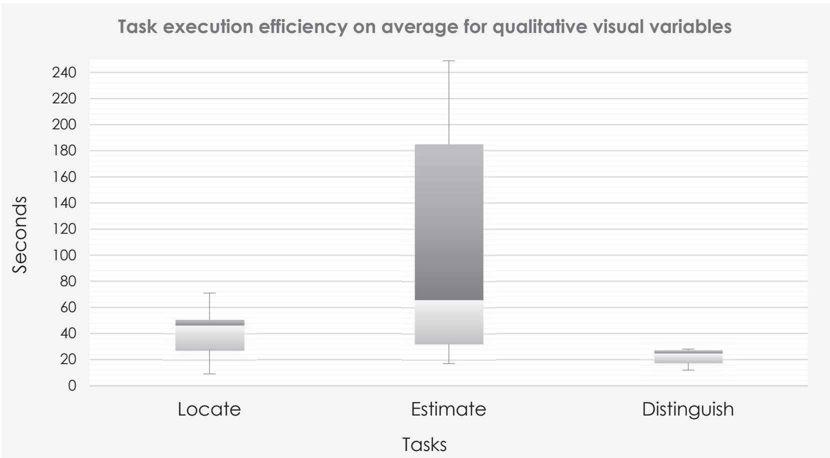



Figure 6.26 Average task efficiency (as derived from Figure 6.25).

During the performance of the task *locate* no comments were made about difficulties to complete it with the displayed design alternatives. For the task *distinguish* TP5 complained that the task could not be performed because the information is not visible. However, the eye movement recordings revealed that this participant could clearly distinguish information in the third view by matching with colours in the legend.

According to the background characteristics derived earlier (section 6.3.3), TP5 had no experience with the STC before. In addition, during the experiment he emphasized difficulties with realizing that the vertical axis of the STC represents the time dimension. Accordingly, it is assumed that the reason of task deviation could be a low self-confidence.

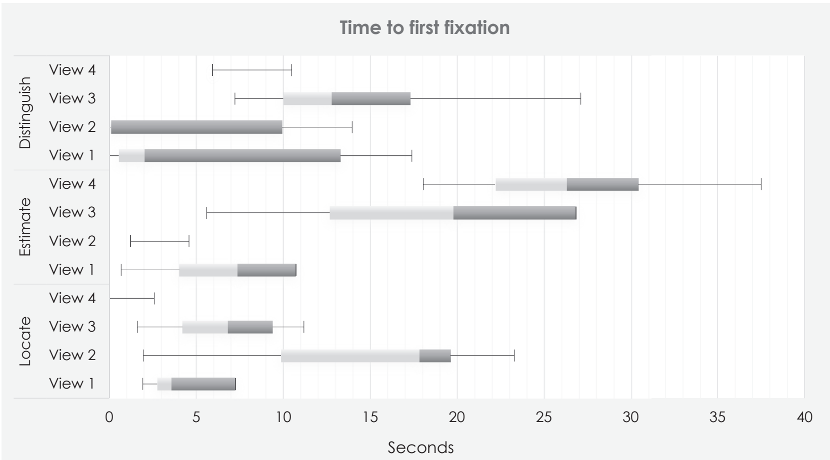



Figure 6.27 Time to first fixation in AOIs during the task execution for qualitative visual variables with simple datasets.

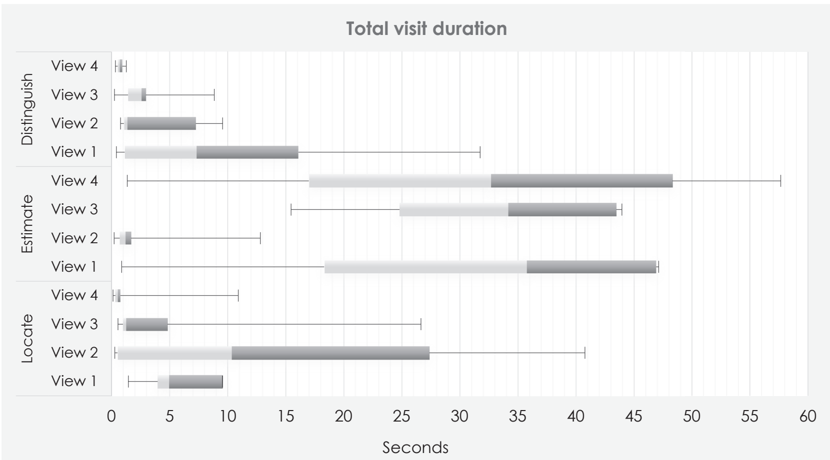



Figure 6.28 Total visit duration in views during the task execution for qualitative visual variables with simple datasets.

Figure 6.27 represents the eye movement metrics on the 'time to first fixation' for the design option as presented in Figure 6.17 during the execution of the three tasks. It reveals that to complete the task *locate,* on average, the participants first looked at the design option located in the upper left view 1 (M=3.58s), lower left view 3 (M=6.8s) and then focus their attention on the right upper view 2 (M=17.18s) comparatively longer.

View 4 located in the lower right corner of the screen was not noticed for the execution of this task. After finishing this task, they were expected to *estimate* the number of trajectories at the point of intersection between trajectories and the city. Similar to the previous task, the results of the analysis reveal a different use of the design alternatives. In particular, test subjects ignore view 2 while focusing on view 1 (M=7.4s), view 3 (M=19.7s) and view 4 (M=26.3s). For the task *distinguish*, the use of the design options was different from the previous two. At the beginning, participants briefly looked at view 2 (M=0.13s) but then their attention moved towards view 1 (M=2.05s), view 4 (5.95s) and view 3 (M=12.79s). The usability metrics on 'time to first fixation' clearly show the time duration of fixations in particular AOIs related to the task execution in each design alternative.

The objective of this experiment was to understand the use of the displayed design alternatives for the given tasks. For this reason, usability metrics on the 'total visit duration' of fixations within views were obtained. Figure 6.28 shows an unequal intensity of use of the design options for the execution of the three tasks.

For the task *locate* the minimum visit duration was recorded for view 4 (M=0.5s) and the maximum for view 2 (M=10.3s), followed by view 1 (M=4.9s) and view 3 (M=1.2s). Examination of the corresponding think aloud recordings shows that TP1, TP3, TP5, and TP14 only expressed critics and were negative about the design option represented in view 2. Figure 6.29 represents a Heat Map that accumulates the absolute fixation duration during the execution of the three tasks. For the task *locate* it shows a high concentration of fixations for the visual variable orientation in view 2. However, the reason of TPs' attention was trying to understand the representation and establish the link between the STC and the legend (OR) view. As a result, test subjects reported difficulties with the visual perception of patterns. The horizontal and vertical orientation of pattern in combination with the depth cue shading appeared to be very disturbing and difficult to differentiate when rotating the STC in a 3D visual environment. In addition, TPs faced difficulties in memorizing the legend. Thus, during the execution of the task *locate*, TPs considered the design alternative displayed in view 2 to be useless for data visualization in the STC. Contrary to view 2, view 1 and 3 were preferred for data exploration. The majority of TPs completed the task *locate* using view 1, but were at the same time observing results in view 3. As for view 4, test subjects did not find it useful for this particular task.

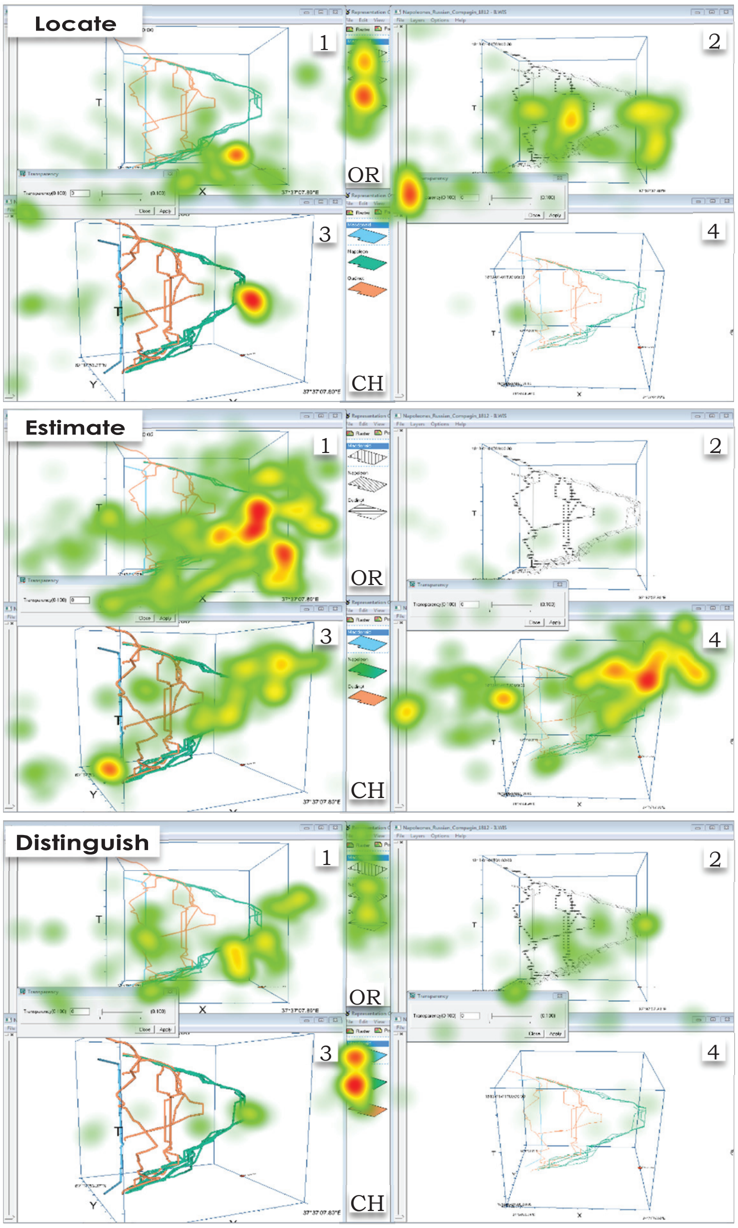



Figure 6.29 Heat Maps representing the use of the design options and legend for the execution of the tasks estimate, locate and distinguish. View 1 – color hue & thick st-path, view 2 – orientation & shading, view 3 – color hue & shading, view 4 – color hue & thin st-path, OR – legend for orientation visual variables, CH – legend for color hue visual variables.

For the task *estimate* the difference between view 1 (M=35.7s), view 3 (M=34.1s) and view 4 (M=32.6s) is insignificant. This can be seen in

Figures 6.28 and 6.29, representing an almost even use of view 1, 4 and 3. The design alternative in view 2 (M=1.1s), was refused because of their earlier critics. During the execution of this task, participants did not express any negative attitude to the design alternatives, though TP1, TP2, TP4, TP3, and TP15 clearly considered data overlap to be an obstacle for estimating the amount of trajectories. Only TP14 expressed a positive opinion in favour of view 4 for the task *estimate*. It represented corpses with thin trajectories that supposed to facilitate visual overlap of tangled trajectories and make it possible to *estimate* amounts without much visual tension. However, the light visibility of thin trajectories in the 3D visual environment of the STC made it difficult to see information without proper zooming in. TP14, TP1 and TP3 preferred the design alternative in view 1 by arguing that colours and trajectories are well visible and that it is easy to see the information. However, the majority of TPs preferred the design option in view 3, even though they admitted that the combination of color hue and shading makes it impossible to *estimate*.

Some clear differences in the use of the design alternatives was revealed for *distinguish* (see Figures 6.28 and 6.29). Participants mainly interacted with the design option in view 1 (M=7.3s) and view 3 (M=2.6s). Despite the time difference, the combination of the eye movement and think aloud protocol revealed the participants' self-confidence with view 3, which provided answers immediately. The reason was that this design alternative allowed one to perceive information well in the 3D visual environment of the STC. As for the options in view 2 (M=1.3s) and view 4 (M=0.7s), the participants disapproved the designs because of the poor visibility of the trajectories.

Another interesting aspect was the option to use transparency in the introduced design alternatives. As the task sessions proved, the transparency option was not found very useful, but was not rejected either. Participants discovered that this option did not work in the legend view when using it for representation.

In order to understand the participants' preferences for the design options, they were asked to rank them on a scale ranging from 1 to 10 (see Figure 6.30). Participants made a selection regarding to the most and less useful design options for answering the question given during the first task execution session (*How many corps arrived in Moscow and who was the leader?*). The results proved that the most preferred option was offered by view 3 while view 2 was less preferred.

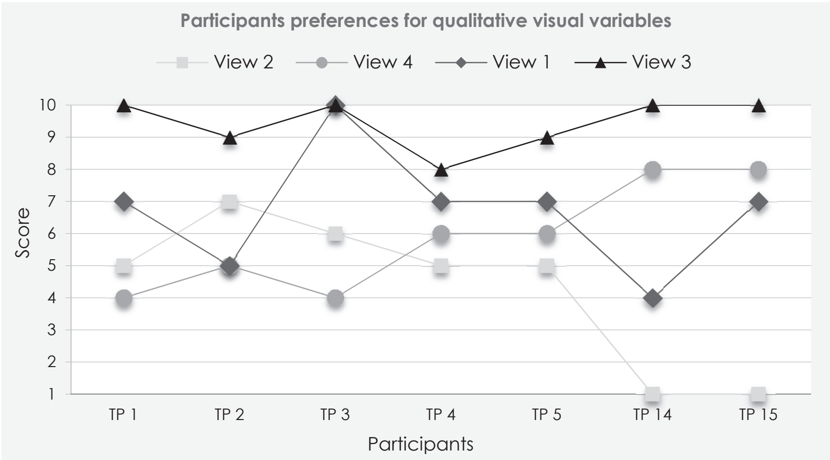



Figure 6.30 Participants' preferences based on the rank results for the views with the qualitative visual variables. View 1 – color hue & thick st-path, view 2 – orientation & shading, view 3 – color hue with shading, view 4 – color hue & thin st-path.

**User interviews**

During the user interviews, the results of the task session were summarized. Participants clearly emphasized that they did not have difficulties to distinguish features with the color hue visual variables, but patterns appeared to be a problem. Visual clutter was considered to only influence the task *estimate*. However, the design alternative in view 3 and view 1 were considered as easy options to answer the given question. These options afforded a clear match with the legend and a precise location of movements. In the end, the most preferred option was view 3.

**Analysis of task execution with quantitative visual variables**

The outcomes of the second task session show the effectiveness of the tasks *locate* and *estimate* with the quantitative visual variables (see Figure 6.31). A significant difference in task efficiency can be observed. Figure 6.32 shows that for executing the task *locate* participants spent on average M=40s, while for the task *estimate* it was M=67s. The TPs' overall eye movement behaviour for both tasks shows that, in the beginning of the task, participants were able to complete both tasks visually. However, observation of the participants' exploratory behaviour shows a constant comparison of information between the different views and this influenced the efficiency metrics.


Figure 6.31 Time spent by participants to accomplish the tasks using quantitative visual variables. The colors in graph represent the different tasks. If the task is done, it is considered effective.

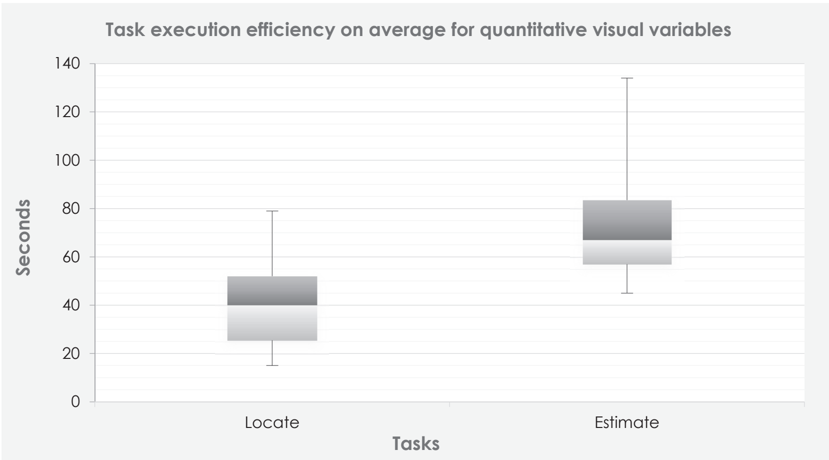



Figure 6.32 Average task efficiency (as derived from Figure 6.31).

In order to *locate* the place where most corps are together, test subjects had different preferences for design options. For instance, TP1 stated that he prefers the design option in view 6 over others because of its clarity. While TP2, TP3, TP4, TP5 and TP15 indicated that to answer the given question, the design alternative in view 7 was the best option. In this regard, TP14 emphasized that from a purely scientific perspective the option in view 8 is the best, but for the given question is was easier to use view 7. Similar to the task *locate*, for the task *estimate* view 7 was preferred. However, eye movement behaviours revealed a continuous movement of visual attention to other views too. Despite this, at this stage of the experiment TPs preferences were clear. Careful observation of the design alternatives helped to define why some views were ignored or preferred.

Figure 6.33 shows the eye movement metrics on 'time to first fixation' for each task for the different design options. For the execution of the task *locate,* on average TPs first looked at the option displayed in the right upper view 6 (M=3.08s) followed by the left lower view 7 (M=3.22s), left upper view 5 (M=5.44s) and right lower view 8 (M=10.76s). That supposedly indicates a combined use of the design alternatives. The task *estimate* shows a different use of the views. Here, participants first looked at view 5 (M=1.32s) and view 7 (M=2.16s), and, when necessary information was to be derived, view 6 (M=5.35s) and view 8 (M=12.36s) were revisited. The time to first fixation for both tasks is significantly different. Besides, Figure 6.33 shows that the time to first fixation for the task *estimate* in view 5 was relatively short, which could mean that not all participants have looked at this view.

The usability metrics on 'total visit duration' in Figure 6.34 reveal a non-uniform use of the design options for the two tasks. The task *locate* was performed in a relatively short time. The minimum visit duration was found for view 6 (M=1.52s) followed by view 8 (M=2.6s) and view 5 (M=4.83s), while in view 7 visit duration was on average M=5.91s. According to the analysis of the screen interactions and the think aloud protocols, participants considered view 5 useless for exploration purposes. Similar to view 4, the barely visible thin trajectories in the 3D visual environment of the STC represented by color value made the representation of view 5 illegible. A better design option was view 6. It allowed the participants to link the design and the legend and compare color gradations, but it still was not considered to be a good visualization. Differing from view 5 and view 6, view 8 was preferred over all other alternatives, followed by the design option of view 7. The Heat Map in Figure 6.35 represents absolute fixation durations of TPs for the tasks *locate* and *estimate* for each view.

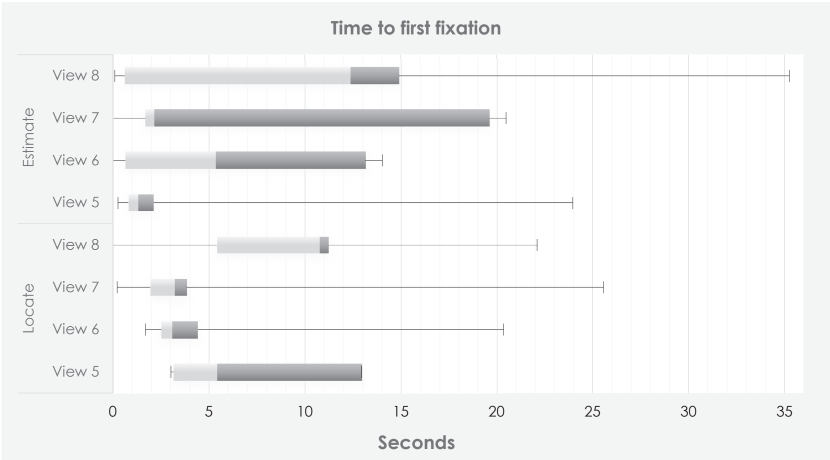



Figure 6.33 Time to first fixation in AOI during task execution for quantitative visual variables with simple datasets.

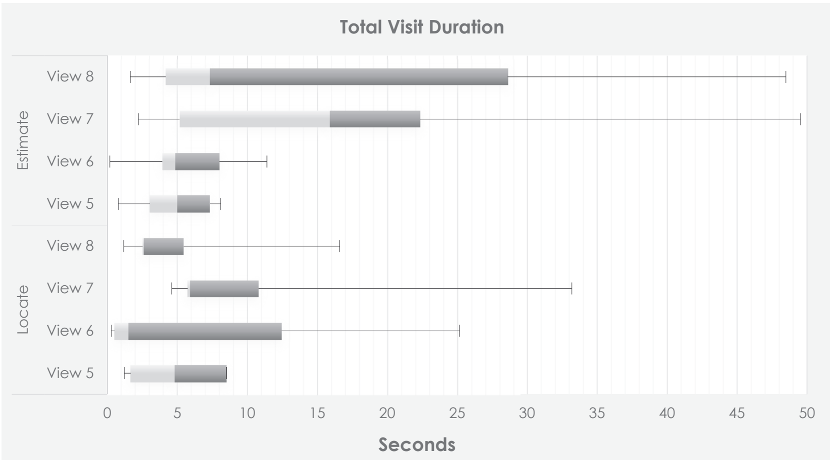



Figure 6.34 Total visit duration in views during the task execution for quantitative visual variables with simple datasets.

The experiences gathered during the previous session allowed TPs to make a quick link between the design alternatives and the task. This was confirmed by the confident opinions provided by TPs. The maximum visit duration for the task *estimate* was found for view 7 (M=15.89s), while the minimum was for view 6 (M=4.86s), followed by view 5 (M=5.0s) and view 8 (M=7.33s).

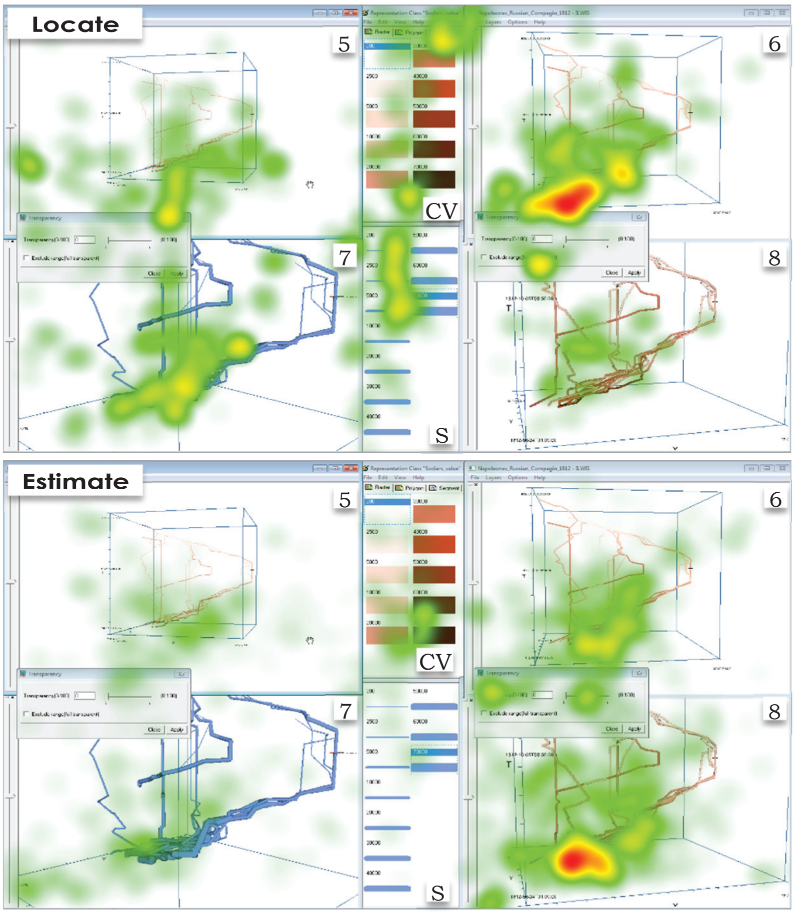



Figure 6.35 Heat Maps representing the use of the design options and legends by test subjects for the tasks locate and estimate. View 5 – color value & thin st-path, view 6 – color value & thick st-path, view 7 – size & shading, view 8 – color value & shading. CV – legend for color value, S – legend for size visual variables.

The observations of the test session recordings and Heat Maps in Figure 6.35 show that the legends for view 5, 6 and 8 were used more intensively for information identification than for view 7. This could mean that the design option in view 7 allowed users to estimate amounts in trajectories at one glance without much use of the legend. Despite this, view 8 was preferred over view 7. The reason was the clear link between view 5, 6 and 8 with their legend, while the smooth variation of the trajectories in view 7 was found hard to match with the values in its legend. Thus, for the design options in view 5, 6 and 8 no comments were made, but view 7 was the focus of the discussion. In particular, the legend of the visual variable size did not change while zooming-in to get insight into the data for details. In addition, participants complained that while using size the visual overlap increased, thus blocking the visibility of other trajectories.

From this perspective, the visual variable size was not considered to be very useful. Despite these arguments, everyone admitted that, as overview, view 7 was still the best to understand general information without legend for the task *estimate*.

Similar to the session with the qualitative visual variables, the transparency option was used actively to improve the visibility of trajectories at cluttered locations to see whether hidden trajectories are different in volume or color. However, overall, transparency was found useless, because in view 5, 6 and 8 the light gradation of color value became barely detectable, while for size it was difficult to detect tangled trajectories with a similar color.

Similar to the previous task session, TPs were asked to rank each design alternative on a scale 1 to 10 (see Figure 6.36). They made decisions regarding to the most and less useful design options in relation to the question asked during the task session. The results show that the most preferred design option was view 8 while the least preferred was view 5.

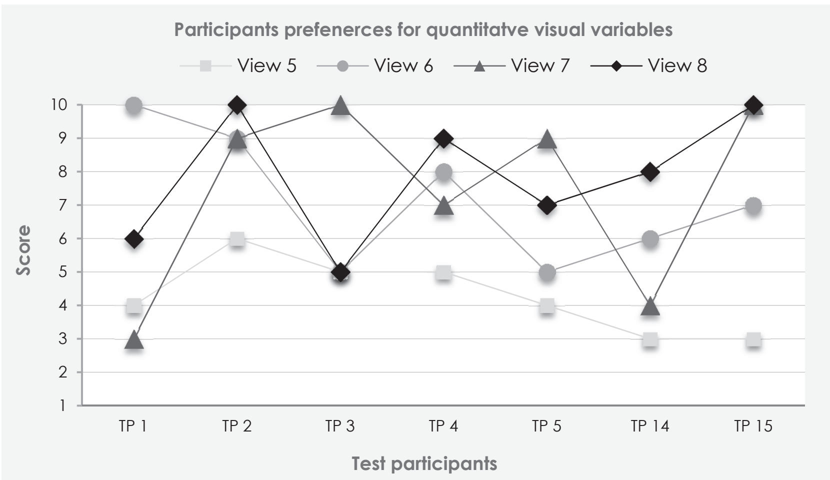



Figure 6.36 Participants' preferences based on the rank results for the views with the quantitative visual variables. View 5 – color value & thin st-path, view 6 – color value & thick st-path, view 7 – size & shading, view 8 – color value & shading.

**User interviews**

To differentiate between features with quantitative visual variables appeared to be not too difficult for the test subjects. Several participants' emphasized difficulties with the visual variable size, while others preferred size over color value. The TPs who preferred size reasoned that its ability to represent movements more clearly is better than that of color value. The others, who preferred color value, indicated that a moderately thin size of the trajectories would reduce visual clutter compare to the size visual variable, and give flexibility to distinguish between trajectories. Despite these arguments, participants emphasized that visual clutter did not influence the task exploration process.

### 6.4.2 Complex dataset – pedestrian movements in city center of Delft

The map use tasks *locate, distinguish* and *compare* were used for the evaluation of the design options for the complex dataset (see Figure 6.19). For the first evaluation session, participants were expected to perform the analytical tasks *locate* and *distinguish*, and for the second evaluation session *compare* and *locate*. While performing these tasks they could interact via zoom in/out, pan and rotate. The results of the analysis show that, in the beginning of both test sessions, participants started by observing the design alternatives and legend views to understand the differences. This process took a little time (M=15s) but was important for the task completion process. The analysis of the results revealed a difference in usability metrics between the qualitative and quantitative visual variables.

#### Analysis of task execution with qualitative visual variables

Test results reveal a slight difference in performance of the tasks *locate* and *distinguish* with the complex dataset compared to the simple dataset. Figure 6.37 represents the effectiveness and efficiency results for each TP, while Figure 6.38 shows the average task completion efficiency. Seven test subjects out of eight were able to perform the map use tasks with the qualitative visual variables. Similar results were found with simple datasets, where only TP5 could not perform task *distinguish*. For the task *distinguish* (M=42s) participants took significantly longer than for the task *locate* (M=19.5s). For the small dataset distinguish (M=24.5s) was also performed faster than task locate (46s). The main reason is that the majority of TPs start the interaction with the design alternative located in upper left hand view 1. That view appeared to be incomprehensible and the task was continued with the other three views. Based on this experience, for the execution of the task *locate,* participants ignored view 1, and immediately focused their attention on the other views. TP8 was not able to complete any tasks. The eye recordings show his quick overview of the display at the beginning of the test session, but the think aloud protocol revealed his apparent confusion. It was also obvious that TP8 saw the different colors and could distinguish male and female trajectories, but he could not complete the tasks, although he commented that there is ‘not too much difference between days.’

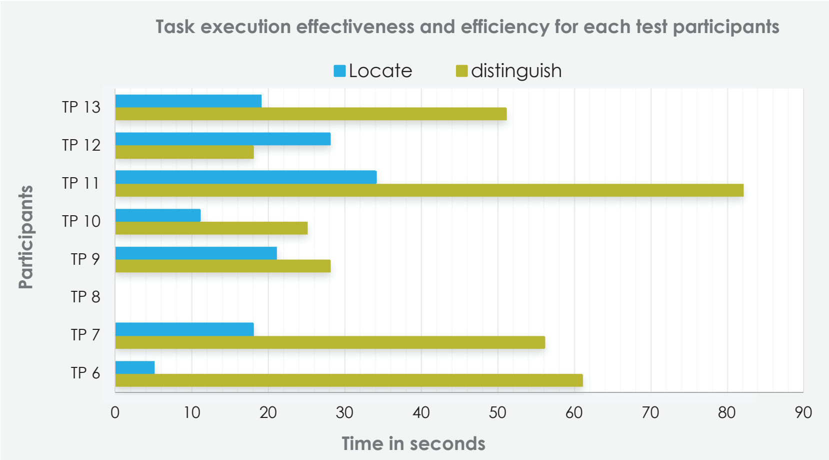



Figure 6.37 Time spent by participants to accomplish the tasks using qualitative visual variables. The colors in graph represent the different tasks. If the task is done, it is considered effective.

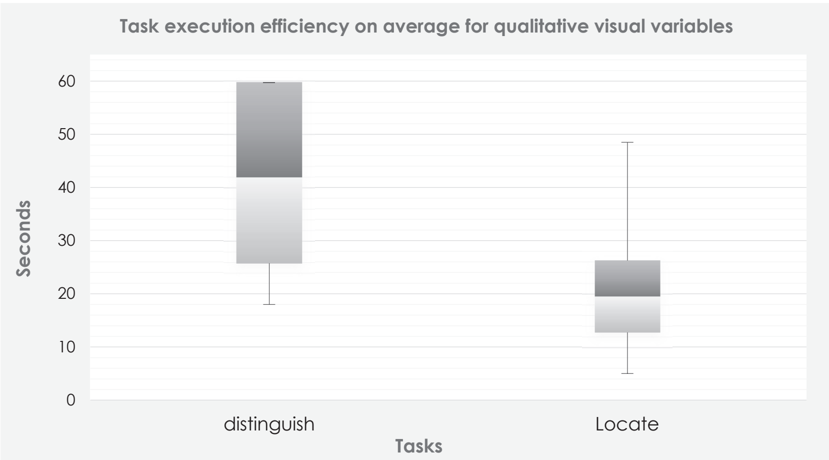



Figure 6.38 Average task efficiency (as derived from Figure 6.37).

The other usability metrics derived from the eye recordings were related to the 'time to first fixation' in AOIs during the execution of the two tasks. Figure 6.39 shows that the average time of first fixation in the evaluated design alternatives took longest for *distinguish*. According to the time metrics, for executing the task *distinguish* participants first looked at view 1 located in the upper left hand corner of the screen for an average M=2.02s. In this particular case, these metrics indicate a participants' short visit because of its ineffectiveness. The other three views were more effective to *distinguish* features in the 3D visual environment of the STC. Thus, for task completion TPs mainly focused attention on view 3 (M=4.38s) located at the lower left hand side of the screen, then on the upper right hand view 2 (M=6.51s) and finally on the lower right hand view 4 (M=10.21s). Here, similar to the simple data set TPs looked for a very short time at the visual variable orientation meaning this option was considered unsuitable for task performance. For the task *locate* a different order of use of the design alternatives was found. After ignoring view 1 (M=0s), TPs shortly looked at view 2 (M=3.59s), followed by view 3 (M=9.63s) and view 4 (M=10.06s).

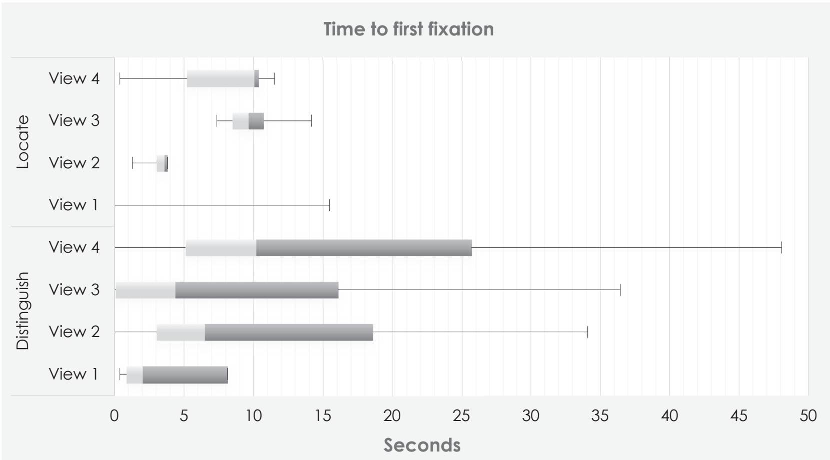



Figure 6.39  Time to first fixation in AOI for task execution for qualitative visual variables with complex datasets.

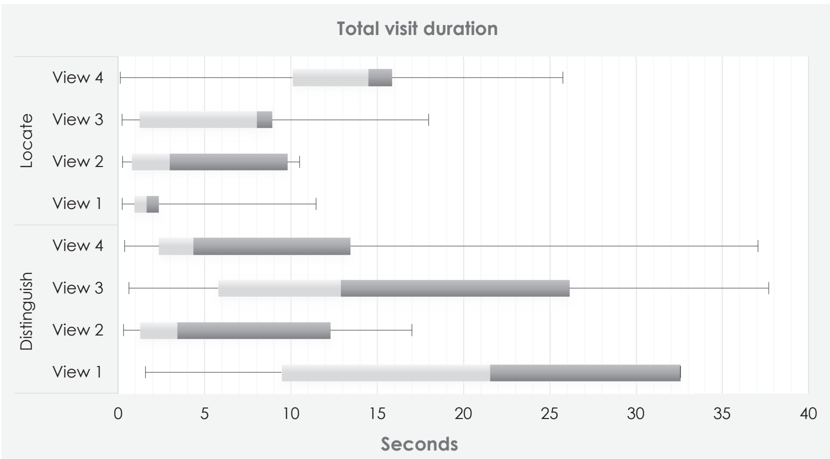



Figure 6.40  Total visit duration in views design alternatives for qualitative visual variables for complex datasets.

The usability metrics of the ‘total visit duration’ for the two tasks are shown in Figure 6.40. The shortest visit duration for the task *distinguish* was recorded in view 2 (M=3.43s) and the longest in view 1 (M=21.54s).

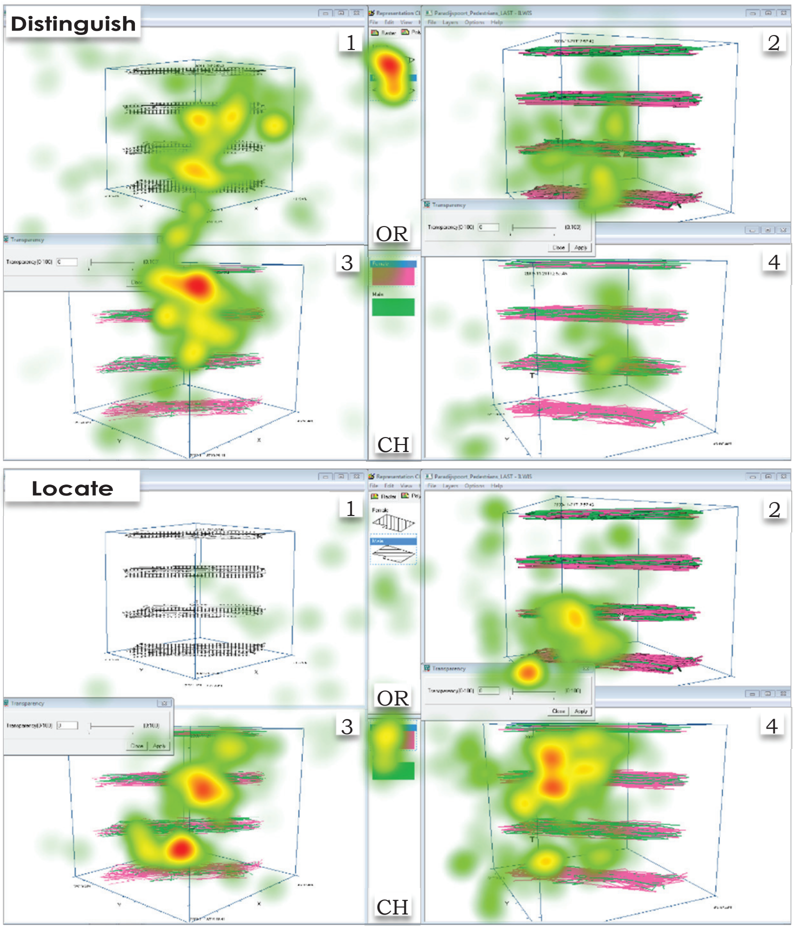



Figure 6.41 Heat Maps representing the use of design options and the legend for the execution of the tasks distinguish and locate. View 1 – orientation & shading, view 2 – color hue & shading, view 3 – color value & thin st-path, view 4 – color value & thick st-path, OR – legend for orientation visual variable, CH – legend for color hue.

View 4 took on average M=4.35s and view 3 M=12.88s. According to the analysis of the think allowed data, the reason of the long interaction with view 1 was the user's desire to understand the representation of the visual variable orientation to be able to distinguish between two different types of data. Despite their efforts to match the representation with the legend contents, TP6, TP7, TP11, and TP13 could not extract any information. They also faced difficulties to remember the legend content without looking at it when searching information in the STC. The reason was the orientation of vertical and horizontal lines that increased the disorder between occluded trajectories. Therefore, participants were constantly staring at the legend (OR) view during the execution of the task *distinguish* as can be seen in the Heat Map shown in Figure 6.41.

Accordingly, the use of this design option for the complex dataset resulted in negative opinions, similar to the results for the simple dataset. Besides, as the participants' comments show, the design alternatives in view 3 and 4 could not offer a clear idea of movement directions. Moreover, during the test session it was indicated that the tangled trajectories influenced human vision negatively, especially with view 2. However, for view 3 and view 4 this was seen less problematic. Noteworthy is the fact that the TPs could not get a clear notion of directions or see any kind of trend from view 3, while view 2 and view 4 did support good visibility of trajectories. Thus, the think aloud protocols and screen recordings revealed that the majority of test subjects preferred the design options in view 2 and view 4, while a minority gave preference to view 3.

For the task *locate*, the participants' total visit duration with the design alternatives was relatively short (see Figure 6.40). The results reveal the shortest visit duration for view 1 (M=1.64s), while the longest visit duration was found for view 4 (M=14.49s) followed by view 3 (M=8.04s) and view 2 (M=2.96s). The different visit durations for the different views were explained after analysing the think aloud protocols. For instance, to find the best option for her task completion, TP6 had deployed view 2, 3 and 4 in the same position and compared them. As a result, she appointed view 2 as the best design alternative to perform the task *locate*. The reason for that choice could be the influence of her experience with 3D modeling in urban planning. However, other participants also shared the same opinion. Different from TP6, TP10 and TP12 made their selection of the preferred design alternative during the practice session and performed the task in view 2. TP10 emphasized that, due to the thin trajectories, "view 4 would actually show the data clearly," but preferred view 2 as an easy solution to see movement directions despite the obvious overlapping problem. Similarly, TP12 emphasized the advantage of the shading depth cue for the visual perception in the 3D visual environment. Besides, she made a judgment in favour of view 4 over view 3 due to the well visible thick trajectories. However, view 2 was her preference. TP7 somehow agreed with TP10 and TP12 when mentioning that view 2 gives a clear idea of directions in the dataset. However, he pointed to the visual over-clutter influencing vision and the exploration process. Alike TP12, TP7 also indicated view 4 as the best option to see the trends because of the different colours. Similar to TP7, TP9 also performed the task *locate* mainly in view 4 by arguing that it shows an obvious increase and decrease of different categories for different days. However, he expressed the opinion that the design shown in view 4 is too thin for trajectories, while in view 2 it is too thick. Having something in between with the shading depth cue could be the best option for data investigation. TP13 considered view 4 as a user-unfriendly design. In particular, he perceived the displayed option as a flat 2D representation not allowing to distinguish the upper and lower layers without rotation of the STC. Different from view 4, view 3 could provide the same information as view

2 despite its thin trajectories. Thus, because of the weak visibility problem, he considered view 3 as acceptable but appreciated view 2 most. Contrary to the other test subjects, TP11 rejected view 2 due to the volume trajectories and focused on view 3 and 4. After comparing them, he concluded that both options represent the differences nicely, but view 3 looked less complex and is therefore the best alternative.

The use of the transparency option did not improve the visibility of representations for the majority of TPs, but some comments were made. For instance, transparency applied in view 3 was considered to be effective and efficient because of the good visibility to trace colours that allows users to recognize different patterns. They mention that the selected colours influenced effective use of the transparency option. In particular, the chosen green color was less transparent than pink and this make easier to differentiate between the two patterns. The use of transparency for view 1 was ineffective. The different orientation of the lines resulted in a complicated view. With view 2, tracking single trajectories was easier than before, but not completely acceptable. As for view 4, TPs could not see any big improvements with the help of the transparency option.

At the end of the task session, TPs ranked the design options based on the given tasks. The results of their preferences are shown in Figure 6.42. It shows that the majority of TPs preferred the design option in view 2, followed by view 3 and view 4. As for view 1, it was rejected.

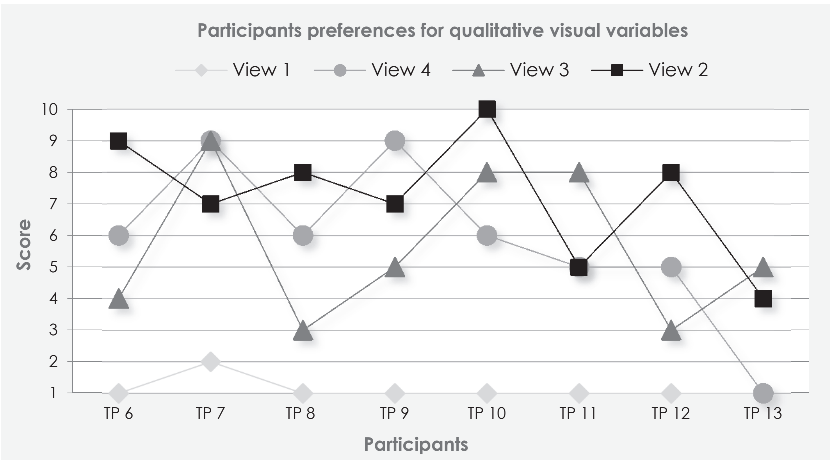



Figure 6.42 Participants' preferences based on the rank results for the views with the qualitative visual variables. View 1 – arrangement & shading, view 2 – color hue & shading, view 3 – color hue & thin st-path, view 4 – color hue & thick st-path.

**User interviews**

The participants said they could differentiate between features during the task execution session, but the overlapping trajectories were seen as the major issue for the information extraction. This problem was specifically mentioned in relation to the visual variable orientation in view 1. As for the design option of color hue (view 2, 3 and 4), the test subjects gave a different preference compared to what could be derived from the think aloud data: their choice was between view 2 and 3. The participants also offered suggestions related to the analytical capabilities of the visual environment. For instance, TP7 desired a possibility 'to select one of the lines and make the others a little bit transparent in a way to still see them.' These aspects will be evaluated in the last phase of this research, as reported in chapter 7.

**Analysis of the task execution with quantitative visual variables**

Similar to the first test session, the second test session also involved two map use tasks. The task execution of *locate* and *compare* with the design alternatives developed for the quantitative visual variables took longer than expected. Figure 6.43 shows the results of task effectiveness and efficiency, while Figure 6.44 represents the average task efficiency. According to Figure 6.43, the task *compare* was completed more effectively and efficiently than the task *locate* because more persons where able to complete it. The task *compare* could be performed by seven TPs out of eight, whereas the task *locate* was completed by only five participants. The task efficiency graph in Figure 6.44 shows that the average efficiency time metrics for the task *compare* (M=51s) were only a little shorter than for the task *locate* (M=55s). Similar to the previous session, again TP8 was not able to complete the tasks (see Figure 6.43).


Figure 6.43 Time spent by participants to accomplish the tasks using quantitative visual variables. The colors in graph represent the different tasks. If the task is done, it is considered effective.

As eye recordings reveal, he could differentiate between different colours in view 3, but did not look at the legend to understand the content of the displayed information. Perhaps the given question was misunderstood. The majority (5) of participants could *compare* the different compositions of the information over four days by *locating* the fourth day as different. However, TP6 and TP13 could not complete the task, although they did understand the question.

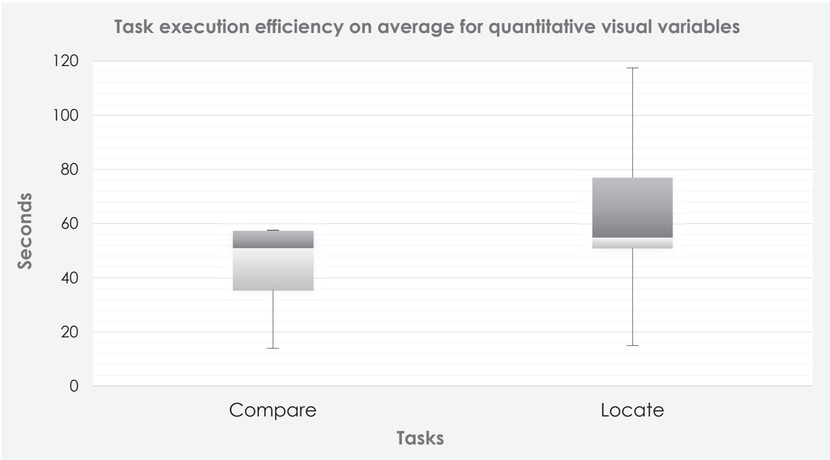



Figure 6.44 Task efficiency graph (as derived from Figure 6.43).

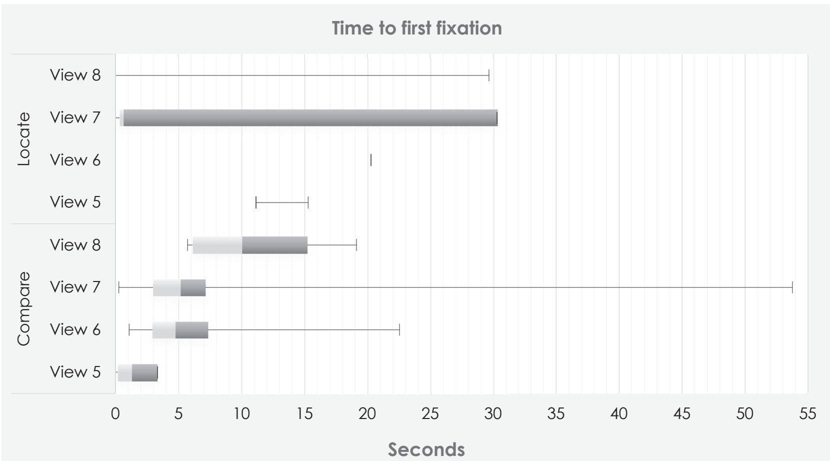



Figure 6.45 Time to first fixation in AOI during task execution for quantitative visual variables with complex datasets.

Figure 6.45 shows the eye movement metrics on 'time to first fixation' for the evaluated design options during the task execution. It shows that, while performing the task *compare*, the TP's first looked at the design alternative located in the upper left hand view 5 (M=1.28s) followed by upper right side view 6 (M=4.75s), lower left hand side view 7 (M=5.14s) and after that they focused their attention to view 8, located at the lower right hand side (M=10.04s). The majority used view 5 at the beginning of the test session. However, they faced difficulties to differentiate between classes and rejected this design alternative. The screen recordings show that the participants constantly interacted with the different design alternatives, and the eye recordings reveal constant comparison of the results derived from other views. Contrary to the task *compare*, the results of the task *locate* reveal purposeful use of design alternatives by the test subjects. At the beginning, the test subjects' attention was given to view 7 (M=0.64s), followed by view 5 (M=11.16s) and view 6 (M=20.28s). View 8 (M=0s) was ignored for the execution of the task *locate*.

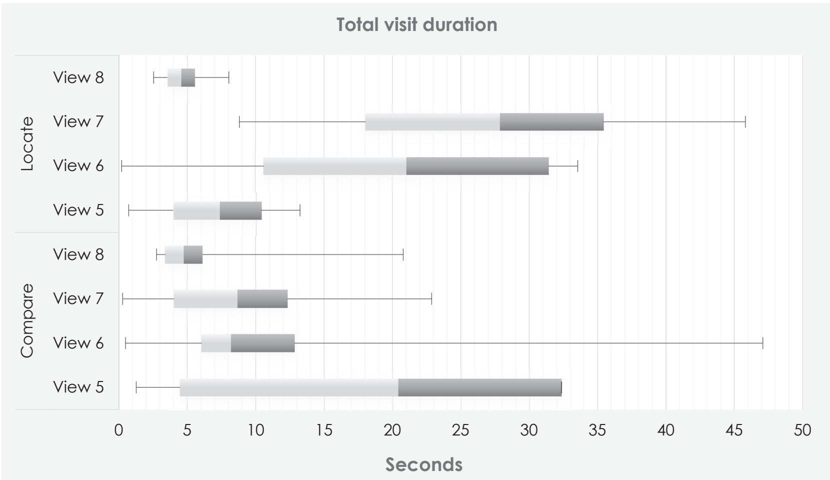



Figure 6.46 Total visit duration in views during task execution for quantitative visual variables with complex datasets.

The other significant metric derived from Tobii Studio is related to the 'total visit duration' of fixations in views. The results are represented in Figure 6.46. According to this graph, on average, the minimum visit duration for the task *compare* was recorded for view 8 (M=4.76s) and the maximum for view 5 (M=20.43s) followed by view 7 (M=8.67s) and view 6 (M=8.18s). Despite the long visit duration for view 5, the examination of the think aloud protocols uncovered a negative attitude of the participants towards views 5 and 6. They indicated difficulties to identify and read information. The color gradation of different age groups was difficult to differentiate among overlapping trajectories. However, view 6 still allowed a better distinction between the trajectories due to the depth cues. Whereas the majority of TPs appreciated view 7 for the execution of this task over view 8. The Heat Maps in Figure 6.47 show the use of the design options and their corresponding legends during task execution process.

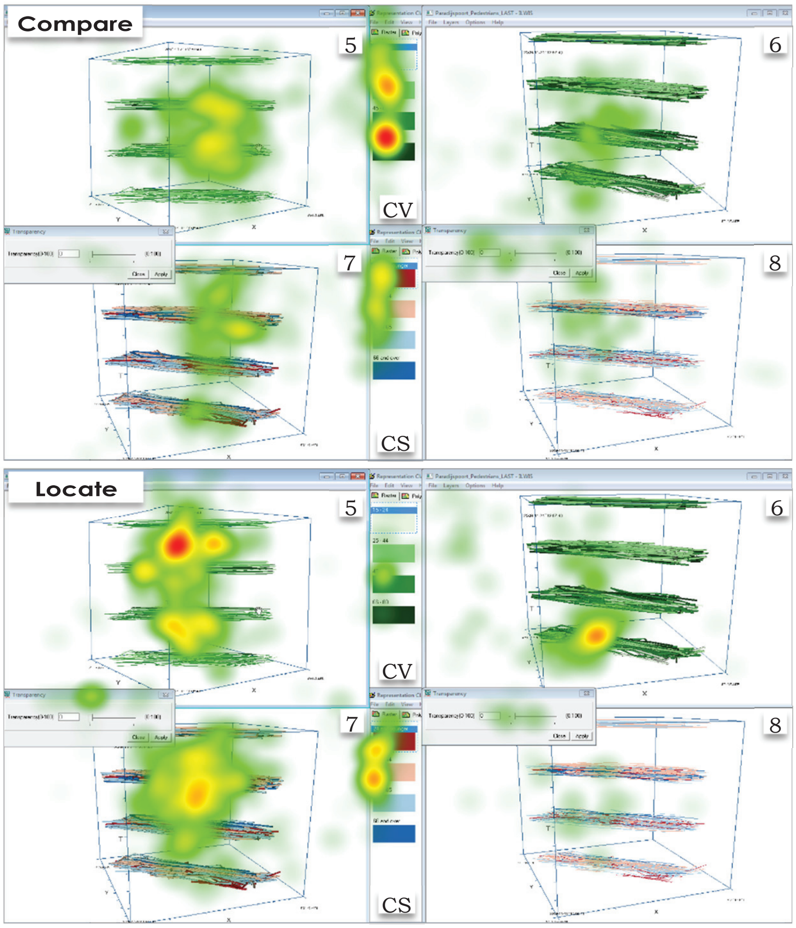



Figure 6.47 Heat Maps representing the use of the design options and the legend for the execution of the tasks distinguish and locate with the complex dataset. View 5 – color value & thin st-path, view 6 – color value & shading, view 7 – color saturation & shading, view 8 – color saturation & thin st-path, CV – legend for color value, CS – legend for color saturation (scheme).

For the execution of the task *locate,* the maximum visit durations of the test subjects were recorded for view 7 (M=27.85s) and the minimum for view 8 (M=4.55s), followed by view 5 (M=7.36s) and view 6 (M=21.0s). This result clearly indicates the participants' preferences regarding the design options. Similar to the task *compare*, for the task *locate* bad visibility issues in view 5 were highlighted, and this design was disregarded for use. Surprisingly, only TP7 mentioned that view 5 could give a quick idea on the different age groups in an efficient way. Besides, TP6 and TP7 considered view 6 to be comparatively better. According to them, it allows to differentiate color gradation easier because of the depth cues. TP9, TP10, TP11 and TP13 considered color gradation in view 5 and view 6 more or less similar and hard to distinguish. Therefore, they did not approve them for the visualization of complex data. TP12 ignored view 5 and view 6 during the exploration by arguing that 'they bring hard visibility problem for the eyes.' Differing from view 5 and view 6, view 7 and view 8 were considered to be the most suitable options for the visualization of the complex dataset. TP7 and TP11 considered view 7 just like view 8, although view 8 comparatively better allowed one to see the color differences for the trajectories. It allowed to differentiate age groups and to understand where do people move. Similar to view 8, view 7 also allowed one to recognize trajectories and follow directions. However, it was hard to differentiate between them due to the limited space occupied by the shading depth cue. Differing from TP7, TP9 preferred view 8 because of the distinct colours to detect movement, but with a clear emphasis on the impact of the depth cue on the representation. Similar to the task *compare*, for the task *locate* he again preferred a design option just in between view 7 and 8. TP10, TP12 and TP13 stated that they enjoyed the neat look of view 7, although it brings 'clutters when things are obscuring each other.'

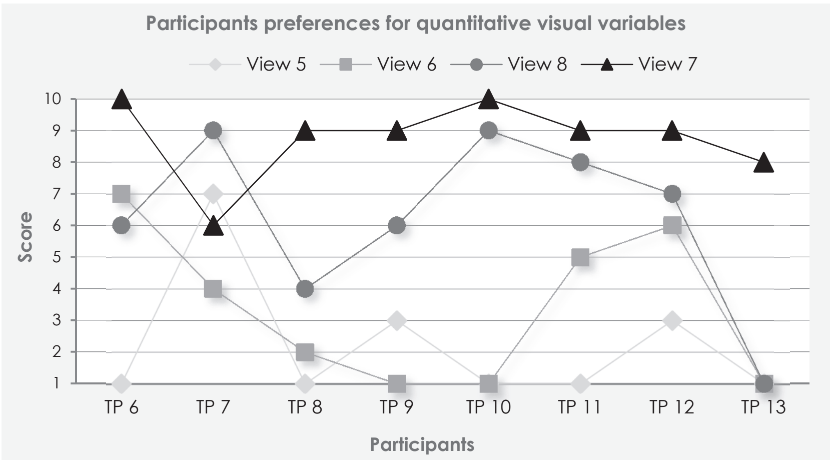



Figure 6.48 Participants' preferences based on the rank results for the views with the qualitative visual variables. View 5 – color value & thin st-path, view 6 – color value & shading, view 7 – color saturation & shading, view 8 – color saturation & thin st-path.

The transparency option was found to be effective for view 7 and 8 to compensate for the visual overlap and to extract information through distinctive color contrast. It allows to gain an overall idea of movement patterns. With view 7, transparency helped to overcome the overlap problem and to see areas of interest mainly with the applied depth cue options. However, TPs did not see big improvements using transparency. For views 5 and 6 it revealed movement directions, but was ineffective to detect change in value gradation in order to read the information.

After completing the tasks, the TPs were asked to rate the usability of the introduced design options considering the performed tasks. As Figure 6.48 shows, the most preferred option was view 7 and the least preferred one view 5.

#### User Interviews

The majority of participants had no difficulties to differentiate between features within the complex dataset, although visual overlap was named as an impeding factor on task execution. The design options in view 7 and 8 were approved for the visualization of quantitative information in the complex dataset. The majority preferred the use of depth cues due to the 3D perception, while a minority complained on the inaccurate overlap of trajectories, blocking information visibility. However, all considered them as an effective alternative to distinguish trajectories on the screen. View 5 and 6 were disapproved for the visualization of complex datasets. These options required consistent observation of differences between categories that were hard to see in overlapping trajectories. In addition to the above comments, participants suggested the effective use of transparency to improve the visibility of information in views 7 and 8. In particular, they suggested to make everything else transparent when particular samples are selected.

### 6.4.3 Complex annotation – travel log data of Estonia

The task execution session for this experiment consisted of three map use tasks: the test subjects were expected to perform the *locate, estimate* and *identify* while they could zoom in/out, pan and rotate the images. Similar to the experiments described above, the starting point for the execution was a visual investigation of the design alternatives and their respective legend views. This approach helped the test subjects to understand the differences between the design options and to define preferences for further exploration.

#### Analysis of the task execution with qualitative visual variables

The analyses of the results shows no differences in task performance effectiveness, but it revealed a big difference in efficiency metrics. The graph in Figure 6.49 shows the effectiveness and efficiency of the completed tasks for each TP. Figure 6.50 represents the average task performance efficiency.

According to the efficiency graph in Figure 6.50, participants could perform the tasks *locate* (M=18s) and *estimate* (M=20s) faster than *identify* (M=41.5s). A detailed analysis of the recordings also shows that the majority of TPs started the task execution by identifying the information in the legend views. The reason was an overwhelming amount of annotations occupying a comparatively small space in the representation. Therefore, to reduce the problems during the search for information in complex annotations, TPs first identified information in the legend view. Not all annotations shown in the legend view were always visible in the STC view.


Figure 6.49 Time spent by participants to accomplish the tasks using qualitative visual variables. The colors in graph represent the different tasks. If the task is done, it is considered effective. For TP16 technical failure in recordings was found.

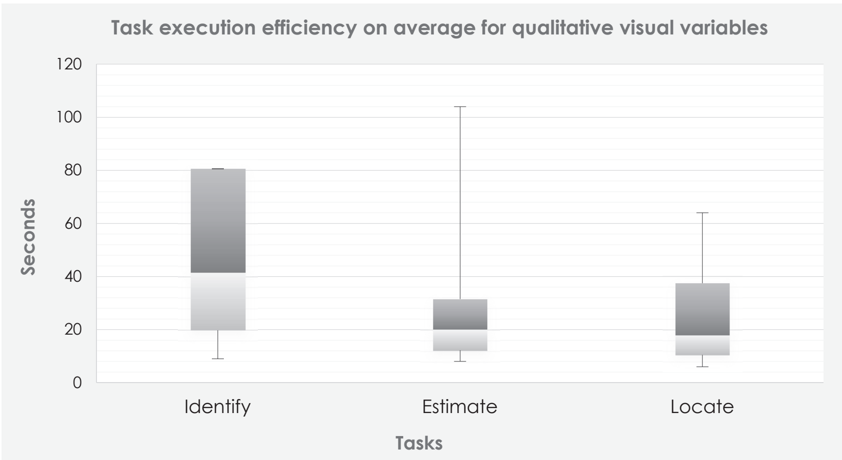



Figure 6.50 Task efficiency graph (as derived from Figure 6.49).

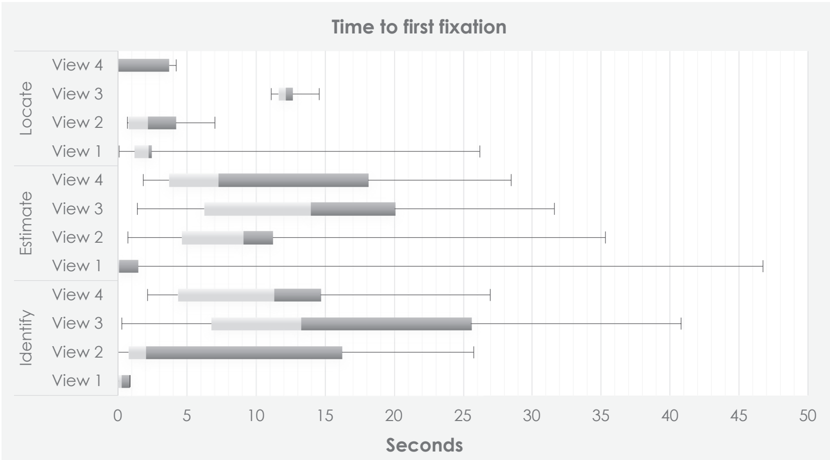



Figure 6.51 Time to first fixation in AOI during task execution for qualitative visual variables with complex annotations.

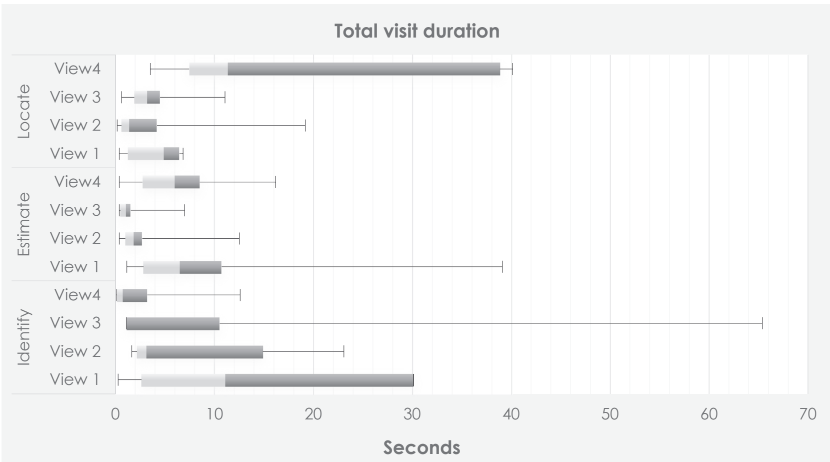



Figure 6.52 Total visit duration in views during the task execution for qualitative visual variables with complex annotations.

The eye movement metrics on 'time to first fixation' during the execution of the three tasks are shown in Figure 6.51. These time metrics clearly show in what order participants looked at the design alternatives during the completion of the map use tasks. For the execution of the task *identify*, on average, the majority of test subjects first looked at the upper right hand view 1 (M=0.25s), followed by the upper left hand view 2 (M=2.02s) and the lower right hand view 4 (M=11.31s). Only later, their attention was directed in lower left hand view 3 (M=13.26s) which was different in design from the other three views. According to the results of the think aloud protocols, participants criticized and expressed a negative opinion on view 3, while view 1 was considered to be unsuitable for visualization. After identifying different attribute information, TPs were expected to *estimate* the amount of annotation types. The metrics on 'time to first fixation' on average reveal a similar order of use of the views as for the task *identify*. Thus, TPs first looked at view 1 (M=0.07s), then at view 2 (M=9.06s), followed by view 4 (M=7.26s) and view 3 (13.96s).

The time metrics for the task *locate* were shorter compared to those of the tasks *identify* and *estimate*. This indicates that, after performing two tasks, TPs get familiar with the visual environment and accomplish the third task in a relatively short time. The test participants first gave a short attention to view 1 (M=2.21s) followed by view 2 (2.18s) and view 3 (M=12.15s). As for view 4 (M=0s), TPs did not fixate at the selected AOI in the stimulus during the execution of the task *locate*.

The usability metrics on the average 'total visit duration' are represented in Figure 6.52. It reveals uneven eye fixations in the views for each design alternative. These uneven fixations of eye movements during task execution are also shown in the Heat Maps (see Figure 6.53). For the task *identify,* the maximum visit duration was recorded in view 1 (M=11.07s), while the minimum was detected for view 4 (M=0.77s), followed by view 3 (M=1.13s) and view 2 (M=3.24s). The think aloud protocols revealed that some TPs considered view 1 and 2 as similar but give preference to view 2. A minority of TPs first identified the annotations in the legend, and then started to search for symbols in the overcluttered places in view 2, 1 and 3. After an intensive search, they realized that in the representation annotations on drawings are simply missing. Besides, they made remarks on colours, e.g. that red and purple could cover orange, which makes it difficult to identify visually without intensive observation. Similar comments were made for view 3 when emphasizing the poor visibility of annotation types among clustered symbols without a proper zoom in. The analysis of the eye and screen recordings for views 1 and 2 revealed that participants focused their visual attention on cluttered annotations where red symbols were dominant. This obviously indicates visibility issues when it comes to detect other types of annotations. In general, for the task *identify*, participants rejected view 1 and 3 due to the bad visibility, while view 2 was marked comparatively better due to the dual representation of annotations.

For the task *estimate* participants could indicate the represented amount of information. For this purpose, the minimum visit duration was recorded for view 3 (M=1.08s), followed by view 2 (M=1.85s), view 4 (M=5.95s) and view 1 (M=6.48s). The majority of the participants again criticized views 1 and 3. For view 3 it was hard to see small amounts of annotations of text and videos among the large number of pictures designed in a similar style of symbols. View 2 was appreciated, but view 4 was seen as the best alternative to perform the task *estimate*.

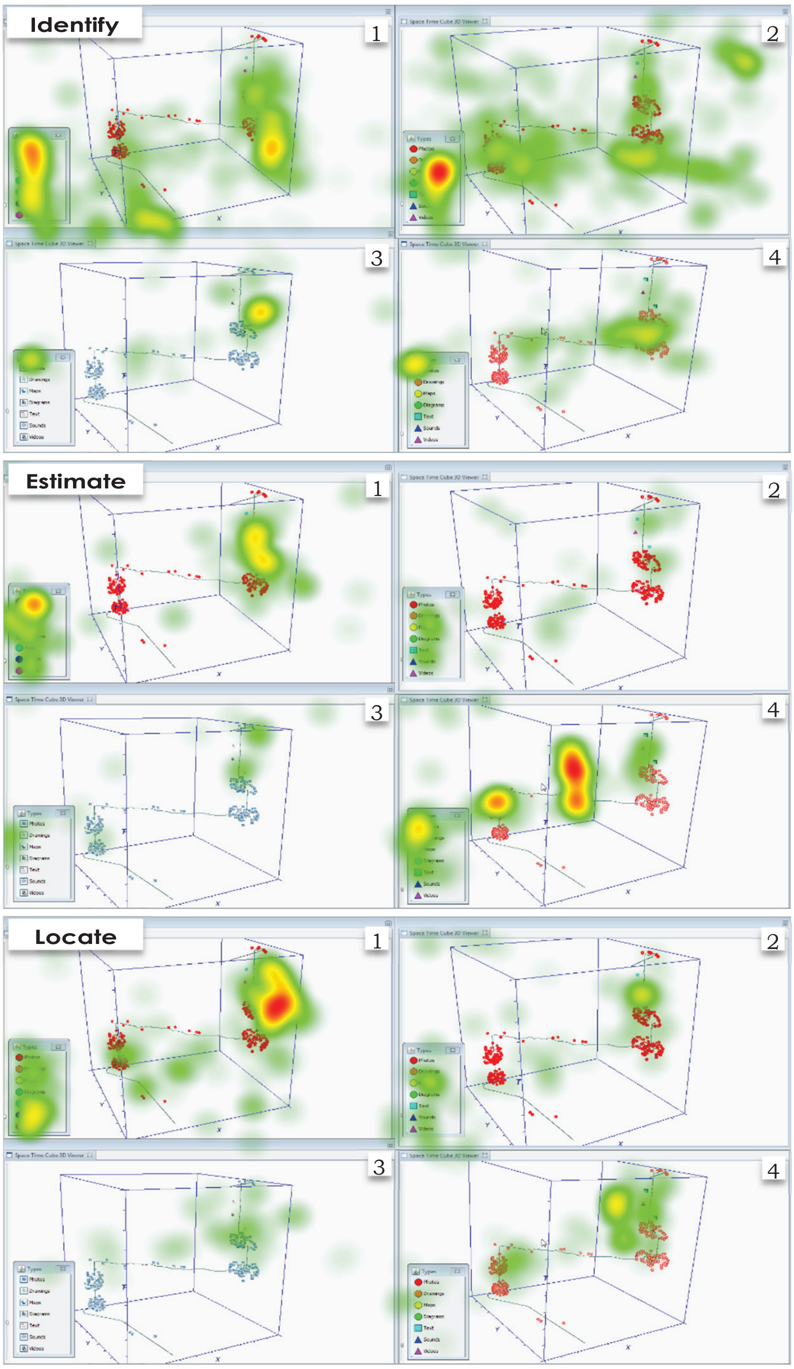



Figure 6.53 Heat Maps representing the use of the design options and legend for the execution of the tasks identify, estimate and locate. View 1 – color hue, view 2 – color hue & shape, view 3 – icons, view 4 – color hue & shading.

This also followed from the think aloud protocols. Here, TPs commented that view 4 was easier to interpret than view 2 because of the use of shading. Thus, the colours introduced in views 1 and 2 were well distinguishable in view 4 due to the shading depth cue. Despite this, TP21 observed missing links between the representation in view 4 and the legend. In particular, during the execution of the task *estimate*, symbols between the STC view and the legend did not match, because the depth cue shading as used in the STC was not used in the legend. The task *locate* was easy to perform with the introduced design alternatives. The interaction experience gained during the previous two task was helpful for the participants to manipulate the STC representation. Thus, the maximum visit duration for the task *locate* was found in view 4 (M=11.36s), while the minimum was in view 2 (M=1.37s), followed by view 3 (M=3.2s) and view 1 (M=4.85s). These results clearly revealed the participants' attitude towards the design alternatives. They mainly interacted with view 4 as the best alternative. This obviously indicates an advantage of depth perception in the 3D visual environment of the STC.

Test subjects also found one more difference between the design alternatives. As it appeared, for the design options in views 1, 2 and 4 they used the legend intensively to identify the represented annotated symbols. While for view 3 participants could identify the information via their visual memory by recognizing universal icons. Despite this, there were complaints on difficulties to see the adopted original symbols in the 3D visual environment of the STC. During this experiment, TPs were not introduced to transparency as an additional option.

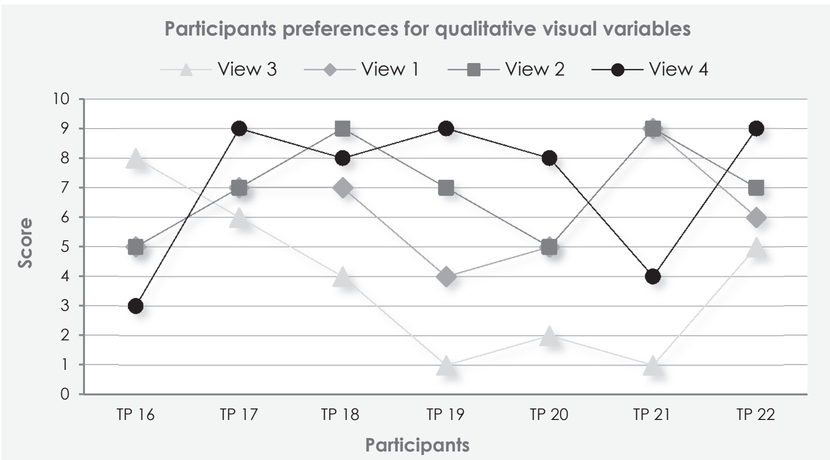



Figure 6.54 Participants' preferences based on the rank results for the views with the qualitative visual variables. View 1 – color hue, view 2 – color hue & shape, view 3 – icons, view 4 – color hue & shape & shading.

Similar to previous experiments, at the end of the task session test subjects were asked to rate the evaluated options on a scale from 1 to 10. The resulted preferences coincide with the attitudes they expressed during the experiment. In particular, the most preferred design option was view 4, while the less preferred views were 3 and 1 (see Figure 6.54).

**User interviews**

The majority of participants was positive about how the features in the given design alternatives could be differentiated. They stressed a careful use of color in complex annotations to support the exploration process. Although the majority indicated visual clutter as obvious influencing factor, they found it somehow manageable. In this regard, view 1 was disapproved to represent complex information due to the difficulties to differentiate the grouped annotation types. Besides, the majority did not see a big difference between views 1 and 2, but view 2 was slightly better appreciated. Contrary to these options, view 4 was the most preferred design alternative. This representation appeared to be more clear and understandable, even with overlapping annotations. The reason of that attitude was the soft look of the colors brought about by the shading depth cue. Only TP16 considered view 4 almost similar to the design alternative in view 2. As she mentioned, the applied shading did not change the design too much, but the use of other colors might improve the view. The majority considered view 3 useless. They remarked that it was difficult to see annotations due to their soft colors and similar symbol shape, even in the legend view. To improve this, participants suggested to make this option more distinctive and understandable for the user. The other comments made were related to the improvement of analytical tools that would allow to see hidden annotations. Another suggestion was to incorporate view 4 and 3 so as to provide information in a relatively short time. TP21 mentioned that, '...I'm not so sure how you can improve it, but I would say that the time aspect is not something that you just get immediately.'

## 6.5 Influence of Data Complexity on the Use of Cartographic Design

This experiment focused on the evaluation of the hypotheses introduced in Table 6.1. The outcomes are shown in Table 6.5 below. It shows that some of the hypotheses can be accepted, while others have to be rejected. The evaluation of the simple dataset resulted in some differences between the defined hypotheses and the test results. The use of *color hue* with thin trajectories did not result in a positive outcome for both the overview and zoom steps of the simple dataset. The reason was barely visible trajectories in the 3D visual environment, although, initially, this option was introduced to help TPs in estimating the number of trajectories in the zoom step. *Color hues* attached to thin trajectories proved to be effective for complex datasets, especially for the zoom level that allowed a better differentiation between trajectories. For complex annotations *color hue* did not get TPs' sympathy and was considered to be less effective.

The *color hue & thick st-path* appeared to be a satisfactory option for simple datasets at the overview and zoom levels, but was seen as a less effective alternative for complex datasets. In simple datasets, this option allowed one to detect and differentiate trajectories visually, while for complex datasets it created color patterns and a blocked visibility of st-paths.

Table 6.5 Test results on the effectiveness and efficiency of design options

| Design combination \ Data complexity | | Simple dataset | | Complex dataset | | Complex annotations | |
|---|---|---|---|---|---|---|---|
| | | Overview | Zoom | Overview | Zoom | Overview | Zoom |
| Qualitative | Color hue | + | _ | _ | + | + | _ |
| | Color hue & thick st-path | + | _ | _ | _ | × | × |
| | Color hue & shading | + | + | _ | _ | × | × |
| | Color hue & shape | × | × | × | × | + | _ |
| | Color hue & shape & shading | × | × | × | × | _ | _ |
| | Orientation & shading | | | | | × | × |
| | Icons | × | × | × | × | _ | _ |
| Quantitative | Color saturation | × | × | _ | + | × | × |
| | Saturation & shading | × | × | _ | + | × | × |
| | Color value | | | | | × | × |
| | Color value & thick st-path | _ | _ | × | × | × | × |
| | Color value & shading | _ | _ | + | _ | × | × |
| | Size & shading | + | _ | × | × | × | × |

– Most efficient and effective
– Efficient and effective
– Less efficient and effective
– Poor effect
× – Not evaluated
\+ – Hypothesis accepted
_ – Hypothesis rejected

The evaluation of the simple dataset resulted in some differences

*Color hue & shading* turned out to be the most effective option for both experiments at both steps in the visualization strategy. Test subjects considered it even to be the best design alternative for data visualization in the STC, despite the expanded volume of st-paths, which is limiting the space between trajectories in a complex dataset. Obviously, good perception of movement trajectories in the 3D visual environment of the STC is important. This approach expanded the trajectories' volume and affected the number of correctly completed tasks *estimate*. This was foreseen and incorporated in the hypotheses. To overcome this problem, color hue attached to simple st-paths was introduced. However, the TPs did not consider color hue with thin trajectories as a convenient solution to derive information from.

Not surprisingly, pattern *orientation & shading* was disapproved for both use case studies. TPs found it the most difficult solution to use to distinguish information, although it was considered to be a useful option for colour-blind users.

The combination of *color hue & shape* for complex annotations appeared to be effective. The combination of *color hue & shape & shading* got the highest preference of participants. This design alternative provided a pleasant representation for complex annotations in the 3D visual environment of the STC to execute tasks. Expectations for the *icon* design alternative were high, but the experiment proved the opposite due to the bad visibility of symbols and their colours.

The apparent differences revealed in preferences regarding the qualitative visual variables were somehow expected. Color hue proved to be the better alternative compared to the pattern visual variable. The research results for the visualization of simple and complex datasets in the STC show the importance of depth cues for a better perception of information in the 3D visual environment of the STC. Surprisingly, the users approved the same rules for the visualization of complex annotations.

For the use of quantitative visual variables, participants appreciated *color saturation* with thin trajectories for the complex dataset and saw it as an effective solution for both overview and zooming. The *color saturation & shading* option was even seen as a better alternative for the exploration of the complex dataset.

The hypothesis that *color value* with thin trajectories would not be effective for simple datasets was confirmed, but it was rejected for complex datasets. The *color value & thick st-path* was recognized as equally effective for the overview and zoom steps of the visualization strategy in simple datasets. It somehow allowed to detect a visual transition between different color gradations to extract amounts. *Color value & shading* appeared to be the best option to explore simple datasets, but was a less effective design option for complex datasets. The visibility of color gradations in simple datasets to represent different amounts was better and allowed users to detect the exact amount for particular segments. However, this design is not recommended for the visualization of a large number of classes.

Differing from the hypotheses defined in Table 6.1, the outcomes of the experiment proved that the *size & shading* option is not the best alternative for simple datasets because of the visual clutter of trajectories caused by depth cues. Participants indicated that it is an effective option for a convenient overview of the data, but not for the details on demand, because a proper link between the STC and the legend was missing. The legend also did not include a smooth transition between different amounts (volume) as the STC did, and this proved to be problematic when the trajectories were tangled. The hypothesis that overview and zoom levels would require different designs was proved true for the *size & shading* option.

Initially, it was thought that the most preferred design options would be visited longer than the less preferred ones. However, the experiment revealed that in several cases participants spent more time looking at the rejected design alternatives to provide argumentations and to describe their opinion, while for the most preferred design option the visit duration was only short with short arguments. As the think aloud protocols revealed, they spent more time trying to understand the 'bad' designs.

## 6.6 The STC and the Perceptual Properties of Visual Variables

According to Bertin (1983, pp. 65), each visual variable has its perceptual property to represent associative, selective, ordered and quantitative to represent phenomena (section 3.4.2). The evaluation showed that some visual variables had different perceptual properties than expected, depending on the data complexity in the STC. However, the findings also indicate that the perceptual properties of most evaluated visual variables are indeed guiding the visual attention as described by Bertin (1983). In particular, color value and color saturation are effective and efficient to guide the user's attention in the 3D visual environment of the STC. These variables allowed users to perceive a ranking (order) in the represented information and enable them to distinguish similar elements (selection). However, increased data complexity might blur these results due to the visual clutter. Color hue guides the user's attention to similar categories of variations (association) for both simple and complex datasets, and allows him / her to distinguish elements of a particular category (selection). Here color hue had a clear advantage over color value and color saturation.

According to Bertin (1983, pp 97), size is the only visual variable with three perceptual properties (selection, order and quantity). Test results reveal that the visual variable size can be considered as effective and efficient to estimate amounts (quantity) and distinguish a ranking among different categories (order) of data. For this particular task, the selective property of size only worked for overview level. The visual variable orientation appeared to be the less effective and efficient variable, as expected. It even prevented the participants to execute their tasks. As Bertin (1983) states, the visual variable orientation is associative and emphasizes similarity. Our results do not support this idea. It could be because it was only applied to line symbols (the paths). The experiment also revealed an insignificant influence of the transparency option on the improvement of design alternatives for the task execution process, although well-chosen colours play an important role here. Contrary to transparency, the user's preferences show an obvious advantage for shading depth perception in the 3D visual environment of the STC.

## 6.7 Discussion

The objective of this chapter was to verify the design guidelines developed during phase two of this research project. The focus for cartographic design was a typology of visual variables combined with the depth cue theory. In case of the STC, it was extended to three-dimensional st-paths in the 3D visual environment. The depth cues can strengthen the visualization when used rationally with visual variables, especially in situations where the data are likely to be cluttered. But in all situations a logical organization of the displayed information is required. Such organization of the information revealed some unexpected results with respect to the use of the design alternatives for the different types of data.

The design alternatives developed, based on the combination of visual variables and depth cues, led to interesting results for different levels of complexity in the evaluated datasets. These outcomes did not always coincide with the hypotheses developed initially. However, it gives new criteria for the use of design alternatives in regard to the small and complex datasets. In most cases the results did not show a tight relation between the design alternatives and the Information Seeking Mantra (Shneiderman, 1996) as hypothesized initially. When a design option is useful at the overview step, then it is useful at the zoom step too and vice versa. The only exception was found for *size & shading* that appeared to be effective for the overview level, but ineffective when zooming in. Besides, some contradictions in effectiveness were found when using *size & shading* compared to *color value & shading* for the simple dataset. The combination of *color value & shading* appeared to be the worst alternative compared to *color saturation* with thin trajectories and *color saturation & shading* in complex datasets. At the same time, *color & shape & shading* was a preferred combination for complex annotations. It was expected that shading depth cues with combination of visual variables would be rejected because of the visual complexity. In conclusion, color in combination with the shading depth cue appeared to be the best option for the visualization of qualitative and quantitative information in simple and complex datasets.

## References

Bertin, J. (1983). **Semiology of Graphics: Diagrams, Networks, Maps**. The University of Wisconsin Press, Madison (first published in French in 1967, translated to English by Berg W.J. in 1983).

Bojko, A. (2009). 'Informative or Misleading? Heatmaps Deconstructed', in **Human-Computer Interaction. New Trends**, ed. by Jacko, J., pp. 30-39, Springer Berlin Heidelberg, NY.

Goldberg, J.H. and Kotval, X.P. (1999). **Computer interface evaluati on using eye movements: Methods and construts**, 'International Journal of Industrial Ergonomics', 24, pp. 631-645.

Green, M. (1998). **Toward a Perceptual Science of Multidimensional Data Visualization: Bertin and Beyond**, ERGO/GERO Human Factors Science. From: http://www.ergogero.com/dataviz/dviz0.html

Shneiderman, B. (1996). **The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations**, in the 1996 IEEE Symposium on Visual Languages. BouIder, Colorado, pp. 336 - 343.

Strandvall, T. (2009). 'Eye Tracking in Human-Computer Interaction and Usability Research', in **Human-Computer Interaction – Interact 2009**, ed. by Gross, T., Gulliksen, J., Kotzé, P., Oestreicher, L., Palanque, P., Prates, R. O., and Winckler, M., pp. 936-937, Springer Berlin Heidelberg, NY.

URL 3, From: http://atlasti.com

URL 8, From: http://www.tobii.com/

# CHAPTER 7

# EVALUATION OF THE USE OF THE STC IN A GEOVISUAL ANALYTICS ENVIRONMENT

## 7.1 Introduction

The results discussed in previous experiments revealed that the utilization of visual variables and depth cues is influenced by data complexity. At the same time, graphic design has a significant influence on the performance of user tasks. Based on the findings presented in the previous chapter, this chapter aims to understand the context of the use of the STC. In particular, phase six of the research project investigates the use of the STC in a GeoVisual Analytics (GVA) environment. These GVA environments have been developed based on the requirements of the use case related domain experts, and on the user tasks formulated on the basis of the initial research questions, which were derived from the first and third phases (see section 3.3 for simple datasets and complex annotations and chapter 4 for large datasets and complex datasets). The usability evaluation in phase six consists of three different experiments. The first experiment looked at two different use cases, a simple dataset (use case 'Napoleon') and complex annotations (use case 'Estonia'). In the second experiment (use case 'Delft'), the GVA environment was evaluated based on the requirements of domain experts, and also to get even more feedback to refine the design. The third experiment evaluated the use case (use case 'Tallinn') of the large datasets with two different groups of the users to compare and understand the difference in the use of the GVA environment. During the experiments a range of qualitative and quantitative usability methods to collect valuable materials were used. The information extracted from each of these experiments are analysed and summarized, and results compared to draw conclusions on the usability metrics on the STC embedded in a GVA environments.

## 7.2 Evaluation Purpose and Execution

The usability experiment designed for this phase aims to find out how the STC performs in a highly interactive GVA environment. In other words, to understand the user's work activities in a GVA environment in order to be able to design an application that will effectively support similar task execution processes. In the GVA environment, the STC is linked to other graphic visualizations such as parallel coordinate plots, graphs and maps. This allows an interaction with location, attribute and time components of the data. The experiment should reveal whether the STC is still enough effective and efficient in a GVA environment. If so, what makes it useful, and if not, then how and when can we make it more effective and efficient, if that is at all possible? It will also potentially reveal other usability problems in the developed visual environment.

To answer these questions, three different experiments focusing on the evaluation of interactive environments based on the use cases described in section 3.3 have been set up. Two groups of test persons were involved, experts and non-experts. The expert group included scientists belonging to research groups involved in phase 3 (chapter 4). The non-expert group consisted of scientists from the geo-domain, who were not familiar with the datasets, but who were aware of the graphs incorporated in the developed visual environments.

The interactive environments were designed in the uDig and Ilwis programming environments. Both programs contain a STC plug-in, graphs, maps and various functionalities for a flexible analysis and manipulation of the data. Based on the research questions identified in section 3.3 and chapter 4 the effectiveness, efficiency and user satisfaction of the combination of graphic representations in the visual environments was judged. A number of qualitative and quantitative evaluation methods was used. These included video/audio/screen/eye recordings, think aloud protocols and user interviews and allowed drawing final conclusions on user performance metrics and preferences.

The experiment involved all four use case studies as discussed in section 3.4, in a GVA environment in which the STC operates together with other graphic representations of location (2D map), attribute (Parallel Coordinate Plot (PCP)) and time (time wave, time graph, Street Profile Graph (SPG)) of the data. The test participants had to execute different categories of tasks (comparison, attribute-based, etc.) while following the workflows in a GVA environment. This made it possible to derive usability metrics on response accuracy (effectively completed tasks) and response time (time required to achieve the tasks).

Experiment I aimed to find out whether the same GVA environment could be suitable for the exploration of different types of data. Accordingly, it evaluated the simple dataset (use case 'Napoleon', Figure 3.10) and the complex annotations (use case 'Estonia', Figure 3.8) in two sessions. The two GVA environments developed for this experiment in uDig program environment were identical (see Figures 7.1 and 7.2) and evaluated with the same group of non-expert users in the usability laboratory at the University of Twente.

Experiment II aimed to find out whether the GVA environment, developed in the Ilwis program, and based on the user requirements was usable. In this experiment, the evaluation took place with the complex datasets of the ‘Delft’ use case (see Figure 3.12). Domain experts in urban planning were visited in their own working environment.

The experiment III intend to evaluate a large dataset (‘Tallinn’ use case, Figure 3.11) in a GVA environment constructed in the Ilwis program environment (see Figure 7.19). In this case, the evaluation strategy was different and involved domain experts and non-domain expert. The evaluation results of these two groups were analysed and compared for more conclusions. The domain experts evaluated the GVA environment at their working place, and the non-domain users did that in the usability laboratory.

For the realization of these usability studies in phase six, a combination of qualitative and quantitative evaluation methods of task execution, think aloud, screen/video/audio recordings and user interviews was used. In addition, the method eye recording was used for the studies in the usability laboratory. The user tasks have been defined based on the initial research questions as identified in the first and third phases of the research (section 3.3 and chapter 4). Based on these tasks, the test subjects were expected to provide feedback on the usability of the GVA environment by discussing the different steps of their actions while completing the tasks. This would help to construct the task execution strategy as executed by the participants. In addition, based on the task completion, error rates and user satisfaction results, conclusions will be drawn regarding to the developed GVA environment and in particular to the STC. The materials derived will also be used to detect existing usability issues.

## 7.3 Experiment I

### 7.3.1 Development of a GVA environments for the simple dataset of ‘Napoleons march to Moscow’ and complex annotations of ‘Travel log data of Estonia’

The GVA environment constructed for this usability experiment consisted of four different representations: a 2D map, STC (Kraak, 2008a), Time Wave (TW) and Time Graph (TG) developed in the uDig GIS program environment (URL 2; Li and Kraak, 2008; Li, 2010). The visual representations incorporated in the interactive visual environment allow users to analyse complex geographic datasets from a spatial, temporal and attribute perspective. Besides, the analytical tools developed offer the user a highly interactive functionality for an effective exploration and human judgements.

The 2D map allows the user to get a quick spatial overview over the whole dataset. The TW and TG enable a different, integrated attribute and temporal analysis of the data. The STC allows a focus on the integration of space and time, with an additional option for attribute information.

The four representations are linked and allow query and interaction activities like panning and zooming. Figure 7.1 shows the test configuration for the Napoleon dataset and Figure 7.2 the setup for the annotated st-paths of 'Travel log data of Estonia' (Kraak and He, 2009).

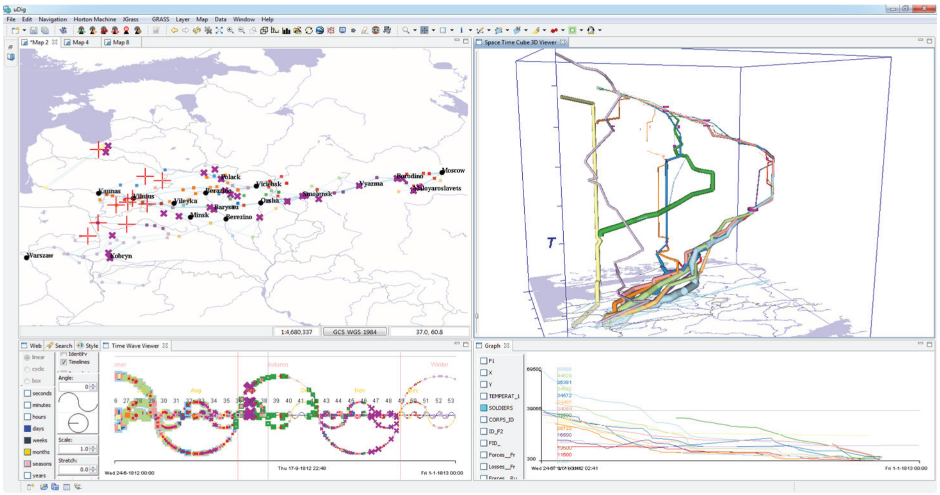


Figure 7.1 Interactive visual environment constructed for the evaluation experiment with the simple dataset of 'Napoleons march to Moscow.'

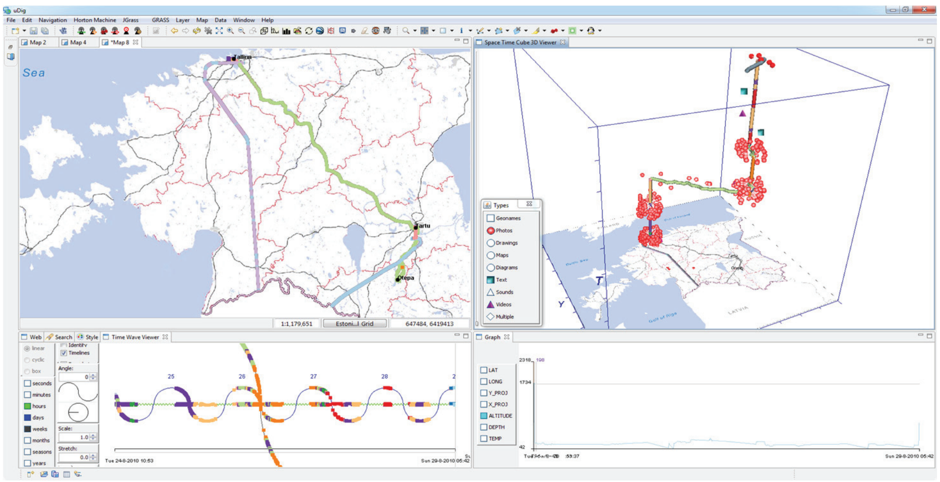


Figure 7.2 Interactive visual environment constructed for the evaluation experiment with the complex annotations of the 'Travel log data of Estonia.'

## 7.3.2 Task execution scenarios

During the test sessions, the users were expected to manipulate the highly interactive environment independently and execute the four tasks *locate, identify, compare* and *characterize*, identified on the basis of existing literature (Knapp, 1995; Zhou and Feiner, 1998; Gotz and Zhou,

2009) (see section 3.2.2). The manipulation scenario itself was the object of observation for the experimenter to understand how particular visual representations can be used in interactive visual environments to support the data investigation process for the task execution.

The analysis of task performance will help to achieve answers on the effectiveness, efficiency and user satisfaction for each visual representation in the developed GVA environment. The respective task scenarios are:

**Use case I – Napoleon's march to Moscow**

| | |
|---|---|
| TASK 1 | Please describe how long different corps were traveling to Moscow and back? |
| EXPECTED TASK EXECUTION | Participants should *locate* the 2D base map of the STC at the point of intersection between Moscow and the trajectories to find the time of arrival. Then continue to move the 2D base map up to the time axis of the STC to *identify* the time of departure from Moscow and the end of the campaign. |
| TASK 2 | Napoleon's invasion of Russia began in June 1812 when the *Grande Armée* was powerful. But, over time, several factors influenced its strength.<br>Please look at the STC and TG and compare the difference between the beginning and the end of the campaign. Characterize the factors / reasons that influence the strength of the *Grande Armée*. |
| EXPECTED TASK EXECUTION | The participants are expected to *compare* the number of soldiers at the beginning and at the end of the campaign through the TW and STC. Then they should look at information on temperature on the TG to *characterize* change. |

**Use case II – Annotated st-path of Travel log data of Estonia**

| | |
|---|---|
| TASK 1 | Please describe how long the traveller stayed at different places? What do you think was the purpose of the stay / visit? |
| EXPECTED TASK EXECUTION | Expected participant behaviour is to *locate* the base map at the places of the long stops (stations) to *identify* their temporal duration. Then focus on TW, TG and the 2D map to *characterize* the purpose of the stay. |
| TASK 2 | Please observe the types of annotations and find the area / place where the most diverse materials / information were collected? |
| EXPECTED TASK EXECUTION | Participants should *compare* different annotations in the STC to find the place with the most diverse information. |

## 7.3.3 Selecting and scheduling of test participants

A group of seven test persons participated in the experiment. Two female and five male participants completed a user profile questionnaire distributed online through the 'SurveyMonkey' application (URL 12) (see Appendix 7). The people were all linked to the Faculty of Geo-Information

Science and Earth Observation (ITC) of the University of Twente. They were of different age groups and were all scientists or PhD candidates with 4 – 25 years of experience of working in the geo-domain (see Table 7.1).

Table 7.1 Professional background characteristics of TPs in Experiment I

| TP № | Gender | Age group | Occupation | What is your field of interest and how it is related to the geo-domain? | How many years of experience do you have in geo-domain? |
|---|---|---|---|---|---|
| **TP 1** | Male | 41 – 50 | Geographer-cartographer | Geovisualization | 20 |
| **TP 2** | Female | 31 – 35 | PhD Student | Geovisualization, visual analytics, movement analysis | 14 |
| **TP 3** | Female | 20 – 25 | PhD Student | Urban Planning and Management , Geo-spatial analysis | 4 |
| **TP 4** | Male | 41 – 50 | Lecturer | Cartography, geo-web applications, GIS | 25 |
| **TP 5** | Male | 41 – 50 | Lecturer | Data management | 20 |
| **TP 6** | Male | 31 – 35 | PhD student | Data mining, data processing, spatial analysis | 5 |
| **TP 7** | Male | 36 – 40 | GIS Lecturer | Environment, Cartography, 3D Visualization | 8 |

The majority of the TPs indicated they are using maps once a day or at least 2-3 times in a week for purposes such as finding directions, navigation, teaching, entertainment, communication, visualization, etc. (see Table 7.2).

Table 7.2 Interactive map use experience of TPs in Experiment I

| TP № | How often do you use maps in your daily life? | For what kind of purposes do you use them? | What is your experience with interactive 2D maps and how often do you use them? | What is your experience with interactive 3D maps and how often do you use them? | Are you familiar with the STC? | Have you ever used the STC in an interactive environment? | If yes, what was the last time you have used the STC? | What is your experience with interactive graphs and how often do you use them? |
|---|---|---|---|---|---|---|---|---|
| **TP 1** | 2 – 3 times in a week | To visualize geo data | 2 – 3 times in a week | Once a week | Yes | Yes | 1 or 3 month | 2 – 3 times in a week |
| **TP 2** | Once a week | Research or navigation | Once a week | Once a year | Yes | Yes | 3 month – 1 year | Once a week |
| **TP 3** | 2 – 3 times in a week | Searching for the location of some places | Sometimes | Sometimes | No | No | - | 2 – 3 times in a week |
| **TP 4** | Once a day | Navigation, teaching, visualization | Once a day | 2 – 3 times in a week | Yes | Yes | 1 month ago | Once a day |
| **TP 5** | I use a map every time I see a good use for it | Navigation, entertainment, communication | Very often, sometimes even multiple times a day | Not very often. I only use them for recreationa purposes | Yes | Yes | I have used it two or three times in my life | Not much |
| **TP 6** | Once a day | Get directions, generate output of analysis, read data, etc. | Once a day | Once a day | Yes | No | - | Once a day |
| **TP 7** | 2 – 3 times in a week | Finding streets | 2 – 3 times in a week | Once a week | Yes | Yes | 1 week ago | Once a week |

Most used 2D interactive maps, but 3D interactive maps are used rarely: according to the survey, only 2 participants out of 7 are using 3D maps regularly. 6 TPs out of 7 claimed to be familiar with the STC, while 5 test subjects had used it in an interactive environment before this experiment. As for the intensity of use, only 2 TPs have used the STC one week or less before the experiment, while others 1 to 3 months ago.

As Table 7.3 shows, all test subjects appeared to be experienced in map making. Five of them were familiar with an interactive 2D and 3D STC in an analytical environment for geo-spatial analyses, investigating movement data, or other purposes. The majority of TPs rate themselves as very good or fair to orient themselves in an analytical environment, and only 1 participant ranked himself as good.

Table 7.3 Interactive analytical environment use experience of TPs in Experiment I

| TP № | Have you ever designed or constructed maps yourself in any program environment? | If yes, how often do you do this? | Are you familiar with the above mentioned graphical representations (2D map, 3D map, and graphs) in an analytical environment? | If yes, please indicate for what kind of purposes did you use that analytical environment? | Please, rank your ability to orient yourself in such an analytical environment. |
|---|---|---|---|---|---|
| **TP 1** | Yes | 3 years ago | Yes | To explore movement data | Fair |
| **TP 2** | Yes | 2 – 3 times in a year | Yes | For research | Very good |
| **TP 3** | Yes | Sometimes, not frequently | Yes | Geo-spatial analysis | Fair |
| **TP 4** | Yes | Once a day | Yes | Mostly research into the environment itself | Very good |
| **TP 5** | Yes | Once a week | No | Education | Good |
| **TP 6** | Yes | 2 – 3 times in a week | Yes | - | Very good |
| **TP 7** | Yes | 2 – 3 times in a year | No | - | Fair |

## 7.3.4 Design of the experiment

**Materials**

The GVA environment constructed for the first experiment consisted of four equally divided different views, as described in section 7.3.1 (see Figure 7.1). For the simple dataset, the first view with the 2D map was showing basic geographic information on boundaries between countries, hydrography (lakes, rivers and seas) and populated areas required for the exploration of the dataset. In addition, the 2D map was representing places of battles and 15 different corps of the *Grande Armée*. The second view with a STC was showing the same information as the 2D map, but from a time perspective. In particular, the base map of the STC contained basic geographic information, while the 15 different corps were represented as st-paths and battles as stations (see Figure 7.1). The third view with the TW was representing attribute characteristics on the amount of soldiers and battles at particular times. The fourth view with the TG (bottom right hand corner in Figure 7.1) was displaying attribute characteristics on amounts of different corps and temperature on a time line.

For the complex annotations, the 2D map was also displaying basic geographic information on district boundaries, hydrography (lakes, rivers and seas) and populated areas required for the exploration of the data. Besides, it was also representing different trajectories made by travellers. In the second view, the base map of the STC was displaying the same information as the 2D map. However, the trajectories made by travellers were shown as st-paths and different activities as annotations (pictures, videos, text document) in the STC (see Figure 7.2). The TW in the third view was displaying only traveling characteristics on a time line and the TG in fourth view the altitude of the terrain of visited places at particular times registered by GPS.

**Setup**

The experiment was performed on a Windows 7 workstation running Tobii Studio 3.2 software to capture eye movements, screen activities, video and audio recordings of test subjects. The developed GVA environment, running in uDig, was displayed on a 24 inch LCD flat panel display with a 1680 x 1050 screen resolution. A Tobii X 60 Eye Tracker on a 60Hz resolution was used to capture eye movements. The standard keyboard and mouse were prepared for interaction and manipulation activities.

### 7.3.5 Procedure

The evaluation experiment with the use cases of ‘Napoleons march to Moscow’ and ‘Annotated st-path of Travel log data of Estonia’ took place at the usability laboratory of the ITC Department of Geo-Information Processing, University of Twente (see Figure 7.3).

Test participants were informed that the experiment consisted of three sub-sessions. The first sub-session intended to be an evaluation study with the simple dataset, while during the second sub-session they had to work with the complex annotations (see Appendix 8). As for the user interview at the end, they had to provide their opinions and share their experience on the previous two sessions (see Appendix 9). A printed document was issued to the TPs, describing the usability research methods, usability ethics and the content of the simple dataset. After reading this document, the experimenter demonstrated how the visual environment functions and presented the analytical tools required for the task execution process. After that, the participants were given 15 minutes to familiarize themselves with the environment. When the practice session was completed and the participants felt ready for the test, the eye recording was briefly explained and the eye calibration procedure started. Next, the participants were given a printed task document and the session started.

Figure 7.3 Task execution process of use case studies in the ITC/GIP usability laboratory.

### 7.3.6 Analysis of the results

The recordings generated in Tobii Studio were divided into segments based on the task execution and user interview sessions for both use case studies (see Figure 6.22). The resulting segments were later integrated in task and interview groups for further analysis. In this way, the organization of the recordings made it easy to extract the required qualitative and quantitative information. For quantitative metrics, AOIs were identified in the segmented videos, and efficiency metrics related to the time spent and error rates were derived (see Figure 6.23). The AOIs were also used to generate GazePlots and compare the effectiveness of visual representations during task execution for both use case studies. During the experiment, technical issues were detected with eye movement recordings of TP5. Therefore, these recordings were not used for the analysis of annotated st-path.

The qualitative analysis of the segmented videos was based on verbatim transcription in the qualitative research software ATLAS.ti (URL 3). The results of the think aloud, eye tracking, screen actions and video/audio recordings of sessions were incorporated (see Figure 6.24). This resulted in a detailed document containing information on error rates, participant screen actions, behaviours, expressed opinions, suggestions and interviews (see Appendix 10). During this transcription, particular attention was given to the task execution strategy.

For better analysis, depending on user actions, comments, etc. different segments of the transcript document were associated with particular codes and organized in four different families: evaluation, task, action and representation. The resulting coding structure of the transcript document is shown in Table 7.4.

Table 7.4 The coding structure in ATLAS.ti for the analysis of transcript documents for Experiments I, II and III

| Evaluation | Task | Action | Representation |
|---|---|---|---|
| Confusion | Compare | Pan | 2D Map |
| Eye movement not recorded | Distinguish | Rotate | STC |
| Help | Identify | Zoom in/out | Time Wave (TW) |
| Negative sense | Locate | Map overview | Time Graph (TG) |
| Positive sense | Estimate | Use label | PCP |
| Observation | Filter | Use legend | SPG |
| Remark | Describe | Use Base map | 2D STC |
| Session start | Characterize | Switch on/off | Overview Map |
| Session end | Select | | |
| Usability problem | | | |
| Tech problem | | | |

## 7.3.7 Results for the simple dataset

Four map use tasks: *locate, identify, estimate* and *characterize* were to be executed by the seven TPs while working with the simple dataset (Napoleon's march to Moscow). They were expected to perform these analytical tasks in the GVA environment. In doing so, test subjects could judge each visual representation and provide comments and suggestions on their possible improvement.

**Locate and identify**

In order to answer the first question to complete the task *locate*, most TPs started to move the base map in the STC to the point of intersection between Moscow and the trajectories as it was expected. However, two experienced participants (TP1 and TP5) ignored the task *locate* because they could not read the map well in the cube. Others (TP3 and TP6) used the 2D map view. They did not grasp the functionality of the STC. The majority found Moscow on the 2D map and then continued their exploration of temporal aspects in the STC. Such exploration behaviour indicates the constant control and comparison of information in the GVA environment. However, the TPs had more troubles with identifying time than space.

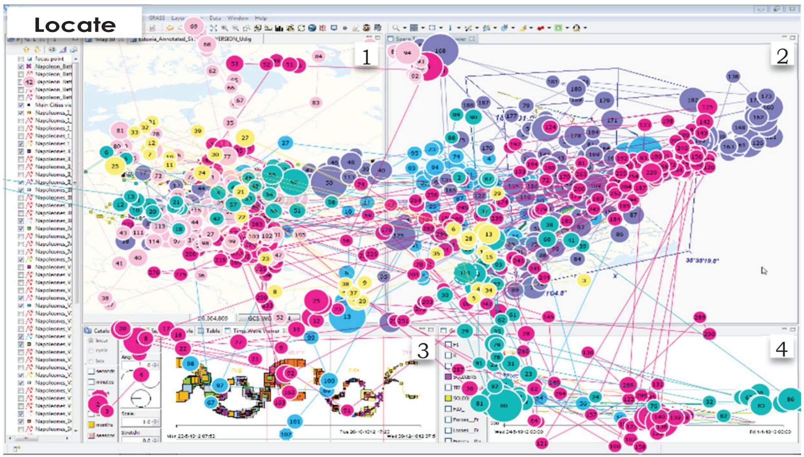
Their task execution strategy showed that the use of the 2D map for finding the spatial location of particular objects was more convenient to them than the STC. This was because the 2D map provided spatial overview. The participants did realize that the 2D map was limited in seeing additional information and would not be very useful to extract especially temporal information

Another interesting observation was that some participants had difficulties to remember or notice the button located on the left side of the STC view to move the base map along the time axis. Instead, they effectively used the interactive links between the base map and time slider of the TG. By moving the time slider of the TG, the base map was moving along the time axis of the STC, indicating the spatio-temporal location of the corps. Since the TW does not represent spatial locations it was not used for the task *locate*. The eye movement GazePlots of the use of the GVA environment for the task *locate* are shown in Figure 7.4.

The task *identify* appeared to be easy to perform in the STC. During its completion, several TPs could also explore the movement behaviours of the corps that never arrived in Moscow. The minority of the test subjects preferred to complete the task *identify* with the TG and TW together (see Figure 7.4). Several TPs found it easier to extract time related information from the TG and see the duration of the campaign without interaction activities.

An interesting exploration strategy for the task *identify* was observed for TP4. He decided to derive temporal information from the TG by selecting in the STC the corps that was active during the whole campaign. In this process, he emphasized his difficulties to differentiate between tangled trajectories in the STC view without using the zooming function. Thus, based on a combined use of the time line of TG and TW, he determined the duration of the time by seasons in the selected trajectory. In doing so, he was not able to *identify* the right time of arrival of the corps in Moscow. Later, TP4 realized that in this process, the use of the base map of the STC is an important help to find spatio-temporal intersections effectively.

In order to *identify* the beginning and end time of the historical event, some TPs used the time values shown on the time axis of the cube, while others focused on the time line of the TG and TW. Despite the multiple options to complete this task, the results of the task execution analysis revealed that the participants were somewhat confused about the overall functioning of the GVA environment. An interesting observation was to see the participants' confusion in using both the STC and TG together. Most probably, this was caused by the nature of the dataset and the different ways of representing the data in both. Napoleon moved towards Moscow and back, but in the TG this is represented as a 'straight' line with its beginning and end on a linear time line with Moscow in the middle. The end of the campaign shown in the TG, was by some considered to be Moscow because in the cube Moscow is most east. Most probably, the 2D map increased this confusion.



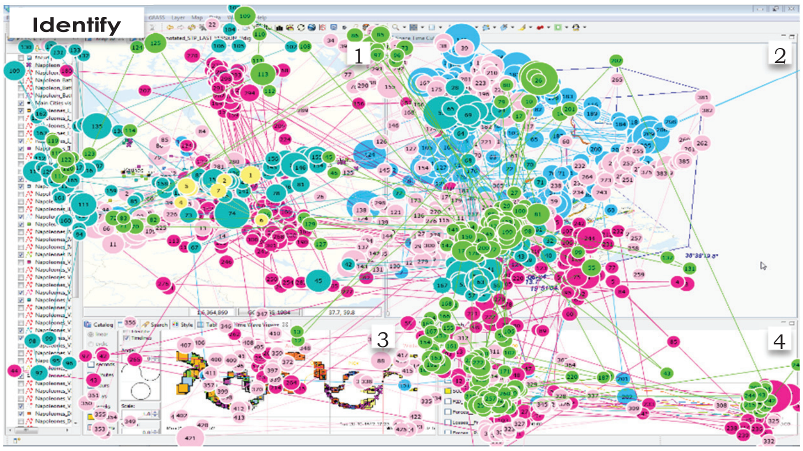




Figure 7.4 GazePlots representing the use of the visual representations during the execution of the tasks locate and identify with the simple dataset in Experiment I. View 1 – 2D map, view 2 – 3D STC, view 3 – TW, view 4 – TG. Each color represents a test participant.

The example above shows that despite the eagerness of test subjects to perform the given tasks, some of them were not able to use the visual environment effectively, because either they did not understand the concepts behind the graphics or could not operate the environment.

#### Compare and characterize

The second question given to the participants involved the tasks *compare* and *characterize*. The task execution strategy for the task *compare* did not reveal any performance problem, but proved a more effective use of visual representations than for the previous tasks (see Figure 7.5). For instance, the majority of the participants was able to *compare* differences between the beginning and end of the campaign in one glance of the graphic representations. For this reason, some used only the STC and others explored the differences through the TG. By moving the time slider of the TG, TPs found it easy to follow the dynamic development of an event. In order to *compare* the difference between the beginning and end of the event, a minority of participants studied the sizes of the corps in the STC, but for further details, they used the TG and TW. During the execution of the task *compare,* TP4 mentioned that, 'from a 1D graphical representation it is easy to see what happened, because the TW allows to compare battles and size of the corps together overlapped and makes it easier to draw conclusions.'

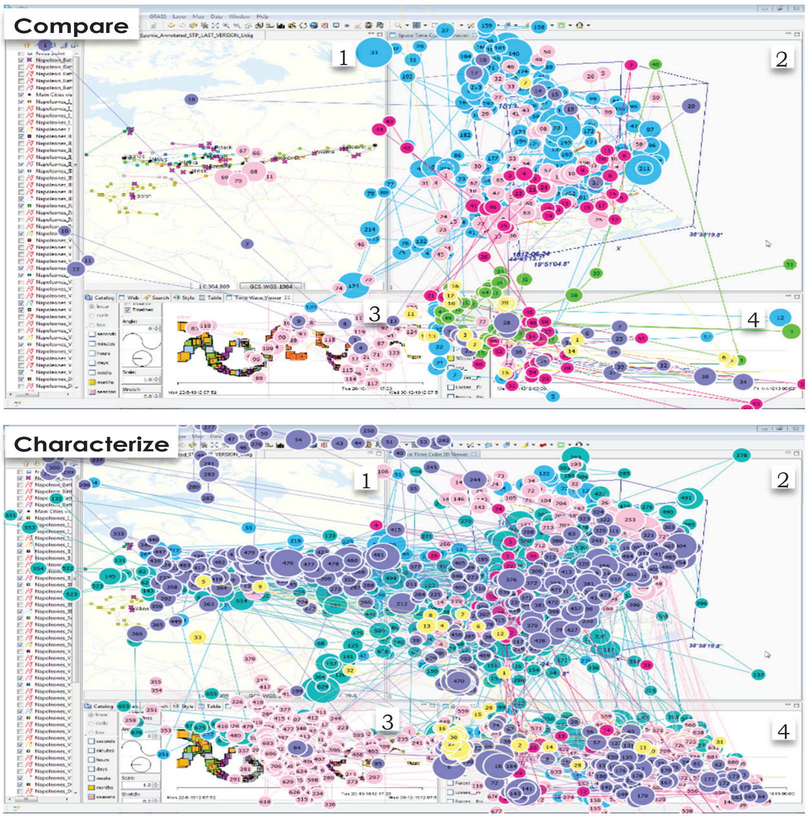



Figure 7.5 GazePlots representing the use of the visual representations during the execution of the tasks compare and characterize with the simple dataset in Experiment I. View 1 – 2D map, view 2 – 3D STC, view 3 –TW, view 4 – TG. Each color represents a test participant.

The execution of the task *characterize* can be considered as effective but not efficient due to the required time it took to complete it. All seven TPs were able to perform this task successfully and provided consideration on missing information. By now, the TPs were able to freely manipulate the visual environment and in some cases revised answers to tasks completed previously. Observation of the task execution revealed one specific exploration strategy. In particular, test subjects first identified the corps' arrival in Moscow as the place showing a difference in amount of soldiers between beginning and end in the STC. And then, they used the TG and TW to see the difference in temporal duration moving forward and then backward. However, to *characterize* the factors influencing the campaign, observation of some attribute information was required. To do so, TPs extracted information on the number of soldiers per corps and the air temperature from the TG. Overall, during the performance of this particular task, different strategies were followed.

The experiment clearly revealed different exploration behaviour of participants resulting in different ways of use of the visual environment. However, none of these behaviours was different from the hypothesis initially identified. Test participants also provided suggestions to improve the GVA's analytical functionality. Several suggestions were related to how to represent data. For instance, to make battles more visible or even audible. Another idea was to offer textual information on events such as a battle. Several suggestions were related to the improvement of the base map. Finally, they advised to implement a function for the STC that would help to - depending on the temporal scale differentiate by day and night or by the season through a color change of the base map.

### 7.3.8 Results for complex annotations

Similar to the first session, in the second session participants were given two questions constituted of four map use tasks. They had to *locate*, *identify, characterize* and *compare* information in the GVA environment.

**Locate, identify and characterize**

To complete these tasks, the TPs first observed the data followed by interaction with the STC. By rotating the dataset in the STC, they studied annotations from different perspectives, and then started *locating* the base map along the time axis to explore temporal aspects. In this process, the majority of the TPs was synchronously observing other graphic representations to see the changes. While a minority first observed the temporal distribution of annotations in the STC, and then focused on the legend menu to understand map elements and annotation types. Thus, the execution of the task *locate* appeared to be easy for the exploration of the temporal component of the data in the STC, especially based on the places of long stops (stations) that were well visible and required no visual effort to see. The places of long stops were also well detectable on the 2D map through the focus point that was moving synchronously to the base map. Similar to the previous test session, a minority of the participants completed the task *locate* through the time slider of the TG and TW. The GazePlots in Figure 7.6 show TPs' eye movement behaviours during the execution of this task.

The task *identify* was easy to perform for the majority of the participants. For this task, TPs were expected to find relevant time information to define the duration of stops (see Figure 7.5). When observing the data in the different representations, the majority of the users realized that, because of the overlapping annotations, it will be difficult to see the relevant information. Thus, they started filtering information from the legend view to observe their spatial and temporal distribution in the STC and *identify* time durations. Again different strategies where followed. Some used the time labels along the STC's time axis and focus point on 2D map, while others used time slider of the TW and TG. While doing so, they performed interaction activities of zooming in /out, rotating and filtering the data. The majority looked happy with the TW but were less happy with the TG, although *identifying* time labels in both TG and TW appeared not to be a problem.

After identifying the places of long stops, TPs *characterize* traveling activities. Most of the participants start this task from the STC by filtering annotations and observing the legend of the 2D map to match colors for different activities. Also here, some TP's followed different strategies, such as working with the TW and the STC to investigate annotations at the places of long stops and characterize traveling activities. Only one participant mentioned that information shown on the TW could be represented on the TG too. Interesting was that, while TPs were switching between the STC and 2D map, they discovered differences in colors shown on the 2D map and in the STC view for traveling activities due to the shading depth cue used for the st-paths in the STC. This appeared to be confusing to at least one participant. A similar confusion was noticed with TP22 in his evaluation of the design alternatives for the annotated st-paths (see section 6.4.3).

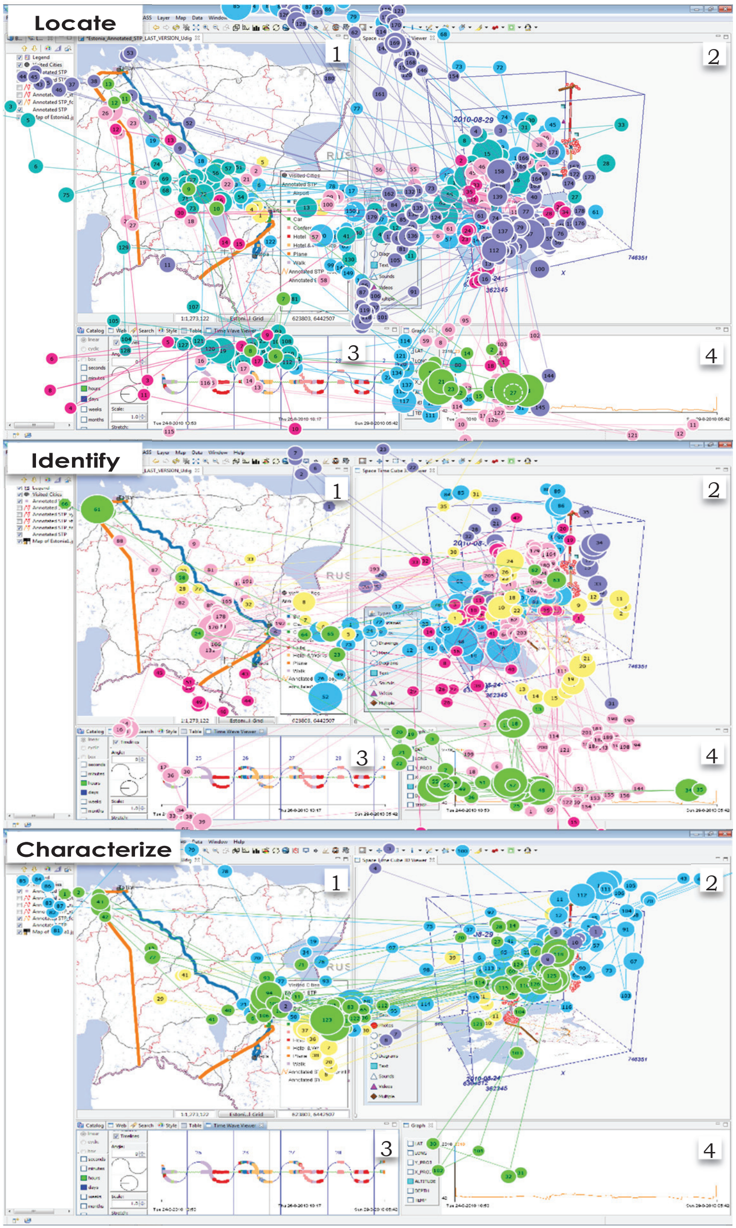



Figure 7.6 GazePlots representing the use of the visual representations during the execution of the tasks locate, identify and characterize with the complex annotations in Experiment I. View 1 – 2D map, view 2 – 3D STC, view 3 – TW, view 4 – TG. Different colors represent the individual test persons.

**Compare**

The annotation types could be seen in the STC only and, therefore, it was not surprising that the task *compare* was performed in the STC (see

Figure 7.7). Based on intensive interaction activities, the participants first observe again the travel activities and link them to the annotation types. In order to derive information on the diversity of annotations, the filtering option available in the STC legend menu was used effectively. During the execution of this task one minor issue was revealed related to the selection of annotations. Overall, the TPs could *compare* place with the most diverse annotations effectively and efficiently. The reasons for this were the experiences gathered during previous tasks performances. This is a confirmation that during these test the TP's learn.

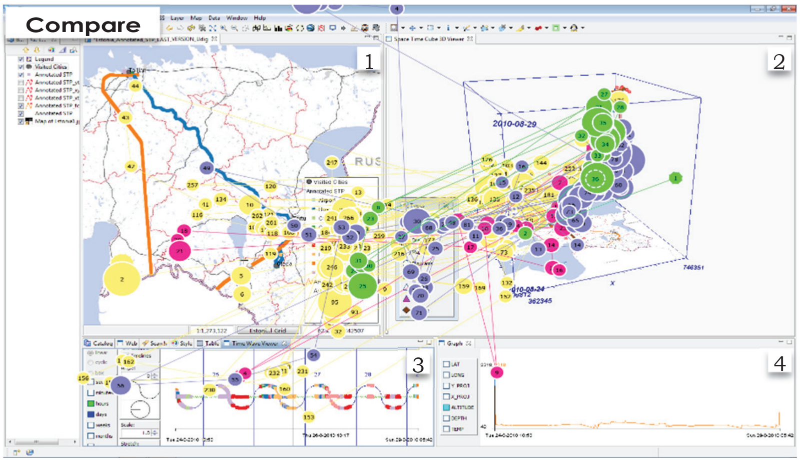



Figure 7.7 GazePlot representing the use of the visual representations during the execution of the task compare with complex annotations in Experiment I. View 1 – 2D map, view 2 – 3D STC, view 3 – TW, view 4 – TG. Different colors represent the individual test persons.

## 7.3.9 User satisfaction analysis

The majority of the participants considered the developed GVA environment used in Experiment I to be useful because they could manipulate data from location, attribute and time perspectives, while a minority expressed the idea that the combination of the STC and TG was enough to answer when, where and what questions. The orientation in this GVA environment did not appear to be a difficult task either, but several remarks were made to add extra geographic features for orientation in the detailed views.

During the interviews, the task *characterize* for the simple dataset was indicated as relatively difficult. As it appeared, to guess on some factors which are not shown on the map confused some users. At the same time, finding the places of long stops was no problem for them. The STC was considered to be a useful representation to target time related questions and to identify forward and backward in simple datasets, although visual clutter was noted as a disturbing problem. For the improvement of the STC, an option for automatic rotation was suggested. Others emphasized that they had difficulties to find information in the STC without other visual representations. It was suggested to make the base map of the STC interactive to allow the selection of objects to be seen in the 2D map view. In addition, the base map should indicate time, such as day and night, or summer and winter. The TW was found to be a little bit cluttered for the simple dataset, while with complex annotations it can represent traveling activities in an effective way. The participants could derive general sequential trends for both use case studies and see time periods or cycles. However, for the simple dataset it was difficult to see temporal granularity for each corps, although TW allows to represent each trajectory separately. However, this option was not part of the usability study (see more information in Li (2010)). The TG was useful for the exploration of the simple dataset, but useless for the complex annotations because of the represented attribute information. The convenient interactive link with the STC allowed to control time information in an easy way in the GVA environment, but the test persons would like to see more options to zoom in/out.

The 2D map and its focus point were useful to start the data exploration and to understand the dynamic process as a whole. However, an animation was seen as even more useful.

The most appreciated aspect of a GVA environment was interactivity and synchronous relocation of the base map, focus point, and time slider between the STC, TG, and TW that allows deriving different information from each. The majority of the participants used a combination of visual representations while executing the given tasks. Despite this, the interactivity between the STC, TW and 2D map was considered to be weak.

The filtering options for the time, space and attribute variables were seen as an important component of a GVA environment. The participants considered the environment capable of dealing with simple datasets and complex annotations to perform the given tasks. However, improvements are required to facilitate the task execution process. A better synchronization among the representations was highly recommended.

### 7.3.10 Measurement of task performance

The analysis resulted in usability metrics of task performance for both use case studies (see Figure 7.8). In the experiment with simple datasets, six participants out of seven could perform all given tasks effectively. While for the complex annotations, five TPs out of seven were able to complete all given tasks. The results showed some difference in the performance of similar tasks in similar GVA environment for the two different datasets. For instance, five participants out of seven were able to complete the task *characterize* effectively with complex annotations, while for the simple datasets six participants could complete it.

Furthermore, the task *compare* was performed well by six test subject for both use case studies. In general, the task *characterize* was identified as the most ineffective task, and the tasks *identify and locate* as the most effective tasks for the complex annotations. Besides, during the experiment TPs demonstrated a more consecutive strategy for the task execution with the simple dataset than for the complex annotations.

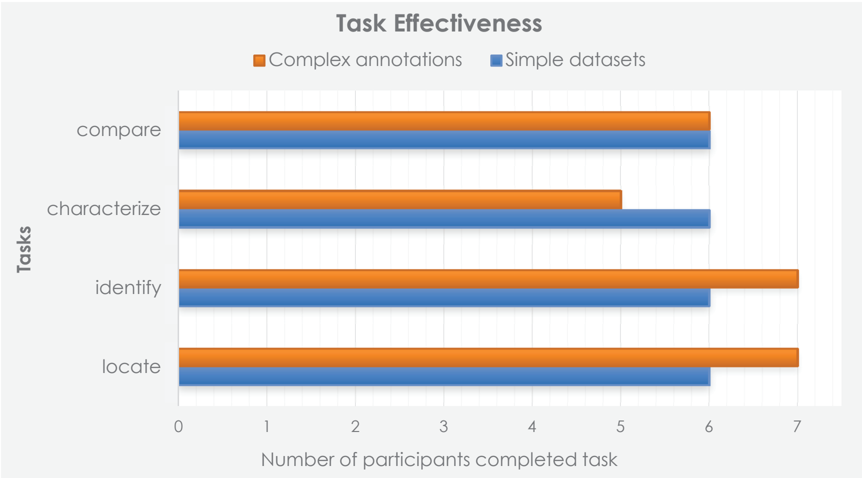



Figure 7.8 The task effectiveness performed by TPs during Experiment I.

Similar to task effectiveness, the task efficiency also revealed some differences (see Figure 7.9). The statistical analysis shows that the tasks locate, identify and characterize were performed in a relatively shorter time for complex annotations than for the simple dataset. On average, the task locate for complex annotations took M=28.65s, while for simple datasets it took M=56.91s. Similarly to the task locate, the efficiency of the task identify with complex annotations on average was M=38.22s, and M=83.08s with the simple dataset. Alike the above two tasks, the task characterize was performed effectively with the simple datasets but more efficiently with the complex annotations. However, only five TPs could complete this task with the complex annotations and six participants with the simple dataset. Besides, for the simple dataset the analysis of this task was more detailed than for the complex annotations. Thus, the task efficiency for the task characterize with complex annotations was M=88.27s on average and with the simple dataset M=149.18s. The efficiency metrics for the task compare were relatively short for the simple datasets. According to the graphs in Figure 7.9, the task compare with the simple datasets was performed in M=42.84s on average and for the complex annotations in M=55.79s. The reason of the differences in efficiency metrics between two use cases was the large number of annotations in the complex annotations evoking a visibility problem without a filtering option, while for simple dataset there was no need for analytical actions and the comparison could be made immediately.

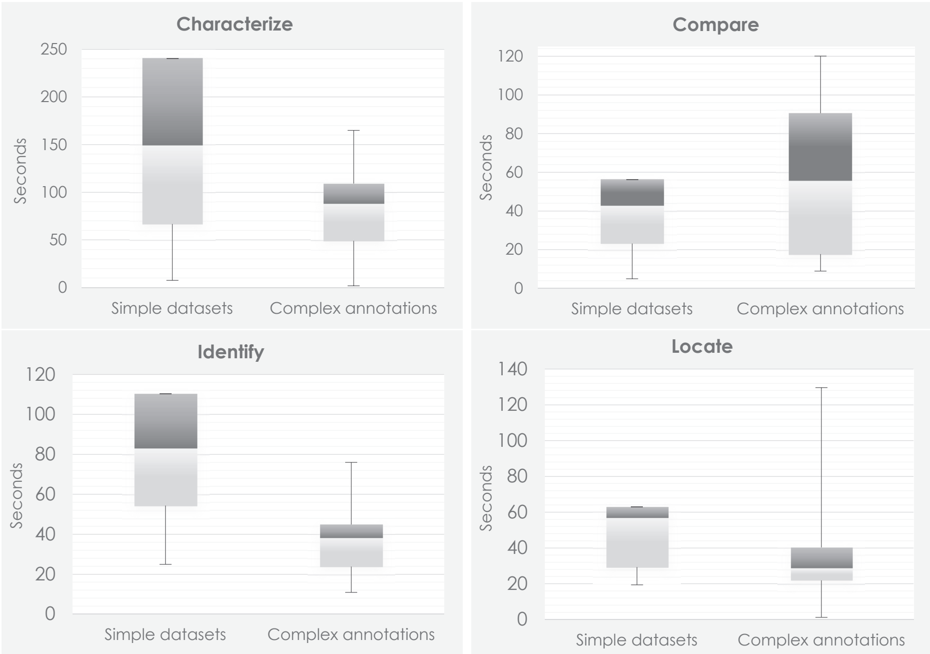



Figure 7.9 Task efficiency metrics for the two use case studies in Experiment I.

### 7.3.11 Measurements of usability of the GVA environment

The experiment revealed the use strategy of the GVA environment for two different use case studies (see Figure 7.10). According to these results, we can conclude that the most used visual representation in this GVA environment was the STC for both use cases. However, significant differences in the intensity of the use of the different visual representations were detected. As figure 7.10 shows, test subjects have used the interactive visual environment more effectively for the simple datasets to accomplish the given tasks than for the complex annotations. In complex annotations, the tasks *identify* and *locate* were completed for 64% in the STC, while for *characterize* and *compare* this figure reaches more than 70%. For the completion of these tasks, other representations were used less extensively. The other visual representations that were used for task performance were the 2D map and TG. This last representation was used for completion of the tasks *locate* and *identify.*

For the simple dataset, the interactive visual environment was used more generally and effectively. Although it is obvious that, alike the complex annotations, the major visual representation used was the STC, it did not exceeded 53%. Next to the STC, TPs used the TG and the 2D map to perform tasks. For instance, for the completion of the task *compare,* a combination of the STC and the TG was used for the simple dataset, while for the complex annotations it was the STC and the 2D map.

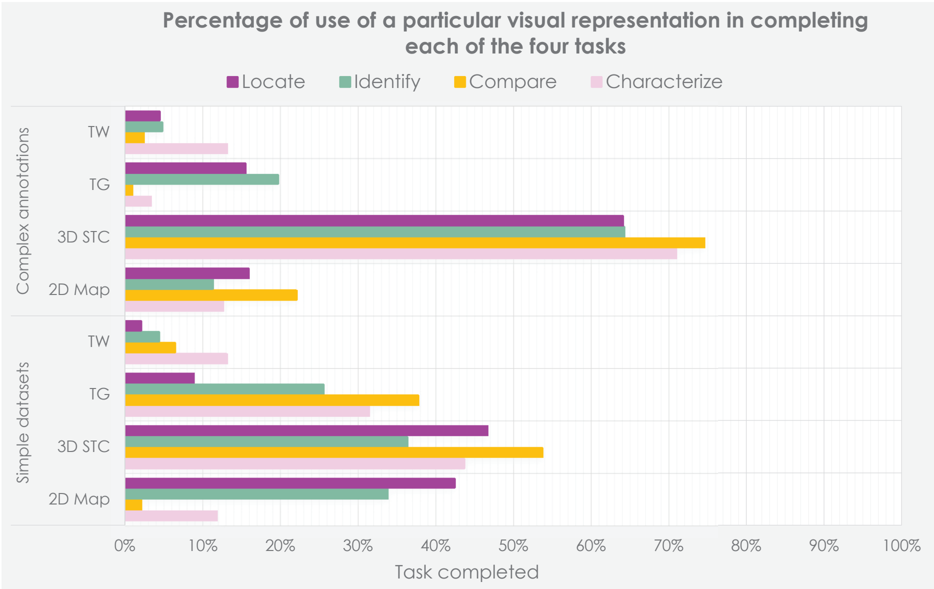



Figure 7.10 Percentage of use of a particular visual representation in completing each of the four tasks in the two use cases during Experiment I.

For executing the task *locate* in simple datasets, TPs used the STC and the 2D map. As for complex annotations, they additionally used the TG, although this happened because of the intensive use of the time slider of the TG to locate the base map in the STC view. For the execution of the task *characterize,* participants used the combination of four visual representations, although the use of the TG was passive with complex annotations. As for the task *identify,* a similar use was detected of the visual representations for both use case studies. All in all, the results derived from the experiment, partly coincided with what was hypothesized initially in section 7.3.2.

# 7.4 Experiment II

## 7.4.1 Development of a GVA environment for the complex dataset of 'Pedestrian movements in the city center of Delft'

The interest of the domain experts was to differentiate shopping activities in pedestrian movements during daytime. To accommodate this, the GVA environment with the STC was extended with a so-called Speed Profile Graph (SPG) to support the exploration of pedestrian movement speed. The graph represents distance along a specific street on the horizontal axis, and time on the vertical axis. In Figure 7.11 the graph represents the Choorstraat. Thus, time and distance in the SPG are measured along a street of interest.

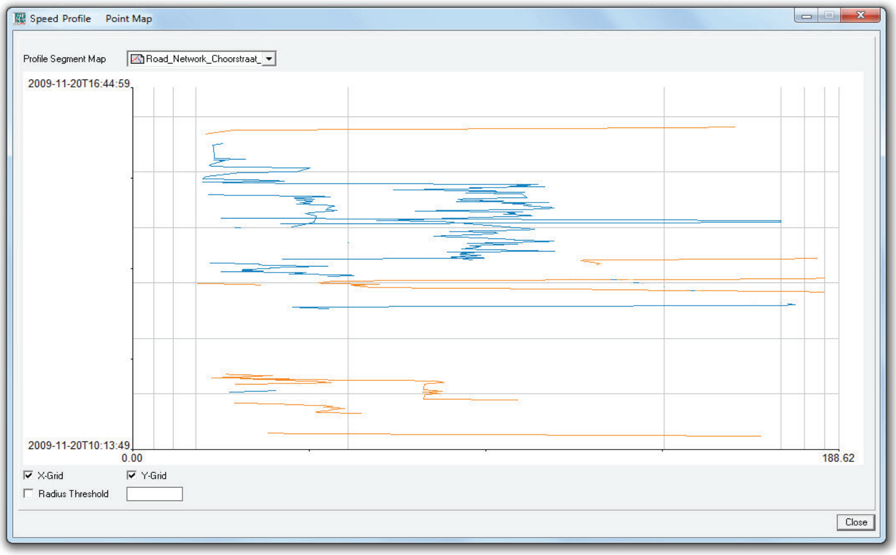



Figure 7.11 Speed Profile Graph (SPG) of the Choorstraat. The vertical axis indicates time and the horizontal axis represents the street distance. The vertical grid lines are located at positions along the street where it clearly changes direction or where side streets join. The horizontal grid lines refer to time. The blue trajectories are pedestrians from the Phoenix garage and orange trajectories are pedestrians from the Southport garage.

The start and end time on the vertical axis can be determined manually and is linked to the time line of the STC (see Figure 7.12). The horizontal and vertical grid lines may optionally subdivide the SPG. Horizontal grid lines divide the time-axis into regular time intervals for easy reference. Two types of vertical grid lines can be added: one at regular intervals for dividing the distance-axis into regular intervals, and one at the positions along the street where it changes direction (for reference), and at crossings (for both reference and further analysis, since some pedestrians might enter or come from side streets). The peculiarity of the SPG is that, a location on the x-axis could meet a pedestrian's track multiple times: one time when he/she goes into a certain direction, once again when he/she returns, and perhaps even more times if he/she cannot make up his/her mind and stay at the same location. The SPG's objective is to act as a 1D version of the STC with the specified projection of the X-coordinate along a street to make comparison of patterns easier. Such a graph is suitable for the visual analysis of visits to locations of interest along a specific path. The SPG was implemented in Ilwis software and interacts smoothly with the previously developed STC. Thus, the SPG becomes another view in the GVA environment. By clicking a location in the graph, the user determines a moment in time. Both the SPG and the

STC react, by changing their selected time value. If a pedestrian's track is located at the mouse-location, the track is selected not only in the graph and the STC, but also in the attribute table.

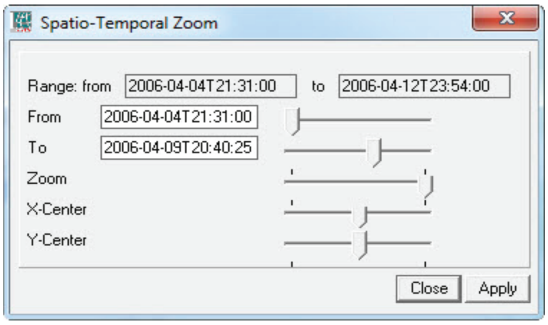



Figure 7.12 The Spatio-Temporal Zoom (STZ) window allows the user to manipulate datasets from a spatial and temporal perspective. The Range indicates a time-period related to the whole dataset. The box *From* and *To* indicates the time the user already zoomed in using the side sliders or by typing in manually. The Zoom refers to the spatial zooming of the 2D base map and consequently the whole cube's content. X-Center helps to pan the STC to East or West, while the Y-Center pans to North and South.

Another analytical tool developed to explore time is the Spatio Temporal Zoom (STZ) (see Figure 7.12). The STZ can be used to determine the start and end time of the SPG and the STC. The start and end times will match synchronously at all times. It allows the user to define the view space / selection of the STC along the x, y and time axis. The user is able to zoom in on a particular time-period using sliders or typing the dates / times manually. The other options (Zoom, X-Center and Y-Center) refer to the spatial zoom of the STC content including the 2D base map. It is important to know that one STZ window could be open for one STC view. Closing and reopening the STZ window would automatically restore the initial content of the STC.

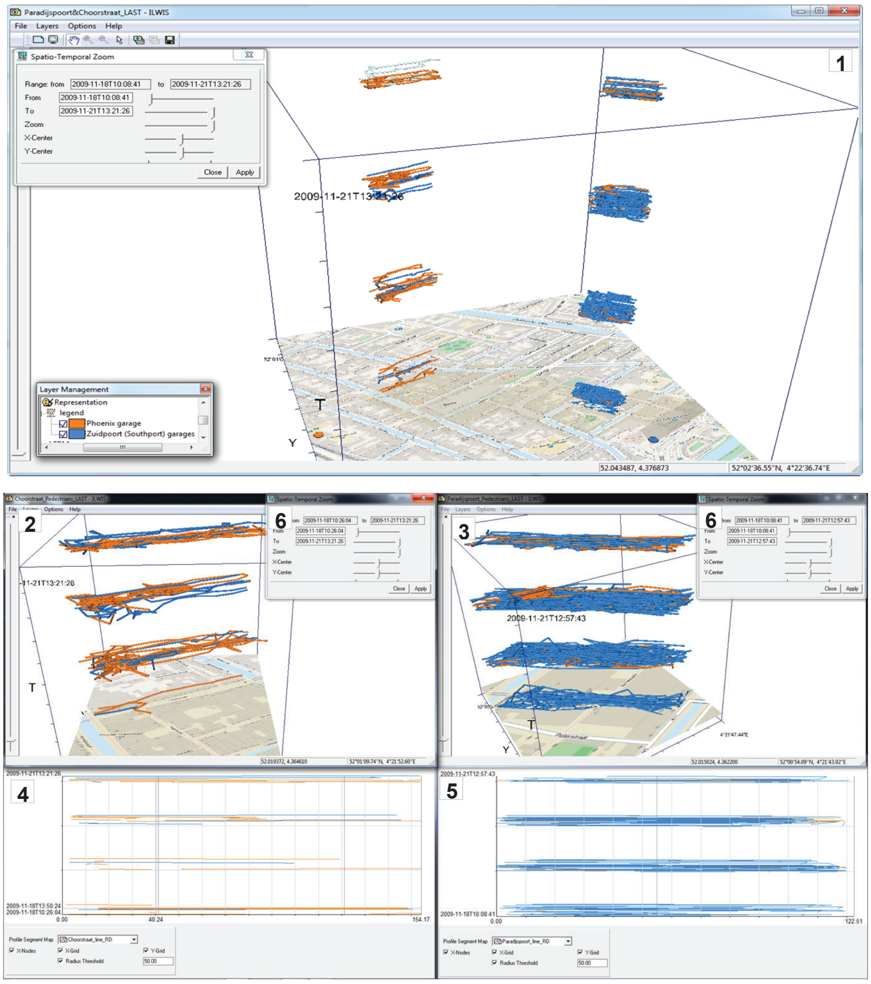


Figure 7.13 The interactive analytical environment introduced to the domain experts during Experiment II. This environment was developed to explore pedestrian movements on the Choorstraat and Paradijspoort in the city center of Delft. The overview map of the STC is shown in view 1. The STC for Choorstraat is represented in view 2 and the STC for Paradijspoort is shown in view 3, the corresponding SPGs are shown in view 4 and 5, the view 6 shows STZ.

The existing STC plugin for Ilwis was enhanced and extended with the option to use OpenStreetMap (OSM) (URL 4) as a base map. Thus, with the help of the developed SPG and STZ tools a new GVA environment was constructed (see Figure 7.13). For better use of the screen space, the legend and other required functionality were placed in a layer management window under the option menu. TPs could open hidden functionalities upon their demand. Manipulation tools such as panning, zooming in/out, entire screen, were located under the right button of the mouse. In the STC, one could identify information for each trajectory through the highlight function. The same approach worked for the SPG. In the development of the environment pop-up windows were avoided.

### 7.4.2 Task execution scenarios

The domain experts were expected to use the developed interactive environment for the execution of the tasks *characterize, select, compare* and *distinguish*, as identified in literature (Knapp, 1995; Zhou and Feiner, 1998; Gotz and Zhou, 2009) (see section 3.2.2). Their interaction activities had to reveal the utilization of each visual representation during data investigation. The analysis of the results of the task completion should lead to understanding effectiveness, efficiency and user satisfaction of each visual representation, and the STC in particular, in this GVA environment. The expected task completion scenarios are the following:

| | |
|---|---|
| TASK 1 | Please characterize the movement patterns of pedestrians in the Choorstraat and Paradijspoort over four days by considering:<br>• Location of the garage<br>• The purpose of the visit<br>• Shopping activities |
| EXPECTED TASK EXECUTION | Participants should observe information for both streets in the STC. Then *characterize* visitors by *selecting* garage, purpose of the visit and shopping activities using the STC and SPG. |
| TASK 2 | Compare the shopping behaviour between the Choorstraat and Paradijspoort, based on the speed of the pedestrian movements. Shopping behaviour is characterized by:<br>- Window shopping – walking in shops to admire goods but not intending to buy them<br>- Efficient shopping –visit a shop to buy the product they want<br>- Pass by/no shopping – moving along the street to go to another street |
| EXPECTED TASK EXECUTION | Domain experts should *compare* shopping activities for both streets in the SPG and *distinguish* between window shopping, efficient shopping and no shopping |

### 7.4.3 Selecting and scheduling of domain expert participants

In the experiment, eight persons of the Faculty of Architecture & the Built Environment of Delft Technical University acted as participants. One female and seven male participants were asked to complete the user profile questionnaire distributed online through 'SurveyMonkey' (see Appendix 7). All of them were scientists and PhD students with 0.5 – 30 years of experience of working in various fields in the geo-domain and of various ages (see Table 7.5).

Table 7.5 Professional background characteristics of expert test participants in Experiment II

| TP № | Gender | Age group | Occupation | What is your field of interest and how it is related to the geo-domain? | How many years of experience do you have in geo-domain? |
|---|---|---|---|---|---|
| **TP 1** | Male | 31 - 35 | Postdoc in GIS technology TU Delft | Geomatics, maps, various-scale, higher dimensional modelling | 14 |
| **TP 2** | Male | 20 - 25 | Student | Informatics, minor, previous experience | 0.5 |
| **TP 3** | Male | 26 – 30 | Academic researcher | 3D GIS inside building structure. It is a new approach of applying spatial analysis inside building. | 10 |
| **TP 4** | Male | 36 - 40 | Professor | Urban design; applying data; data driven design | 10 |
| **TP 5** | Male | 41 – 50 | Assistant Professor | 3D / Tessellations / LBS | >25 |
| **TP 6** | Male | 41 - 50 | Associate Professor | Urban design | 10 |
| **TP 7** | Female | 51 - 60 | Associate professor | 3D GIS, DBMS, 3D modelling | 30 |
| **TP 8** | Male | 20 – 25 | PhD student | Geomatics, 3D city modelling, spatial databases | 2 |

According to the survey, half (4) of the test subjects are using maps once in a day (see Table 7.6), the others 2 – 3 times a week or even less. The main reason of the map use appeared to be navigation and way finding purposes, as well as weather forecast, projecting data and analysis. As for the use of interactive 2D maps the pattern is nearly similar, but for 3D maps the frequency of use is far less as the table shows. Overall, only 7 participants seem to be experienced with interactive graphs by using them 2 – 3 times in a week or at least once in a month.

Table 7.6 Interactive map use experience of expert TPs in Experiment II

| TP № | How often do you use maps in your daily life? | For what kind of purposes do you use them? | What is your experience with interactive 2D maps and how often do you use them? | What is your experience with interactive 3D maps and how often do you use them? | Are you familiar with the STC? | Have you ever used the STC in an interactive environment? | If yes, what was the last time you have used the STC? | What is your experience with interactive graphs and how often do you use them? |
|---|---|---|---|---|---|---|---|---|
| **TP 1** | Once a day | navigation, research | Once a day | 2 – 3 times in a week | Yes | Yes | 3 month – 1 year | 2 – 3 times in a week |
| **TP 2** | Once a month | route planning | Once a week | Once a year | Yes | Yes | 1 month ago | Never |
| **TP 3** | 2 – 3 times in a week | navigation and path planning | 2 – 3 times in a week | 2 – 3 times in a week | No | No | | 2 – 3 times in a week |
| **TP 4** | Once a day | projecting data (i.e. tracks), analysis, orientation | 2 – 3 times in a week | Once a month | Yes | Yes | 1 month – 3 month | Once a week |
| **TP 5** | 2 – 3 times in a week | weather forecast; routing | 2 – 3 times in a week | Once a week | Yes | Yes | 1 month ago | Once a month |
| **TP 6** | Once a day | navigation, research | Once a day | Once a week | Yes | No | | Once a week |
| **TP 7** | Once a day | navigation, orientation | Once a day | 2 – 3 times in a week | Yes | No | | Once a month |
| **TP 8** | 2 – 3 times in a week | navigation | 2 – 3 times in a week | Once a week | Yes | No | | Once a month |

Seven of the eight participants claimed to be familiar with the STC, but only four had interacted with them. The last part of the survey was related to the personal experience in maps construction and use of interactive visual environments (see Table 7.7). All TPs had experience in designing and constructing maps themselves, but not all with the same intensity. Their experience with the different graphics in an interactive environment is because of track analysis, data exploration, navigation, etc.

Table 7.7 Interactive analytical environment use experience of expert TPs in Experiment II

| TP № | Have you ever designed or constructed maps yourself in any program environment? | If yes, how often do you do this? | Are you familiar with the above mentioned graphical representations (2D map, 3D map, and graphs) in an analytical environment? | If yes, please indicate for what kind of purposes did you use that analytical environment? | Please, rank your ability to orient yourself in such an analytical environment. |
|---|---|---|---|---|---|
| **TP 1** | Yes | Once a day | No | | Fair |
| **TP 2** | Yes | Only last semester | No | | Fair |
| **TP 3** | Yes | 2 – 3 times in a week | Yes | Use 3D maps and graphs to finish the task of navigation and evacuation research | Good |
| **TP 4** | Yes | Once a month | Yes | Analysing tracks (movement) | Fair |
| **TP 5** | Yes | | Yes | Data exploration | Good |
| **TP 6** | Yes | Once a month | Yes | GIS, remote sensing | Good |
| **TP 7** | Yes | 2 – 3 times in a year | Yes | Research interests | Very good |
| **TP 8** | Yes | 2 – 3 times in a year | Yes | For analysing the usage of transportation modes in GPS tracks | Very good |

## 7.4.4 Design of the Experiment

**Materials**

The GVA environment constructed for the experiment consisted of four different views, two STC's, and their corresponding two Street Profile Graph (SPG) views (see Figure 7.13). The STZ was introduced as a part of the STC to manipulate temporal aspects in visual environment. One of the STC's displayed the pedestrian movement behaviour on the Choorstraat (view 2) and its corresponding SPG was shown below it (view 4). The second STC (view 3) showed the movement behaviour of people on Paradijspoort street, and its corresponding SPG was also located below it (view 5).

For the contextual exploration of the displayed trajectories, OSM was the base map used in the STC. The same movement trajectories were displayed in the corresponding SPG. Attribute characteristics of the pedestrian movements, such as gender, age, occupation, marital status, purpose of visit, etc. were used for data exploration during the experiment to complete the tasks.

The data provided by the domain experts were prepared for the visualization in the STC. In particular, the collected GPS tracks contained highly detailed data with an accuracy of 5 seconds (see section 4.4.), which was not necessary for visualization in the STC. Therefore, the data were processed and filtered for further use (see Figure 7.14, and Appendix 11).

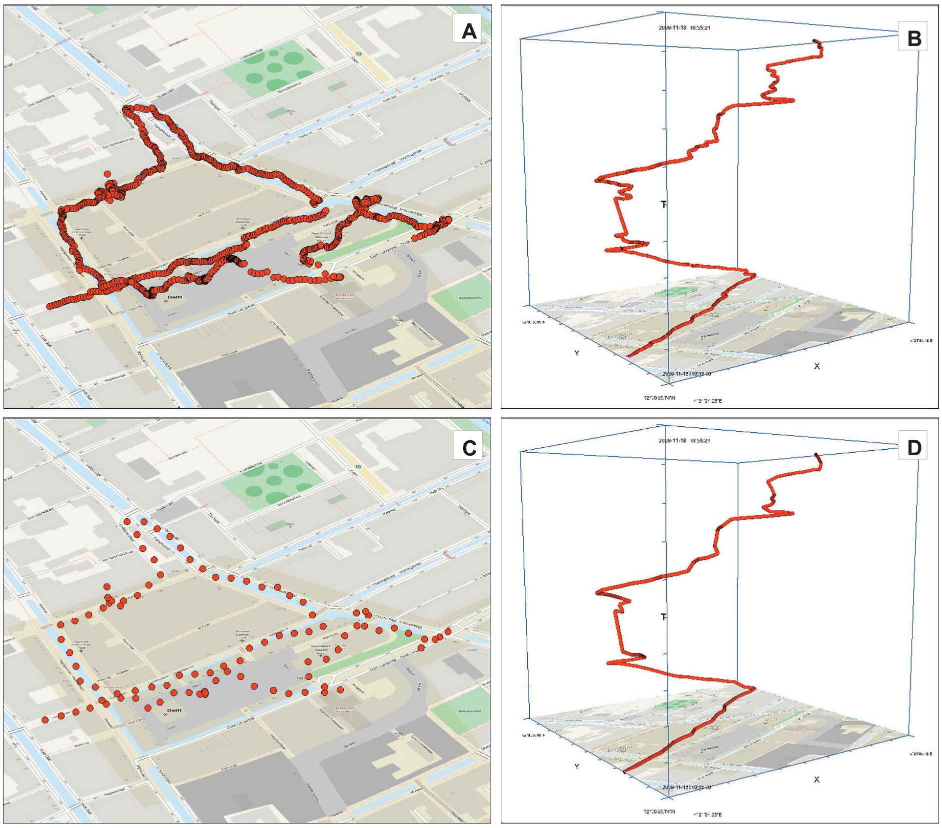



Figure 7.14 Pedestrian movement data in Delft before (A and B) and after filtering (C and D).

**Setup**

For the experiment with the domain experts, a high-performance 15.4 inch MacBook Pro laptop with an Apple Macintosh Operating System was used. This laptop's display parameters were 2880 * 1800 native resolution at 220 pixels per inch, with an integrated 720p face time HD camera. The Ilwis software was displaying the GVA environment, while the audio/video/screen capturing software Camtasia studio (URL 7) was prepared to record the test sessions. For the interactive manipulation of the evaluated visual environment a standard mouse and keyboard integrated in the laptop were used (see Figure 7.15).

Figure 7.15 Evaluation environment during the test session for the Delft use case in Experiment II.

### 7.4.5 Procedure

The evaluation experiment with the complex dataset took place at the Technical University of Delft. The participants were told that the experiment consisted of two sub-sessions. The first sub-session was the task execution with the use case 'Pedestrian movements in the city center of Delft,' and the second sub-session was an interview. The test subjects were given a printed document to explain the purpose of the experiment, the content of the use case study, the applied user research methods and ethics (see Appendix 12). This was followed by a demonstration of the analytical tools and functionalities in the visual environment that were required for the task execution process. Then, participants were given 15 minutes to practice and get familiar with the interactive visual environment. Thereafter, the test subjects were given the printed task document and the session started. After completing the task session, TPs were interviewed and also these sessions were recorded (see Appendix 13).

### 7.4.6 Analysis of the results

The data collected during the experiment through Camtasia studio for the Mac were processed and turned into a verbatim transcript in ATLAS.ti for detailed analysis (see Table 7.4). For a quantitative analysis, each video recording was divided according to task and interview segments in Camtasia Studio 7. From the task segmented videos, information on the analytical task performance was derived. According to the results, all participants were able to complete the tasks while using different exploration strategies. The results of the quantitative analysis were linked to the qualitative outcomes and conclusions were made on the effectiveness and efficiency of the developed visual environment. The results of the experiment are reported in the next section.

### 7.4.7 Results for the complex dataset

**Characterize and select**

The exploration strategy for the tasks *characterize* and *select* was different for each of the test subjects. In general, each TP was starting the session by observing the dataset in the STC. However, for a better understanding of the locations of the two garages and streets, the overview map constructed in a separate view of the STC was required. At the start of the execution of the task *characterize,* the majority of the participants found it easy to observe differences in the amount of trajectories between the two STC views. In order to *characterize* movements, TPs needed to understand at the overview level how pedestrians walked but they faced difficulties in finding out in which direction people were moving. In order to make that information visible, several test subjects suggested to use arrows for the trajectories. The use of the SPG revealed that discovering movement directions appeared to be difficult for most TPs because of the time scale (four days).

In order to be able to complete the task *characterize,* they were able to use different attribute information and filter the data in the STC depending on their demand. They studied the purpose of the visits to the city center and shopping activities using the STZ function to narrow down to one day. However, OSM did not show enough detail, such as the use of buildings located along the Choorstraat and Paradijspoort to determine for which purpose pedestrians went there. There were some complaints that the orientation on the base map of the STC was difficult due to the missing North arrow. Several suggestions were made to improve the environment. The majority of TPs indicated that it would be helpful if both STC's would rotate synchronously to see the data from a similar perspective, as it now requires time to get them in the same position. The overcrowded trajectories on Paradijspoort were seen as the big distinction between the two streets. TPs were also able to see the influence of the location of the garages on the pedestrians' movements. In the end, some participants found it easy to manipulate the GVA environment while some others were confused and required much more time to perform the task *characterize*.

In such a visual environment, the performance of the task *select* proved to be easy for the participants. All eight participants effectively performed the selection of different types of information and individual trajectories in the STC or SPG. The selection of the required attribute information in the layer management was easy, but due to the many options, some TPs needed help. The selection of individual trajectories in the STC views was simple but required all the time a switch between the selection and pan functions and that was not convenient for the participants. Ineffective was the highlight color of the selected objects in the STC. All participants complained about difficulties to see the selected trajectories and distinguish them from the others. The selection of the individual trajectories in the SPG view was rather simple for the participants and did not require any change between different functions. The selection color in the SPG differs from that in the STC and was comparatively easy to distinguish. For several TPs the use of the STZ for time selection was complicated but the majority could manipulate this option effectively.

**Compare and distinguish**

For *comparison* of shopping activities between the two streets, the majority of the participants selected a single day using the STZ and looked for differences. The one obvious difference between the two streets was a more overcrowded Paradijspoort. The *comparison* of different shopping activities was starting from the STC view. Several observations were made. It proved to be difficult to see which shopping purposes are most popular on Paradijspoort because of the high number of trajectories. TPs found that the walking speed was different for both streets and pedestrians were active during the same period over four days. This information was also visible in the SPG, although several participant expected pop-up windows to *characterize* trajectories. Thus, overall, the task *comparison* of the two streets appeared to be easy to perform in this GVA environment. In addition, this task also revealed the influence of the data complexity on cartographic design. For instance, two participants preferred Paradijspoort without the shading depth cues due to the overlapping trajectories.

In order to *distinguish* between shopping activities, test subjects interacted intensively with the STC. Based on these active interaction activities, they could *distinguish* trajectories with comparatively long of stops at particular places which might be efficient shopping. During this task, the importance of a detailed map to find information on the shops where pedestrians stayed for a while was highlighted. The identification of the trajectories through the SPG appeared to be effective for the participants. Using this SPG, they observed the inclination of the trajectories and they found whether pedestrians cross streets and continue walking further or reach their destination at the end of the street and then return. Besides, from the SPG they could also *distinguish* the speed of movements. Also based on the stationary stops the execution of this task was easy.

### 7.4.8 User satisfaction analysis

The user interviews clarified additional information on user satisfaction with the developed GVA environment. Overall, this GVA environment was considered to be capable to analyse the data. However, it was difficult to really get insight because it needed a more detailed base map. To deal with time as a third dimension was seen as quite interesting, although interactivity between views and working in small views with cluttered data was considered something to be improved. In this respect, layer management was advised to make it more user friendly. The majority found it easy to orient themselves in the visual environment but a North arrow sign and some analytical functions were seen as important elements to add. According to a minority, characterizing and comparing information was difficult to perform, and detecting the speed was not easy either for them. However, the majority found it easy to determine the speed for shopping activities and comparing the information for two streets. In this regard, both the STC and SPG were seen as useful and in most cases, they were used in combination to perform tasks. For the STC, TPs appreciated the possibility to observe data from a different perspective, but also to highlight space and time intersections for trajectories through the base map and using different temporal granularities. For them, the STC views require synchronous manipulations and a time slider on the STC frame, whereas the SPG needs analytical functions to discover shopping activities in the data. Despite this, the introduced GVA environment was seen as satisfactory for executing the tasks, as well as a big improvement compared to 2D maps to see movements through space and time. For a convenient and sophisticated analysis was suggested detail base map, but also to incorporate statistical functions to count and measure how much time, how long, how fast, etc., as well as a function that helps to flip trajectories with similar movements together to see piles of movements.

### 7.4.9 Measurement of task performance

The results of this experiment show that the domain experts were effective in their task performance: all eight TPs were able to perform the tasks *characterize, select* and *compare*. As for the task *distinguish*, only seven TPs completed it. One participant stated that this task cannot be completed in this GVA environment. The overall observation of the task execution strategies showed that the domain experts preferred to perform the tasks *distinguish* and *compare* when *characterizing* movements. The reason for this could be a reasonable incorporation of the STC and SPG for effective knowledge extraction.


Figure 7.16 Task efficiency metrics derived from Experiment II.

The task efficiency metrics derived from this experiment also revealed differences in task completion (see Figure 7.16). According to the statistical analysis, on average, the most effective and efficient task for domain experts was *compare* (M=120.59s). Not surprisingly, *Characterize* appeared to be the less efficient and took on average M=435.53s. The completion of the task *select* took M=171.7s on average, and the task *distinguish* M=275.56s.

### 7.4.10 Measurement of usability of the GVA environment

The analysis focused on the use of the visual representations in the interactive visual environment during the execution of each task. The graph in Figure 7.17 shows that the most used visual representation within this experiment for all tasks was the STC. According to the hypotheses introduced in section 7.4.2, this result was surprising, because an intensive use of the SPG was expected.

For the execution of the different tasks, domain experts used a varying combination of visual representations. The task *distinguish* was mainly performed in the STC (68.21%) and in the SPG (29.75%), it was only for a short time that domain experts looked at the overview map (1.44%). The relatively small use of the SPG was unexpected, because the SPG was developed particularly for studying pedestrian shopping behaviours and speed. Similar results were found for the tasks *characterize* and *select.* The task *characterize* was completed for 71.74% in the STC and for 23.33% with the SPG, while the task *select* was completed for 71.83% in the STC and for 21.22% in the SPG. For both of these tasks the overview map was used only briefly (7%). The use of the visual representations for the task *compare* did not differ from the other tasks, although the SPG and overview map were used comparatively longer. In particular, 13.80%

of this task was completed with the overview map, followed by the SPG (23.03%) and the STC (63.17%).

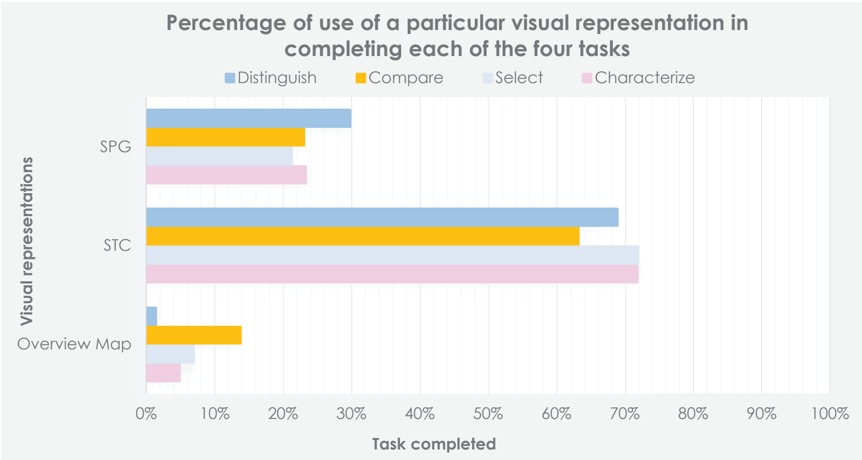



Figure 7.17 Percentage of use of a particular visual representation in completing each of the four tasks in the two use cases during Experiment II.

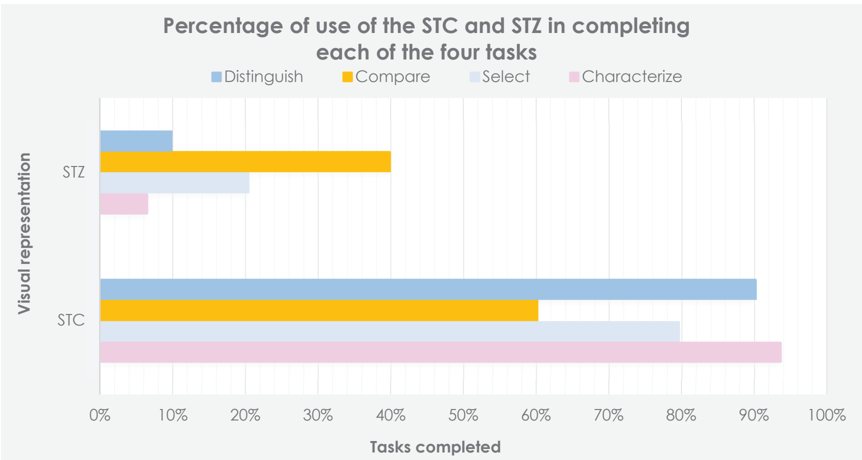



Figure 7.18 The use of the STC and STZ during Experiment II.

From Figure 7.17 arose the idea that the reason for the intensive use of the STC for all four tasks could be the incorporation of the STZ function in the STC. This function is also required to study different temporal granularities in the SPG. To find out more information on the intensity of the use of the STC and STZ separately, the original screen recordings were revisited and information on their use were extracted separately. As Figure 7.18 shows, the domain experts used the STZ with different intensity for the different tasks. However, none of them exceeds 40%, whereas the STC still is the preferred option for the task execution. Even the tasks *compare* and *distinguish* with the hypothesis that the domain experts would perform them in the SPG appeared to be completed in the STC mainly.

## 7.5 Experiment III

### 7.5.1 Development of a GVA environment for the complex dataset of 'Tallinn suburban commuters'

Based on the requirements of the domain experts identified in phase three (see section 4.3), a GVA environment with a prominent place for the STC was developed (see Figure 7.19). Three different visual representations were embedded in this GVA environment to assist the users in finding answers from spatial, temporal and attribute perspectives. In order to build such an environment a Parallel Coordinate Plot (PCP), a 2D OSM base map and a STC with various interactive tools for data exploration were integrated in an Ilwis software environment. The PCP was implemented because of the requirement to analyse complex characteristics of large datasets. The 2D OSM was incorporated to provide information on the spatial distribution of the commuters' movements over the investigated area, whereas the STC offers options for temporal analysis of different granularities. Based on these three visual representations, six different views were created in a new GVA environment (see Figure 7.19). These views are linked to ensure a high interactive support for knowledge discovery.

In order to leave space for visual interaction and emphasize the data in all views, all required buttons and options needed for the experiment were located in a layer management window placed under the 'Options' menu. The rest of the tools to manipulate the 2D OSM and the STC (pan, rotate, zoom in/out) were placed under the right button of the mouse. For the PCP, a mouse-over action reveals the selected variables via a pop-up label in the bottom left hand corner of the PCP. Besides, the STZ used in the second experiment was also used here to manipulate different temporal granularities in the data (see section 7.4.1). One particular function used for this experiment is a 2D map option incorporated within the STC view as an easy transition between 2D and 3D, allowing users to change representations through a checkbox in the layer management window (see Figure 7.20).

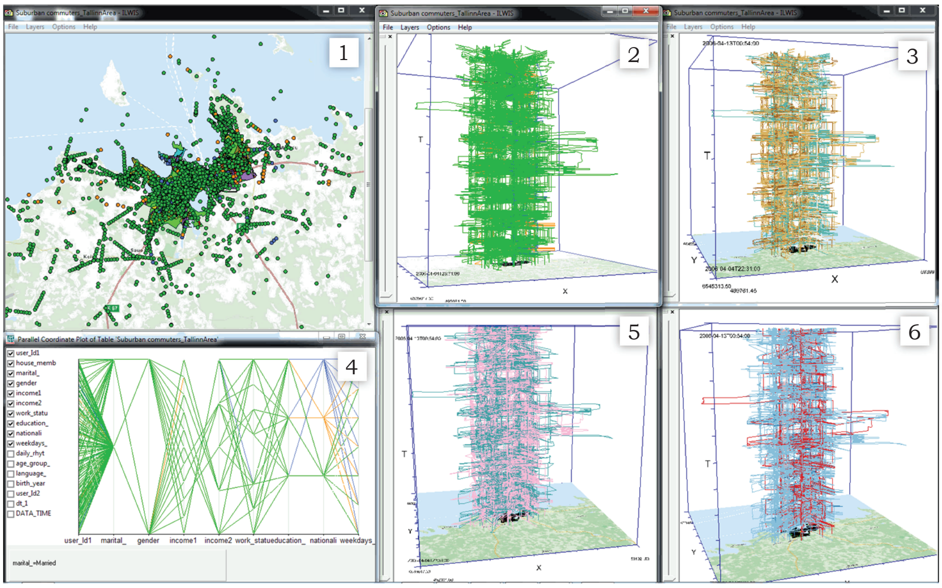


Figure 7.19 Evaluation environment presented to the test participants during Experiment III: View 1 – different ethnic groups on the 2D Openstreet map. View 2 – different ethnic groups in the Space-Time Cube (STC). View 3 – different education groups in the STC. View 4 – different ethnic groups in Parallel Coordinate Plot (PCP). View 5 – gender groups in the STC. View 6 – income groups in the STC.

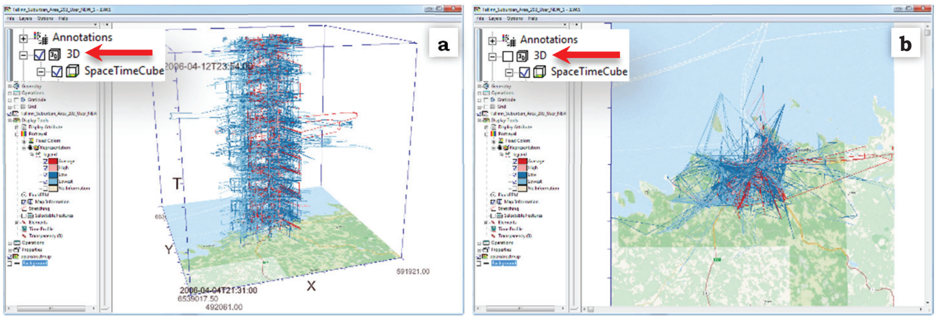


Figure 7.20 Manipulation of 3D and 2D representations within the STC view: **a**. The STC view and **b**. 2D map option of the STC view (2D STC).

## 7.5.2 Task execution scenario

For both groups users the experiment consisted of applying several exploration actions when completing the use tasks. In order to evaluate the capabilities offered by the interactive environment, eight different tasks (obtain, filter, describe, identify, compare, distinguish, locate and characterize) were identified from existing literature (Knapp, 1995; Zhou and Feiner, 1998; Gotz and Zhou, 2009). The expected exploration behaviour of the participants for each task was hypothesized as follows:

| | |
|---|---|
| Task 1 | Please characterize the overall movement patterns: where do people move / go to? |
| Expected task execution | Expected participant behaviour is to have an overview of the data content in the developed visual environment. By interacting (pan, zoom in/out) with the 2D map they have to orient themselves and *obtain* directions into which people move. |
| Task 2 | Are there any spatial and temporal differences in the movement behaviour of ethnic groups? Why? |
| Expected task execution | Participants are expected to choose the second view in the proposed visual environment. By *filtering* information from the legend menu, they should observe and *describe* spatial and temporal differences in movement patterns. |
| Task 3 | What are the socio-economic characteristics (e.g. age, income, gender, etc.) of the individuals moving out of Tallinn during the weekend? |
| Expected task execution | To complete this task, participants should *identify* only the weekends in the STC view. Then they should select trajectories moving out of the city and look at the PCP to *compare* attribute characteristics by income, gender, age, or education groups.<br>Alternatively, *identify* only weekends in the STC view and look at the movements in other STC views too to *compare* attribute characteristics by income, gender, age, or education groups. |
| Task 4 | During the day, people stay in different places in Tallinn (e.g. in the business area, the old town, the harbour area, etc.). These areas are shown in the land use map.<br>Describe different patterns of where people stay in the course of a day. |
| Expected task execution | Based on the stationary and inclined trajectories, participants should *distinguish* a daytime. Then *locate* on the screen from the land use map the most occupied areas in the course of a day. |
| Task 5 | How do the activities of people change over the week? |
| Expected task execution | Participants are expected to observe day and night activities by moving the 2D base map along the time axis and *characterize* temporal rhythms of movement patterns over the week. |

## 7.5.3 Selecting and scheduling of test participants

The experiment was designed for two groups of users, the domain experts who were the owners of the data (see section 3.3.4 and 4.3), and non-domain experts who were unfamiliar with the data and the research problems, but familiar with visual representations incorporated in the developed GVA environment. Similar to previous experiments, they also were asked to complete the user profile questionnaire distributed online through 'SurveyMonkey' (see Appendix 7).

**Domain experts**

The group of seven domain experts consisted of three female and four male researchers of the Department of Geography of the University of Tartu. The participants of different age were researchers and PhD students with a great interest in different geo-domains and with experience between 7 to14 years (see Table 7.8).

Based on a questionnaire, other background characteristics important for the experiment were derived (see Table 7.9). As it appeared, most of the TPs are using maps in their daily life at least once a day for data analysis, finding routes, visualization, etc. The interactive 2D maps are used much more often than the interactive 3D maps and graphs. Besides, three participants out of seven indicated that they are familiar with the STC and have interacted with it some time ago.

Table 7.8 Professional background characteristics of domain expert test participants in Experiment III

| TP № | Gender | Age group | Occupation | What is your field of interest and how it is related to the geo-domain? | How many years of experience do you have in the geo-domain? |
|---|---|---|---|---|---|
| **TP 1** | Female | 31 – 35 | Researcher | Human geography, spatial analyses | 10 |
| **TP 2** | Female | 26 – 30 | GIS - specialist | Mobile positioning, geo-databases | 9 |
| **TP 3** | Male | 31 – 35 | Researcher | GIS, mobile positioning, spatio-temporal behaviour | 16 |
| **TP 4** | Male | 31 – 35 | PhD Student | PhD student in geo-informatics | 13 |
| **TP 5** | Male | 31 – 35 | PhD student | Mobile positioning, work-related, school-related | 14 |
| **TP 6** | Female | 26 – 30 | PhD student | Human geography | 7 |
| **TP 7** | Male | 31 – 35 | PhD student | Human mobility | 10 |

The other questions of the survey provided information on the participants' experience with analytical environments (see Table 7.10). Six participants had indicated that they are experienced in creating maps themselves, and are doing it at least 2-3 times in a week.

All are familiar with interactive graphs, 2D and 3D maps in an analytical environment, because of analytical purposes of their research. In addition, three domain experts indicated that they have a good ability to orient themselves in an analytical environment, while others rank their ability as very good and fair.

Table 7.9 Interactive map use experience of domain expert test participants in Experiment III

| TP № | How often do you use maps in your daily life? | For what kind of purposes do you use them? | What is your experience with interactive 2D maps and how often do you use them? | What is your experience with interactive 3D maps and how often do you use them? | Are you familiar with the STC? | Have you ever used the STC in an interactive environment? | If yes, what was the last time you have used the STC? | What is your experience with interactive graphs and how often do you use them? |
|---|---|---|---|---|---|---|---|---|
| **TP 1** | Once a day | To illustrate my study results, reading other's study results, looking for some place | Once a day | Once a month | Yes | Yes | More than 1 year | Once a day |
| **TP 2** | Once a day | Data analysis | Once a day | 2 – 3 times in a year | No | No | | 2 – 3 times in a year |
| **TP 3** | Once a day | Learning, spatial analysis, way finding | Once a day | Once a week | Yes | Yes | Today | Once a day |
| **TP 4** | Once a day | Finding places or routes, visualizing work results | Once a day | Once a week | No | No | | Once a day |
| **TP 5** | Once a day | Mostly work | Once a day | 2 – 3 times in a year | Yes | Yes | 3 month – 1 year | 2 – 3 times in a week |
| **TP 6** | 2 – 3 times in a year | For travelling purposes | 2 – 3 times in a week | Once a month | No | No | | 2 – 3 times in a week |
| **TP 7** | 2 – 3 times in a week | To visualize data | Once a week | Once a year | No | No | | Once a month |

Table 7.10 The use experience of interactive analytical environments of the domain expert test participants in Experiment III

| TP № | Have you ever designed or constructed maps yourself in any program environment? | If yes, how often do you do this? | Are you familiar with the above mentioned graphical representations (2D map, 3D map, and graphs) in an analytical environment? | If yes, please indicate for what kind of purposes did you use that analytical environment? | Please, rank your ability to orient yourself in such an analytical environment. |
|---|---|---|---|---|---|
| **TP 1** | Yes | 2 – 3 times in a week | Yes | To illustrate my study results | Good |
| **TP 2** | No | | No | | Good |
| **TP 3** | Yes | 2 – 3 times in a week | Yes | Research | Very good |
| **TP 4** | Yes | 2 – 3 times in a week | Yes | Spatio-temporal analysis of mobile positioning data | Very good |
| **TP 5** | Yes | 2 – 3 times in a year | Yes | Data analysis | Good |
| **TP 6** | Yes | Once a month | Yes | | Fair |
| **TP 7** | Yes | Once a month | Yes | | Fair |

**Non-domain experts**

The second sub-experiment was executed by one female and six male participants of the ITC Department of Geo-Information Processing of the University of Twente. The participants varied in age between 26 and 60 years old and included PhD students, lecturers and researchers in the geo-domain. They had experience between one and a half to over forty years in different GeoInformatics topics (see Table 7.11) (see Appendix 7).

Table 7.11 Professional background characteristics of the non-expert test participants in Experiment III

| TP № | Gender | Age group | Occupation | What is your field of interest and how it is related to the geo-domain? | How many years of experience do you have in the geo-domain? |
|---|---|---|---|---|---|
| **TP 1** | Female | 26 – 30 | PhD student | Geovisualization | 4,5 |
| **TP 2** | Male | 51 – 60 | Teacher - Cartographer | Cartographic design and thematic mapping | 41 |
| **TP 3** | Male | 31 – 35 | Teacher | Spatial-temporal index, spatial query, 3D geological data model | 10 |
| **TP 4** | Male | 26 – 30 | PhD Student | Spatiotemporal modelling | 8 |
| **TP 5** | Male | 31 – 35 | Researcher | Geospatial, LBS, Geo-intelligence, Geo-HCI | 10 |
| **TP 6** | Male | 26 – 30 | Tutor | Spatio-temporal analysis | 5 |
| **TP 7** | Male | 31 – 35 | PhD student | Geovisualization & visual analytics | 1,5 |

Their map use experience is similar to that of the human geographers (domain experts). All non-domain experts are using maps in their daily life for purposes such as finding pathway, addresses, research, transport, navigation, etc. (see Table 7.12).

Table 7.12 Interactive map use experience of non-expert test participants in Experiment III

| TP № | How often do you use maps in your daily life? | For what kind of purposes do you use them? | What is your experience with interactive 2D maps and how often do you use them? | What is your experience with interactive 3D maps and how often do you use them? | Are you familiar with the STC? | Have you ever used the STC in an interactive environment? | If yes, what was the last time you have used the STC? | What is your experience with interactive graphs and how often do you use them? |
|---|---|---|---|---|---|---|---|---|
| **TP 1** | 2 – 3 times in a week | Looking for addresses | 2 – 3 times in a week | 2 – 3 times in a year | No | No | | 2 – 3 times in a week |
| **TP 2** | Once a day | Plan my trips, Find locations, Analyse spatial relations, Analyse the representation | Once a day | Once in a week | Yes | No | | Once a month |
| **TP 3** | Once a month | Find path to somewhere | Once a year | Once in a week | Yes | Yes | 1 month ago | Once a month |
| **TP 4** | Once a day | Research, transportation | 2 – 3 times in a week | 2 – 3 times in a year | Yes | Yes | 1 month – 3 month | Once a day |
| **TP 5** | Once a month | Finding Location, calculating travel time | Once a month | 2 – 3 times in a year | Yes | No | | Never |
| **TP 6** | Once a day | Navigation, mapping the spatial distribution | Once a day | Once a year | Yes | Yes | 1 month ago | 2 – 3 times in a year |
| **TP 7** | Once a day | Planning & Navigation | Once a day | 2 – 3 times in a year | Yes | Yes | 3 month – 1 year | Once a day |

A different frequency of use was detected for interactive 2D maps and 3D maps. For 2D maps, three participants indicated that they use them at least once a day and others 2-3 times in a week. As for the interactive 3D maps: no one is using them in daily life, but once in a week or 2-3 times a year. The survey also provided information on the participants' skills with interactive graphs. As it seems, most of them are using graphs only once in a month or 2-3 times in a year. Six test subjects out of seven are familiar with the STC, but only four of them have interactive experience. All non-domain expert participants are experienced with designing maps themselves. Two participants are doing this 2-3 times in a week, three participants once in a week, and the rest only 2-3 times in a year.

Three participant out of seven indicated that they are using interactive graphs, 2D maps and 3D maps in an analytical environment for research for various spatio-temporal analyses (see Table 7.13). Finally, four test subjects rank themselves as good to orient themselves in such an interactive environment and the others as fair.

Table 7.13 The use experience of interactive analytical environments by the non-expert test participants in Experiment III

| TP № | Have you ever designed or constructed maps yourself in any program environment? | If yes, how often do you do this? | Are you familiar with the above mentioned graphical representations (2D map, 3D map, and graphs) in an analytical environment? | If yes, please indicate for what kind of purposes did you use that analytical environment? | Please, rank your ability to orient yourself in such an analytical environment. |
|---|---|---|---|---|---|
| **TP 1** | Yes | 2 – 3 times in a year | No | | Fair |
| **TP 2** | Yes | Once in a week | Yes | I use it mainly to develop exercises for our programs, e.g. to detect demographic changes over different years | Good |
| **TP 3** | Yes | 2 – 3 times in a year | No | | Fair |
| **TP 4** | Yes | 2 – 3 times in a week | No | | Good |
| **TP 5** | | | No | | Fair |
| **TP 6** | Yes | Once a month | Yes | Spatio-temporal trends | Good |
| **TP 7** | Yes | 2 – 3 times in a week | Yes | | Goodz |

## 7.5.4 Design of the experiment

**Materials**

In the constructed GVA environment (see Figure 7.19), the movement behaviour of suburban commuters in the Tallinn district area was represented (see section 3.3.4). The additional supporting tool used as an important factor in the data exploration process was a land use map. Thus, view 1 was generated by overlaying the points of mobile phone call signals of suburban commuters on a 2D OSM and land use map (see Figure 7.19-1). The 2D base map of the STC, located at the bottom, was identical to this 2D OSM (enclosing the land use map). The STC's were displaying mobile phone signals as movement trajectories in space and time (see Figure 7.19-2, 3, 5, 6). The four views of the STC were displaying the movements of suburban commuters from different attribute perspectives: view 2 – ethnic groups, view 3 – education, view 5 – gender and view 6 –income. Overall, the 2D OSM (view 1), the PCP (view 4) and the STC (view 2) were representing the same information on different ethnic groups. While views 3, 5 and 6 were intended to support the data characterization and exploration process.

**Setup**

The first sub-experiment, executed by domain experts, was administered and performed on a high-performance 15.4 inch MacBook Pro laptop with an Apple Macintosh Operating System. The laptop's display parameters were 2880 * 1800 native resolution at 220 pixels per inch, with an integrated 720p face time HD camera. Ilwis software was used to construct the GVA environment. The mouse and the laptop keyboard could be used to interact with the GVA. In order to record the user's screen manipulations, video and audio activities simultaneously, the screen capturing and recording software Camtasia studio was used.

The second sub-experiment, executed with non-domain experts, was designed and performed on a Dell Windows 7 workstation running Tobii Studio 3.2 software. The GVA environment developed in the Ilwis software program was shown on a 24 inch LCD flat – panel display with 1680 * 1050 screen resolution. Participants had to use a standard mouse and keyboard to interact with and manipulate the displayed views during the task execution sessions. A Tobii X 60 Eye Tracker at a 60 Hz sampling resolution was used to capture eye movements, screen activities, video and audio simultaneously.

### 7.5.5 Procedure

The first sub-experiment took place in a room at the Geography Department of the University of Tartu, which was specifically reserved for this usability experiment (see Figure 7.21). The domain experts were given documents explaining the objective and purpose of the evaluation study, test procedure, usability ethics on respondent confidentiality and the usability methods used in the experiment (see Appendix 14). Particular attention was given to the think aloud method, in which they were asked to express their opinions and attitude about the introduced interactive environment. After this introduction, the test subjects were explained how to operate the GVA environment and demonstrated the required functionality for the task execution. This was followed by a 15 minutes practice session to familiarize the TPs with the visual environment and allow them to experiment with the newly introduced functionality. Once the participants felt ready, the actual experiment sessions were started.

Figure 7.21 Working environment for domain experts in Experiment III.

Figure 7.22 Working environment for non-domain experts in Experiment III.

Participants were given a document containing eight different tasks to perform. During the task execution process, the experts were free to use the visual environment as they would think right or comfortable. They were able to minimize and maximize the 2D OSM and STC views, but were not allowed to remove them. Also, they were free to change any attribute characteristics in any visual representation they would think to be needed to complete the task. Sometimes, the test moderator was providing some help when they got stuck and the moderator also stimulated the think aloud actions. After completing the tasks, participants were interviewed (see Appendix 15). They were asked to confirm opinions expressed earlier during the task execution session and to share their experiences about the graphic representations used in the experiment.

The second sub-experiment took place in the usability laboratory of the ITC Department of Geo-Information Processing of the University of Twente (see Figure 7.22). The procedure for the non-domain experts was similar to that of the domain experts. They were given a document with test instructions, explaining the purpose of the experiment, the used evaluation methods, etc. (see Appendix 14). Participants were then demonstrated the required functionality for each graphic representation and were given 15 minutes to practice it, so as to be sure that they could easily find the location of each function. Similar to the domain experts, the non-domain participants were also asked to think aloud during the test session to formulate their personal opinions on the visual environment regarding to the given questions. After the practicing session was completed, participants were introduced to the working principles of the eye tracker and took a comfortable position for eye calibration. When the eye tracker was calibrated through Tobii studio software, the actual test session started. Participants were given the task document and similar to the domain experts they were free to use the visual environment depending on their own decisions, i.e. moving views over the visual environment, minimize/maximize, etc. After the task session was completed, each participant was interviewed to confirm the expressed opinions on each graphic representation and about the interactive visual environment as a whole (see Appendix 15).

### 7.5.6 Analysis of the results

Data collected during the first sub-experiment through Camtasia Studio 7 were processed and made into a verbatim transcript in ATLAS.ti for detailed qualitative analysis (see Table 7.4). For a quantitative analysis the recordings were divided in video segments for each task to derive information on the effectiveness and efficiency of task completion. These analyses revealed that all participants were able to complete the tasks using different strategies and time-periods.

The recordings derived from the second session with non-domain TPs were also divided in video segments in Tobii Studio to derive usability metrics. Based on the time required to accomplish the given tasks, quantitative measurements were made. Similar to the first session verbatim transcripts were made in ATLAS.ti for qualitative analysis. The results obtained from both experiments are reported on in the section below.

### 7.5.7 Results for the large dataset

**Obtain directions**

This task intended to find out whether the visual environment was simple enough for the users to understand and orient themselves when describing overall movement patterns. To accomplish the task *obtain*, most of the domain experts emphasized to have no need for a 3D representation. In general, they mentioned that, to answer questions related to the spatial distribution, a 2D map is enough, although the task was completed in combination with the STC. From the 2D map, participants were able to determine busy areas and movement directions. But to obtain information on the same trajectories from a temporal perspective, the use of the STC was necessary. Observation of the exploration behaviour revealed an intensive use of the top middle window (Figure 7.19-2). The use of basic interaction activities (zoom in/out, pan and rotate) helped to study, understand and describe movement behaviors from various perspectives. Observation of the task execution revealed that participants were unhappy with the way the movement data were represented on the OSM. They preferred lines instead of non-connected dots. This could be realized using the 2D STC view (see Figure 7.20). The strategy for the task *obtain* revealed two major approaches. The first is an overall observation referring to the overview step and describing movement patterns in general from a spatio-temporal perspective. The second is more detailed and includes an analysis of the attribute characteristics from spatio-temporal perspectives. The participants complained that the STC not allows to find specific patterns due to the overlapping issue. Also, the color of the selection option was considered to be hard to see.

Similar to the domain experts, the non-experts also started their task performance by selecting the top middle view (Figure 7.19-2). For *obtaining* movement directions, the majority of the TPs applied the STZ to narrow down to single day activities, and by moving the 2D base map along the time axis of the STC they were able to derive information on the daily behavior of suburban commuters. Later on, they moved back to the overview level to obtain information on general movement activities over the week by moving the base map in the STC.

The non-domain experts had the same problem with the dots on the OSM as the experts. They also preferred lines instead. The results of the analysis of the task *obtain* for non-experts also revealed two strategies of execution. The first is the overall observation of trajectories to describe movement patterns from a spatio-temporal perspective, and the second, detailed strategy, focuses on the daily rhythms and attribute characteristics to judge the commuters' movement behaviors on other weekdays. Similar to the domain experts, the non-experts also considered the spatio-temporal exploration of the dataset as important.

**Filter and describe**

These tasks intend to find out whether test participants were able to manipulate the data content in the interactive visual environment. The experience gained during the previous task made the completion of the task *filter* easier for the domain experts. They were able to manipulate data from the legend menu and compare spatio-temporal differences. Some TPs studied movement behaviors of ethnic groups in the STC and completed the task *filter* effectively, while others preferred the 2D STC. It was obvious that the spatio-temporal observation of data in the STC was convenient but they needed to see the distribution of the movements in 2D space too. Some followed different strategies. These included starting from the STC or map, move from detail to overview and vice versa, as well as apply filter on attributes working with the PCP. According to a minority of the test subjects, the 2D STC does not provide much content to describe temporal aspects of the movements, while another minority preferred to study these movements in the 2D STC to see the spatial distribution of movements.

The task execution strategy for *describe* was different. Some test subjects could perform this task by studying the data from a temporal perspective in the STC. While others based their findings on the overview of the data and stated that differences in sample sizes make it difficult to draw specific conclusions. In order to collect information on different nationalities, a minority used the PCP as additional possibility of exploration. During the interaction, test subjects were able to manipulate the order of the attribute characteristics, or filter information to reduce disturbance on the display. This exploration experience allowed them to say that the PCP is useful for studying different characteristics. The observation of the task performance revealed that the participants did not interact much with the 2D STC or the 2D OSM for their performance of the task *describe,* while the STC required interaction to see data from different perspectives.

For the execution of the task *filter,* non-experts first looked at the overview in the STC based on the attribute characteristics. Most of the non-experts stressed that the large number of trajectories makes it difficult to see movements of different ethnic groups over the week. To make the movements observable, they used the STZ and selected a single day to describe movements of Estonians and Russians. A minority of participants studied differences between ethnic groups directly using the *filtering* option of the legend view. They were able to see groups one by one and *describe* them as initially hypothesized. A minority used a slow motion of the STZ slider to study spatio-temporal behaviours of different ethnic groups on the 2D STC. This option was found not enough to *describe* temporal aspects in the data. So, the test observation revealed different strategies for executing the task *describe*.

The observation of task executions through the recordings of the eye movements revealed that TPs had difficulties to find information efficiently from the layer management window. They were confused by the many options and took a long time to select the relevant functionality.

**Identify and compare**

These tasks aimed to find out whether the interactive visual environment was able to help the user's visual perception to memorize the spatio-temporal distribution of movements. During the task *identify* they were required to look at different characteristics of the suburban commuters moving outside of Tallinn in the course of the weekend. Most of the participants started this task as hypothesized, *identifying* weekends using the STZ and selecting attribute characteristics for weekdays to analyse the data. A minority of the participants could *identify* weekends from the attribute characteristics by coloring weekdays in the STC, and then they decided to select trajectories moving outside of Tallinn city. A minority first selected trajectories moving outside of the city and then observed them in the PCP to explore attribute characteristics. The domain experts suggested an improvement of the PCP by implementing a counter to provide information on how many trajectories are located under a certain category (gender, age group, etc.).

For the execution of the task *compare,* the domain experts were expected to use small multiple views of the STC or PCP showing all attribute characteristics together. The first option was considered as time consuming and participants preferred to compare characteristics within one STC view by selecting and deselecting different attributes. The reason was that the STZ was working only with one STC view at a time and applying it all over again was uncomfortable for them. Besides, they liked to see the data characteristics in one big view of the STC. The majority of the participants found it difficult to understand the PCP. They tried to explore the data by interacting with them but the data complexity did not allow to see information effectively in the PCP. Therefore, TPs preferred to continue their data investigation in the STC and 2D STC. During the execution of the task *compare*, a usability issue related to the filtering option in the legend menu was revealed. It was loading the whole dataset over and over again when applying new attribute information. However, the majority could solve this problem by using the STZ and then *compare* different characteristics.

Different from the domain experts, the non-domain experts used the STZ to *identify* weekends. Then, without many interactions, they *compared* the different characteristics of weekend patterns one by one, mainly in the STC. A minority of the non-experts could *identify* weekends visually from the overview of the STC and instead of using the STZ option, they located the base map to *compare* different attribute characteristics. The non-expert participants sometimes applied unique strategies, not always leading to a result or proving to be very time consuming. For instance, one TP used the base map of the STC to observe the awaking time indicated by a sudden movement of trajectories towards the city center, and a sudden movement back to the home location. Such similar daily rhythms with sudden movements of trajectories were not observed during two days, which were *identified* as weekends. After identifying the weekends, a minority of the participants also applied the PCP to *compare* different characteristics, but could not perform this task.

**Distinguish and locate**

These tasks intend to detect whether the users of the STC were able to understand temporal aspects of the data in the interactive visual environment. When *distinguishing* busy areas in the Tallinn city area, the domain experts pointed to the large number of trajectories creating spots with clutters on the map. Considering the knowledge of the domain experts of the use case data, they could also logically guess the most occupied places. However, they preferred to complete the task in the proposed GVA environment by using attribute characteristics on the 3D and 2D maps. To perform this task on the land use map, some test subjects changed categorized data into one color. Then they applied the STZ to examine data in the STC from various perspectives. The other observed exploration strategy was moving the base map along the time axis of the STC to *locate* the most busy areas on the map over the course of a day. However, it could not help to avoid the clutter problem. For simplifying the exploration process the participants used information on daily rhythms, i.e. movement behaviours in the morning, afternoon, evening and night. The other observed strategy to perform the task was to use the 2D OSM and STZ by selecting one day in the STC. The test subjects plotted trajectories on the 2D OSM to *locate* the most occupied areas in the daytime. Some even used a slow motion animation from the STZ slider to observe increase or decrease of activities over a day and l*ocate* the most occupied places. Some test subjects first observed land use categories on the 2D STC and then returned to the STC view to look at daily rhythms. Regarding this task a suggestion was made to implement an additional slider with which a user can fix several hours difference and track the movements (perhaps a slider like the one applied in Google Earth). Another suggestion was to develop functionality that will allow the selection of land use districts and trajectories within the area to obtain their quantity. Such functionality should also allow the identification of movement activities of selected trajectories within other areas for other time-periods as well. This approach should be a flexible solution for studying small areas overlaid with a large number of trajectories. A similar suggestion was to develop a window that will show the percentage of distributed dots in each land use area and the different nationalities in it.

Based on the STZ, a majority of the non-experts selected a single day and *distinguished* daytime in the STC view. Then, some of them applied spatial zoom to enlarge the Tallinn city area. For the next step, the test subjects focused on the exploration of the land use map and later they started moving the base map along the time axis to observe the distribution of the trajectories in Tallinn city. During this process, some test subjects were able to *locate* the busiest places in Tallinn city. Some TPs were able to perform the task *locate* through the 2D OSM but could not *distinguish* daytime. A minority decided to use spatial zoom on the city center and *locate* busy areas over the course of a day. So, different TPs provided individual solutions to fulfill this task.

**Characterize**

This task was supposed to reveal whether the users are able to detect temporal changes from the overview level. The task *characterize* was considered to be easy to perform in this GVA environment. During the other tasks, the TPs had already given a kind of overview characterization. The majority of the participants completed the task *characterize* by describing the spatial distribution of the movements. Often by moving the base map along the time axis in the STC, they could describe the movement behaviors consistently. They did not discover very big differences between days. It was easy to follow patterns and *characterize* them.

A majority of the non-experts also had already performed this task in combination with earlier completed tasks. The non-domain experts could visually *characterize* the movement patterns over the week by moving the base map along the time axis.

### 7.5.8 User satisfaction analysis

**Domain experts**

According to the analysis of the interview sessions, the developed visual environment proved to be satisfactory for most of the domain experts. However, the experts stated that they need more experience to get used to work with such an interactive application. They also mentioned that it was difficult to remember the location of the tools, but after using the environment once it already became easier to orient and explore the data. All participants gave suggestions for the improvement of the analytical capabilities of the GVA. For instance, they wanted to be able to combine tasks. Such as, *identify/compare* and *distinguish/locate,* which are seen as difficult to complete in the current GVA environment.

Most participants considered small multiple views of the STC to be useful, although in the beginning they did not understand the idea. But when the tasks were completed, they understood how the environment could function for the given tasks. As for the PCP, most of the domain experts did not use it when executing the tasks, but all of them confirmed its flexibility to deal with different attribute characteristics in complex datasets. The 2D OSM was considered to be a necessary visual representation to be visible all the time, to see the spatial distribution of movements. According to the interviews, participants did not complete any of the given tasks in a single visual representation only. However, by observing the results it was made clear that time related questions were done in the STC, while attribute and location related questions were tackled in combination with the 2D STC. The idea of having 2D and 3D representations in one environment was considered to be useful. Overall, the GVA environment was appreciated and especially the possibility of data exploration from temporal, spatial and attribute perspectives. Positive feedback was made about the possibility to use several 2D or 3D STC views simultaneously. Thus, this GVA environment was considered as acceptable for data exploration purposes.

#### Non-domain experts

The non-domain experts saw no need for four different views of the STC. They were convinced that one view of the STC in the visual environment should be enough. Similar to domain experts, it was mentioned that it takes time to get used to the visual environment, but after a while it becomes easy. Non-domain users also expressed different opinions when naming the most difficult tasks to accomplish. The PCP was not used often, but was still named as a useful representation to investigate attribute characteristics. Instead, most of the participants indicated they had executed most tasks using the STC only or in combination with the 2D STC. The option to analyse from location, attribute and time perspectives was seen as positive. They were a bit skeptic about confronting novice users with the STC. Similar to domain experts, they also emphasized missing functionalities for analytical purposes. Overall, the non-domain participants classified the visual environment as nice to look at but they still saw a need for improvements.

### 7.5.9 Measurement of task performance

The results of the analysis show that domain experts were more effective in their task performance than non-domain users (see Figure 7.23). In the first experiment, five domain experts out of seven were able to complete the given eight tasks. While in second experiment, only three non-domain experts out of seven could complete all eight tasks. The task *distinguish* proved to be the most ineffective task for domain experts, and the task *compare* was the most ineffective for non-domain participants. The observation of the task execution strategies revealed some similarities between both groups. In this process, experts were more logical when completing the tasks. Non-expert participants did not pay much attention to a logical sequence of task completion. The reason of such differences can be the simple motivation of domain experts to explore their own data using the newly developed GVA environment.

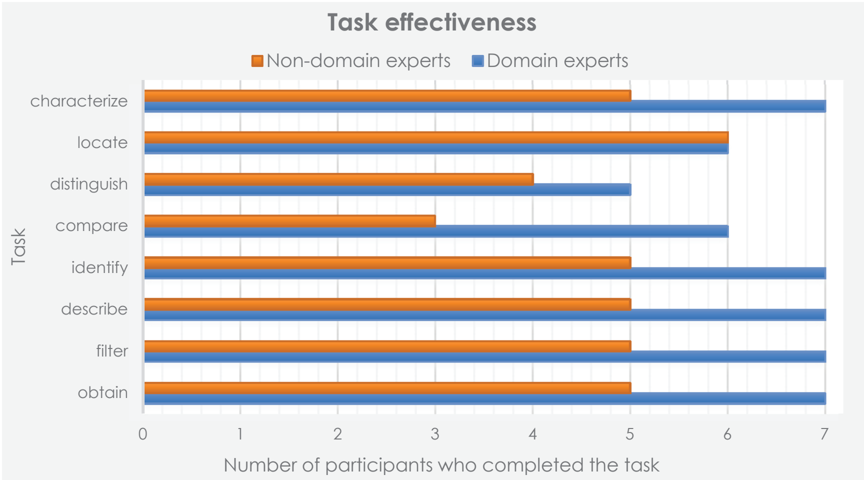



Figure 7.23 Effectiveness of the task performance by expert and non-expert test participants in Experiment III.

According to the statistical analysis (see Figure 7.24), non-domain participants performed the tasks: *obtain, identify* and *compare* in a relatively short time. On average, the task *compare* took M=259s, *identify* took M=53s, and the task *obtain* M=193s for the non-domain experts. But for the domain experts these figures were: *compare* M=506s, *identify* M=57s and *obtain* M=227s. However, Figure 7.23 revealed significant differences in task performance effectiveness between these two groups. In particular, only three non-domain experts completed the task *compare* and only five the tasks *obtain* and *identify*. Besides, the during test sessions domain experts provided a more detailed analysis on tasks than the non-domain experts.

The statistical measurements on efficiency for the other five use tasks reveal an obvious lead of the domain experts. According to the graphs presented in Figure 7.23, the tasks *characterize* (M=79s) and *distinguish* (M=41s) yielded the average shortest response times for the domain experts (non-domain experts: *characterize* M=151s, *distinguish* M= 61s). Also, for non-domain users (M=239s) the task *locate* took significantly longer than for the domain experts (M=179s).

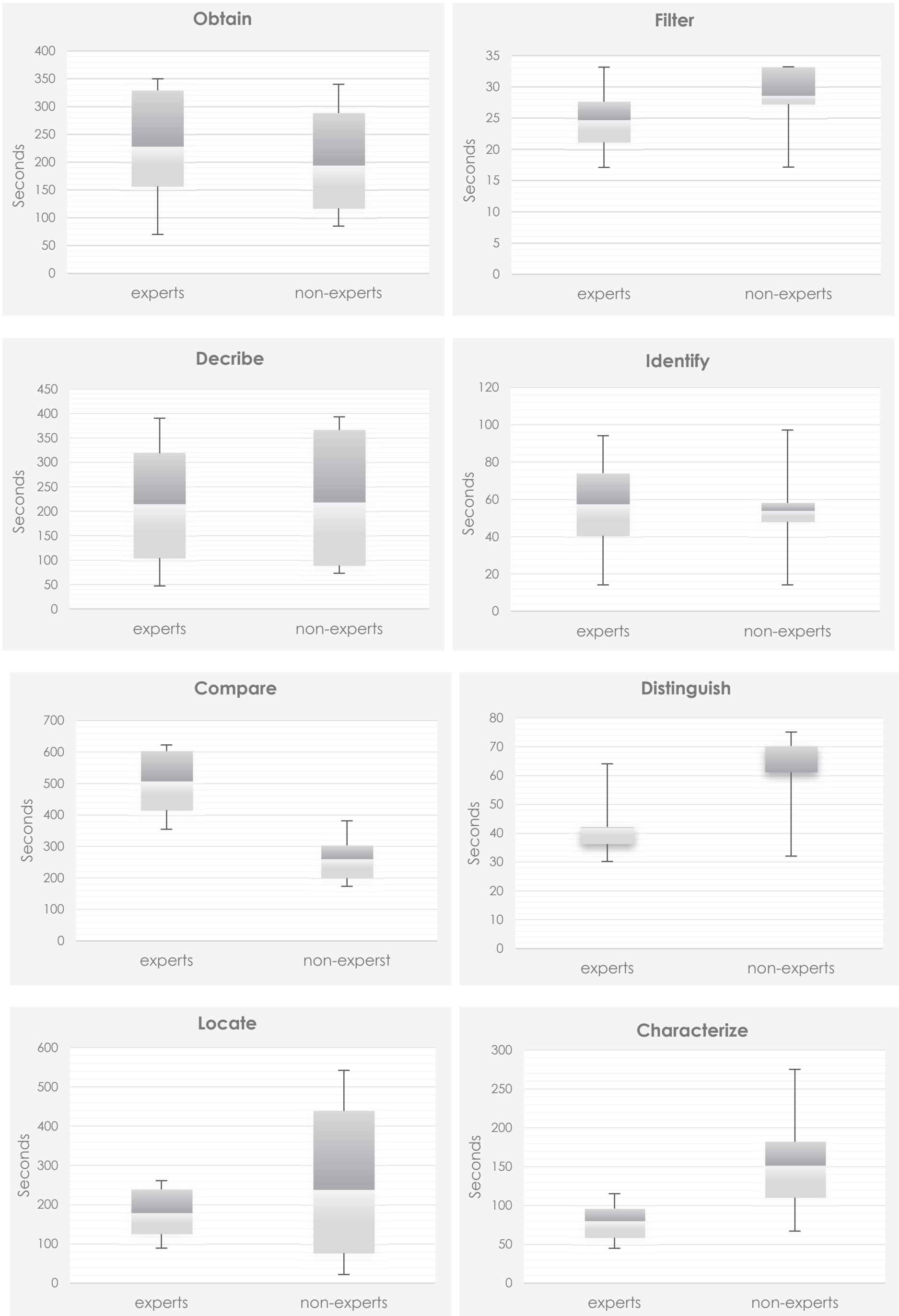



Figure 7.24 Task efficiency metrics of experts and non-experts in Experiment III.

For the other three use tasks, comparisons do not reveal essential differences. The task *filter* was accomplished by the domain experts in, on average, M=25s and by the non-domain experts in M=28s. And also no considerable difference was found for the tasks *describe* and *identify*. Domain experts completed the task *describe* in, on average, M=215s and non-domain users in M=218s. The task *identify* was completed by the domain experts in M=54s and by the non-domain experts in M=57s.

### 7.5.10 Measurement of the usability of the GVA environment

The use of the different visual representations during the execution of the tasks differs among experts and non-domain experts (see Figures 7.25 and 7.26). Despite the fact that the non-domain experts have skills in the use of various visual representations they obviously preferred to complete their tasks mainly in the STC (see Figure 7.25).

On the other hand, the domain experts used all visual representations. According to Figure 7.26, the domain experts have completed the given tasks mainly in the STC and 2D STC. The PCP and 2D OSM were not used often, although they were used for the exploration of the spatial and attribute characteristics of the data. For instance, the PCP was used in combination with the STC and 2D STC when *comparing* different attribute characteristics and describing the behavior of ethnic groups (STC–80.11%, 2D STC–12.68% and PCP-7.22%). The 2D OSM was utilized to find spatial distributions when locating the view on the most busy areas and obtaining directions of people movements.

The task *obtain* was completed in the 2D OSM (11.58%), the STC (61.05%) and the 2D STC (27.37%) and the task *filter* in the STC (66.61%) and 2D STC (33.39%). A combination of the PCP (21.22%), STC (57.78%) and 2D STC (21.20%) was used by the domain experts to complete the task *describe.* The combination of the 2D OSM (3.21%) and STC (96.79%) was used actually when completing the task *identify* to derive the temporal distribution of movements. Similar to the task *identify*, the task *distinguish* was also performed in the STC (91.50%) and 2D STC (8.50%). As for the task *characterize,* both experts and non-experts performed this task completely in the STC (100%). Thus, considering the use of visual representation, different categories of tasks were completed differently. The questions related to the temporal and attribute aspects of the data were mainly performed in the STC, while those for spatial distributions in the 2D OSM and 2D STC.

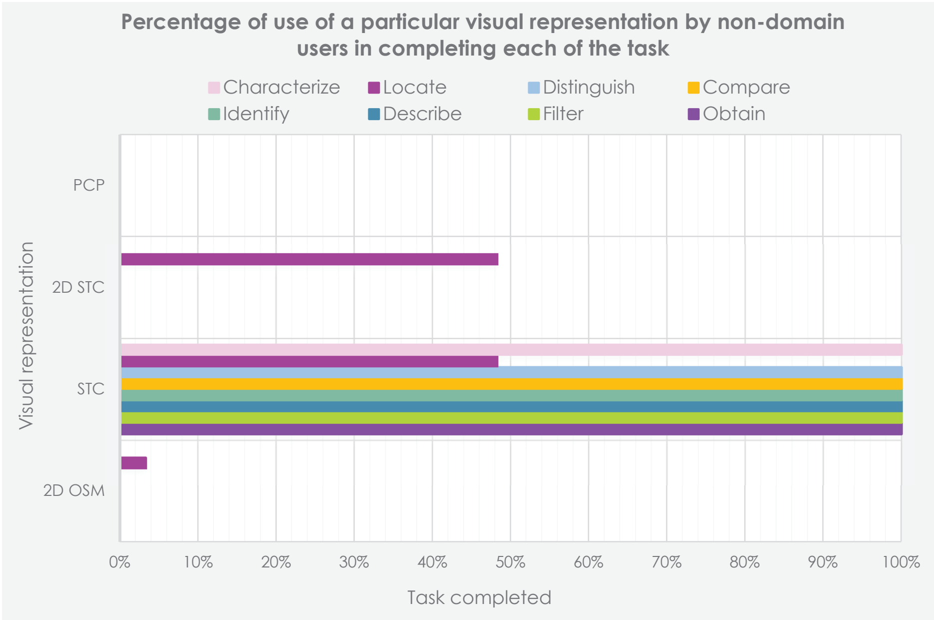



Figure 7.25 Percentage of use of a particular visual representation by non-domain experts in completing each of the tasks in use case during Experiment III.

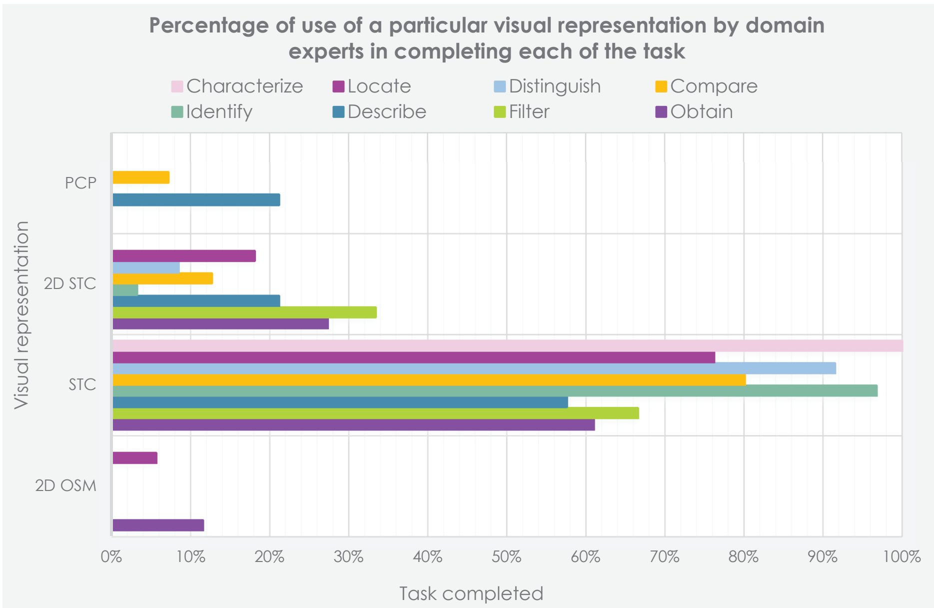



Figure 7.26 Percentage of use of a particular visual representation by domain experts in completing each of the tasks in use case during Experiment III.

Despite the fact that the non-domain experts were more experienced with different graphic representations, they limited themselves almost solely to the STC. This was surprising, but based on the remarks during the interviews this is probably because of the enthusiasm for the STC. Only for the task *locate*, the 2D map and 2D STC view were used as well. The 2D STC view was even preferred above the map in the 2D map view. The diagram of the domain experts (see Figure 7.26) shows a much wider variety, although here the STC was also the favorite to support the execution of the tasks. This was expected because the STC can best deal with the temporal components of the movement data and most questions had time involved. The experts also barely used the map in the 2D view. As was explained during the interviews, nearly all participants would have preferred to see the movements as trajectories/lines and not as dots on the map to make it useful. The PCP was used only to support the execution of two tasks. This can be explained partly by unfamiliarity with this graphic, and partly because only a few questions required interaction with multiple attributes.

## 7.6 Discussion

The development of the three comprehensive GVA environments described in this chapter was based on systematic usability studies. The initial starting point was the problem determination and establishment of the requirements of domain experts. These steps were essential to construct these interactive visual environments, but a continuous cooperation with the end users to iteratively improve the GVA environments and better meet the user requirements was needed as well. This chapter reported on the results of usability experiments executed for these novel GVA environment based on the requirements of human geographers, urban planners, historians, and travelers. The proposed visual interactive environments aimed to support the user's analytical activities during their exploration process. In order to judge their interactivity and analytical capabilities, three experiments were designed intending to involve different groups of end users. The first experiment involved non-expert users only, while the second experiment focused on domain experts. The last experiment was done with both non-domain and domain experts.

The analysis of the experiments in general revealed a number of usability issues regarding to the use of the visual representations and their coordination. The idea of Multiple Coordinated Views appeared to be very helpful and nice for the exploration of datasets of different complexities. However, the tools implemented for one dataset cannot always be completely useful for other datasets as well and in most cases require improvement and sophistication. The experiment also showed differences in usability metrics during the completion of the tasks. Experiment I revealed that the nature of the data has a big influence on which graphic representation is useful to support problem solving. For instance, in case of the simple datasets the TG performed well, but it was not used in case of the complex annotations.  Experiment II with complex datasets obviously showed the importance of the coordination between multiple linked views, such as the STC and SPG to derive the required information. In experiment III with large datasets, a difference in the use of the graphic representations in the GVA environment between domain experts and non-experts was observed. In some cases non-experts did not understand where to look for the right answers, although they did know the how to manipulate the graphics in the visual environment. Thus, the experiment revealed that no specific knowledge is required to manipulate such interactive environments, but the motivation or purpose of why to use it is a very important factor.

As for the aspects related to the design of the interactive environments with multiple linked views, user feedbacks proved that in some cases there is no need for two or more similar visual representations in one environment, unless for specific exploration purposes. In order to strengthen the current demands of data exploration, users asked for the enhancement of GVA environments to incorporate analytical tools for visual representations enabling data analysis from location, attribute and time perspectives. The integration of the 2D OSM in such an interactive environment with novel visual representations was considered to be important. Other user suggestions were related to extended analytical capabilities of the STC for a more flexible analysis.

## References

Gotz, D. and Zhou, M.X. (2009). **Characterizing users' visual analytic activity for insight provenance**, 'Information Visualization', 8, 1, pp. 42-55.

Knapp, L. (1995). 'A task analysis approach to the visualization of geographic data', in **Cognitive aspects of human-computer interaction for geographic information systems**, ed. by Nygers, T. L., Mark, D. M., Laurini, R., and Egenhofer, M. J., pp. 355 - 371, Kluwer Academic Publishers, The Netehrlands.

Kraak, M.J. (2008). 'Geovisualization and Time – New Opportunities for the Space–Time Cube', in **Geographic Visualization**, ed. by Dodge, M., McDerby, M., and Turner, M., pp. 293-306, John Wiley & Sons, Ltd, UK.

Kraak, M.J. and He, N. (2009). **Organizing the neo - geography collections with annotated space - time paths**, in ICC 2009 : Proceedings of the 24th international cartographic conference ICC : The world's geo - spatial solutions, International Cartographic Association (ICA). Santiago, Chile, pp. 7.

Li, X. (2010), **The time wave in the time space, a visual exploration environment for spatio-temporal data** Geo-Information Processing, University of Twente, ITC.

Li, X. and Kraak, M.J. (2008). **The Time Wave. A New Method of Visual Exploration of Geo-data in Timespace**, 'The Cartographic Journal', 45, 3, pp. 193-200.

URL 2, From: http://udig.refractions.net/

URL 3, From: http://atlasti.com

URL 4, From: http://www.openstreetmap.org/

URL 7, From: http://www.techsmith.com/camtasia.html

URL 12, From: https://www.surveymonkey.com/

Zhou, M.X. and Feiner, S.K. (1998). **Visual task characterization for automated visual discourse synthesis**, in Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. LA, USA, pp. 392-399.

# CHAPTER 8

## DISCUSSION AND CONCLUSIONS

### 8.1 Summary

This research project examined the potential of the STC application with a focus on the question, 'under which circumstances can the STC efficiently and effectively display spatio-temporal data to support problem solving'. The spatio-temporal data are often related to movements that can have multiple attributes next to their spatial and temporal components. This research studied the STC in the context of real world problems based on the requirements of domain experts. To realize the research goals a User Centred Design (UCD) research methodology was followed.

**CHAPTER 2** gives an overview of the STC applications and demonstrates their increasing use over the past few years for exploration and analysis. As a visual representation of spatio-temporal data, the STC has been employed to display large and complex datasets of movements that become widely available nowadays. Moreover, it has been integrated in highly interactive GeoVisual Analytics (GVA) environments to support knowledge discovery in such large streams of data. However, little is known whether the cube is truly efficient and effective to satisfactorily display complex datasets as stand-alone visual representation or as a part of a GVA environment. Earlier usability research did not offer directions on how the STC content should be designed from a cartographic perspective, or whether it is influencing the exploration process. The lack of such evaluation studies for the STC to visualize data is the main driver of this research.

In **CHAPTER 3** a conceptual framework is proposed that incorporates knowledge from different disciplines and follows methodologies required to addressing the defined objectives (see Figure 3.1). The framework provides descriptions of elements of the UCD based methodology used in this research. This offers an approach to the evaluation of the STC content with special attention for cartographic design aspects and the environment in which the STC has to function. The cartographic design guidelines are linked to suggested visualization strategies and allowed the development of hypotheses for extensive usability studies. These systematic studies had to identify the strengths and weaknesses of the STC under different conditions. In the evaluation, four use case studies based on real world data of different complexity are used. The evaluation consisted of six different phases, each with a different focus. The first phase deals with the context of the use and user requirements, while phase two focuses on the design and visual solution strategy to address problems encountered during the first phase. Each of the other four phases were discussed separately in the next four chapters.

**CHAPTER 4** discusses phase three that intended to evaluate the developed applications with domain experts who 'owned' the case studies. Two experiments were designed and executed in the working environment of the domain experts at their home universities. The objective of the experiments was to gain deeper insight into the further needs and experiences of the domain experts to potentially extend and improve the STC application. Thus, by measuring and studying confusions, disorientations, satisfactions and success of their activities during the interaction with the application as well as the expectations they expressed, the requirements for the design and tools were identified.

Phase four, as discussed in **CHAPTER 5,** had as objective to obtain information on the cartographic design aspects for the STC content. It reports on the results of a usability study conducted with nine experts from the geovisualization domain. A focus group experiment was the starting point for a discussion on the use of the design alternatives hypothesized in Table 3.8. The experiment included tasks to encourage the discussion process. The experts from the geovisualization domain judged the suitability of the different design options in the context of the 'overview' and 'zoom' steps of the visualization strategy. The results reveal that the use of these design alternatives is influenced by the size of the data sets used. Nevertheless, color hue and color saturation were advised as the most suitable solutions for data visualization. However, at the same time remarks were made that only design will not be able to deal with the exploration of such datasets and that additional analytical functionality is just as important.

In **CHAPTER 6**, phase five focussed on the evaluation of the hypotheses presented in Table 6.1. A usability study of design alternatives was done via a task-based experiment with 22 participants who were unfamiliar with the STC. During this experiment, participants were asked to think aloud while executing the given tasks. This process was video/audio/screen/eye recorded by Tobii Studio software. After completing the tasks, the participants were interviewed to share their opinions, attitudes and experience gathered during the experiment. The materials derived from these qualitative experiments, resulted in a transcript protocol, and the outcomes derived from eye tracking and task execution resulted in quantitative metrics. These studies were the basis for the judgement of 13 different design alternatives. The outcome of the experiment revealed various reasons for the acceptance or rejection of the design options.

For a simple dataset, color hue & shading was preferred for the visualization of qualitative data. For quantitative data, again color was preferred. In particular, the option of color value & shading was preferred above size & shading. This last result was unexpected and did not coincide with the hypothesis in Table 6.1. The reason could be the observed usability issues related to the legend implementation.

For the complex dataset, the outcome was slightly different. For qualitative data, there was also a preference for color hue & shading. But for the presentation of quantitative data, the participants preferred color saturation & shading. The results coincided with what the geovisualization experts suggested during the focus group evaluation.

The preferences for design alternatives for complex annotations were almost similar to the two previous outcomes. Here, for the representation of qualitative information, test subjects preferred the color hue & shape & shading option.

All in all, the experiment conducted in phase five, revealed a clear preference for the visual variable color to visualize different types of data complexity in the STC.

The perceptual properties of visual variables worked as predicted with the exception of size. Size is known as the only visual variable with three perceptual properties, but this experiment could only partly confirm its selective perceptual characteristics. It worked for ordered (non-quantitative) data (a few, a lot), but not for absolute numbers. The reason could be that in some situations too many classes were used to allow a proper distinction between the paths, and in other situations non-classified paths where used, both deviations from Bertin's (1983) suggestions. For this reason, size is suggested for overview only.

In **CHAPTER 7**, the results are presented of phase six, an extensive usability study of the STC in three different GVA environments, incorporating the results of the earlier phases. The task-based experiments employed a mix of qualitative and quantitative user research techniques. Similar to the previous experiments, test participants were asked to think aloud while executing tasks. This process was video/audio/screen recorded in Camtasia Studio for those experiments conducted at the work place of domain experts. Other experiments were executed in a usability lab with additional eye movement tracking, using Tobii studio. After completing the tasks, the participants were interviewed to derive more information on their experiences during the experiment. The qualitative studies resulted in a transcript protocol, and the eye tracking and task execution resulted in quantitative efficiency metrics.

The first of the three main experiments with different GVA environments focused on a simple dataset and on complex annotations and was executed in the usability lab. The 7 test participants were expected to perform four analytical tasks. Based on their attitudes, opinions and task performance the usability of the visual representations within the first GVA environment could be judged. This GVA environment consisted of a STC, a 2D map, a time graph (TG) and a time wave (TW) (see Figure 7.1 and 7.2).

The results of the analysis show that the appreciation for each of these visual representations in the GVA environment differs depending on the data and environment. The TG was considered useful for the simple datasets, but useless for complex annotations. On the other hand, the TW was seen as being effective for complex annotations and ineffective for simple datasets. Both the 2D map and the STC were not seen as very useful either. The 2D map required more contextual information and was difficult to interact with. The STC was seen as being suitable for the representation of temporal aspects but was lacking analytical functions.

The second task-based experiment was conducted at the working place of the domain experts to evaluate another GVA environment, consisting of STCs and Speed Profile Graphs (SPG), to judge the requirements set in phase three (see Figure 7.13). 8 Domain experts performed four analytical tasks. Based on their opinions, feelings, task performance, etc., as derived from the recordings and user interviews, the usability of this GVA environment could be judged. Overall, the results show that solving research questions in such an interactive environment is experienced as being useful. However, some minor usability issues related to the GVA interface were noted. And, similar to the previous test results, this experiment also revealed a need for more flexible analytical tools.

The third experiment intended to evaluate the third GVA environment (consisting of STCs, a 2D map and a Parallel Coordinate Plot (PCP) (see Figure 7.19), developed for large datasets with two different user groups, domain experts and non-domain experts. The first group of 7 domain experts was aware of the research problems related to the dataset and the experiment was conducted in their working environment. The second group of 7 non-domain experts had never seen the data before, but was aware of the visual representations incorporated in this GVA environment. The experiment for the second group was conducted in the usability lab. Similar to previous experiments, a mix of qualitative and quantitative user research techniques was used to register the participants' opinions, attitudes, usability issues, etc. Based on task completion, attitude, observation, etc. the usability of each visual representation within the GVA environment could be judged. The results show that the frequency of the use of the different visual representations in the GVA environment was different between the two groups. The domain experts demonstrated a more effective use of the GVA environment than the non-domain experts. The non-domain experts mainly used the STC to perform tasks while the domain experts also used the other visual representations regularly. The 2D (OpenStreet) map did not appear to be very useful for time related questions, but still test participants considered it to be a useful component of the interactive visual environment. The STC was clearly useful to derive knowledge about temporal aspects, but as the observations show, despite the spatial STC options, the domain experts still preferred to find answers to space related questions in the 2D map. The PCP was seen as a useful representation to analyse complex characteristics of the data but needed improvements for a better implementation. Similar to the previous experiments, the participants advised to develop more analytical tools that would help to explore the dataset in a more flexible way.

In conclusion, the positioning of the STC in various GVA environments offers better exploration options and a better understanding of temporal events, multiple data characteristics and the geography.

## 8.2 Revisiting the Research Questions

In conclusion, the results are summarized by answering the research questions posed in section 1.3.1:

*RQ 1. What are the fundamental characteristics of the STC and on what principles is it based?*

The STC is part of the Time Geography approach and allows the visualization of movements in space and time. The three major elements of the STC are space-time paths (st-path), stations and the space-time-prism (st-prism). This study is limited to the st-paths.

The movement of objects (people, animals, cars, etc.) are influenced by constraints. If multiple objects are studied, they can co-exist in time, in space, and in space and time. When many individuals co-exist in time and space, they form bundles, often found at the location of stations.

*RQ 2. What kinds of applications of the STC have been developed over time? How has the cartographic design theory been applied in the developed applications?*

The STC applications have been created in different domains, to study movements of various objects, and have seen an increase in use since GIS software has made it easier to create applications and the increased use of GPS has made data abundant. The st-paths were used to understand movement behaviours of different ethnic groups, gender groups, study historical events, etc. The station concept was used to explore non-movement activities such as earthquakes, archaeological digs, disease, etc. St-prisms are mainly used in transportation accessibility studies. The range of STC applications shows that most STC content was displayed using the visual variables color and size. In some examples, the depth cues shading and transparency were added to improve the 3D experience.

*RQ 3. What are the known limitations of the STC, and did these change over time?*

In the early years of the STC, both data and visualization options have been limited. Scientists have now replaced diary data with GPS data and the tedious pencil drawings have been replaced by interactive displays to visualize the data. What can be witnessed today is even a data overload with huge and complex datasets that results in cluttered and illegible STC content, which requires a new approach (visualization strategy).

RQ 4. *What kind of alternative opportunities does the STC offer to represent multi-dimensional combinations of spatio–temporal data in a GVA environment, and what are the functions required?*

As existing examples reveal, the integration of the STC in a GVA environment increased its value to offer insight in temporal aspects of the data. Complex movement data containing multiple variables have to be studied in a visual environment with linked graphics representation, to show the data from multiple perspectives and in combination with analytical functionalities.

*RQ 5. What are the suitable visual variables for visualization of the STC content, and how does the complexity and nature of the data influence their use?*

In theory, all visual variables can play a role in visualizing STC data content. However, the nature of the data and its complexity influences their effectiveness and it has been proven that not all of them are suitable, partly because we deal with lines (paths) mainly.

In this process, depth cues have to be considered too, because the visual perception of the 3D representation of the STC is important to the user. As existing examples show, data complexity has a significant influence on the design, when it comes to retrieve information in an effective and efficient way. A ‘wrong’ design will hamper this process.

*RQ 6. How to construct design guidelines based on the cartographic design theory to visualize the content of the STC?*

Based on the cartographic design theory hypotheses were formulated with expectations on the performance of single visual variables and different combinations of visual variables and depth cues to represent the STC content in varying complexity. The combinations included those found in existing STC applications and some additional ones. One of the assumptions was that the depth cues should not be used for complex datasets.

*RQ 7. How to apply the design guidelines to effectively and efficiently design STC content depending on user task scenarios in different contexts? How can the 'Information Seeking Mantra' or 'Visual Analytics Mantra' be applied in the workflow of those scenarios?*

In order to apply design guidelines effectively and efficiently a workflow for each task has to be defined and followed. By involving domain experts in the development of the tasks scenarios, realistic workflows can be defined. In this process, the Information Seeking Mantra or the Visual Analytics Mantra offer a logical sequence of workflow steps considering data complexity. For instance, for a task scenario related to simple datasets, the 'overview ↔ detail' (ISM) approach can be suitable, while the 'query ↔ visualization ↔ exploration' (VAM) approach is more helpful for large and complex datasets.

RQ 8. *How to create a suitable GVA environment with the STC embedded that allows the user to execute visual and analytical tasks?*

Development of a GVA environment, with the STC embedded in it, is based on existing open source GIS programs. The core of such an environment is the integration of geocomputational functions with different (carto)graphic representations. The visual representations, among which the STC, are linked via coordinated multiple views which will stimulate data exploration and knowledge discovery by offering alternative views on spatial and temporal relationships. In this research, the GVA environments constructed for simple datasets and complex annotations, consisted of basic visual representations. The GVA environment developed for large datasets and complex datasets was extended with some dedicated analytical tools required by the domain experts, such as a space-time selector and a time graph. All were constructed using open source software.

*RQ 9. What are the requirements of domain experts to visualize movement data?*

Based on interviews and discussions, as well as some usability testing, the experts' requirements could be established. These are related to the visualization and analysis of temporal aspects of the data and included suitable visual representations with flexible analytical tools supporting their quest for answers related to their research problems.

RQ 10. *How can the visual variables be used to represent the content of the STC, resulting in design guidelines, and what is the influence of the selected workflows as defined by domain experts?*

The visual variables can be applied to represent STC content similar to how it is done with other (carto)graphic representations. Proper choices are influenced by the nature and complexity of the data. Some theoretical options turned out to not fully work as expected, while others did. The workflow did influence the choice of visualizations. Depth cues proved not to be that useful on the overview level, especially with large or complex datasets. In conclusion, the application of the design guidelines depends on the nature of data to be analysed and the path of the workflow.

*RQ 11. Haw do the domain experts judge the suggested design guidelines while executing their visualization strategy, and what additional requirement did they voice?*

The domain experts were encouraged to interact with the STC and to try to answer their research questions, as defined earlier. This allowed them to better understand the context of the STC use to fine tune their research questions. The tasks they had to execute confronted them with the different STC designs and based on the usability metrics derived from the evaluations it was possible to retrieve their opinions. These opinions lead to the acceptance and rejection of some of the hypotheses formulated about the design guidelines. When working with the STC, they also realized that without additional visual representations it would be difficult to explore all aspects of the multivariate data important to their research. They appreciated the STC a lot and became so enthusiastic that they asked for more analytics functions linked to the STC to get more out of their data. This resulted in indications on what type of visual representation might be helpful to the domain experts.

*RQ 12. What is the opinion of geovisualization experts on the revised design guidelines in respect to the visual variables in the context of the STC environment?*

The focus group discussion revealed that the use of the design guidelines is influenced by data complexity on both the overview and the zoom steps of the workflow. For effective and efficient design of the STC data content, the focus group members strongly advocated to use color to visualize all data. In addition, they saw filtering as an option that might simplify the exploration of different data characteristics in the STC. Similar to the domain experts they concluded that visualization alone cannot support all tasks related to large datasets, and that analytical tools are required.

*RQ 13. How was the implementation of the design guidelines and visualization strategies appreciated in the STC?*

The different visualization options offered during the experiments allowed the participants to voice preferences depending on the complexity of the data. Some options were seen as less suitable while others were considered more suitable. But in nearly all situations color was seen as the best alternative. Shading was considered as the depth cue to be preferred. However, in some situations (large datasets) the use of depth cues did not work.

*RQ 14. How was the implementation of the design guidelines and visualization strategies in the STC as part of a GVA environment appreciated?*

In general, the implemented GVA environments were appreciated in all three experiments. However, the evaluation showed different types of usability issues. The most common problem was the lack of interactivity between different representations and missing analytical tools for data exploration.

## 8.3 Scientific Contributions

This research contributes to Time Geography in general and the usability of the STC in particular. The value of the STC as an elementary part of Time Geography to get insight in all kinds of movement data has been proven by using four different case studies in this research. The usability of the STC has not only been studied as a stand-alone visual representation, but has been placed in the context of a GeoVisual Analytics environment that allows working with large and complex datasets.

The particular scientific contributions of the research are:

1. The proposed conceptual framework is an interdisciplinary approach that integrates knowledge from Time Geography, and Geographic Information Science and is based on a User Centered Design approach. It stresses the importance of the harmonious coexistence of cartographic design theory and visualization strategy.
2. The empirical investigation of cartographic design aspects confirmed the expected influence of data complexity on design options for the STC. Four different case studies, used in the experiments, clearly show that design has its limitations when it comes to visualizing large and complex datasets. In such situations a simple design is preferred above more 'fancy' designs with shading and paths as 3D-tubes.
3. The known perceptual properties of the visual variables proved to be valid in the STC as well, with some minor deviations.
4. The empirical investigation of GVA environments with an emphasis on temporal aspects of the data showed that the STC functions well in such environments.

## 8.4 Recommendations for Future Work

- Despite the extensive usability experiments executed during this research it proved to be impossible to deal with all potential options.

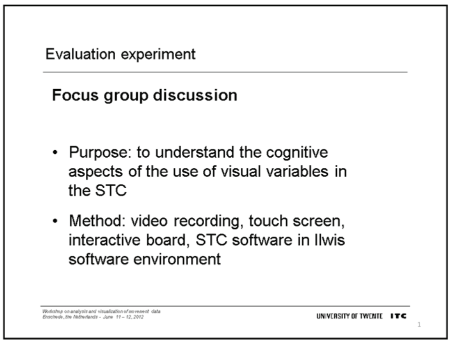
For instance, the visual variables were only combined with four depth cues. As explained in Chapter 2 more options exist and even more usability studies might be needed to also judge these.

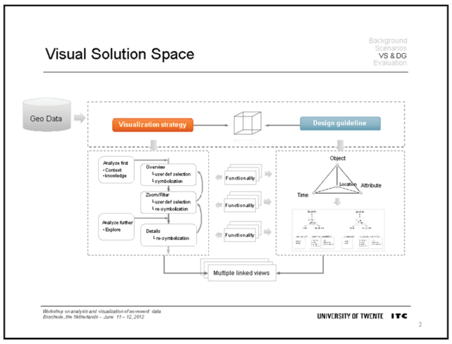
- This research only focused on the st-paths of the STC and somehow neglected stations and st-prisms. However, literature review revealed their active use in different domains as well, especially the st-prism in accessibility studies. Here, the different (mathematical) models used could benefit from a visual support.
- The evaluation of the GVA environments revealed that the participants would have appreciated the option to select their own base map content to support their actions.
- The used GVA environments revealed various usability issues. The participants face some troubles with the interface and were missing analytical tools and functions (such as statistics metrics of the STC content).
- Eye movements are registered in relation to where participants look at on the screen. With the high interactive applications as tested here (the rotating STC, zoom and pan) a GazePlot does not always tell the whole story. For instance, whereas a participant may keep the eyes fixed on a ‘moving’ path, a GazePlot might not register this as a fixation because the cube is rotated.

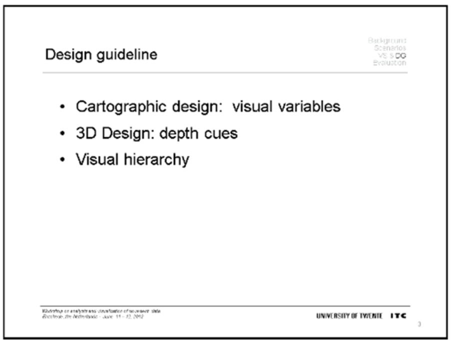
During the experiments, some ‘technical’ issues were observed that require attention:

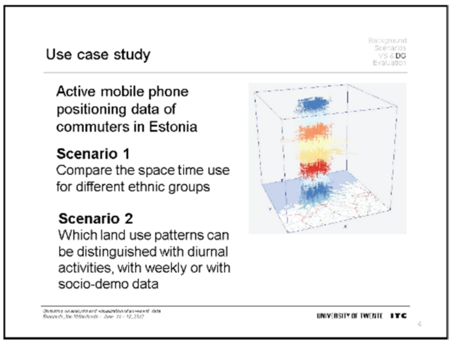
- GVA software: the legends design implemented with the STC and some other graphics did not always match in looks, in (3D) orientation, or in interaction options.
- User activities registration software: Tobii Studio had difficulties to run synchronously with software such as uDig, because of the required processor capacity. Camtasia Studio created large files slowing down the recording process.
- Eye tracking: during the eye recordings is it important to have a separate display on which the test moderator can monitor whether the eye tracker indeed registers the eye movements. Sudden movements of the participants will sporadically interrupt the eye movement recordings, making them useless for further data analysis.

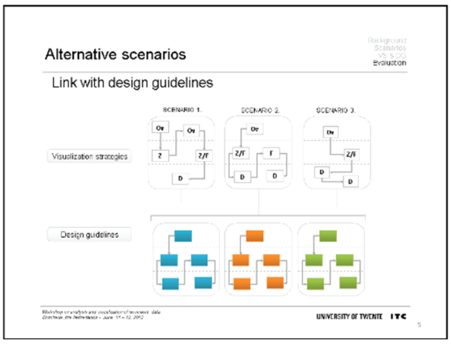
# APPENDIX 1: PHASE 4: EVALUATION OF THE DESIGN ALTERNATIVES FOR THE STC CONTENT DURING FOCUS GROUP DISCUSSION

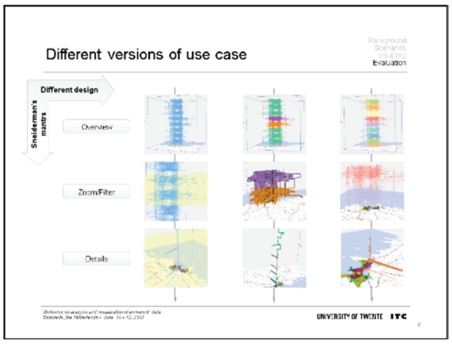


# APPENDIX 2: PHASE 5: THE USER TASKS DEVELOPED FOR EVALUATION OF THE DESIGN ALTERNATIVES

## Simple datasets

The use case study 'Napoleons march to Moscow' represents the well-known story of the French invasion of Russia. The dataset contains information on the relocation of Napoleons 'Grande Armée' in different times, the number of corps/troops in the Armée, the number of soldiers in each corps, the names of the leaders of the corps, and the temperature.

For this evaluation session, based on the above described use case study you should complete 2 different tasks/questions. For first question, on your screen are shown 4 different view designed differently, and each of them contains a legend to explain the information represented. In order to complete the task, you should use all given four view. You are free in choice from which one to start and how to execute task. After you will complete the task I will ask you several questions about your preferences. Besides, you should rate to each design version in table given below.

After the first question, I will open for you the next four viewers to complete the second question, and each view will also contain legend to explain the information content. Similar to the first task, you are free in use of these view for task execution. Also, after the finishing the task you will be asked several questions, and later you should fill again table to rate for different design versions.

Please read the questions and answer:

The displayed view are representing information about the leaders of the troops/corps. Please look on the representations and estimate visually:

1. How many corps arrived in Moscow, and who was their leader?

______________________________________________

______________________________________________

______________________________________________

Please rate how helpful each of the displayed designs was in answering the task above.
*Please count the views on your display as following:*

| | |
|---|---|
| View 1 | View 2 |
| View 3 | View 4 |

| User satisfaction / view | Low | | | | | | | | | High |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | | | | | | | | | | |
| 2 | | | | | | | | | | |
| 3 | | | | | | | | | | |
| 4 | | | | | | | | | | |

The displayed view are representing the number of soldiers in the troops/corps. Please look on the representations and estimate visually:

2. When did the corps have their highest strength/number of soldiers?

________________________________________

________________________________________

________________________________________

Please rate how helpful each of the displayed designs was in answering the task above.
*Please count the views on your display as following:*

| | |
|---|---|
| View 1 | View 2 |
| View 3 | View 4 |

| User satisfaction / view | Low | | | | | | | | | High |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | | | | | | | | | | |
| 2 | | | | | | | | | | |
| 3 | | | | | | | | | | |
| 4 | | | | | | | | | | |

## Complex datasets

The use case study represents 'pedestrian movements within the historical city center of Delft' over four days and contains information on their age, gender, occupation, visit purpose, etc. From the entire dataset we are using the information collected on the street 'Paradijspoort'.

For this session, based on the above described use case study you should complete 2 different tasks/questions. For first question, on your screen are shown 4 different view designed differently, and each of them contains a legend to explain the information represented. In order to complete the task, you should use all given four view. After you will complete the task I will ask you several questions about your preferences. Besides, you should rate to each design version in table given below.

After the first question, I will open for you the next four view to complete the second question, and each view will also contain legend to explain the information content. Similar to the first task, you are free in use of these view for task execution. Also, after the finishing the task you will be asked several questions, and later you should fill again table to rate for different design versions.

Please read the questions and answer:

On your screen, four different viewers are representing the information on gender. Please look on the representations and estimate visually:

1. Are there any differences between female and male trajectories/movements over four days?

________________________________________

________________________________________

________________________________________

Please rate how helpful each of the displayed designs was in answering the task above.
*Please count the views on your display as following:*

| | |
|---|---|
| View 1 | View 2 |
| View 3 | View 4 |

| User satisfaction / view | Low | | | | | | | | | High |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | | | | | | | | | | |
| 2 | | | | | | | | | | |
| 3 | | | | | | | | | | |
| 4 | | | | | | | | | | |

The displayed viewers are representing pedestrian by the age groups. Please look on the representations and estimate visually:

2. Do you see differences in the composition of age groups on different days?

________________________________________

________________________________________

________________________________________

Please rate how helpful each of the displayed designs was in answering the task above.
*Please count the views on your display as following:*

| | |
|---|---|
| View 1 | View 2 |
| View 3 | View 4 |

| User satisfaction / view | Low | | | | | | | | | High |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | | | | | | | | | | |
| 2 | | | | | | | | | | |
| 3 | | | | | | | | | | |
| 4 | | | | | | | | | | |

## Complex annotations

The third use case study represents movement of travellers in Estonia. The dataset contains information on visit details for several days.
On your screen four different viewers are represented. All view are displaying the same annotated information in a different way. In order to read the information content, view have an explanation of symbol types in legends. To complete task, you should use all given four view. You are free in choice from which one to start and how to execute task. . After you will complete the tasks you should rate to each design version in tables given below. Besides, I will ask you several questions about your preferences.

Please read the question and answer:

1. Please look on annotations in the viewers and answer, how many types of information are annotated?

___

___

___

2. Please list, what are the content of the information represented by annotations?

___

___

___

Please rate how helpful each of the displayed designs was in answering the tasks above.
*Please count the views on your display as following:*

| | |
|---|---|
| View 1 | View 2 |
| View 3 | View 4 |

| User satisfaction / view | Low | | | | | | | | | High |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | | | | | | | | | | |
| 2 | | | | | | | | | | |
| 3 | | | | | | | | | | |
| 4 | | | | | | | | | | |

# APPENDIX 3: PHASE 5: USABILITY TESTING PRE SELECTION QUESTIONNAIRE

**Pre-selection questionnaire**

**Cartographic design of the STC content**

**1. What is your name and surname?**

**2. What is your country of origin?**

**3. What is your gender?**

- Male
- Female

**4. Which age group do you belong to?**

- 20 – 25
- 26 – 30
- 31 – 35
- 36 – 40
- 41 – 50
- 51 – 60

**5. What is your highest educational degree?**

- Bachelor's degree
- Master's degree
- PhD degree

Other (please specify)

**6. In which domain was that degree that you obtained?**

**7. What is your occupation?**

**8. How often do you use maps in your daily life?**

- ◯ Once in a day
- ◯ 2 – 3 times in a week
- ◯ Once in a week
- ◯ Once in month
- ◯ 2 – 3 times in a year
- ◯ Once in a year
- ◯ Never

Other (please specify)

**9. Do you know what visual variables are?**

- ◯ Yes
- ◯ No

**10. Have you ever designed a map yourself?**

- ◯ 1 Never
- ◯ 2
- ◯ 3
- ◯ 4
- ◯ 5
- ◯ 6
- ◯ 7
- ◯ 8
- ◯ 9
- ◯ 10 Very often

**11. Do you use glasses or contact lenses?**

- ◯ Yes
- ◯ No
- ◯ Only for reading

Other (please specify)

**12. Are you colour blind (in any way)?**

- ◯ Yes
- ◯ No

**13. How often do you use interactive (computerized) maps?**

- Once a day
- 2 – 3 times in a week
- Once a week
- Once a month
- 2 – 3 times in a year
- Once a year
- Never

Other (please specify)

**14. Are you familiar with the Space-Time Cube (STC) (i.e. have you seen it ever before)?**

- Yes
- No

**15. If your answer was 'Yes' on the previous question, have you ever used the STC in an interactive environment?**

- 1 Never
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10 Very often

Dear participant, I would like to thank you for your time and consideration.
Your participation in this usability test is greatly appreciated

With kind regards,
Irma Kveladze

Done

# APPENDIX 4: PHASE 5: INSTRUCTIONS TO THE TEST ON THE USE OF THE STC'S VISUAL ENVIRONMENT

Dear participant,

- This usability research aims to determine the effectiveness and efficiency of the visual variables in the Space-Time Cube (STC) through qualitative and quantitative empirical usability research. In order to achieve usable results four use case studies have been selected varying in a data complexity and thematic nature. This evaluation session focuses on one use cases study and will take about *20 minutes*.
- Please, consider that the intention of this test is to judge effectiveness and efficiency of the design in the STC. Therefore, feel free to provide your ideas and findings gained during the test.
- During the evaluation session, several methods will be used: eye tracking (which includes: screen, audio-video and eye tracking recordings), think aloud and interview questionnaires. Based on the given tasks/questions you should give answers and also speak out loud about your thoughts and feelings and what you see.
- The design of the information is related to the qualitative or quantitative nature of the data. For each data type (qualitative or quantitative) one task is formulated that you can accomplish by using several design alternatives. In other words, each task has to be completed in different views that I will display for you. During these changes, recordings will not be stopped, but the unnecessary recordings will be deleted later during the test analysis.
- During session you will be able to formulate your opinions on the most effective and efficient design version. These opinions are important and interesting for the research. Accordingly, after the completing each task you will be interviewed and asked to express your opinions and preferences regarding to the different designs.
- You should interact with all displayed views by zooming in/out, panning and rotating the STC. All viewers have to stay in an order and size (do not minimize or maximize) set by the moderator. You can interactively manipulate the STC and play with transparency of the STC content, but you cannot switch the legend on/off or move it in the window.
- During the think allowed I will follow your comments, and in case they are not clear to me, or if you stop talking, I might ask you questions like: Why do you think so? Could you please explain what do you mean? What are you think about? What are you looking for?
- Now I will demonstrate to you the STC environment and all necessary functions that you need for the test

## Instructions for the Simple dataset in Ilwis program environment

The Space Time Cube (STC) represents a 3D visual representation, in which the vertical axis represents time (T) and the horizontal axes represent space (X, Y) (Figure 4). For information visualization a STC plugin was implemented in the

Ilwis and Udig GIS environment. These interactive environments allow STC manipulation using various functionalities.

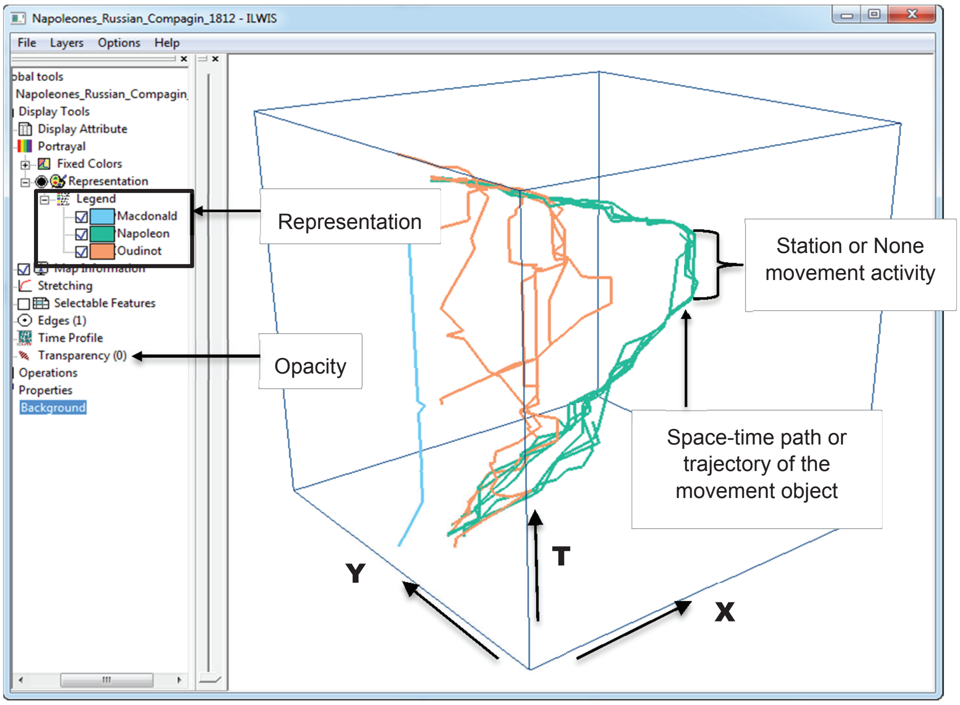



Figure 4. A. Space time cube and its environment

- Movements in the STC viewer are represented as trajectories or space-time paths (Figure 4).
- The number of space-time paths or trajectories indicates the number of moving objects while color indicates information about these objects.
- When object did not move, this is represented as vertical lines or stations in the STC.
- The interactive environment gives the possibility to rotate the STC in the viewer. By continuously pressing the left button of the mouse and moving it, you can rotate the STC in a different direction – left, right, up or down.
- To have a detailed view of the map content you should zoom in/out the cube. For this, you can use the middle scroll button of the mouse or press it continuously and move.
- It is possible to move the STC in the viewer without rotating and zooming. For this option you should press continuously the right button of the mouse and move it (left, right, up, down).
- For answering the use case questions you need to know several functions:
  - ✓ ***Representation/legend*** – lets you to see displayed information and identify content through visual variables

✓ ***Transparency/opacity*** – is a feature that can help you for some visualization problems. With this option, you may be able to find some valuable information.

## Instructions for the complex dataset in Ilwis program environment

The Space Time Cube (STC) represents a 3D visual representation, in which the vertical axis represents time (T) and the horizontal axes represent space (X, Y) (Figure 1). For information visualization a STC plugin was implemented in the Ilwis GIS environment. These interactive environments allow STC manipulation using various functionalities.

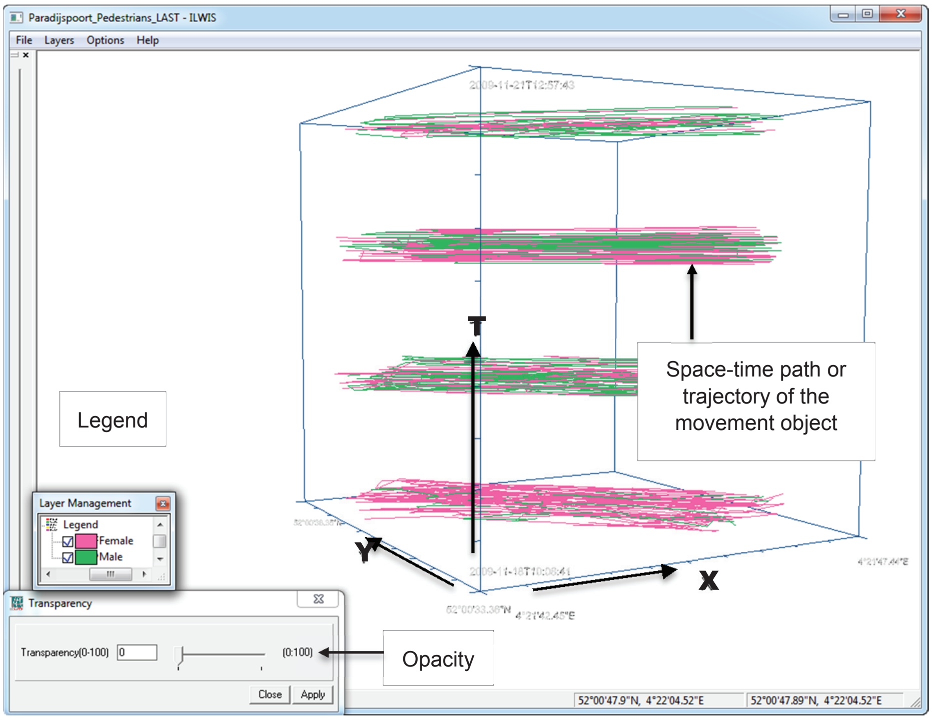



Figure 1. A. Space time cube and its environment

- Movements in the STC viewer are represented as trajectories or space-time paths (Figure 1).
- The number of space-time paths or trajectories indicates the number of moving objects while color indicates information about these objects.
- The interactive environment gives the possibility to rotate the STC in the viewer. By continuously pressing the left button of the mouse and moving it you can rotate the STC in a different direction – left, right, up or down.
- To have a detailed view of the map content you should zoom in/out the cube. For this you can use the middle scroll button of the mouse or press it continuously and move.

- It is possible to move the STC in the viewer without rotating and zooming. For this option you should press continuously the right button of the mouse and move it (left, right, up, down).
- For answering the use case questions you need to know several functions:
  - ✓ ***Representation/legend*** **–** lets you to see displayed information and identify content through visual variables
  - ✓ ***Transparency/opacity*** – is a feature that can help you for some visualization problems. With this option you may be able to find some valuable information.

## Instructions for the complex annotations in uDig program environment

The Space Time Cube (STC) represents a 3D visual representation, in which the vertical axis represents time (T) and the horizontal axes represent space (X, Y) (Figure 1). For information visualization a STC plugin was implemented in the Udig GIS environment. These interactive environments allow STC manipulation using various functionalities.

- Movements in the STC viewer are represented as trajectories or space-time paths (see Figure 1).
- The number of space-time paths or trajectories indicates the number of moving objects while color indicates information about these objects.
- The interactive environment gives the possibility to rotate the STC in the viewer. By continuously pressing the left button of the mouse and moving it you can rotate the STC in a different direction – left, right, up or down.
- To have a detailed view of the map content you should zoom in/out the cube. For this you can use the middle scroll button of the mouse or press it continuously and move.

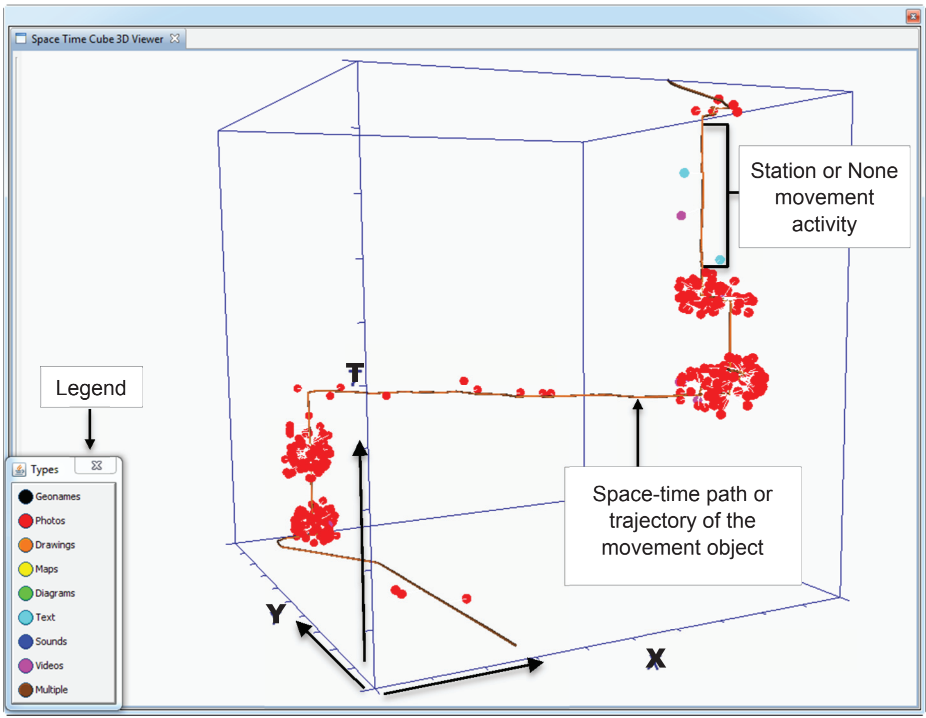



Figure 1. A. Space time cube and its environment

- It is possible to move the STC in the viewer without rotating and zooming. For this option you should press continuously the right button of the mouse and move it (left, right, up, down).
- For answering the use case questions you need to know several functions:
  - ✓ ***Legend / Types* –** lets you to see displayed information and identify content through visual variables / annotations

# APPENDIX 5: PHASE 5: GVA USABILITY TESTING INTERVIEW QUESTIONS FOR DESIGN ALTERNATIVES

This questionnaire aims to collect and clarify some additional information about the effectiveness, efficiency and user satisfaction of the design of the information in the STC. The interview will be conducted with individual participants.

## Simple dataset: Napoleons march to Moscow

*Qualitative information – first session:*
Interview questions:

1. Was information easy to recognize through visual contract/visual difference between features, *to distinguish one feature from another visually*?
2. Did visual clutter influence your answers, and how did it influence?
3. What do you think about color hue? Was it readable and understandable/legible?
4. What do you think about patterns? Was it also readable and understandable/legible?
5. Do you have any comments and recommendations?

*Quantitative information – second session:*
Interview questions:

1. Was information easy to recognize through visual contract/visual difference between features, *to distinguish one feature from another visually*?
2. Did visual clutter influence your answers, and how did it influence?
3. What do you think about color value? Was it readable and understandable/legible?
4. What do you think about size? Was it readable and understandable/legible?
5. Do you have any comments and recommendations?

## Complex datasets: Pedestrian movements in the city center of Delft

*Qualitative information – first session:*
Interview questions:

1. Was information easy to recognize through visual contract/visual difference between features, *to distinguish one feature from another visually*?
2. Did visual clutter influence your answers, and how did it influence?
3. What do you think about color hue? Was it readable and understandable/legible?
4. What do you think about patterns? Was it readable and understandable/legible?

5. Do you have any comments and recommendations?

*Quantitative information – second session:*
Interview questions:

1. Was information easy to recognize through visual contract/visual difference between features, *to distinguish one feature from another visually*?
2. Did visual clutter influence your answers, and how did it influence?
3. What do you think about color value? Was it readable and understandable/legible?
4. What do you think about diverging color scheme? Was it readable and understandable/legible?
5. Do you have any comments and recommendations?

## Complex annotations: Annotated space-time path

Interview questions:

1. Was information easy to recognize through visual contract/visual difference between features, *to distinguish one feature from another visually*?
2. Did visual clutter influence your answers? How did it influence?
3. What do you think about using color hue to represent different annotations/annotated information?
4. What do you think about using color hue and shape visual variables to represent different annotations/annotated information?
5. What do you think about using the combination of color hue, size and depth cues to represent different annotations/annotated information?
6. What do you think about using icons to represent different annotations/annotated information?
7. What are your final comments and recommendations?

# APPENDIX 6: PHASE 5: EXAMPLE OF TRANSCRIPT DOCUMENT FOR ONE TEST PARTICIPANT

## Qualitative visual variables

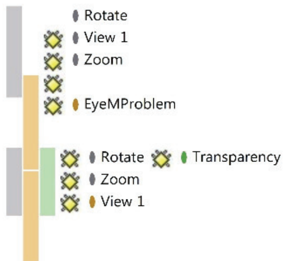
**TP 2.** But I did not see before there was... I could see also the numbers

TP say this after she read the given tasks and started interaction with 1st view by zoom in/out. I reminded her that she has to estimate information visually. She again reread first question and continue interaction with first view.


M. you can interact with all four views

**TP 2.** aaa, this is Moscow? Ok I did not see it before (she is still in first view, **color value with thick path**)

Here she was interacting with 1st view by zooming and rotating it. When she rotated the STC and look, on it little bit from top she saw the Moscow point at the bottom of the STC (she was moving on the chair continuously and eye tracker recorded her eye movements sporadically. She particularly moved towards to the screen, therefore, I do not know where she was looking at that moment). Besides, she used transparency to find out its effect. Then she again moved in 1st view and continue interaction.

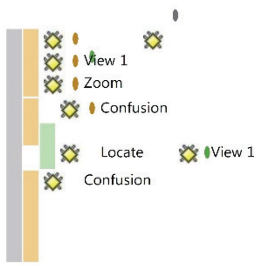



TP 2. I'm checking…so this is the time line? so, I'm just checking where
I can get numbers

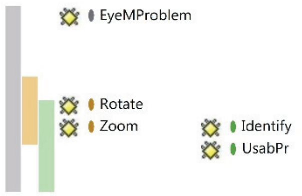
M. I think you have to identify it visually. Is that possible?

TP 2. If this is the space and time.. so, do I know any.....

After she moves back to 1st view she zoom out STC and then start moving 2D map button on time axis. Then I ask what she was looking for, it seems that she wanted to see some particular numbers in STC. Numbers she also completed the task locate in 1st view. Here I reminded again that she has to find answer visually. Then she again reread the question, and say that did not understand word corps.

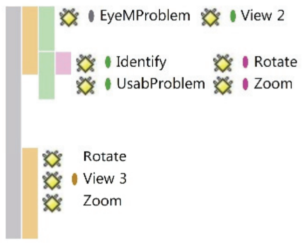


TP 2. ouu wait, this is because I did not understand the word corps, it is not persons you mean troops like group of people, right... ok I have to count these lines




After she again ask that question was about group of people and not persons, and she has to count lines and not expect any particular number. After she again continue interaction with first view by rotating and zooming it. After several rotation she probably count the trajectories and say 3 corps

TP 2. Three (3). But I want...yes it's the same




After 1st view, she moves in 2nd view for a second probably and then in 4st view. Then she continue interaction with 4st view, she again count corps and confirm that are 3 corps. Interesting that she did not zoom in on to the very detail to see closer what was happening at that point. Also from my observation, it is visible that she has difficulties to see them clearly. After she moved in 3rd view, again start interaction by zooming and rotating, but did not search any information

TP 2. and who was the leader....Napoleon


When looking for this answer she looked at 1st view, then on the legend for color hue and immediately mentioned names.

From the beginning participant started to search the number of the troops, only at the end she mentioned leader and immediately answer it. When she looked at view for leader information eye recordings appeared and I saw how she looked at 1st view and then locate cursor at legend view

**Answer completed (Half): '3 leaded by Napoleon'**

## Interview session

1. Could you easily differentiate between features, so as to be able to distinguish one feature from another visually?

TP 2. If the trajectoryies of the corps are more or less same it is kind of difficult,

Negative

at this moment test participant is playing (interacting) with the first view

Rotate
Zoom

TP 2. you mean if here I could see that there are three (she appointed on the place where several trajectories are at Moscow location), in this case I see only......(she moved near to the screen and started to observe or calculate trajectories), like...one exit goes away, another exit....yeah, to be honest now maybe I change my mind.... it is a bit...because I do not know what is in and out

Negative
Rotate
Zoom

M. did u try to put in the same position information in other views?

TP 2. Yes, I also...from the beginning I thought it was not useful (now she is looking on the pattern view and interacting with it) for me, because ...ou wait, this is more clear...yeah, without zoom in it I thought I…

Positive
Rotate
Zoom

M. so, what do you think now?

TP 2. Maybe this is more clear, because it has more three…

Positive
Rotate
Zoom

(She is still on 2nd view)

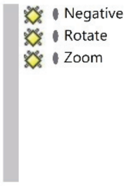
M. what about another view (means 4st)? TP

2. I did not see others, I was too compare

M. what do you think now?... you can zoo in more if you would like with 4st view and was trying to

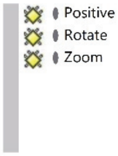
at this moment TP was interacting with 4st view to observe the cluttered please of Moscow area to find out the quantity of the trajectories

TP 2. Yeah, I was not looking correct, because actually if this (she is interacting with 1st view).... (she started to count corps) yeah but this is means that they split.. Let's see (now she moved to the 2nd view and start to interact with it)...it is difficult question aaa




M. no, you should estimate just visually if it is fine for you, you should say that it is visible and if it is not visible, you can say it is not visible

TP 2. aaa, it is a bit confusing, but...because they were more or less in the same place the few corps…and probably this one gives better (indicates on the 2nd view), because it gives 3D impression




M. what about this 3D (indicates 3rd view, color hue with depth cues)

TP 2. This one? This one I did not check yet, and TP started to interact with view


M. this is also depth cues, mean 3D

TP 2. This is same...wauu, this maybe gives...the problem is I did not check all of them I was trusting...so, there are a lot here. One is arriving here, another one is arriving here, so it is one, two, I do not know, one two are coming from the

same spot

M. so it means that visual clutter influence your answer. Yes? Now you say that ate the same moment several corps arrived and they overlap each other, so it means that there is visual clutter and it is influencing your answer

TP 2. What is visual...? (She is asking about clutter)

M. well, several corps just you say, they are arriving together and because they are at the same time at the same location it is difficult to distinguish between them, or how many

TP 2. Yes, correct, it is difficult to distinguish how many...one, two, tree, four...now I think this is better, best one (she was interacting with 3rd view)

Positive
Rotate
Zoom

1. What do you think about the differences in color hue? Was it readable and understandable / legible?

TP 2. I think thick is...this two gives...easier to visualize this two (according to the eye movements she is looking on 2nd and 3rd view) but that is because it gives a shape and it is easier to recognize when the lines overlap

Positive
Rotate
Zoom

M. so, you mean that from those two views difficult to get answer on 'how many'

On this comment TP was bit confused, she did not understand the context of the question and ask if she has to rank for the difficulty. After I again explain that there was question about how many corps and if she is thinking that, the 2nd and 3rd views are conveniently designed to answer the questions like 'how many'. While I was trying to explain the context of the question, she mainly was looking in 2nd and 3rd view but interaction was bit passive.

TP 2. Yes,

Positive

M. and about the leader also, in which view it was visible

TP 2. Yeah, in color it is much easier than with shapes or black and white. Actually, I disregarded, I did not want to look at this one (she is interacting with 2nd view), because it is like... it is not for...yeah in the end it gives....

Positive
Rotate
Zoom

M. if you will apply transparency, can it help?

At this moment she follow to my suggestion and started to play with transparency for 2nd view

M. so, can transparency help somehow?

TP 2. Let me...

she is still interacting with 2nd view where now is applied transparency on 38, she also increase and decrease the number of the transparency and then tried to compare it to the legend, remarkable that legend do not reacts on the transparency probably she was not expecting this from legend view

TP 2. I mean, of course you can use it, you can distinguish it, but you have to choose I select colors. I am sensitive to colors, so I like colors

Positive

During this question have been discussed the patterns as well, therefore I did not ask again as separate question on patterns

1. What do you think about the application of patterns? Was it also readable and understandable / legible?

1. Do you have any further comments and recommendations?

TP 2. No.

**End**


# Ranking

During the ranking, TP ones again looked on the views. She started from 4st view, interact with it and mentioned that 'this one is like .... 'She means useless. After she did not interact with other views and just by looking at them rank.

**View 1 (color hue with this lines) - 5**

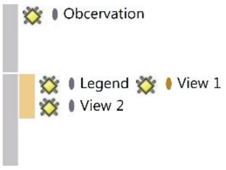
**View 2 (patterns with depth cues) - 7**

**View 3 (color hue with depth cues) - 9**

**View 4 (color hue with thin lines) - 5**

# Quantitative visual variables

for this session TP read the question and for breaf overview first look at 2nd view then at 4st, 1st and 3rd. afther she agin continiu to read the question, then looked at 1st view after moved in 2nd view alos looked at legend and find out that the colors were indicated inlegend



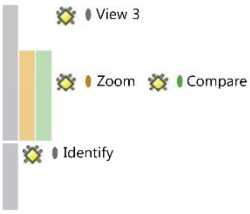

TP 2. aaa. this is in the legend now

she obcerve several seconds legend view, and was so courious if some aother information was hiden there that desided to activate and chesk legend view. afther she continiu observing views and when moved in 3rd view also looked at legend mentioned that it is nice. from observation perspective I can mention thet all this short time she did not interact with views.


TP 2. wauu this is nice here (at this moment she looked at the 3rd view)

she again reread the question, and after looked at the 3rd view and

the tubes were to large and imediately mentioned 'in the begining'

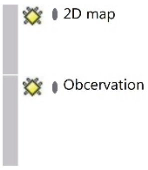



TP 2. In the begining

M. what do you think ?

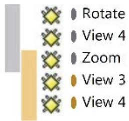
TP 2. it is thicker here

after, she find answer she start to move 2D map button on time axes to identify time more presize, also for me not clear why she is looking for time information. then she desided to look at other views but not interact with them




M. what are you tring to compare now?

TP 2. compere the data you mean?




when I ask what she was looking for, she was interacting with 4st view by zoming and rotating, according to her eye movements she was observing begining of the compagn in 4st view and then comparing it to 3rd view. she was observing 4st view quite long time, also was interecting by zooming and rotationg, besides was moving 2D map on time axis. from her behaviour is very clear that she could easily understand the main actions to excute the task in the STC.


TP 2. I'm just checking time line if it is gives zeroo.....I was looking on darkest (she was interacting with 4st view) color here, but that is the begining of the battle, invasion, so it is zero. I was just playing with a...I was wandering if there was something below zero and there is nothing. But becouse in the previous question I was not paing attention ot the other maps now I'm checking all of them to be sure that I have all informatioan and to be sure which one is easy to see.... to be onest now I do not knwo the difference (at this moment she was loking on the 4st view, comparing it to the 3rd and 2nd view). you give me oportunity to experiment so I'm interacting (here she is using trancparency on 4st view)

M. and trancparency is helpful there?


TP 2. It was more helpful before (I do not know what she mean in' before', she used trancparency in this task first time, maybe she is talking about previous task). maybe in this one (she moved at 1st view) becouse the contrast is not so clear, but...yeah (after appling tharncparency on 1st view trajectories almost disapear). becouse of the size trancparency is helping only a bit here (now she is looking at 3rd view). here becouse lines are bit thicker and it is a lot easiers to recognize from the begining, and trancparency actually ...for me zero was ok (meand persentage of transpatency). she apply trancparency again on 2nd view again and mentioned that 'it halps', but it is so clear for me (she means without trancperency) and so logical that amount of troops from the begining was large

after she desided to fix answer, she again looked on the screen at the 3rd view.

**Answer compleated: 'In the begining of the trip'**

**End**

## Interview session

1. Could you easily differentiate between features, so as to be able to distinguish one feature from another visually?

Positive

TP 2. it is a lot clear for me with size then with color. with volume (she is inrearcting with 1st and 3rd view and comparing probably), so I mean the route for me is more clear here (apoints 1st view) then here (apoints 2rd view)

2. Did visual clutter influence your answers, and how did it influence them?

Positive

TP 2. no, this was really simple, becouse also the type of question, you were asking me 'when', so that is something that I can point there (at this moment she egain is looking on the 3rd view at the begining of the campagin)

3. What do you think about the differences in colour value? Was it readable and understandable / legible?

Positive

TP 2. yes, even if I prefere this one (she looked at 3rd view, size) I do not know why, becouse you are tolking about size, so maybe it is just more intuitive, that you talked about size of the troops, and you see size of the corps is bigger, I do not know is it the reason. the otehr ones also give me information (at this moment she is interacting with 3rd view, 2nd view and 1st view) and, I think it is also clear but, of course it is a lot more clear when line is thicker. the colors give me information even if I will zoom in, they should be bigger (she was looking on the 1st view).

Becouse in this question she discuss size application too, I did not ask separate question.

5. Do you have any further comments and recommendations?

TP 2. no

**End**

Sesion End

# Ranking

**View 1 (color value thin path) - 6**

**View 2 (color hue with thick path) - 9**

**View 3 (color value & size) - 9**

**View 4 (color value & shading) - 10**

she commented that difference is very low, probably means color value.

# APPENDIX 7: PHASE 6: USABILITY TESTING PRE SELECTION QUESTIONNAIRE FOR A GVA ENVIRONMENT

**Pre selection questionnaire**

**The STC in a GVA environment**

**1. What is your name and surname?**

**2. What is your gender?**

- Male
- Female

**3. Which age group do you belong?**

- 20 – 25
- 26 – 30
- 31 – 35
- 36 – 40
- 41 – 50
- 51 – 60
- 61 – 70

**4. What is your occupation?**

**5. What is your field of interest and how it is related to the geo-domain? Please describe in several keywords.**

**6. How many years of experience do you have in geo-domain (e.g. in geography, cartography, geodesy, surveying, etc.)?**

**7. How often do you use maps in your daily life?**

- Once in a day
- 2 – 3 times in a week
- Once in a week
- Once in month
- 2 – 3 times in a year
- Once in a year
- Never

Other (please specify)

**8. If you use maps, for what kind of purposes do you use them?**

**9. What is your experience with interactive (computerized) 2D maps and how often do you use them?**

- Once a day
- 2 – 3 times in a week
- Once a week
- Once a month
- 2 – 3 times in a year
- Once a year
- Never

Other (please specify)

**10. What is your experience with interactive (computerized) 3D maps and how often do you use them?**

- Once a day
- 2 – 3 times in a week
- Once a week
- Once a month
- 2 – 3 times in a year
- Once a year
- Never

Other (please specify)

**11. Are you familiar with the Space-Time Cube (STC)?**

- Yes
- No

**12. Have you ever used the STC in an interactive environment?**

- Yes
- No

**13. If you answered 'yes' to the previous question: what was the last time you have used the STC?**

- 1 week ago
- 1 month ago
- 1 month – 3 month
- 3 month – 1 year
- More then 1 year

Other (please specify)

**14. What is your experience with interactive (computerized) graphs and how often do you use them?**

- Once a day
- 2 – 3 times in a week
- Once a week
- Once a month
- 2 – 3 times in a year
- Once a year
- Never

Other (please specify)

**15. Have you ever designed or constructed maps yourself in any program environment?**

- Yes
- No

**16. If you answered 'yes' to the previous question, how often do you do this?**

- Once in a day
- 2 – 3 times in a week
- Once in a week
- Once in month
- 2 – 3 times in a year
- Once in a year

Other (please specify)

**17. Are you familiar with the above mentioned graphical representations (2D map, 3D map, and graphs) in an analytical environment?**

- Yes
- No

**18. If you answered 'yes' to the previous question, please indicate for what kind of purposes did you use that analytical environment?**

**19. Please, rank your ability to orient yourself in such an analytical environment.**

- Poor
- Fair
- Good
- Very good
- Excellent

Dear participant, I would like to thank you for your time and consideration.
Your participation in this usability test is greatly appreciated

With kind regards,
Irma Kveladze

Done

# APPENDIX 8: PHASE 6: INSTRUCTIONS TO THE TEST ON THE USE OF THE GVA ENVIRONMENT FOR SIMPLE DATASETS AND COMPLEX ANNOTATIONS

Dear Participant,

This usability research intends to find out how the STC performs in a visual exploratory environment in combination with other graphics such as a time graph, a 2D map and time wave. In other words, how the STC performs in an interactive geovisual analytics environment that allows interaction with location, attribute and time components of the data.

In Udig program environment, based on the existing analytical tools (time wave, time graph, STC and 2D map) have been developed analytical environment on the use case studies 'Napoleons march to Moscow' and annotated space-time path. The first dataset represents well-known story of the French invasion of Russia. His 'Grande Armée*'* consisted of 15 different corps. For each corps their path and number of troops over time are represented. In addition information on size and location of battles is given, as is the temperature during the campaign.

The second dataset represents travel log data of traveller during one of the business visit in Estonia. The data was collected by *Global Positioning System* (*GPS*) over the week. But, besides the location and time information also was collected materials such as pictures, documents, etc. related to the visit.

Please consider that the intention of this experiment session is to evaluate the developed analytical environment. Therefore, feel free to express your ideas and feelings during the test, because they are essential for further improvement.

During the evaluation session several evaluation methods will be used: eye tracking (which includes: screen, audio-video and eye tracking recordings), think aloud and interview questionnaires. In order to find out how the developed environment works, you will be given tasks to complete during the test. While you are working on them, I will ask you to think aloud on what you think or feel or how you are going to accomplish the particular task.

While you are working on the tasks, I will listen and follow your thoughts during your 'think aloud'. In case you stop talking or the action taken by you is not clear to me, I might ask you questions like: What are you think about? What are you looking for? Why do you think so? Could you please explain why you think so?

In the analytical environment you will have four viewers. The viewer at the left shows a 2D map, the viewer on the right shows 3D STC, the one below of the 2D map is time wave, and the viewer next to the time wave is the time graph (Figure 1). 2D map represents relocation of corps/or person, while 3D STC represents relocation in a temporal context undertaken by the corps/or traveller during the trip. The time wave helps to identify time duration and repetition of the activities, with possibility to zoom in/out information in the places of interest. The time graph shows information about the amount of the soldiers in corps/or altitude of a terrain regarding to the different time moments and locations. In a moment, I will demonstrate to you how all these views are functioning.

During the evaluation you should interact with these viewers by zooming in / out, by panning, rotating, selecting, filtering, etc. Also, you will have legend windows for the 2D and 3D STC views to identify information context. You have to interact with represented views, but you cannot change their order on the screen or minimize / maximize. After you will complete the tasks with first use case study, the second use case study will be displayed. During this time recordings will not be stopped, however, recorded unnecessary materials later will be ignored.

Now let me to demonstrate to you the functions that you need for the task execution.

## Instructions for the use of the GVA environment for simple dataset and complex annotation

The Space Time Cube (STC) represents a 3D visual representation, in which the vertical axis represents time (T) and the horizontal axes represent space (X, Y) (Figure 1). This interactive environment allows the STC manipulation using various functionalities. *Please go to the program environment and see*.

- Movements in the STC view are represented as trajectories or space-time paths.
- The number of space-time paths or trajectories indicates the number of moving objects while color indicates information about these objects.
- The interactive environment gives the possibility to rotate the STC in the view. By continuously pressing the left button of the mouse and moving it you can rotate the STC in a different direction – left, right, up or down. By pressing continuously the right button of the mouse you can move the STC on the screen
- To have a detailed view of the map content you should zoom in/out the cube. For this, you can use the middle scroll button of the mouse or press it continuously and move.
- First view demonstrates 2D map and base information to identify locations for corps / or traveller. The st-path will represent additional attribute information.
- Second view of the STC represents the same information as first. The trajectories show additional information on the size of the corps for the first use cases study. And different traveling characteristics of traveller and annotations on activities, i.e. pictures, videos and text documents.
- Third view represents Time Wave and shows information on amount / or traveling characteristics. It allows zoom in/out for studying different temporal granularities, i.e. demonstrates the occur and repetition of different activities in different time.
- Forth view Time Graph demonstrates the number of the soldiers in corps/ or altitude regarding to the particular time period. You are able to change shown attribute characteristics on the left side of the representation by selecting and deselections characteristics. Time graph can only display one attribute characteristic.
- Select/highlight – possible by clicking on the trajectories in the STC, on 2D map or on the time graph. During the evaluation, you might need to use it several times.

- Time wave do not allows direct highlighting but it indicates all time aspects related to the selected future. Besides, you can move time slider forward and backward to explore different time aspects or zoom to look at different temporal granularities.
- Time graph allows moving time slider in a different directions and identifying represented information.
- By moving time sliders on time graph and time wave, you can also move 2D base map in the STC. But, the STC has its own button to move it along the time axis.
- Legend lets you to see displayed information and identify content through visual variables in all views.

## APPENDIX 9: PHASE 6: GVA USABILITY TESTING INTERVIEW QUESTIONS FOR SIMPLE DATASET AND COMPLEX ANNOTATIONS

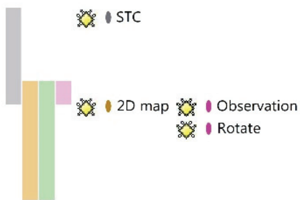
1. What is your overall impression of the visual environment and its analytical capabilities?
2. Was it easy to orient yourself in the visual environment and to execute the given tasks?
3. What was the most difficult task for you? Why?
4. What was the easiest task for you? Why?
5. What do you think about the STC in this visual environment? Was it useful during the task execution? Why?
6. What do you think about the time graph in this environment? Was it useful for task execution? Why?
7. What do you think about the time wave in this environment? Was it useful for task execution? Why?
8. What do you think about the 2D map in this environment? Was it useful? Why?
9. Did you execute any task by just using the STC, time graph or time wave, or 2D map (alone)?
10. What did you like most about the visual environment?
11. What did you not like about the visual environment?
12. Do you feel there is anything missing? What exactly did you miss?
13. Would you say that you are satisfied with the visual environment?
14. What are your final comments and recommendations?

# APPENDIX 10: PHASE 6: EXAMPLE OF TRANSCRIPT DOCUMENT FOR ONE TEST PARTICIPANT

## Simple datasets

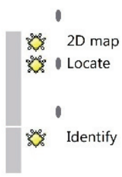
1. **Please describe, how long different corps were traveling to Moscow and back?**

TP was introduced the STC in uDig program environment. After he read the question and starts interaction with the STC view. First he observe trajectories and then rotate the STC, after he find the button for moving 2D map on time axis and start move it up.




So, first I'm going to put 2D map on a time, place where they reach the Moscow

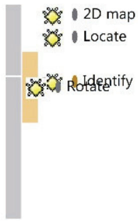
TP move 2D base map on time axis and located it at the place of the intersection of the Moscow point and trajectories. When located it he could identify the time label on time axis of the STC.




So, I presume...this...except for four corps (he means 4 corps that never arrived in Moscow) the rest of the corps travel to Moscow and reach by October 12 of 1812.

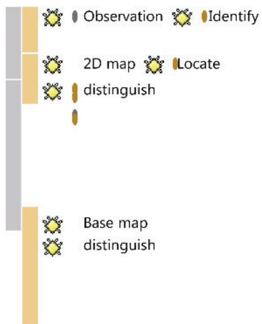

After he identified time label on the STC's time axis, he start identifying the corps that never arrived in Moscow and corps that arrived in Moscow. Remarkable that while mentioning arriving time he read time label -1812-09-12 as October, actually it is September. I think it is just small mistake

And back they travel to the state in Moscow for till about the month.




Here TP again move 2D map up to the time axis and locate it at last point of intersection between Moscow and trajectories, and then he identified time label on time axis. After he starts rotating the STC and observes 2D map and trajectories to say the exact time

So, somewhere here  they started...18th of October they started. ouu and that was 9th (means arrival time), then it was September. On 18th of October, they started going back and it took them...most of them, so last one arrived back in Poland in 1st of January




for last part, TP first identified time in STC, then he observe the trajectories moving back and then start to move 2D map up along the time axis to see the end time of the campaign. When he moves 2D map on top, he also realizes that some of the corps arrive earlier then others, and just one corps arrived later. He saw this Information from the STC, he mainly sees the trajectory that was moving upper then other trajectories, and this means that this particular corps was latest one. By color, he could identify the same corps on 2D map view. For a short time he moved on to the 2D map view to see the location of arrival of this corps in Poland.

Remarkable also that while working on this question he did not zoom in STC, he rotate just rotated it to observe some particular

Perspectives of corps movements. This answer was derived from entire view of the STC.

1. **Napoleon's invasion of Russia began in June of 1812 when the *Grande Armée* was powerful. But, over time several factors influenced its strength.**

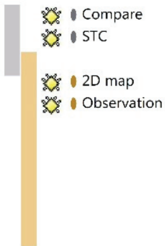
   **Please look on the STC and time graph, and compare the difference between the beginning and the end of the campaign, characterize the factors / reasons that influence the strength of the *Grande Armée*.**

First TP put 2D map again on the bottom of the STC and after he shortly looked at several places from the beginning until the top to observe the size of tubes.

Observation

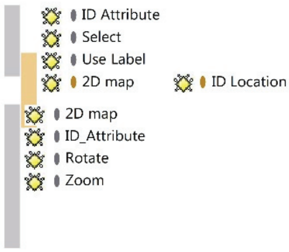
You can see in STC immediately that number of soldiers in each corps is reducing...so, that mast be...since they started in June started reducing still September a lot.

When answering this question TP was observing the size of the tubes almost everywhere. Then he realizes that at particular place their size it invisibly reduced and start moving 2D map along the time axis. He located it at the place of the intersection of Moscow and trajectories. Stay there few seconds and then again continue moving 2D map up to observe size of the tubes. And after, again put 2D map at the bottom of the STC.




Actually, these are two troops (means VI and II corps) that stayed...let's see what is this place...

Here TP selected in the STC VI and II corps to identify their names, and then he tried to identify their location on the base map, because it was not given on 2D map view. For this, he rotated STC and looked on the location from top. Besides, he starts to move 2D map along the time axis to see the intersection point and read the name of the populated area. When he located map on the intersection place, he again zoom in to read the name.




What are you looking for?

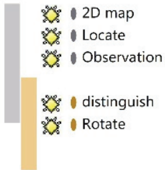
I want to see the place that they stayed, it looks to be regional...Belarus...there is two troops...there is one troops here but number of soldiers is somehow small. For general...

He could not read the name of the place that he was interested, but he could identify the country where was this place belong. Then he zoom out STC for overall content and continue with finding another VII Corps Saxons, he visually could estimate the number of soldiers. Then he looked at middle part of the troops between starting and arriving point in Moscow.


So, the influencing factor as I know before is probably weather, temperature but, something really funny is... it get lower before that already. I mean, I was going from June until September and steadily Napoleon's troops were reducing in number. Especially

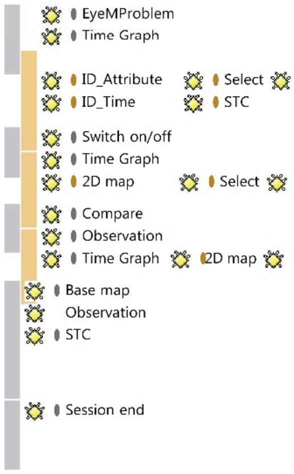
Those which are first stationed (he means corps that did not arrive in Moscow). I do not think that weather really plays that much role. Clearly, that weather was the factor for the retreat.

When describing the reason he again was observing the part between starting point and arriving place in Moscow by locating 2D base map. Also all this time he was rotating STC and looking at time label, and the size of the corps at different places.




If I look carefully on the numbers themselves...lets select this corps first...and I can see that...so number is going down, steadily for all corps. Disregard...I mean September still rainy for that part, it is not that cold winter comparable to French winter. Autumn or French winter maybe...I do not think that differ... maybe. So, there must be something, probably partisan war or something.

Here TP moved closer to the display and start to check the precise number of the soldiers in time graph to be sure in his conclusion. In time graph, he find the precise numbers of soldiers for each corps at specific time by selecting them in STC and highlighting in time graph. he switch on, on the left side of the graph necessary attributes, then again go back to the STC selected one of the corps, then start moving 2D base map along time axis from button and start observing the highlighted line in time graph and numbers on top of it. Then he again moved in STC and start to move 2D map along the time axis to see how the number of soldiers are changing in a different time. then he conclude that weather was not that much influencing factor he start observing 2D map and STC views.

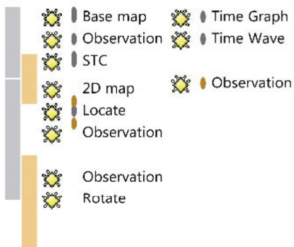



**End of the first session**

# Complex Annotations

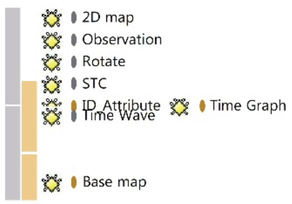
1. **Please describe, how long the traveler stayed at a different places? What do you think was the purpose of the stay / visit?**

TP first look at STC, then move in to the 2D map view, and then shortly at time wave and time graph. After he moved again in STC and starts to rotating it and observes the annotations. At this moment 2D map in cube was located almost in the middle of the cube, but TP so far did not put it at bottom part, he start to observe annotations up of the 2D map and down of the 2D map. Then he start to rotate STC and again observe annotations.




So, again first too look is with in STC. And I'm searching for vertical lines in the STC which indicates the stay, as far as I know.

Then he rotates the STC and look on it from different perspective he probably studied the environment. And after he moved 2D map on the bottom of the STC to study first day. After he start looking on the attribute menu of the time graph, then moved in time wave and looked at 2D map too.

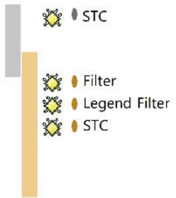



I'll start from the first day

What are you looking for?

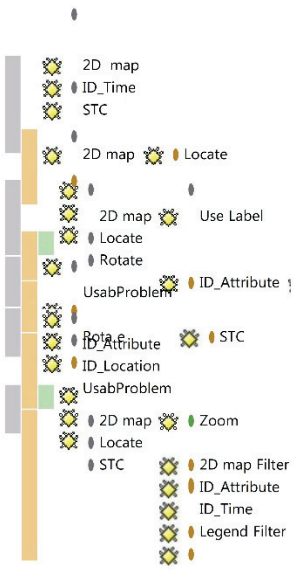
I am trying to see if I can see....

Here TP did not finish, but according to his behaviour, he wanted to filter annotations in the STC. First, he looked in the STC and when realizes that it was too complex, decided to filter out information, therefore ho moved in legend window and switch off picture annotations.



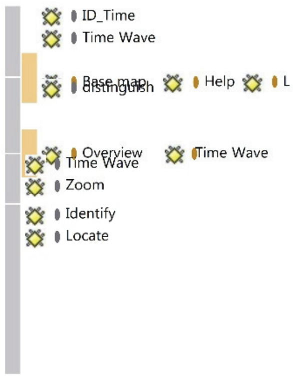

Ok, now I can see...now I can see...the first place is from 24st of august until 26st of august. So 2 days at one place. And from 26st till 29st of august. So, 3 days at another place. at the main time.....Tartu....I'm trying to figure out if there are main cities also. Ok, and second city is....probably for conference in Tartu, so probably at university, but I do not know if possible to get that much details, That's my guess. And another would be the Tallinn. that's also another probably business trip visiting some other people to share information or 2 days workshop, in the main time of course, he/she did lots of pictures. And obviously probably had some evenings to go out.

Arrival data he identified at the bottom of the STC, and then he start to move base map up time axis to find another data and conclude the duration of the stay. Then he again continues to move 2D base map along the time axis to see next station to another place.
After he identified places of long stay, he locates 2D base map on top of the STC and rotate it, in order to see names of those places. Here he looked at legend and tried to see what geo-names mean (mainly for another cities), but nothing have changed in views and he again switched it off. To identify second City TP again start move and rotate top part of the STC. When find Tartu and guessed the reason of the stay, he moved to see the place for stay for first 2 days. And here he could not manipulate view and get lost, to solve it he zoom out whole STC, after he moved 2D base map on the second day (26st of august). After he switch on again the picture annotations from legend and start to observe then in STC view. He start to move 2D map along the time axis in between these two days and see when the annotations were collected.



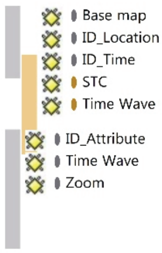

So, if you go to here (means time wave). So, in 25st traveller mostly stay in hotel, and did some walks. 26st he/she went by bus (here he zoom in in time wave), then in hotel and had some workshop. Surprisingly missing information about evenings. And 27st.....so workshop finished by this time then you supposed to travel by bus, no you travel in 26st, here you travel by bus and it took 2 hours, is it 2 hours from Tallinn to Tartu

Yes something like that.




After above part was described, for more detail time information he moved in to the time wave view to see annotations. I remind that there is only the activity represented. He found the meaning of represented information or activities in legend and start to explain the activities done in a different time. Mainly he was looking on overview on time wave, but while studying bus trip he zoom in on time wave to see it more clearly. Then he follows the other activities and moved to another day. So, to identify another day he moved again in the STC and start to locate 2D base map on 27st of august. Then he quickly comes back on time wave and again start to identify more information and measures traveling time by bus.

So, and person had workshop again for a while




While trying to understand if traveling from Tallinn to Tartu needs 2 hours he also looked at map to measure distance visually. After TP mainly was describing visit activities taken in a different time by traveler, mainly from time wave but information he was comparing in the STC. He provide very detail explanations for each day activities and was using well zoom in and out options on time wave.

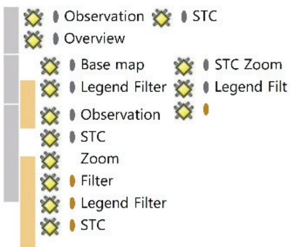
Actually I can say that 24 and 25 was sort of leisure day in Tallinn, test 26 was workshop in Tartu, and in 27 person had conference sessions that the reason for stay.

2. **Please observe the types of annotations and identify the area / place where the most diverse of materials / information was collected?**

TP read question and start interaction from STC

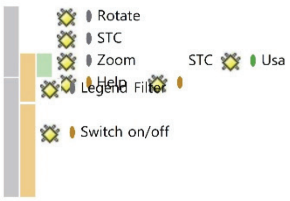

So, obviously it was collected most of the time during the stay

To find out this information TP observed the STC from overview. after he zoom in more detail and find out that the color of the st-path refers to the legend that was given on the 2D map view, and the legend of the annotations was given in to the STC view. After he zooms in even more in the STC and start to observe both type of information even. To explore other information too he switches off photos from legend menu.




The area itself of course is Tallinn, but which part of the Tallinn I probably cannot see from this map.

For this answer, TP was interacting with the STC and rotating and zooming it continuously, at some moment view get lost, here I help to find proper button and put STC in a starting position. He was identifying the annotations in legend, after some findings about other annotations he again switch on pictures



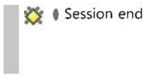

So, and this thing is...videos have been collected there (means

Tartu), and this one is text. So, lots of pictures was collected. Probably most pictures was collected in Tallinn

But most diverse of annotations, how do you think where it was collected?

Clearly, in the Tartu, more pictures were collected in Tallinn, but more diverse was collected in Tartu.

**End of the task session**




# Interview

1. **What is your overall impression of the visual environment and its analytical capabilities?**

Just overall impression is...I have to evaluate all environment. well, I found this time wave first of all thought will be useless, in napoleon case I could not really properly use it, but in this case (means annotations) was really useful....such a detail time scale.

It is useful...I guess so. I think animation also could be as useful, for instance

2. **Was it easy to orient yourself in the visual environment and to execute the given tasks?**

yes, I think so

3. **What was the most difficult task for you? Why?**

Well, relatively probably...I guess to characterize factors (means Napoleon's use case), well relatively because rest of the task wear easy

4. **What was the easiest task for you? Why?**

how long they stay in a place (he mans to find out the stations)

5. **What do you think about the STC in this visual environment? Was it useful during the task execution? Why?**

Yes, I think it is useful, and again you had not so many tracks and it is really easy to, but sometimes it is difficult with the cluttering, sometimes upper part of the map I could not see properly

6. **What do you think about the time wave and time graph in this environment? Were they useful for task execution? Why?**

Time graph I think would be useful, but in second case it is not because of does not display proper information but, I assume that if you would have time graph for instance, simple graph some other same information it will be useful but just altitude I think it is not for me, I do not know. But, time wave first I found too cluttering, but for second case it was somehow useful.

Mainly he wanted to say that, for Napoleon's use case time wave was not useful but time graph was useful, and in second case time wave was useful but not time graph.

7. **What do you think about the 2D map in this**

**environment? Was it useful? Why?**

Well, It could be useful, especially considering that if you would have maybe time component built in like animation, and perhaps could be useful

**8. Did you execute any task by just using the STC, or time wave / time graph, or 2D map (alone)?**

**9. What did you like most about the visual environment?**

The connection between views really nice thing, so you can get different information from different views, that was probably most useful part in my view

**10. What did you not like about the visual environment?**

Crushing

**11. Do you feel there is anything missing? What exactly did you miss?**

yes, I think...well , 2D map did not work in my case, so, 2D map was probably that I miss and I think time graph at least in second case would have more informative if you would have annotations instead of altitude.

**12. Would you say that you are satisfied with the visual environment?**

My honest opinion is that there is very little data, so, it still... to answer and explore this data using this tools. but I do not know, if it would be really good if I have let's say 20 or 50 tracks, I do not know how I would be able to answer this questions. Especially looking on time wave…the case probably will not allow, there we have 15 corps and already time wave I found really not easy

**13. What are your final comments and recommendations?**

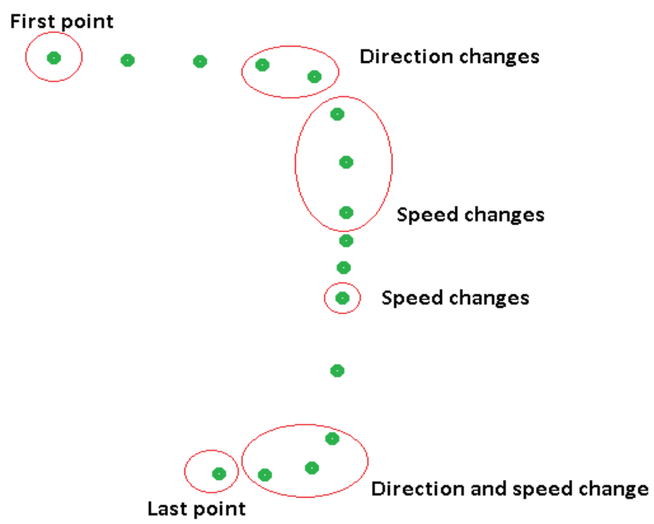
In this probably proper connection...proper background map would be nicer I think, any way people like to have. For instance if I would know which part of Tallinn you were taking pictures. This type of things then gives a bit more information and interpretation

**End of the Interview**

# APPENDIX 11: PHASE 6: FILTERING ALGORITHM APPLIED FOR COMPLEX DATASETS

The objective of this algorithm is to eliminate unnecessary points from a GPX track. By simplifying it while keeping more-or-less the same information (the difference with the original is considered acceptable), so that the STC can easier cope with the large amount of data. The algorithm detects segments in a trajectory where the holder of the GPS device has followed a more-or-less constant direction and speed. This is a straight segment (straight in all 3 dimensions: X, Y and T). For each such segment, the intermediate locations that were placed by the GPS device are eliminated (those are possibly tens or hundreds of locations, one for every second), and only the first and last point are kept. When a significant deviation from the straight segment occurs (e.g. when walking around the corner of a building or when stopping for a traffic light), the corresponding GPS locations are kept in the GPX track. The detection when a deviation is 'significant' is based on user-defined threshold values that are provided to the algorithm, and can be calibrated so that as many as possible intermediate locations are eliminated from the GPX track while not altering the visual impression of the trajectory significantly. The calibration may result in different values for pedestrians and for cars, because pedestrians tend to be less accurate in walking straight then cars.

The figure bellow explains algorithm visually. Based on the timestamps recorded by GPS, possible to define distance between registered points. The example bellow shows movement segment of pedestrian that walks around an obstacle. The green points are the original GPX track. The red circles mark the points that will come into the resulting GPX track after applying the algorithm. These green points do not add any significant information to data for visualization in the STC.



## APPENDIX 12: PHASE 6: INSTRUCTIONS TO THE TEST ON THE USE OF THE GVA ENVIRONMENT FOR COMPLEX DATASET

Dear Participant,

This usability research intends to find out how the STC performs in a visual exploration environment with other graphic visualizations such as a street profile graph and a 2D map. In other words, how the STC performs in an interactive geovisual analytics environment, in which an interaction is possible with location, attribute and time components of the data.

Consequently, we have developed a visual environment based on the requirements of experts from the urban design domain, related to the use case *'pedestrian movements within the city center of Delft'*. The dataset was collected by urban designers from 11 to 14 November 2009. The datasets were collected by GPS receivers from two different locations: the Phoenix and Zuidpoort car parks (Figure 1).

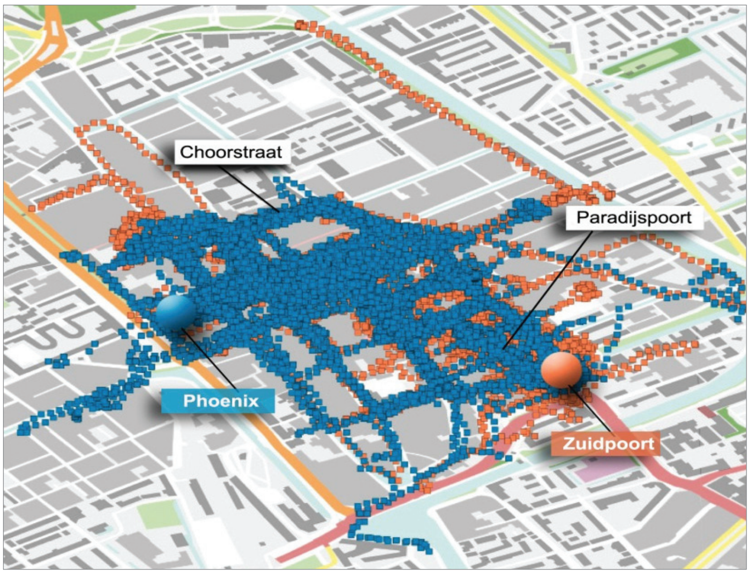



Figure 1.The location of the Phoenix and Zuidpoort car parks and the streets Choorstraat and Paradijspoort in delft city center. *For detail maps see the last pages of this document.*

Totally have participated over 300 individuals. The purpose of data collection was to improve the city center and make it more enjoyable for pedestrians. Therefore, the dataset contains information on the individual's age, gender, shopping purpose, occupation, etc.

Please consider that the intention of this experiment session is to evaluate the developed analytical environment. Therefore, please feel free to express your ideas and feelings during the test, because they are essential for further improvement.

During the evaluation session four different methods will be used: screen recording, think aloud (video observation and audio recording) and an interview.

In order to find out how the developed environment works, you will be given tasks to complete during the test. While you are working on them, we ask you to think aloud on what you think or feel or how you are going to accomplish the particular task.

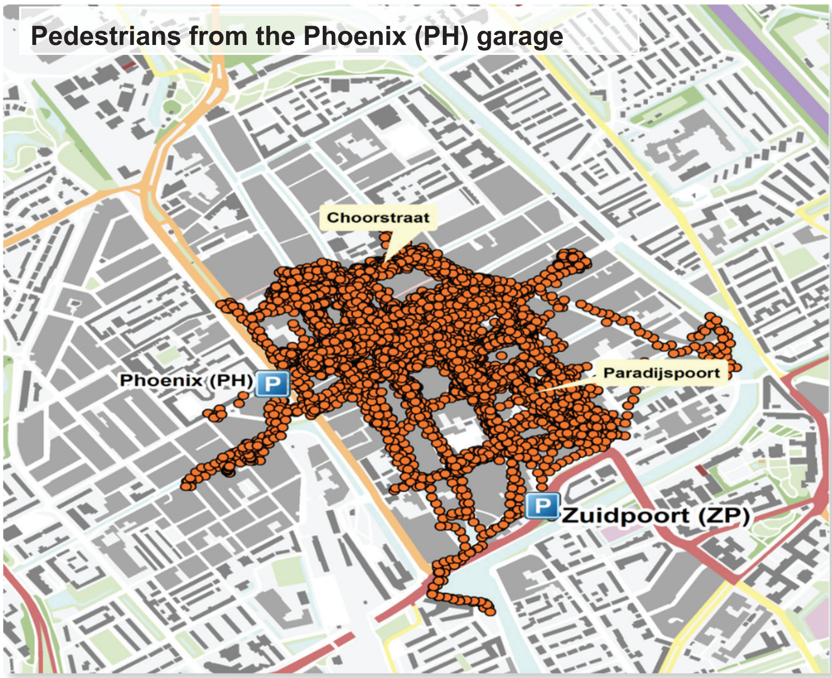
While you are working on the tasks, I will listen and follow your thoughts during your ‘think aloud’. In case you stop talking or the action taken by you is not clear to me, I might ask you questions like: What are you think about? What are you looking for? Why do you think so? Could you please explain why you think so?

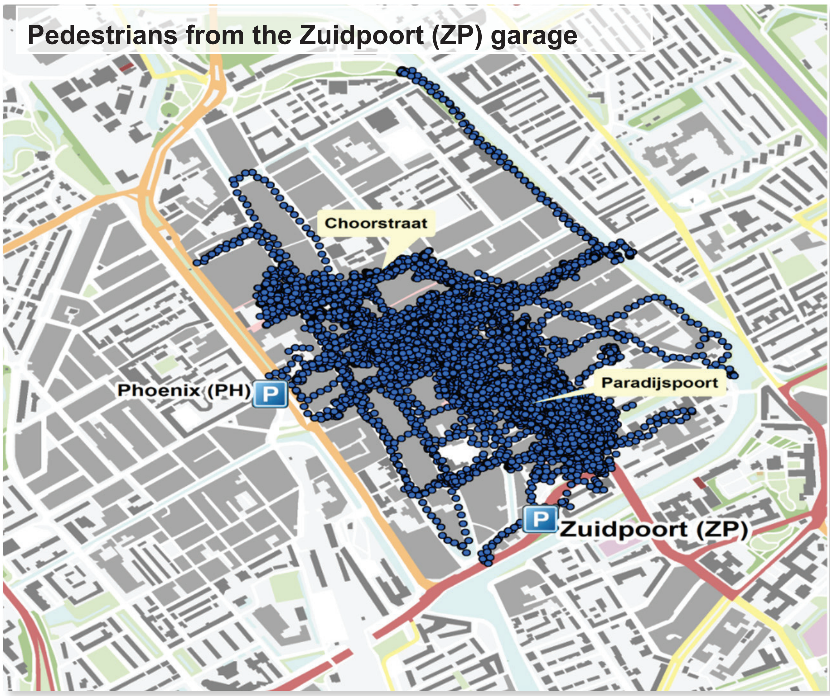
On the screen you see an analytical environment that aims to help you in the comparison of the pedestrian movements along two streets, Choorstraat and Paradijspoort. These streets are shopping areas located in a different part of the city and closer to the different parking garages, please have a look on the 2D map. The proximity to the parking garages can be influential on the use of the above mentioned streets by pedestrians. Therefore, the analytical environment should help you to find out more about the pedestrians’ movement behaviour on the Choorstraat and the Paradijspoort.

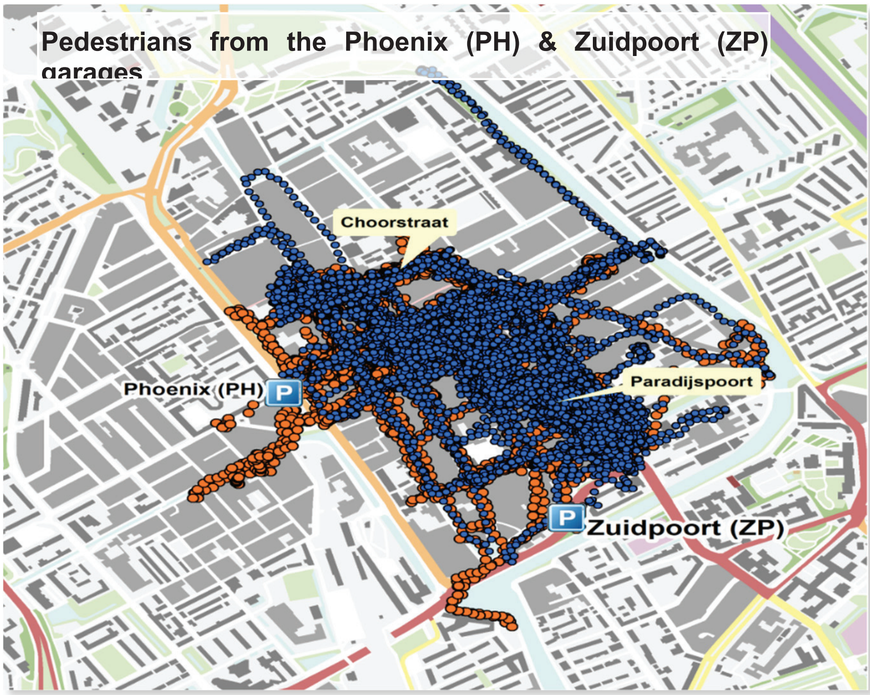
In the analytical environment you will have four viewers in total. The viewers in the top row are representing the street Choorstraat and the Paradijspoort. The viewers in the bottom row are representing the street /time profile graph for each street. The time profile graph shows pedestrian crossings of the streets from a T – time and X – longitude perspective. In a moment I will demonstrate to you how all these viewers are functioning.

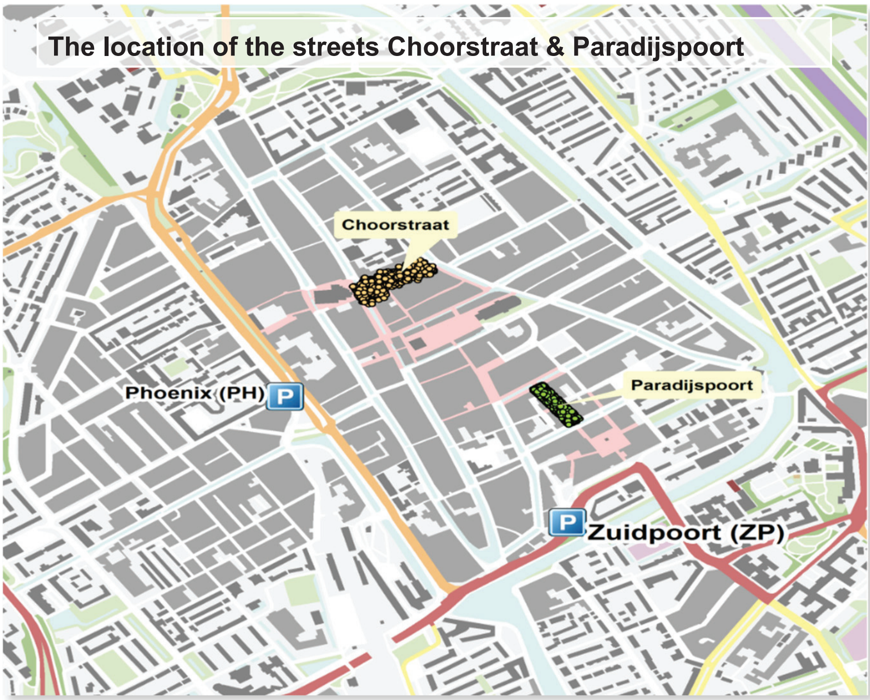
During the evaluation you should interact with these viewers by zooming in / out, by panning, rotating, selecting, filtering, etc. Also, you will have representation legend windows for the 3D STC viewers in order to be able to identify the context of information. You also can minimize or maximize represented viewers, but you cannot change their order on the screen.

Now let me to demonstrate to you the functions that you need for the task execution.


Pedestrians from the Phoenix (PH) garage
Choorstraat
Phoenix (PH)
P
Paradijspoort
P
Zuidpoort (ZP)


Pedestrians from the Zuidpoort (ZP) garage
Choorstraat
Phoenix (PH)
P
Paradijspoort
P
Zuidpoort (ZP)


Pedestrians from the Phoenix (PH) & Zuidpoort (ZP) garages
Choorstraat
Paradijspoort
Phoenix (PH)
Zuidpoort (ZP)


The location of the streets Choorstraat & Paradijspoort
Choorstraat
Paradijspoort
Phoenix (PH)
Zuidpoort (ZP)

## Instructions for the use of the GVA environment for complex datasets

The Space Time Cube (STC) represents a 3D visual representation, in which the vertical axis represents time (t) and the horizontal axes represent space (x, y) (Figure 1). This interactive environment allows STC manipulation using various functionalities.

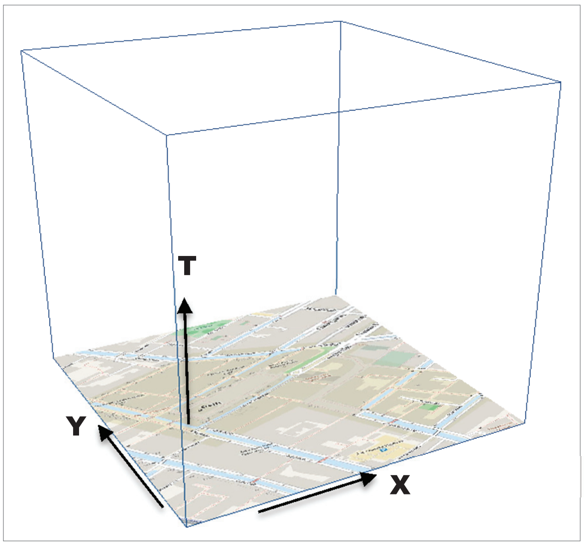



Figure 1. Space (X, Y) and time (T) dimensions in the STC environment.

1. To be able to determine the location of events in the STC you have to use the OpenStreet base map which is located in the bottom of the cube (Figure 2). In the program environment, in this particular case the base map only shows the area related to the movements of the pedestrians in the Choorstraat and the Paradijspoort. *Please go to the program and see.*

2. The base map may be moving vertically along the time axis. To make it movable you should go to the left side of the frame of the STC viewer and find the little slider button. Then you should press and hold the left mouse button continuously and move the slider up and down (Figure 2). *Please go to the program and try.*

3. By moving the base map vertically along the time axis you can identify the time changes on T axis of the STC. This function is necessary to find the right time and explore given datasets from a temporal perspective. *Please go to the program and try.*

4. The STC is an interactive environment and gives a possibility to rotate and move / Pan. By pressing and holding the left button of the mouse you can rotate the cube in a different direction – left, right, up or down. P*lease go to the program and try.*

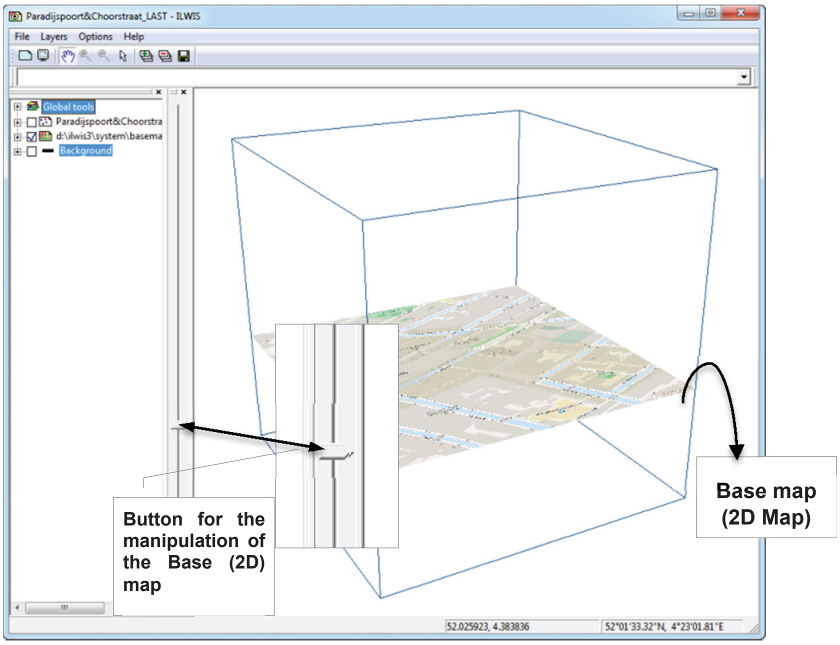



Figure 2. Manipulation of the base map in the STC environment

5. To have a detailed view of the map content you should zoom in/out the cube. For this you can use the middle scroll button of the mouse. *Please go to the program and try.*

6. It is also possible to move the STC in the viewer without rotating and zooming. For this option, you should press and hold the right button of the mouse and move it in a different direction (left, right, up, down). *Please go to the program and try.*

7. In the 'table of contents' on the left side of the STC viewer the layers are shown that you need for answering the questions related to the Delft city center: 'Paradijspoort Pedestrians', Choorstraat Pedestrians' and '…\OpenStreetMap'. *Please go to the program and see.*

8. In the STC viewer, the movement of individual pedestrians is represented as trajectories or space-time paths (Figure 3). Accordingly, the number of space-time paths or trajectories indicates the number of pedestrians.

9. When pedestrians did not move, this is represented as vertical lines or stations in the STC.

10. The inclination of a trajectory indicates the speed of movement. A gentle inclination represents a fast speed; in other words, the person was moving faster. A greater inclination indicates a slower speed, i.e. the person was moving slowly.

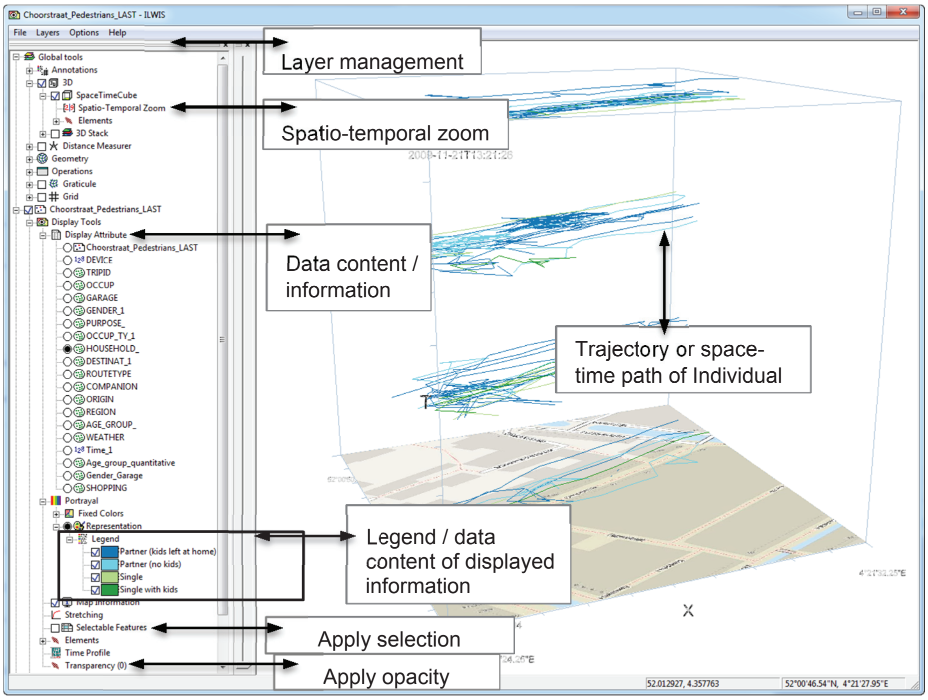



Figure 3. STC view and its functioning

11. The layers of 'Paradijspoort' and 'Choorstraat' contain different information about pedestrians. It is possible to display this information in the visual environment in the following order:

    <u>Choorstraat Pedestrians → Display tools → Display Attribute → HOUSEHOLD</u> or any information, Figure 3 (please go to the program and try).

12. The content of the selected information will result under the representation in legend menu. Figure 3, in STC viewer shows the information about households. Where, the colors attached to the trajectories represent attribute information / data content. For example: dark blue color indicates trajectories of the pedestrian who have kids but visiting city with partners, while light blue color indicates the trajectories of the pedestrian who does not have kids and visiting city with partners.

13. For answering the questions in this user test you need to know several functions (Figure 3):

    - ***Spatio-temporal zoom*** – using this function you are able to zoom to / select represented data content from a temporal or spatial perspective and explore the data in more detail. This function is under the STC option as shown in Figure 3 and it can be opened by double clicking it. Figure 4 shows the window that opens after double clicking.

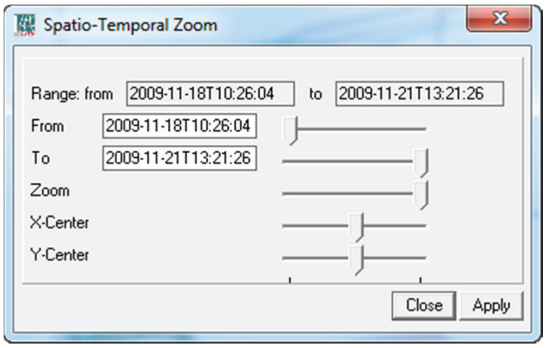



Figure 4. Spatio-Temporal Zoom function

- ***Display attribute*** – you can select and display any attribute information that you would like to explore.
- ***Representation/Legend*** **–** lets you see visualized information ordered by certain categories and represented by specified visual variables (Figure 3).
- ***Selectable features / highlight*** – you can find these in the table of contents under 'Display__Tools' of 'Paradijspoort Pedestrians' or 'Choorstraat Pedestrians' layers. During the evaluation, you might want to use this function to select different trajectories. *Please go to the program and try.*
- ***Pan*** – you can find by clicking the right button of the mouse in the viewer of the STC. It has to be used for manipulation of the STC viewer, rotate, move and zoom in/out.
- ***Entire map*** – you can find by clicking the right button of the mouse in the viewer of the STC. It has to be used when losing the STC from the visibility in the viewer. *Please go to the program and try*.
- ***Transparency / opacity*** – is a features that can help you for some visualization problems. With this option (available under 'Display Tools') you will be able to compare different layers and find valuable information, *please try.*
- ***Time graph (TG)*** – represents the street profile graph for the streets (Figure 5). In the TG you have a X-grid demonstrating the entire distance of the street and divided equally by the graph (Figure 5 – A). The Y-grid shows time duration and is also divided equally (Figure 5 – B). Besides, the TG demonstrates the location of parallel streets crossing the Choorstraat or Paradijspoort. They are represented as bold lines on the X- and Y-grid (Figure 5 – C). In the TG, the time axis is directly linked to the STC T axis and any change applied in one viewer will automatically be reflected on another. In addition, the TG will let you select trajectories and observe them in the STC and 2D map.

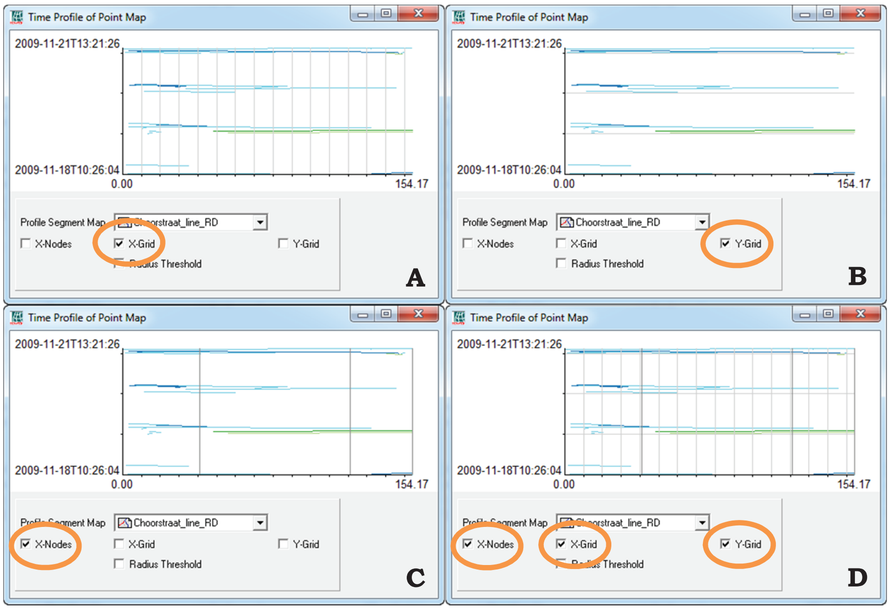



Figure 5. Time profile graph: **A**. X-grid – Street distance, **B**. Y-grid – Time duration, **C**. X nodes – Parallel crossing streets, **D**. All together.

14. It is possible to remove the ‘table of content’ from the visual environment and, in case of necessity, display it again. For this manipulation, in the top menu bar you should go to:

Options → Layer management

## APPENDIX 13: PHASE 6: GVA USABILITY TESTING INTERVIEW QUESTIONS FOR COMPLEX DATASET

1. What is your overall impression of the STC and its visual capability?
2. Was it easy to orient yourself in visual environment and answer on the given tasks?
3. What was the difficult task for you? Why?
4. What was the easiest task for you? Why?
5. How do you like the idea of two STC viewers in developed visual environment? Was it useful during the task execution? Why?
6. What do you think about SPG? Was it useful for exploration of this data? Why?
7. What was the task that you answered just using the STC, or SPG?
8. What did you like most about visual environment?
9. What you did not like about visual environment?
10. Is there anything that you feel is missing? What exactly did you missed?
11. Would you say that you are satisfied with visual environment?
12. What are your final comments and recommendations?

# APPENDIX 14: PHASE 6: INSTRUCTIONS TO THE TEST ON THE USE OF THE GVA ENVIRONMENT FOR LARGE DATASET

Dear Participant,

The goal of this experiment is to define how the STC performs in a visual exploration environment, combined with parallel coordinate plot and 2D OpenStreetMap. In other words, how STC performs in a highly interactive geovisual analytics environment. Especially, when environment allows an interaction with location, attribute and time components of the data. This interaction is an iterative process that lets user to work with program environment and uncover interesting and meaningful patterns. The process of knowledge discovery depends not only on datasets, but also on the method that has to support the exploration.

Please consider that the experiment aims to judge the visual end exploratory capabilities of the developed visual environment and not participant's possibility to execute tasks. Therefore, please feel free to work in program environment and provide valuable comments and ideas for further improvement.

For this experiment you should complete several tasks that you will get after the working exercise in visual environment. During the test session will be used several evaluation methods; video and audio recording, screen logging, think allowed and interview. These recorded materials will be used later, to analyse discovered usability issues in developed environment and will be completely confidential.

## Instructions for the use of the GVA environment for large datasets

Space Time Cube (STC) represents a 3D visual representation, where vertical axis represents time (t) and horizontal axes represent space (x, y) (Figure 1A). For information visualization STC plugin was implemented in Ilwis GIS environment, this interactive environment allows STC manipulation using various functionalities. To be able to identify the location of events in STC you have to use base map i.e. OpenStreet map located in the bottom of the cube. *Please go to the program environment and follow the instruction*.

- In the program environment, in this particular case the base map demonstrates only that area related to the movement of the Tallinn suburban commuters (Figure 1B). *Please go to the program and see.*
- The base map is moving along the time axis, vertically. To make it movable you should go to the left side of the frame of the STC viewer and find little button. Then you should press left side of mouse continuously and move it up and down (Figure 1B). *Please go to the program and try.*

\- By the moving Base map on the time axis vertically you can identify the time changes. This function is necessary to find right time and explore given datasets from temporal perspective. *Please go to the program and try.*

- STC is an interactive environment and gives possibility to rotate and move. By the pressing on the left button of mouse you can rotate it in a different direction – left, right, up or down. P*lease go to the program and try.*

- To have a detail view of the map content you should zoom in/out cube. For this you can use middle scroll button of mouse. *Please go to the program and try.*

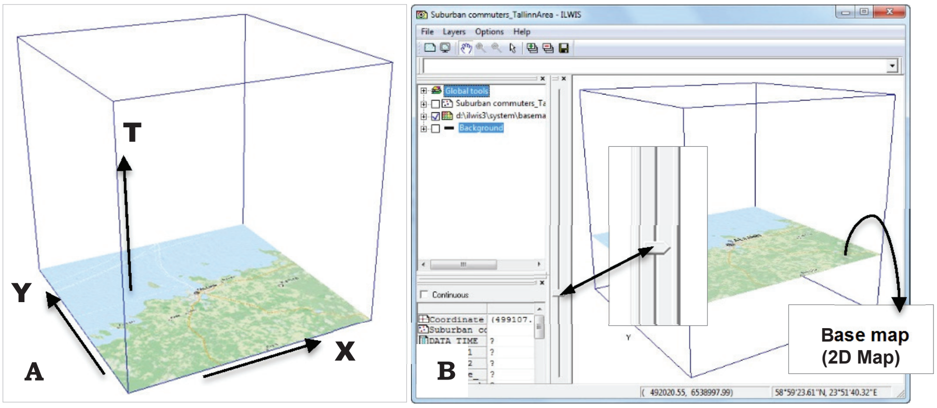



Figure 2. A. Space (X, Y) and time (T) dimensions in STC, and B. Manipulation of the base map in the STC environment

- STC possible to move in the viewer without rotating and zooming. For this option you should press right button of mouse and move it in a different side (left, right, up, down). *Please go to the program and try.*

- On the left side of the STC viewer on the 'table of content' are enumerated the layers that you need for answering the questions; 'Suburban commuters Tallinn' , 'OpenStreetMap' and Land use map od Tallinn area (Figure 3). *Please go to the program and see.*

- The movement of suburban commuters in STC viewer is represented as trajectories or space-time paths (Figure 3). *Please go to the program and see.*

- The layer of 'Suburban commuters Tallinn' contains different information about suburban commuters, but for this experiment will be used: nationality, income, gender and education. This information possible to display in the STC with the following order:

  Suburban commuters Tallinn → Display tools → Display Attribute

- For each attribute information data have been classified beforehand and by selecting the needed attribute information you will have ready design on your screen. *Please go to the program and see.*

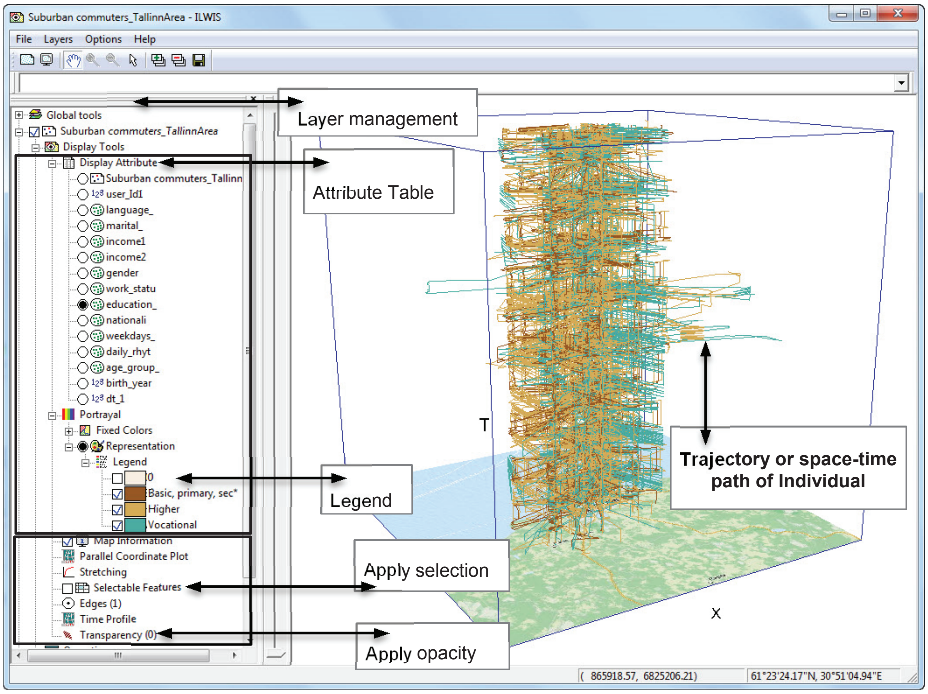



Figure 3. STC viewer and its functioning

- The space-time paths or trajectories indicate the number of suburban commuter's while color is attribute information selected by user.
- For answering the questions you needs several functions to know:
  - ✓ ***Spatio-temporal zoom*** – using this function you are able to zoom represented data content from temporal or spatial perspective and explore it more detail.
  - ✓ ***Display attribute*** – you can select and display any attribute information that you would like to explore
  - ✓ ***Representation*** **–** lets you to see visualized information ordered by certain categories and represented by specified visual variables. Based on the visual variables you are able to filter displayed information by categories.
  - ✓ ***Selectable Features/highlight*** – you can find in table content under the display tools of 'Suburban commuters Tallinn'. During the evaluation, you might need to use it several times.
  - ✓ ***Pan and Entire map*** – you can find them by clicking on the right button of the mouse in the viewer of the STC or 2D map.
  - ✓ ***Transparency/opacity*** – is and features that can help you for some visualization problems. With this option you will be able to compare different layers and find some valuable information
  - ✓ ***Visual variables*** – are set of symbols applied on datasets to represent qualitative and quantitative nature of the phenomena. In our

'representation' blog they can be filtered by removing the tick along the described content (Figure 3).

- In order to save the space in visual environment, the 'table of content' possible to remove and in case of necessity display it again. For this manipulation you should do following steps:

  Option → Layer management

- In visual environment you also have parallel coordinate plot. The order of the displayed information is possible to change. To answer the questions you can organize the order of the displayed fields as you think that is more convenient. You should just drag and drop the filed you would like to move up or down.
- The 2D OSM is interactive and allows to switch on/off represented information, or filter them by characteristics.
- The PCP shows all attribute characteristics related to the displayed data. The displayed attribute information located on the left side can be reordered or switch on/off. The PCP It allows to select and deselect any information you would like. By locating cursor on the trajectories, you can see more info on trajectories. The trajectories selected in the PCP will be highlighted in the STC and 2D OSM too.

## APPENDIX 15: PHASE 6: GVA USABILITY TESTING INTERVIEW QUESTIONS FOR LARGE DATASET

1. What is your overall impression of the visual environment and its visual capabilities?
2. Was it easy to orient yourself in the visual environment and to execute the given tasks?
3. What was the most difficult task for you? Why?
4. What was the easiest task for you? Why?
5. What do you think of the idea to combine several STC viewers in the visual environment? Was it useful during the task execution? Why?
6. What do you think about the Parallel Coordinate Plot (PCP)? Was it useful for the exploration of these data? Why?
7. What do you think about the 2D map in this environment? Was it useful? Why?
8. Did you execute any task by just using the STC, or PCP, or 2D map (alone)?
9. What did you like most about the visual environment?
10. What did you not like about the visual environment?
11. Do you feel there is anything missing? What exactly did you miss?
12. Would you say that you are satisfied with the visual environment?
13. What are your final comments and recommendations?

# Summary


## Space-time cube – design and usability

Over the past decades, we have witnessed increasing achievements of technology that affected the lifestyle of modern society. Wide availability of inexpensive navigation equipment (mobile phones, digital navigation devices, GPS receivers) enables the collection of information on movements more easy than ever before. These recordings provide accurate location (latitude, longitude, altitude), time and attribute information about objects (humans, animals, vehicles, etc.) anywhere in the world. This information on change in space and time is the study interest of experts in various research domains.

Nowadays, a wide range of visual methods as well as interactive techniques, supported by computational algorithms has been developed to support the process of exploration of complex movement datasets. One of these graphics is the Space-Time Cube (STC), which has the ability to model and represent relationships between movement patterns over space and time. The two-dimensional horizontal plane (x, y) represents the location of an object in space and the vertical plane (t) represents its location in time. St-path represents the movement through space-time undertaken by an object. The 'shape' of the trajectory contains information on the nature of the movement. It can answer questions about the where (locations) and when (time), but also about 'how long' and 'how fast'.

The idea of the STC originates from the concept of Time Geography introduced at the end of the seventies of the last century by the Swedish geographer Hägerstrand for studying the spatio-temporal characteristics of human activities. By that time, it was an analytical framework for the exploration of spatio-temporal interactions in people's everyday lives. Until the beginning of this century, the model was used sparsely in studies in human geography. The reason for this was the poor computational development causing tedious manual drawing and data collection. Later on, technological achievements in Geographical Information Systems (GIS) made the implementation of time geography easier. Clearly, in scientific research, space-time movements acquired significant interest of researchers, and scientists renewed their interest in time geography. Nowadays, a wide range of topics such as migration, gender studies, travel behaviour, archaeology, history, transport accessibility, etc. have accumulated complex movement datasets that require visualization in order to accommodate the extraction of knowledge. For this purpose, the STC is a widely used visual representation.

However, little is known whether the cube is truly efficient and effective to satisfactorily display complex datasets as stand-alone visual representation or as a part of a GeoVisual Analytics (GVA) environment. Earlier usability research did not offer directions on how the STC content should be designed from a cartographic perspective, or whether it is influencing the exploration process. The lack of such evaluation studies for the STC to visualize data is the main driver of this research.

The focus of this research is on the development of effective and efficient visualization strategies and design guidelines through systematic usability studies in specially construct GVA environments to facilitate knowledge extraction from various datasets. To be able to realize this goal, the research is divided in three main objectives.

The *first objective* is a systematic investigation of relevant research on time geography, geovisualization and usability disciplines to highlight knowledge in theoretical and practical studies.

The *second objective* is to develop a conceptual framework based on objective 1's findings, by incorporating problem, solution, and evaluation perspectives resulting in the design guidelines and visualization strategies. This offers an approach to the evaluation of the STC content with special attention for cartographic design aspects and the environment in which the STC has to function. The cartographic design guidelines are linked to suggested visualization strategies and allowed the development of hypotheses for extensive usability studies. These systematic studies had to identify the strengths and weaknesses of the STC under different conditions.

The *third objective* concerns the evaluation. During the evaluation, four test datasets in varying size and complexity based on the real world problems in close cooperation with the owners, the domain experts have been used. Combinations of different qualitative and quantitative usability methods have been used. The first allows one to examine people's experiences, actions, behaviour, etc. in detail since it provides complex descriptions of experiences gain during the experiment. Methods include video/audio/screen recordings, think aloud, observation and post experience interviews, and focus group discussions. The second intends to measure, quantify and count research issues identified during a usability study. Methods include task analysis, eye tracking, and pre-selection questionnaire.

The evaluation has been split in six phases. The first phase starts from the problem perspective based on the requirement of domain experts. To realize the research goals a User Centred Design (UCD) research methodology was followed. The second phase links to a solution perspective and is based on theoretical visualization knowledge.

The third phase included two experiments designed for and executed in the working environment of the domain experts at their home universities. The objective of the experiments was to gain deeper insight into the further needs and experiences of the domain experts to potentially extend and improve the STC application. Thus, by measuring and studying confusions, disorientations, satisfactions and success of their activities during the interaction with the application as well as the expectations they expressed, the requirements for the design and tools were identified.

In the fourth phase the experiment's objective was to obtain information on the cartographic design aspects for the STC content. It reports on the results of a usability study conducted with nine experts from the geovisualization domain. A focus group experiment was the starting point for a discussion on the use of the design alternatives hypothesized earlier. The experts from the geovisualization domain judged the suitability of the different design. The results reveal that the use of these design alternatives is influenced by the size of the data sets used. Nevertheless, color hue and color saturation were advised as the most suitable solutions for data visualization. However, at the same time remarks were made that only design will not be able to deal with the exploration of such datasets and that additional analytical functionality is just as important.

Phase 5 consisted of a usability study of design alternatives with the stand alone STC was done via a task-based experiment with 22 participants who were unfamiliar with the cube. During this experiment, participants were asked to think aloud while executing the given tasks. This process was video/audio/screen/eye recorded by Tobii Studio software. After completing the tasks, the participants were interviewed to share their opinions, attitudes and experience gathered during the experiment. The materials derived from these qualitative experiments, resulted in a transcript protocol, and the outcomes derived from eye tracking and task execution resulted in quantitative metrics. The outcome of the experiment revealed various reasons for the acceptance or rejection of the design options. The results coincided with what the geovisualization experts suggested during the focus group evaluation. The experiment conducted in phase five, revealed a clear preference for the visual variable color to visualize different types of data complexity in the STC. The perceptual properties of visual variables worked as predicted with the exception of size. Size is known as the only visual variable with three perceptual properties, but this experiment could only partly confirm its selective perceptual characteristics.

Finally, in phase six the STC was judged in three different GVA environments each with its own data sets, incorporating the results of the earlier phases. Next to the STC the participants could work with a 2D map, a parallel coordinate plot, the time wave and a time graph. The task-based experiments employed a mix of qualitative and quantitative user research techniques. Similar to the previous experiments, test participants were asked to think aloud while executing tasks. After completing the tasks, the participants were interviewed to derive more information on their experiences during the experiment. The qualitative studies resulted in a transcript protocol, and the eye tracking and task execution resulted in quantitative efficiency metrics. The results of the analysis show that the appreciation for each of the visual representations available in the GVA environment differs depending on the data and environment. In conclusion, the positioning of the STC in various GVA environments offers better exploration options and a better understanding of temporal events, multiple data characteristics and the geography.

This research contributes to Time Geography in general and the usability of the STC in particular. The value of the STC as an elementary part of Time Geography to get insight in all kinds of movement data has been proven by using four different case studies in this research. The usability of the STC has not only been studied as a stand-alone visual representation, but has been placed in the context of GeoVisual Analytics environments with other (carto)graphic representations.

The research confirms the importance of the harmonious coexistence of cartographic design theory and visualization strategy. The empirical investigation of cartographic design aspects confirmed the expected influence of data complexity on design options for the STC. In such situations a simple design is preferred. The known perceptual properties of the visual variables proved to be valid in the STC as well, with some minor deviations and a high preference for colour. The research also demonstrates that the STC functions well in GeoVisual Analytics environments.

# Samenvatting

## De ruimte-tijd kubus – ontwerp en bruikbaarheid

De technologische ontwikkelingen van de laatste jaren hebben een enorme invloed gehad op de levensstijl in de moderne maatschappij. De ruime beschikbaarheid van goedkope navigatie apparatuur (mobiele telefoons, navigatie instrumenten en GPS ontvangers) maken het verzamelen van gegevens over bewegingen eenvoudiger dan ooit. De gegevens kunnen overal ter wereld verzameld worden hebben een hoge positionele (lengte, breedte en hoogte) en tijdsnauwkeurigheid en bevatten kenmerken over de objecten (mensen, dieren, voertuigen enz.). Deze gegevens over veranderingen in ruimte en tijd zijn een geliefd onderwerp van studie in diverse disciplines.

Momenteel zijn er diverse visualisatie methoden, ondersteunt door rekenkundige algoritmen, beschikbaar ter ondersteuning van de exploratie van complexe data set met bewegingsgegevens. Een van deze grafische representaties is de Ruimte-Tijd Kubus (RTK), die het mogelijk maakt om relaties in bewegingspatronen te modeleren en zichtbaar te maken in zowel ruimte als tijd. De horizontale assen van de kubus representeren de locatie van een object in de ruimte (x,y) en de verticale de positie in de tijd (t). Een ruimte-tijd pad representeert de beweging van een object in ruimte en tijd. De vorm van het pad bevat informatie over de aard van de beweging. Het kan antwoord geven op vragen als 'waar' en 'wanneer' maar op 'hoe lang' en 'hoe snel'.

De RTK is een begrip dat stamt uit het domein van de Tijds-Geografie, en werd aan het einde van de jaren zestig van de vorige eeuw geïntroduceerd door de Zweeds geograaf Hägerstrand om de ruimte-tijd kenmerken van menselijke activiteit te bestuderen. In die dagen was het het analytische instrument om de menselijk interacties in het dagelijkse leven te bekijken. Tot aan het begin van deze eeuw werd het slecht sporadisch toegepast vanwege de beperkte beschikbaarheid van gegevens en het moeizame visualiseren van de RTK. Uiteindelijk maakte de ontwikkeling van GIS de implementatie van de Tijds-Geografie eenvoudiger. De al eerder genoemde technologische ontwikkelingen hebben de interesse in bewegingsdata doen toenemen en voor een hernieuwde aandacht van de Tijds-Geografie gezorgd. Allerlei studies op gebieden als migratie, gender, reisgedrag, archeologie, geschiedenis en transport toegankelijkheid hebben reusachtige gegevenssets verzameld die visualisatie behoeven om kennis en inzicht te kunnen verkrijgen. Voor dit doel wordt de RTK momenteel veel gebruikt.

Echter, er is slecht weinig bekend of de kubus op zichzelf of in een GeoVisuele Analytics omgeving, inderdaad efficiënt en effectief is om de complexe gegevens naar tevredenheid de visualiseren. Eerder

gebruikersonderzoek doet geen uitspraak over hoe de inhoud van de RTK weergegeven moeten worden op basis van kartografiche kennis en hoe dit mogelijkerwijs het gebruik van de kubus beïnvloed. Het gebrek aan dergelijke evaluatie studies is de drijfveer voor dit onderzoek.

De aandacht van deze studie gaat uit naar de ontwikkeling van effectieve en efficiënte visualisatie strategieën en ontwerp richtlijnen op basis van een systematisch bruikbaarheid onderzoek in een daarvoor speciaal ingericht GVA omgeving die het mogelijk maak kennis te extraheren uit de bewegingsgegevens. Om dit onderzoeksdoel te realiseren is het werk opgedeeld in drie hoofddoelstellingen:

De *eerste doelstelling* is een systematische studie van relevant onderzoek op het gebied van Tijds-Geografie, geovisualisatie en bruikbaarheidsstudies om de huidige theoretische en praktische kennis te inventariseren.

De *tweede doelstelling* is het ontwikkelen van een conceptueel raamwerk gebaseerd op de bevindingen van de eerste doelstelling, waarbij rekening wordt gehouden met een probleem, een oplossings- en evaluatie perspectief resulterend in ontwerprichtlijnen en visualisatie strategieën. Dit biedt de mogelijkheid tot een evaluatie van de inhoud van de RTK met aandacht voor de omgeving waarin de kubus functioneert. De relatie tussen de ontwerprichtlijnen en visualisatie strategieën leidde tot de ontwikkeling van de hypotheses voor de evaluatiestudies. Het doel van deze studies was de identificatie van de sterke en zwakke punten van de RTK onder verschillende omstandigheden.

De *derde doelstelling* betrof de evaluatie. Tijdens de evaluatie is gewerkt met vier dataset variërend in omvang en complexiteit en gebaseerd op realistische problemen aangedragen door de domeinexperts. Combinaties van verschillende kwalitatieve en kwantitatieve gebruiksonderzoeksmethoden zijn toegepast. De eerste bestuderen menselijke ervaring, acties, gedrag enz. via een uitgebreide beschrijving van wat gebeurt tijdens de experimenten. De methoden omvatten onder andere video/audio/scherm registraties, hard op denken, observatie, interviews afgenomen na het experiment als ook focus groep discussies. De tweede meten, tellen en kwantificeren acties tijdens de experimenten. Toegepaste methode zijn taak analyse, de registratie van oogbewegingen en voor-selectie enquêtes.

De evaluatie is verdeeld over zes verschillende fasen. De eerste fase is gericht op de gebruikseisen van de probleemhebbers, de domeinexperts. Om dit te realiseren is gebruikgemaakt van een Gebruiks Gericht Ontwerp van de onderzoeksmethodologie. De tweede fase was gericht op de oplossingen en maakte gebruik van de theoretische visualisatie kennis.

De derde fase omvatte twee experimenten ontworpen voor en uitgevoerd bij de domeinexperts op hun lokale universiteit. Het doel van deze experimenten was het verder in kaart brengen van de behoeftes en ervaringen van de domeinexperts om zo nodig de RTK te verbeteren. Tijdens de experimenten met de RTK is de verwarring, de desoriëntatie, de tevredenheid en succes van de experts geregistreerd, samen met de uitgesproken verwachtingen zodat de gebruikerseisen konden worden geformuleerd.

Tijdens de vierde fase is informatie over het kartografische ontwerp van de inhoud van de RTK verzameld. Dit is gedaan tijdens een experiment met een negental geovisualisatie experts. Tijdens een zogenaamde focus groep sessie zijn de verschillende ontwerp alternatieven besproken. De experts gaven hun mening over de geschiktheid van de ontwerpen. Als uitkomt bleek dat de verschillende alternatieven sterk beïnvloed worden door de complexiteit en omvang van de data sets. De visuele variabelen kleur werd gezien als meest geschikt voor de visualisatie van de ruimtetijd paden. Overigens werd opgemerkt dat met een goed ontwerp alleen je niet alle problemen oplost en dat er voldoend analytische functionaliteit beschikbaar moet zijn tijdens de exploratie van de gegevens.

De vijfde fase bestond uit de studie van ontwerp alternatieven in de op zich zelf staande RTK . Via taak georiënteerde experimenten zijn 22 deelnemers die onbekend waren het de RTK met de kubus aan het werk geweest. Tijdens de experimenten werden de deelnemers gevraagd hard op te denken. Via Tobbi Studio software werd dit samen met oog en schermbewegingen via video opgenomen. Na afloop werden de deelnemers geïnterviewd om hun opinie, houding en ervaringen te delen. Het verkregen materiaal resulteerde in een transcript protocol en kwantitatieve metingen uit de oogbewegingen. De uitkomst van het experiment toonde de redenen voor het al dan niet accepteren van de verschillende ontwerp alternatieven. Er waren veel overeenkomsten met de suggesties eerder gedaan door de geovisualisatie experts. Ook hier een sterke voorkeur voor het gebruik van de visuele variabele kleur. De perceptuele eigenschappen van de visuele variabele werkte zoals verwacht, met als uitzondering de variabele grootte. Grootte is de enige variabele met drie eigenschappen, maar tijdens de experimenten werd de selectieve eigenschap slecht ten dele bevestigd.

Tenslotte werd in fase zes de RTK beoordeeld in de context van verschillende GVA omgevingen, elk met eigen gegevens. Naast van de RTK konden de deelnemers ook gebruikmaken van een 2D kaart, een parallelle coördinaten plot, en tijdsgolf en een tijdsdiagram. De experiment gebruikte weer verschillende kwalitatieve en kwantitatieve gebruiksonderzoek methoden. Net als bij eerdere testen werden de deelnemers gestimuleerd hard op te denken tijden het uitvoeren van hun opdrachten. Na afloop volgde weer een interview om de ervaringen op te tekenen. Het verkregen materiaal resulteerde in en transcript protocol en kwantitatieve metingen uit de oogbewegingen. De resultaten toonde dat de waardering voor elk van de visuele representaties beschikbaar in de GVA omgeving afhankelijk is van de aard van de gegevens. Concluderend kan gesteld worden dat de RTK in een GVA omgeving bijdraagt en de exploratie van de gegevens en leidt tot een beter begrip van temporale gebeurtenissen, de multivariabele eigenschappen van de gegevens en de geografie.

Dit onderzoek draagt bij aan de Tijds-Geografie in het algemeen en de bruikbaarheid van de RTK in het bijzonder. De waarde van de RTK als een elementair onderdeel van Tijds-Geografie om inzicht te verkrijgen in allerlei bewegingsdata is bewezen via de vier verschillende case studies. Het gebruik van de RTK is niet bestudeerd als zelfstandig representatie maar ook in de context van de GVA samen met ander (karto)grafische representaties.

Het onderzoek bevestigd het belang van het gezamenlijk bestaan van de kartografische ontwerp theorie en de visualisatie strategieën. Het empirische onderzoek van de kartografische ontwerp aspecten bevestigd de invloed van de gegevens complexiteit op het ontwerp. In dergelijke situaties is een eenvoudig ontwerp aanbevolen.

De bekende perceptuele eigenschappen van de visuele variabelen bleken ook van toepassing in de RTK, met enkele kleine afwijkingen en een sterke voorkeur voor het gebruik van kleur. Het onderzoek toont ook aan de RTK goed functioneert in een GVA omgeving.

# Curriculum Vitae

IRMA KVELADZE

## ACADEMIC QUALIFICATIONS

2009 **PhD student in the research program STAMP (Spatio-Temporal Analytics, Maps and Processing) on the topic: Space-Time Cube, Design and Usability**, The Netherlands, University of Twente (UT), Faculty of Geo-Information Science and Earth Observation (ITC).

2001 **MSc degree in Cartography, Geodesy and Geo-Informatics**, Georgia, I. Javakhishvili Tbilisi State University (TSU), Faculty of Geography and Geology.

## SPECIAL TRAINING

2011 Summer School and Young Researchers Forum on Moving objects and knowledge discovery, co-organized by the COST Action IC0903 MOVE "Knowledge Discovery from Moving Objects" and the FP7/ICT project MODAP "Mobility, Data Mining, and Privacy", Certificate. Ghent, Belgium.

2007 International Study Course on Application of GIS (Geographic Information System) and RS (Remote Sensing) in Natural Resources Management at ITC, Certificate. Enschede, The Netherlands.

2004 International Study Course from World Tourism Organization (WTO), Certificate. Tbilisi, Georgia.

2001 International Post-graduate Course of Environmental Management, Dresden University of Technology, Certificate. Dresden, Germany.

2000 Study Course in Geographic Information System Geophysical Society of Georgia. Tbilisi, Georgia.

## PROFESSIONAL WORK EXPERIENCE

2012 Organization of the COST-MOVE workshop on: what can the space-time cube do for you? at University of Twente**.**

2008 - 2009 GIS-Assistant at the Caucasian office of WWF.

2005 - 2009 Engineer (GIS specialist) at Caucasian Institute of Mineralogy.

2002 - 2007 GIS-Assistant at the Caucasian office of WWF.

2001- 2009 Co-founder and member of the administrative board of the international environmental organization – "Caucasus Research Centre".

2000 - 2001 Georgian - German joint study project "Establishment of a scientific working group on livestock induced effects on nature in Georgia".

## PUBLICATIONS

### Reviewed publications

2015 I. Kveladze, M.J. Kraak and C.P. I. Kveladze, M.J. Kraak and C.P.J.M. van Elzakker. The Space-Time Cube as part of a GeoVisual Analytics Environment to support the understanding of movement data – the case of Tallinn suburban commuters. *Provisional acceptance, in revision (IJGIS).*

2013 J.M. van Elzakker. *A methodological framework for researching the usability of the space-time cube,* The Cartographic Journal, 3, 50, p.201-210. Presented at 26th International Cartographic Conference, ICC 2013, Dresden.

2012 I. Kveladze, S. van der Spek and M.J. Kraak. *The recognition of temporal patterns in pedestrian Behavior using visual exploration tools*: Presented at seventh International Conference on Geographic Information Science, GIScience 2012, Columbus, Ohio.

2012 I. Kveladze and Kraak M.J. *What do we know about the space-time cube from a cartographic and usability perspective?* Proceedings of AutoCarto 2012: The International Symposium on Automated Cartography. Cartography and Geographic Information Society, Columbus, Ohio.

2010 I. Kveladze & M.J. Kraak. *Design guidelines and visualization strategies for the use of the space-time cube to visualize large amounts of movement data.* In proceedings of the sixth International Conference on Geographic Information Science, GIScience 2010. Ed. By Wallgrün J.O. and Lautenschütz A.K., p. 59-62, Springer, Switzerland, Zurich.

2007 G. Liparteliani, I. Kveladze and R. Gagnidze. *Mapping of endemic species of the Caucasus Red List plant.* Caucasus Geographical Revue, 7, p.150-157.

2007 R. Maisuradze, I. Kveladze and L. Lashauri. *The landscape structure of state nature reserve of Kintrishi.* Actual topics of geography, collection of works, University press, Tbilisi, Georgia.

2004 R. Maisuradze, I. Kveladze, et al. *Some ecological characters of landscape structure, a case study on Great Caucasus.* Geography of Georgia, 3.

2004 G. Liparteliani, R. Gagnidze and I. Kveladze. *Cartographic provision of the Red Book of Georgia.* Researches on Plant Systematic and Geography*, 44, 45.*

2003 R.Maisuradze, I. Kveladze, L. Lashauri. *Landscape-ecological characteristics of Oni district.* Geography of Georgia, 2.

## Abstracts and professional (conference) publications

2013 I. Kveladze and M.J. Kraak. *Visualize movement data in the space-time cube. Presented at COST-MOVE final conference, Vienna, Austria. See link at:* http://www.youtube.com/watch?v=QyOO7DljKwI

2013 I. Kveladze and M.J. Kraak. *Evaluating cartographic design principles applied to space-time cube content. Presented at* AAG (Association of American Geographers) Annual meeting, Los Angeles, USA.

2012 I. Kveladze, M.J. Kraak and R. Ahas. *Understanding the distribution of activities of urban dwellers using the space-time cube.* Presented at: future research directions in MOVEment, COST-MOVE meeting at Delft University of Technology (TU), Delft, The Netherlands.

2012 I. Kveladze and M.J. Kraak. *Annotated trajectories and the space-time-cube. Presented at Mobile Tartu 2012, Mobile Phones, Geography, LBS. Tartu, Estonia.*

2012 I. Kveladze and M.J. Kraak. *The set-up of an evaluation method to judge the effectiveness of the space-time cube. Presented at* AAG (Association of American Geographers) Annual meeting, New York, USA.

2011 I. Kveladze and M.J. Kraak. *The space - time - cube and the display of large movement data sets: the link between visualization strategies and cartographic design guidelines. Presented at* 25th International Cartographic Conference, ICC 2011, Paris, France.

2010 I. Kveladze and M.J. Kraak. *The space-time cube revisited it potential to visualize mobile data. Presented at Mobile Tartu 2010, mobile positioning, spatial mobility, geography, LBS. Tatu, Estonia.*

2004 G. Liparteliani, A. Gegechkori, I. Kveladze. *The animals of the Red Book of Georgia* (*wall map*). Tbilisi, Georgia

## PRESENTATIONS AT CONFERENCES

2012 I. Kveladze*, Usability evaluation of the space-time cube.* Presented at Workshop on Analysis and Visualization of Movement Data, COST - MOVE workshop at University of Twente (UT), Enschede, The Netherlands.

2002 I. Kveladze and G. Liparteliani. *Tourism impacts on rare and endangered species of plants.* Presented at GIS Users' Conference, Tbilisi, Georgia.

2001 I. Kveladze and G. Liparteliani. *Mapping of the spread of endangered species of plants for Racha-Lechkhumi district.* Presented at GIS Users' Conference, Tbilisi, Georgia.

2001 S. Ghvachliani, N. Mikava, I. Kveladze L. Vephkhvadze, G. Ghambashidze. *Impact of livestock grazing on natural pastures in east Georgia.* Presented at Students' Republic Conference in Ecology - 1$^{st}$ degree diploma, Tbilisi, Georgia.

2000 S. Ghvachliani, N. Mikava, I. Kveladze L. Vephkhvadze, G. Ghambashidze. *Ecological landscape development in Georgia.* Presented at International Conference on 'Nature Conservation in Rural development Regions', organized by Georgian State Agrarian University, German Federal Agency for Nature Conservation, National Committee of UNESCO programme 'Man & Biosphere', State

Department of Forestry of Georgia and Soil Science Society of Georgia, Tbilisi, Georgia.

1999 I. Kveladze. *Impact of color on cartographic design*. Presented at students' 59th Republic Scientific Conference, Tbilisi, Georgia.

1998 I. Kveladze. *Perceptual aspects of color in cartography*. Presented at students' 58th Republic Scientific Conference, Tbilisi, Georgia.

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