Research into the Usability of the Space-Time Cube

Irma Kveladze, Menno-Jan Kraak, Corné van Elzakker

University of Twente, Faculty of Geo-Information Science and Earth Observation (ITC), The Netherlands

Abstract. In recent years, an increased interest in the use of the space-time cube to visualize movement data can be witnessed. However, little is known about whether the cube is truly efficient and effective to satisfactorily display complex movement datasets. The limited usability research that has been done did not lead to details on how the STC content should be designed and whether the cartographic design influences the exploration process. The conceptual framework that is proposed in this paper offers an approach to the evaluation of the STC content with special attention for design aspects and the environment in which the STC has to function. Systematic usability studies have to identify the strengths and weaknesses of the STC under different conditions. Therefore, the framework contains phased studies in which real-world data of four use cases of different complexity are used.

Keywords: Usability, Space-Time Cube, research framework

1. Introduction

The movement datasets accumulated in the last decades are an important source for knowledge discovery and require suitable visual representations for analysis. A wide range of representations as well as interactive techniques have been developed to support the exploration process of complex data. One means of visual representation that requires usability studies is the Space-Time Cube (STC), which has been widely used in different domains for the visualization of spatio-temporal data. Like other visual representations, the STC suffers from overplotting and visual clutter when many trajectories are displayed together. With its increasing use, usability metrics on effectiveness, efficiency and user satisfaction become critically important, but only a limited number of usability studies has been executed.

This observation forms the motivation for the research framework developed in this paper.

First, an overview of STC characteristics is given, followed by a discussion of the literature related to existing STC applications and usability evaluations. A discussion based on a user-centred design approach introduces requirements based on four use cases. In the next section, a visualization strategy is introduced based on cartographic design principles (Bertin 1983) and Shneiderman's (1996) information seeking mantra. This is followed by the description of an evaluation setup.

2. Visualization of Movements

Hägerstrand (1970) proposed a framework of time geography to study social interaction and movement of individuals in space and time. The STC is the visual representation of this framework where the cube's horizontal plan represents space and the 3D vertical axis represents time. The building blocks of the STC are the *space-time path, stations* and *space-time prism* (Lenntorp 1976, Pred 1977, Thrift 1977). The research focusses on the space-time path and stations.

The space-time path represents movement through space and time, and shows when and where individuals move and how long they stay at certain places. They have been applied to study gender differences (Kwan 1999), historical events (Kraak 2009), movements of national park visitors (Orellana et al. 2012), etc.

Stations refer to the locations where people can meet or stay for some period of time and can be recognized as indication of non-movement activities. Stations were also applied in different applications: earthquakes (Gatalsky et al. 2004), forestry (Andrienko & Andrienko 2005), archaeology (Huisman et al. 2009), etc.

Other methods: The STC has been successfully applied in combination with other methods. Romero et al. (2008) used it for the analysis of people's movements derived from video streams. Li et al. (2010) used the cube visually inspect the eye movement data. Demšar and Virrantaus (2010) applied the STC to analyse real-time vessel movements.

Despite the increasing popularity of the STC, brought about by hard- & software developments and the data rich environment, usability research still remains limited. What has been done is summarized in *Figure 1*. In most of this research the cube is compared with other graphic representations. The table also lists the user tasks given and the evaluation methods applied.

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	•				•	•
	Task execution	•	•	•	•	•	•

Figure 1. Usability research (Demissie 2010, Kjellin et al. 2010 a, Kjellin et al. 2010 b, Kristensson et al. 2009, Morgan 2010, Willems et al. 2011) of the STC in existing literature.

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 is still missing. Differing from others, Kjellin *et al.* (2010 b) have discussed aspects of 3D depth cues. 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 paper will look at the usability of the STC from this and from a user-centred design perspective, working with domain experts and real data.

3. Conceptual Framework

For research into the usability of the STC we propose a conceptual framework with three main blocks: problem, solution and evaluation *(Figure 2)*. This section will shortly discuss the goals of these three parts, whereas further sections will provide more complete descriptions of the context of the multiphase flow in each block.

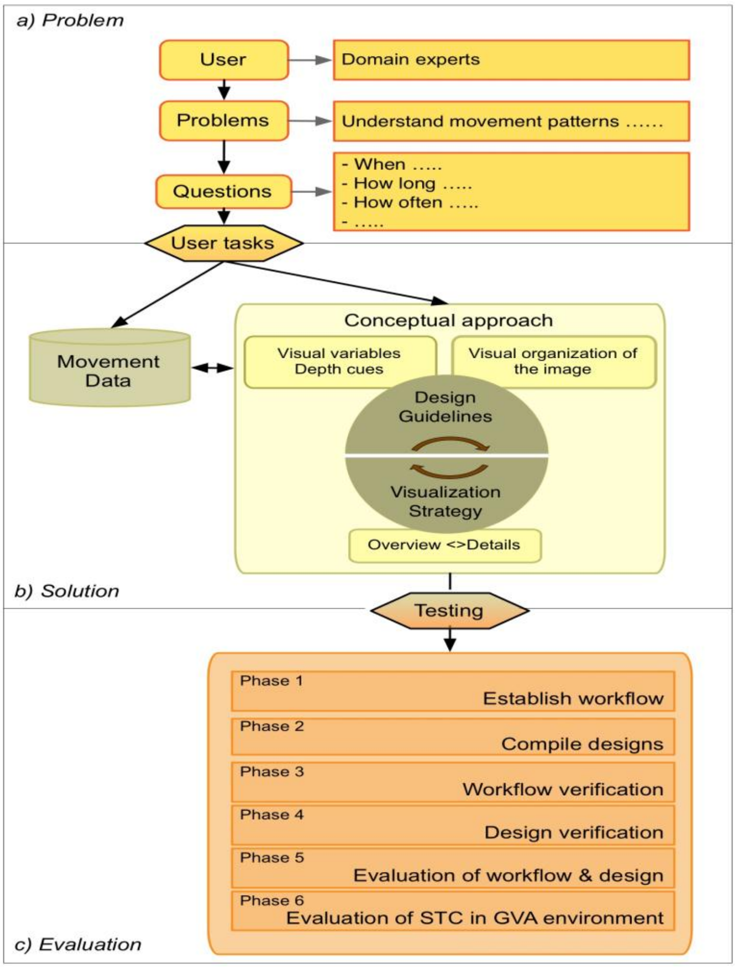

Figure 2. Research framework a) Problem block, a description of case studies and use defined questions to be answered; b) solution block, conceptual framework suggesting visualization strategies and design guidelines; c) Evaluation block, describing the steps of the evaluation process.

The problem identification may be considered as the first part (requirement analysis) of a user-centred approach (van Elzakker & Wealands 2007). Based on four use cases with problems defined by domain experts, user requirements are defined. The four cases differ in data complexity and data quantity. For each of these cases, experts have formulated problems to be solved and questions to be answered. The defined user tasks have to be solved in the proposed solution block.

The solution block describes the environment in which the STC operates. Here, two parts, visualization strategies and design guidelines – which will influence each other, are emphasized. The visualization strategies offer a methodological approach on how information could be explored (workflow) to support the process of the task execution following the overview ↔ detail principle (Keim et al. 2008, Shneiderman 1996). The design guidelines are about 'how to show' the STC content based on the cartographic design theory (Bertin 1967, 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 the depth cues (Marr 1982, 2010, Ware 2006). The visualization strategies and design guideline will influence each other (Kraak 2011).

The evaluation block decribes the setup of the usability testing of the STC. It consists of five 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 known from the visualization strategies. 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 four 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 can express ideas and remarks about the validity of the cartographic design and implementation in the STC. Phase five 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 GeoVisual Analytics (GVA) environment. Here results should lead to clarity about the effectiveness, efficiency of and satisfaction with the use of the STC in different circumstances.

4. Problem Identification with Domain Experts

The Problem block focusses on getting an understanding of the use and user issues and requirements. With the help of domain experts problems have been identified in four use cases:

Use case Estonia. Dataset contains annotated movement trajectories of individuals, collected by GPS (*Figure 3a)*. Travellers interested in analysing the trip back home afterwards are considered to be ‘domain experts’. Their objective is to understand the temporal distribution and diversity of their trips based on mode of transport (plane, bus, etc.) and undertaken activities, and to view multiple annotations based on keyword search. Such users can be tourists or scientists who are doing fieldwork.

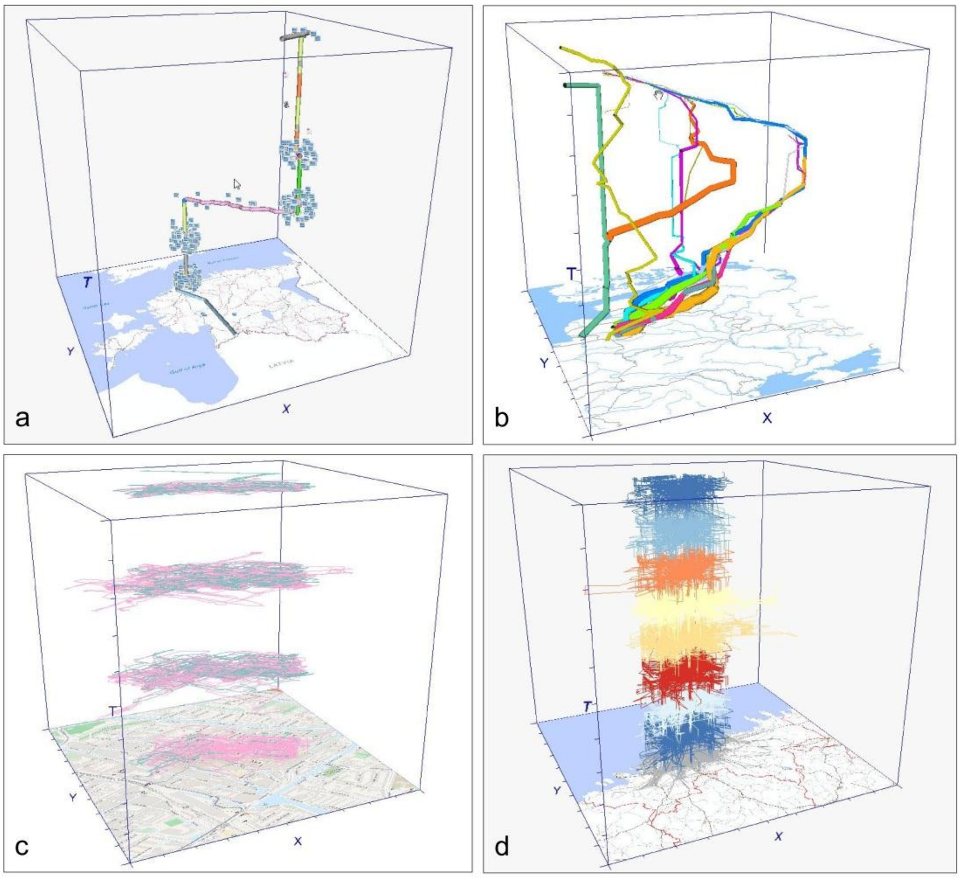

Figure 3. Four use case studies: a) Travel log data: Estonia; b) Historical event: Napoleon’s Russian Campaign; c) Pedestrian movements in Delft city center; d) Passive mobile phone positioning data of commuters, Tallinn.

Use case Napoleon. The data represent the paths followed by 15 different corpses of Napoleon's Grand Army in 1812 *(Figure 3b)*. Domain experts are historians who are interested in the fate of the army. Their objective is to understand the whereabouts of the different corpses over time to get insight into the narrative of the campaign. They also want to comprehend the influence of temperature on the number of soldiers in the corpses.

Use case Delft. The data represent shopping and leisure activities of people (city center inhabitants, neighbourhood residents and tourists/visitors) *(Figure 3c)*. The data were collected during the daytime over four days and contain information on gender, age, occupation, origin, visit purpose, weather, etc. Urban planners who are interested in the peoples' movement activities undertaken during the day were the domain experts. The objective was to understand the spatio-temporal behaviour of the pedestrians in the city center in order to identify the most visited places, selected directions and streets used.

Use case Tallinn. This complex movement dataset represents suburban commuters and their daily life style *(Figure 3d)*. The data were collected over eight days and include the positions of mobile phones. Domain experts are human geographers with the objective to understand the spatio-temporal behaviour of different types of suburban commuters during the week, while considering characteristics such as gender, language, nationality, age, occupation, etc.

5. Visual Solution Strategy

Once the workflows have been decided upon, an appropriate symbolization has to be selected. The guidelines are based on Bertin's (1967, 1983) theoretical framework with a focus on line and point symbolizations in three-dimensional space. This visualization of the space-time paths and stations will depend on their qualitative or quantitative characteristics and the constraints set by the theory.

The link between visualization strategy and design guidelines is seamless *(Figure 4)*. Accordingly, a user is able to make 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 3D cube depth perception has to be taken into account as well. Its correct application 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, etc. Others, like motion parallax, shadow and occlusion can be part of the viewing environment. However, in all situations a logical organization of the displayed information is required, which helps to form a hypothesis for evaluation.

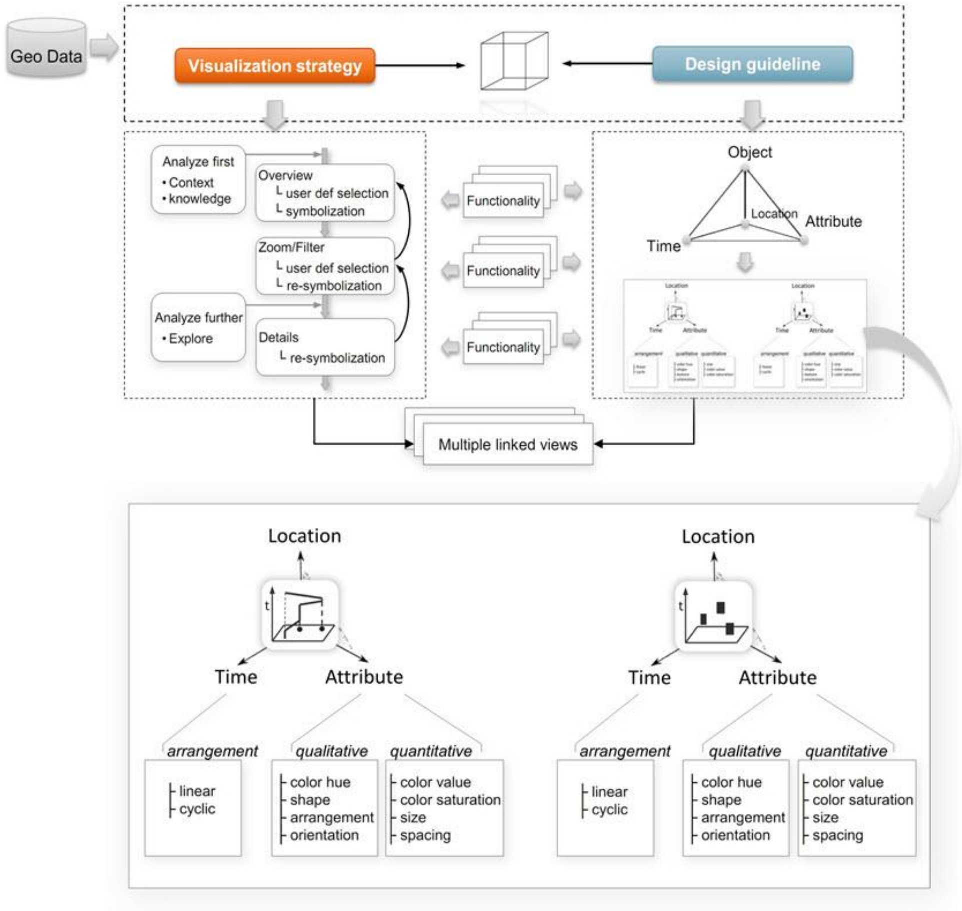

Figure 4. Solution block.

The hypothesis is that each step of the visualization strategy might require a different design, depending on the data complexity (compare e.g.a simple dataset like 'Napoleon's campaign' with complex data like 'pedestrian movements in Delft'). Of course, the graphic design of those data will be different. In particular, at overview level, a small dataset would already allow more sophisticated design with a detailed view of part of a path or station, whereas complex data representation should be done with simple graphics to avoid exaggeration of visual clutter. However, for detail step same approach of the design might work for both.

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, querying, classifying, manipulating visualization parameters, etc. Such an environment will also be part of the evaluation.

6. Evaluation Setup

The basic set-up of the usability research, following user-centred design principles, has already been given in *Figure 1*. Each phase is described below:

Phase one is a knowledge elicitation from domain experts to establish user requirements. The domain experts are embedded because they are the owners of the data and aware of the problems and research questions that have to be answered. Interviews were the user research technique. The one hour interview sessions were the starting-points for developing the visualization strategies, with the purpose to get insight into the data, and to formulate alternative scenarios for answering the questions *(Figure 5)*. The scenario itself includes a workflow on 'how to go about' that is linked to the steps of the information seeking mantra.

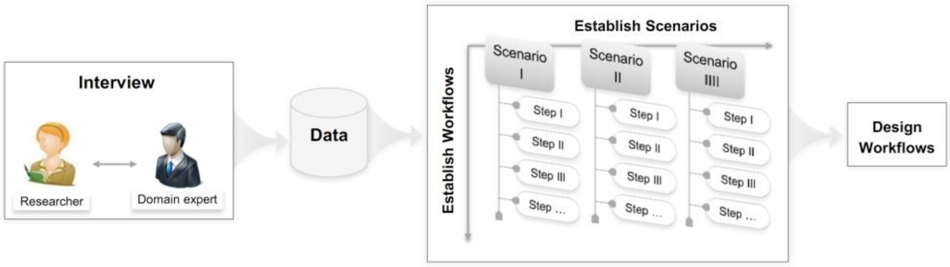

Figure 5. Phase one: establishing workflows and scenarios for visualization strategies.

Phase two is dealing with solution block. Based on literature studies and interviews with cartographers, design guidelines have been formulated and linked to the visualization strategy. The interviews with cartographers aimed at establishing multiple designs of the STC content, with a focus on the combination of visual variables and 3D depth cues. The interview sessions resulted in *Figure 6*. Another factor of importance is the influence of data complexity on the design.

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 • Shading		• Transparency • Shading		• Transparency • Shading	• Transparency • Shading
Shape	3	Simple graphics	• Relative size • Shading	Simple graphics	• Relative size • Shading	Simple graphics	• Relative size Shading	• Relative size Shading
	4		• Transparency • Shading		• Transparency • Shading		• Transparency • Shading	• Transparency • Shading
	5		• Shading		• Shading		• Shading	• Shading
Arrangement	6		• Shading		• Shading		• Shading	• Shading
	7		• Transparency • Shading		• Transparency • Shading		• Transparency • Shading	• Transparency • Shading
Orientation	8		• Shading		• Shading		• Shading	• Shading
	9		• Linear perspective • Shading		• Linear perspective • Shading		• Linear perspective • Shading	• Linear perspective • Shading
Quantitative visual variables								
Color value	10	Simple graphics	• Transparency • Shading	Simple graphics	• Transparency • Shading	Simple graphics	• Transparency • Shading	• Transparency • Shading
	11		• Shading		• Shading		• Shading	• Shading
Saturation	12	Simple graphics	• Shading	Simple graphics	• Shading	Simple graphics	• Shading	• Shading
	13		• Transparency • Shading		• Transparency • Shading		• Transparency • Shading	• Transparency • Shading
Size	14	Simple graphics	• Shading	Simple graphics	• Shading	Simple graphics	• Shading	• Shading
	15		• Transparency • Shading		• Transparency • Shading		• Transparency • Shading	• Transparency • Shading
Spacing	16		• Linear perspective • Shading		• Linear perspective • Shading		• Linear perspective • Shading	• Linear perspective • Shading
	17		• Shading		• Shading		• Shading	• Shading

Figure 6. Phase two: multiple design options of STC content.

In Phase three domain experts were revisited to confirm the workflows developed in the first phase and implemented in phase two. The aim was to let the experts work with the developed scenarios in the STC and to solve the problems defined in phase one *(Figure 7)*. In the evaluation session combinations of different qualitative usability research methods were applied, such as screen logging, thinking aloud and interviews. The target was to achieve sophisticated visualization strategies and to define necessary tools and techniques for effective exploration. For this purpose, a testing environment was created, consisting of three linked views: 2D map viewer, STC viewer and attribute table viewer.

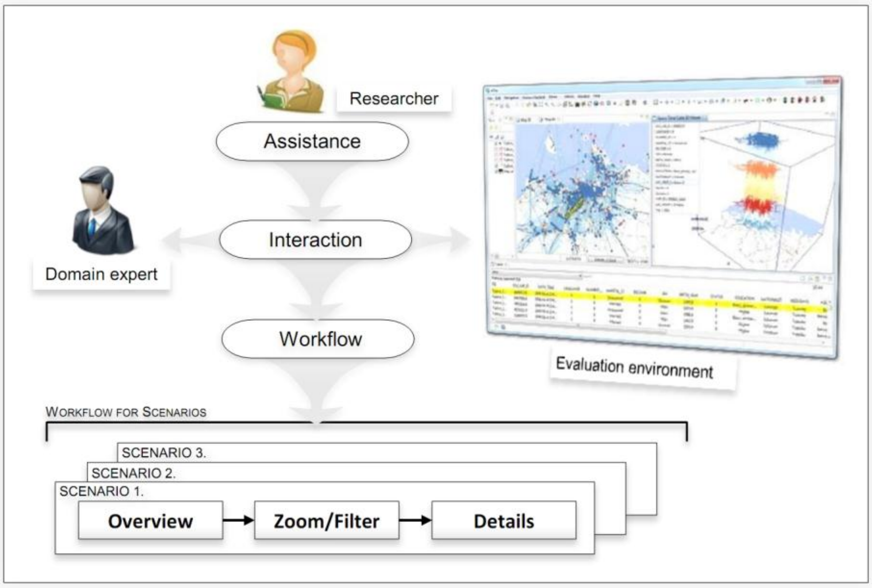

Figure 7. Phase three: confirm workflows and visualization strategies.

Phase four evaluates the design summarized in *Figure 6* on a focus group session with cartographic experts (*Figure 8*). In the focus group session experts judged the effectiveness of the design options defined in phase two in a spatial decision room equipped with interactive touch tables for the Tallinn use case. 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 *Figure 6* and resulted in more realistic hypotheses to be tested through individual laboratory test session.

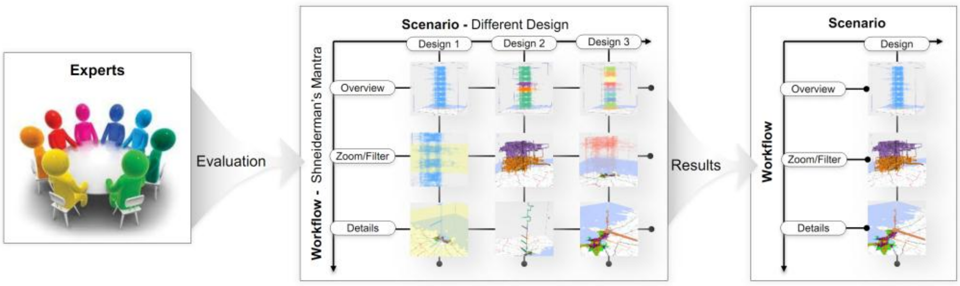

Figure 8. Phase four: experts in cartography and evaluation of the design guidelines.

In phase five, nonexpert participants are involved in the individual laboratory test for three use cases *(Figure 3 a, b, c)*. The design options and hypothesis formulated in the previous phase are objective of the test. Several evaluation methods are applied: desktop screen logging, video recording, eye tracking, task performance and thinking aloud. The results of this test help 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 design will be defined and tested phase six.

Phase six is built on the results of previous experiments and differs by evaluation content *(Figure 9)*. The goal is to define how the STC performs in a visual exploration environment, combined with some other graphic visualizations (scatterplots, parallel coordinate plots, graphs and maps). This environment allows an interaction with the locational, attribute and time components of the data.

This final experiment addresses several hypotheses, and based on task completion, error rates and user satisfaction, conclusions will be drawn regarding the usability of the STC in the geovisual analytics environment. Combinations of several qualitative and quantitative evaluation methods with two different groups of test participants are foreseen. The first test group will be composed of domain experts and the second of non-experts. Based on the analysis of the movement data several questions will be designed with a specific focus on the type of information, i.e. location, attribute and time. Test participants will have to execute different categories of tasks (comparison, attribute-based, etc.) while following the workflows in the geovisual analytics environment. The collected information will be analyzed and summarized, and the results of the two groups will be compared to draw conclusions on effectiveness, efficiency and user satisfaction.

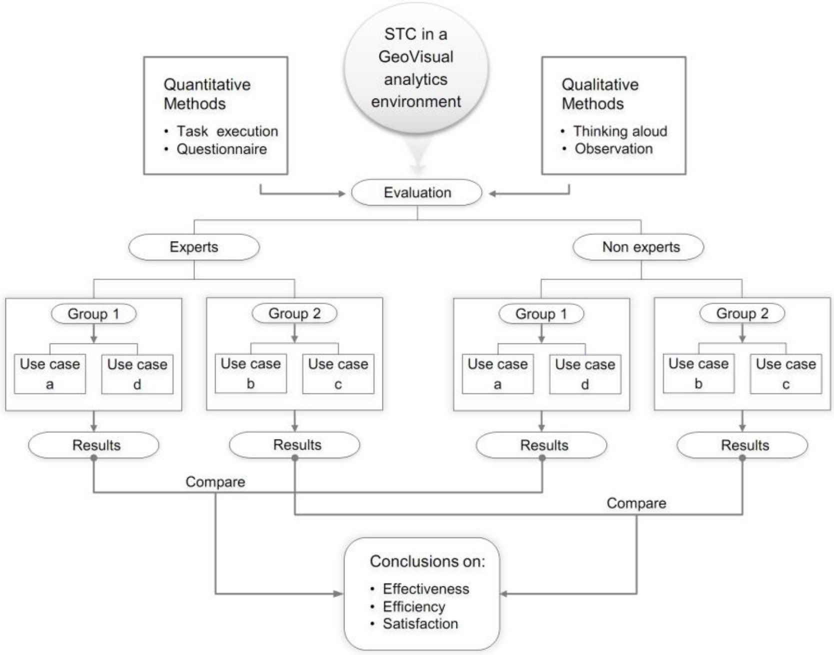

Figure 9. Phase six: evaluation of the solution block with experts and nonexperts.

7. Conclusion

This paper presented a conceptual research framework for a systematic approach to define the usability of the STC. The involvement of domain experts from an early stage has resulted in a set of realistic scenarios, which could be used in the usability evaluation of the STC in order to be able to answer the question: under which circumstances can the STC efficiently and effectively display complex movement datasets to satisfy user expectations.

In the evaluation set-up, specific attention was given to the cartographic design of the STC-content (the paths and stations). Design guidelines have been formulated based on cartographic data analysis methods. In addition, careful attention was given to 3D depth perception. The practical design was somehow limited by what the STC software made possible, but the hypothesis worded in section 5: 'each level of visualization strategies might requires a different design' was evaluated.

The first three phases were defined in close cooperation with the use case experts and cartographers. This cooperation has resulted in scenarios that are input for the last step of the evaluation. Before this last evaluation step will be executed a focus group test to evaluate the STC contents and the workflows from a cartographic design perspective were executed. During the final test, multiple qualitative and quantitative evaluation methods will be used to extract as much information as possible to answer questions about the usability of the cube and to test the hypothesis mentioned above. In this framework, free and controlled task based experiments are considered. The free experiments will allow experts to become acquainted with the STC environment and to experiment with the formulation of workflows. The controlled experiments are to evaluate and compare the developed environment for the use cases. The fact that the case studies differ in complexity should result in a judgement under which circumstances the STC is function.

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