What do we know about the space-time cube from cartographic and usability perspective?

Irma Kveladze and Menno-Jan Kraak

University of Twente, Faculty of Geo-Information Science and Earth Observation (ITC), 7500 AE Enschede, the Netherlands
Email: <kveladze; kraak>@Itc.nl

ABSTRACT: This paper discusses the results of the extensive usability evaluation of the space-time cube based on a user centered design approach. It is characterized by an early involvement of human geographers, who provided rich movement data and their research questions, to be used in use case scenarios during the testing. With the domain experts workflows were established and linked to a visualization strategy based on Shneiderman's mantra. With the question 'What is the effect of the cartographic design on the usability of the space-time cube?' in mind different maps were created applying different visual variables and depth cues. In a focus group based experiment the design was evaluated with eight experts in geovisualization. During this test the suitability of the visual variables was discussed for the 'overview' and 'zoom' steps based on several hypotheses. For the display of the trajectories qualitative data the results were as expected. For the quantitative data some surprising result can be reported. The final results are a good starting point for some more testing with alternative data sets.

KEYWORDS: Space-time cube, usability evaluation, cartographic design, domain experts

Introduction

The advancement of the modern technology such as GPS devices and various tracking systems has resulted in the accumulation of large datasets that attracts the interest of many researchers, because they potentially contain rich and useful information about movement behavior. In this context, the visual interpretation of complex trajectories can support understanding of this behavior. As such visualization plays a prominent role to support the process of knowledge discovery, since it facilitates information extraction, and can lead to insight and understanding (Dykes and Mountain, 2003).

Many types of visual representations can be used to display movements, among them the Space-Time Cube (STC). It was introduced at the beginning of 1970's in the then new domain of time geography. During the last decades the interest in this representation has increased considerably because of hard- and software developments, which allow for easy creation and manipulation of the graphics. As a result, more and more specialists in various domains are using STC to visually analyze complex movement datasets. It now is a common representation for visualization of trajectories (Kraak, 2003; Andrienko and Andrienko, 2011), because it is expected that it supports the understanding of the relationships between individual movements and patterns as a whole. Despite of its wide use in analysis and presentation there are some essential unanswered questions related to the usability of the STC (Kraak and Koussoulakou, 2005). Besides, the STC, just as most other graphics can suffer from visual clutter when many trajectories are displayed together.

In recent years, the usability of the STC has received attention from researchers in the geovisualization domain. The resulting papers are limited in number and mainly report evaluation experiments that compare the STC with other visual representations. In most of these experiments the STC appears to be satisfactory, but none of them considers the effects of a proper cartographic design of its content (space-time paths, stations and space-time prisms). Since for nearly all graphics representations the application of cartographic design guidelines improves the visual communication the question arises: 'What is the effect of the design on the usability of the STC?'

The design should adhere to a use context and therefore the extensive usability evaluation discussed here is set up according the User Centred Design (UCD) methodology (Nielsen, 1993) with assistance of domain experts. The usability evaluation focuses on a realistic case based workflow defined by urban geographers. The research aims to understand the visualization strategy of the experts and apply a design accordingly. The paper reports on two specific evaluation sessions conducted in a different time period with different groups of experts. The evaluation should result in suggestions and recommendation from the cartographic design perspective.

The article is organized as follows. The next section discusses literature related to time geography and usability evaluations. The third section gives an overview of the research methodology. This is followed the usability experiment conducted with human geographers. It will emphasize the requirements of domain experts and the set-up of a realistic workflow for the use case study. The focus of next section is on the content design of the STC and the formulated of related hypothesis. The use case was executed during a focus group discussion. Here experts from geovisualization domain provided comments and ideas on the content design of STC for the different steps in the use case, which were organized according Shneiderman's mantra using the 'overview' and 'zoom/filter' levels.

Related work

The origins of time geography can be traced back to the Swedish geographer Torsten Hägerstrand (1970), who proposed the concept of the space-time cube where space and time are considered as inseparable elements. The idea offers a useful framework to understand the behavior of activities patterns influenced by a various constraints in space and time. Hägerstrand's ideas have been elaborated by number of researchers (Lenntorp, 1976; Pred, 1977; Thrift, 1977; Carlstein et al., 1978; Parkes and Thrift, 1980). The recent revival of the concept of time geography is due to the current data rich environment and the available interactive software to analyze and visualize data. It has been applied in many domains by a number of authors to analyze patterns and their interactions in a space-time context (Huisman and Forer, 1998; Kwan, 1999; Miller, 1999; Kraak, 2003; Gatalsky et al., 2004; Demšar and Virrantaus, 2010). Despite the many applications using the STC, not much is known about its ability to effectively and efficiently display data content and provide sufficient support for visual exploration of patterns. This section offers an overview of the usability research done so far.

The first usability evaluation of the STC was done by Kristensson et al., (2009). They compared an interactive 2D map with an interactive STC. The experiment focused on how the 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 2D map. Despite of 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 if the design of both map and cube are of the same ‘quality’ for a fair comparison.

Another evaluation was published by Demissie, (2010). He compared animation, STC, single static maps, and multiple static maps while searching for the most suitable visual representation for 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 methods. 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., (2010 a) compared the 3D STC with an animation and 2D visualization. Test persons had to predict the meeting place of moving objects based on past history, and decide in what order the moving objects would arrive at specific locations. The first experiment proved that 3D STC and animation were less effective than 2D. After this test the STC content was redesigned and re-valuated against same 2D visualization. Despite the STC improvements the traditional 2D still performed better. The second experiment proved that STC perform comparatively better than 2D. 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. Based on the correctness of the answers and their response time it proved that the STC did not perform as well as they expected. However, STC was successful in identifying lanes tasks for movement features.

In a different experiment Kjellin et al., (2010 b) have evaluated two versions of STC, 3D stereoscopic and 3D monocular visualization with special attention for the depth perception. 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 will have 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 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 experiment and the final 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 identify temporal patterns in their behavior Vrotsou et al., (2010) developed and then evaluated an abstract space based 3D activity-time cube following the STC paradigm, where y-axis is time, x-axis is individual’s track and z-axis the activities. The main purpose of evaluation was to detect whether users are able to identify areas in space with a 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. Base on the 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.

In most cases the main objective of the evaluations described above was to define the effectiveness of the STC in comparison with other visual representations, but also understanding the tools of time geography. The evaluation outcome of Kjellin et al., (2010 a) second experiment proved that design is also important for effective visualization. But, to draw more significant conclusions in relation to the impact of design on effectiveness of the STC further investigation is required. The evaluation discussed here is set up to do exactly this, but specifically in a real world context.

Case study and test setup

To realize a balanced and realistic evaluation of the STC, the research described here follows a UCD approach in which case of a real world problem and the views of domain experts are combined with knowledge of cartographic design. This guarantees the involvement of the 'problem owners' from start to end, and avoid tests with synthetic data or questions.

The domain experts involved are human geographers with the objective to understand the spatio-temporal behavior of different type of suburban commuters in the Tallinn metropolitan area during the week, while considering characteristics such as their gender or language. They are providers of the case study data, the problems to be solved and the questions to be answered. Besides, they offered feedback on the solutions proposed by the authors.

The complex dataset represents the movements of suburban commuters generated via the active mobile positioning (Ahas et al., 2007). The Estonian company Positium LBS extended the positioning data by social characteristics of the commuters, such as age, education, occupation, gender, nationality. The data for 203 commuters was collected over eight days generated with a 15 minutes frequency from 06:00 AM to 00:00 PM, and 2 hours interval from 00:00 PM to 06:00 AM.

The data has been used in previous studies (Ahas et al., 2010). The authors investigated differences in the movement patterns of commuters, and found evidences in temporal rhythms in commuter's relocation during eight days. But, some questions remained unanswered. These are related to the spatial distribution of different groups of peoples in a particular time period.

The basic setup of the usability evaluation is given in Table 1. For each step the objective, the test persons, the evaluation methods, and potential outcome are listed.

Table 1: Structure of the usability evaluation.

Phase	*Objective*	*Test Persons*	*Evaluation Method*	*Outcome*
1	Establish workflow based on user	Human geographers	• Discussion	Develop visualization strategy

	requirement			
2	Compile and design STC content	Cartographers	• Discussion	Develop multiple versions of the design
3	Verification of the workflow	Human geographers	• Screen logging • Thinking aloud • Interview	Validation visualization strategy
4	Verification of the design	Geovisualization experts	• Focus group interview • Observation, video recording	Validation of the design guideline

For phase 1 discussions with domain experts were conducted related to the use case study to get insight in their workflows, to be used during the experiment. In addition two research questions were formulated that would drive the test: ‘Which land use patterns can be distinguished with diurnal activities, with weekly data, or with socio-demo data’, and ‘Compare the space-time use for two different ethnic groups, Estonians and Russians’. To answer the questions the distinguished individual steps of the workflow were linked to the steps of Shneiderman’s (1996) ‘Information Seeking Mantra’.

Phase 2 comprised the application of the design guidelines on the data set. The ideas were discusses among cartographers to guarantee as most optimal visualization. These were ‘limited’ by the possibilities of the software used.

In phase 3 the domain experts were revisited to confirm their workflow. They were asked to interact with STC in order to solve their problems and revisit the research questions formulated in first phase. They confirmed that the workflows made sense and that in their eyes the visualizations were useful. The outcome of this evaluation session is described in the next section.

Phase four was a focus group experiment using a large touch table to judge the design of the STC. Geovisualization experts shared their views and provided suggestions on design, which should lead to the final improvement. The result of the session is reported in section experiment 2.

Experiment 1: the workflow

Setup and procedure

The main objective of this experiment was the verification of the workflow and identification of some additional requirements in relation to the visual data analysis. It took place in the working environment of experts at Department of Geography, University of Tartu. The two experts were introduced to the purpose of the evaluation study and test procedures. The session lasted for one hour for each of the domain expert. During the test three different evaluation methods were applied: screen logging, thinking aloud and interview. It started with a demonstration of the working environment with the STC that contained three multiple linked views; 2D map, 3D STC and attribute table view (see Figure 1). The STC software operates as a JAVA based plugin in the Udig open source GIS.

With the objective in mind no specific tasks were prepared for the domain experts. They were asked to answers their own research questions based on the workflow suggested by them before. During the evaluation session, experts were free to use all functionality of the software. The test moderator was providing assistance during whole session. When the expert started their own exploration screen capture was started and they we asked to think aloud.

Results

While answering their own questions using the STC, the experts made various remarks in relation to the ‘new’ view on their data, and the options offered by the authors. However, soon they after started to comment on missing analytical functionality. This was due to the fact that they now observed their data from a different perspective, which gave them fresh ideas on how to tackle their problems.

The domain experts described the ability to execute a qualitative and quantitative analysis as the main reasons of using STC. The qualitative perspective allowed them to observe and detect patterns of interest in space and time, and develop the strategies for further research. The integrated land use map proved to be an important aspect in this process. The map could be moved along the time axis of the cube and allowed the expert to see the spatial distribution of the commuters at any moment in time.

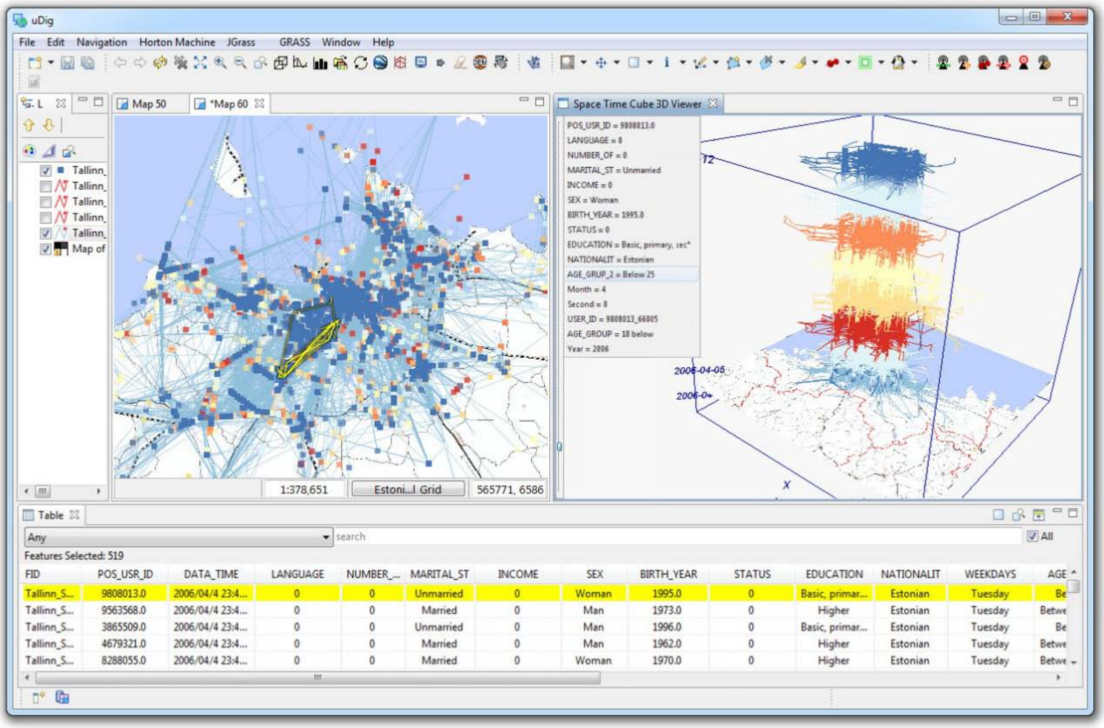

Figure 1: Use case study data and STC environment during discussion

It also played a role in their quantitative study, and was used in the analysis of the relation between land use and the location of the commuters during different time periods. For example, what patterns can be witnessed during the rush hours, where did the commuters come from, made stops and did go to. The patterns define the life style of suburban commuters in Tallinn city.

Looking at these patterns they refined the search based on additional attributes derived from the social data linked to the phone positions. They could drill down starting from age groups to ethnicity or from gender to education and alike.

After the session one more additional evaluation method was used. The experts were interviewed in order to find out how to develop an effective STC application. The summary of the interview session is reported in Table 2.

Table 2: The summary of the interviews with domain experts.

Question	*Answer*
What are the visual representations that normally you use for analysis of this type of data?	Basically, these are 2D maps, but for statistics some graphs. For studying land use of a city, experts have to design functional zones on 2D maps. Sometimes there is he need to use street maps
What are the advantages of those visual representations?	On 2D maps it is easy to plot information and see spatial distributions.
What are the disadvantages of those visual representations?	2D maps do not always provide answers on the all questions. During the study there is need to analyze combined complex information (regions, social characteristics, different time scales, etc.) and they overload the map too much to get answers. Land use maps are often not detailed enough.
What do you expect from the STC?	STC can help in early stage of research to get some particular hints on the data. It shows information in different dimensions and its interactive environment is more useful. STC allows observation of objects and see information about activities and time simultaneously. Also, it can handle all necessary information to get answers on the questions.

Experiment 2: the design

Design of the STC content

This section reports the results of usability experiment of phase 4 (see Table 1). The objective was to verify the design guidelines developed during phase 2. Starting point for the cartographic design is Bertin's (1967) theoretical framework with a focus on line symbolizations. Over the time Bertin's typology of visual variables was extended (Morrison, 1984; Caivano, 1994; MacEachren, 1995; Robinson, 1995) and the web introduce additional variables such as blur and transparency. In case of the STC it was extended in three-dimensional space (space-time path). The visualization of the paths will depend on its qualitative or quantitative character and the constraints set by the theory. This results in using color as preferred visual variable for qualitative aspects and size for quantitative aspects of the data.

These visual variables are key in representing data characteristics, but in the 3D cube depth perception has to be taken into account as well (Marr, 1982; Kraak, 1988; Ware, 2006; Goldstein, 2010). When used well these 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 used to represent the paths or stations. Examples are the various combinations size gradients, and shadow. Others, like motion parallax or stereo can be a part of the viewing environment. The first and will be activated by functions like zoom, pan and rotate, for the second special viewing devices are needed. In all situations a logical organization of the displayed information is required. Besides ordering data layers the application of new visual variable such as transparency can be useful.

The hypothesis is that each step of workflow requires its own design (see Table 3). For instance, the overview of a larger data set should be done with simple graphics, while a detailed view needs a more sophisticated visualization. The interaction process should allow users to change the design when it is necessary. In the test set up the different variation and combinations of ordering of the data, the visual variables, the depth cues will be offered to the users while they discuss and determine the most useful visual variables regarding to the different steps of the mantra.

Table 3: Hypothesis on effectiveness of the visual variables in the STC.

visual variables	*design*	*Steps of mantra*	*Hypothesis*	*The questions of focus group discussion*
Color hues	Simple st-path	Overview	most effective	Q 1.1
	Simple st-path	Zoom	most effective	
	St-path, volume and shading	Overview	poor effect	Q 1.2
	St-path, volume and shading	Zoom	less effective	
Pattern	St-path, volume and shading	Overview	poor effect	Q 1.3
	St-path, volume and shading	Zoom	poor effect	
Color value	Simple st-path	Overview	effective	Q 2.1
	Simple st-path	Zoom	effective	

	St-path, volume and shading	Overview	poor effect	Q 2.2
	St-path, volume and shading	Zoom	less effective	
Size	St-path, volume and shading	Overview	less effective	Q 2.3
	St-path, volume and shading	Zoom	effective	

Focus group interview

The evaluation method used in this experiment was the focus group interview. It is an informal technique for interactive discussion with users and is known as efficient qualitative method for design improvement and development. This method of evaluation involves the use of group interviews where participants are selected purposefully based on the specific criteria. In another words, 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 the participants according to Nielsen, (1993) is 6 to 9 person with average duration 1 to 2 hour. The test person involved were all participants in a workshop dedicated to the STC, and included five senior researchers and three PhD students, all in the geovisualization domain.

This special type of group in terms of size, composition and procedure is different from individual interview and can provide deep discussions on products. Focus group interviews encourages debates on ideas, and opinions that individuals would like to express regarding to the particular issues. During session the test moderator can observe the spontaneous reactions, behaviors, feelings and altitude of the users, as well as the way of exchanging ideas and group dynamics. Thus, in relatively short time period it can generates a large amount of information on the discussed topic. Focus group interview have been used intensively in cartography by number of researchers (Monmonier and Gluck, 1994; Harrower et al., 2000; Suchan and Brewer, 2000; Robinson et al., 2005).

Setup

The group discussion was conducted at the Faculty of Geo-Information Science and Earth Observation of the University of Twente. The experiment took place in a dedicated spatial decision room, which is equipped with interactive touch screen tables and interactive whiteboard. The STC software, an implementation in the ILWIS open source GIS was running on the windows workstation allowing direct manipulation via the table by a single one user, e.g. the display can track only one finger. During the discussion were used two touch screens of 32 and 42 inch size both with a 1024 by 768 pixel screen resolution. Besides the touch options the standard mouse and keyboards were also available. A camcorder registered the whole session.

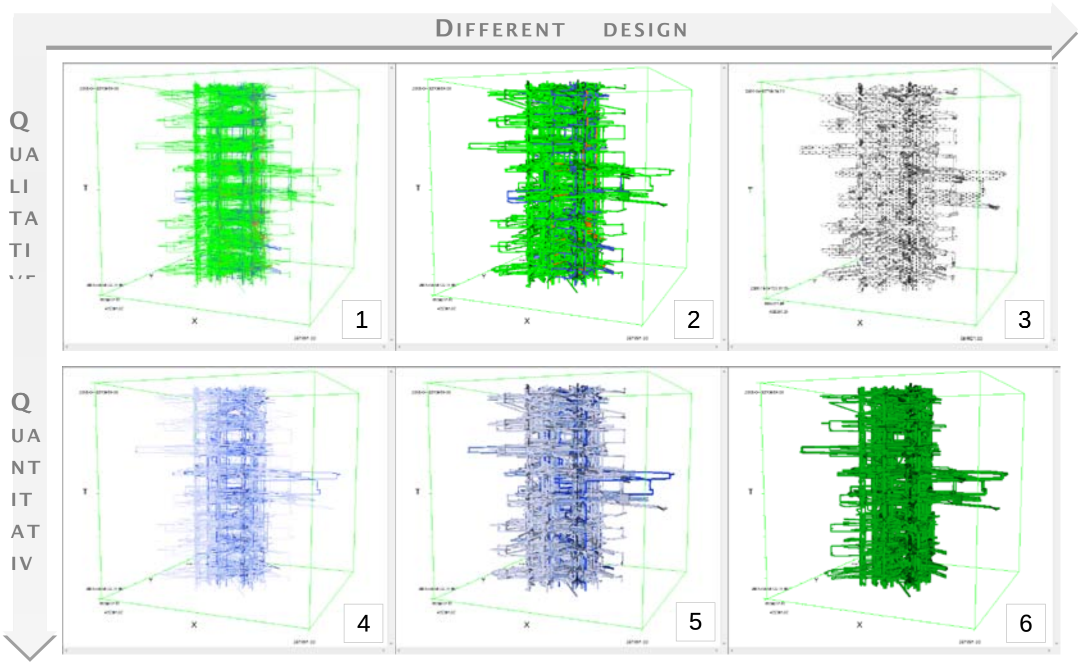

Figure 2: Discussion materials for overview level designed as it is described in Table 3 of hypothesis

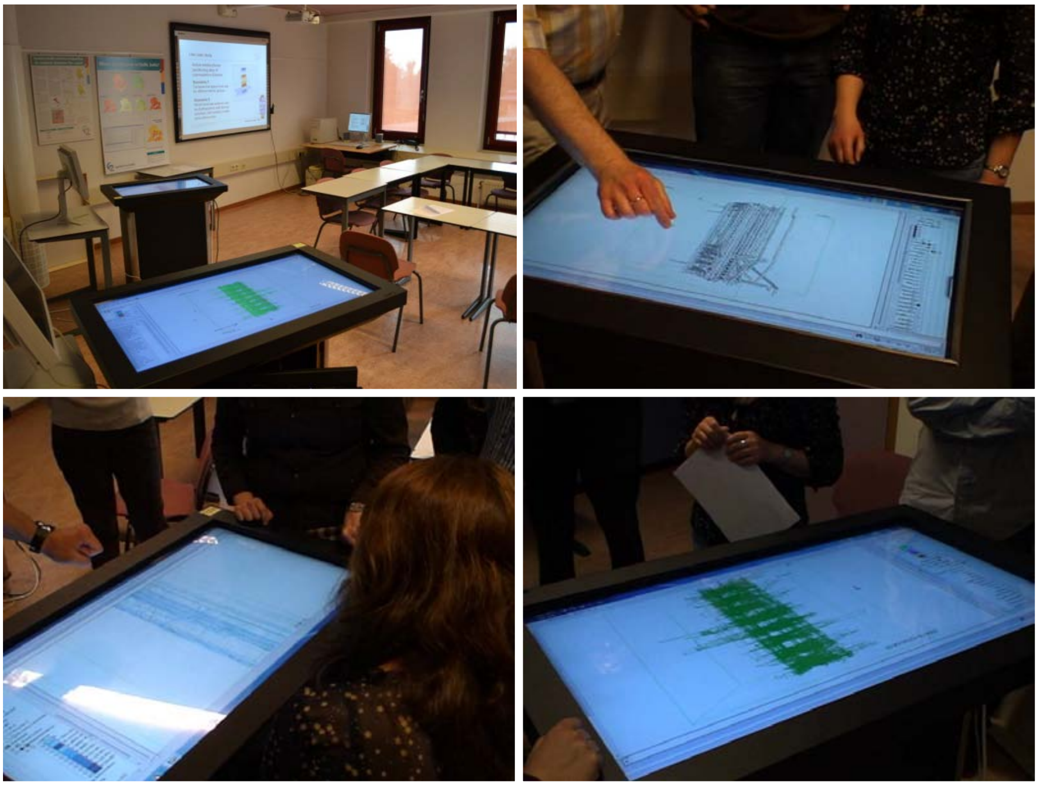

Figure 3: Focus group environment and discussion on visual variables

Materials

For the focus group interview twelve different map designs (see table 2) were prepared of which the six overview designs are shown in Figure 3. The test persons could interactively manipulate the cube using zoom in/out, rotation and panning options. One of the tables was prepared to discuss the qualitative visual variables and the other table the quantitative visual variables.

The ‘qualitative’ scenario started with different ethnic groups of Tallinn suburban commuters. It was developed based on the research questions formulated by the domain experts. Similarly, the quantitative scenario showed different income groups. In both cases the first task on to judge the map on overview level (Figure 2) followed by zoom level.

Procedure

The test session began by welcoming the participants in the decision making room. They were given oral instructions about the applied methods, test environment and objective of discussion. This included a more detailed description of the use case study and scenarios as discussed in previous section.
Around the first touch table the test moderator briefly remind the participants about purpose of focus group discussion, the research questions that ‘human geographers’ set up for exploration. In addition they were explained the basics working principles of the touch screen table.

Results

The whole focus groups session was audio and video taped and the full transcript of the sessions are available. Below a summary of the most important remarks made.

Q1. *What are the qualitative visual variables that can effectively visualize different nationalities on overview level, considering the data complexity? And on zoom level?*

Q1.1 *How effective is color hue to display the different income groups?*

The first image show was one with color hue (Figure 2-1), applied on simple single line space-time paths. Without much discussion the participants agreed that it was an acceptable solution. Color allowed them to easily answer the questions about ethnicity. However, they did discuss the potential problems that might arise when the amount of track would increase a lot. They concluded that this simple design would work well, even considering the data clutter. They had the same opinion for the zoom level. It confirmed hypothesis 1.

Q1.2 *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 (Figure 2-2). To apply the depth cue shading, the widths of the path had to be increased, which also increased the visual clutter in the image. The participants used negative terms to express their opinion about this solution. They commented that with a dataset like this depth cues are not useful and made things even worse. Also for the zoom level the use of the depth cues was not advised. Answering the ethnicity question would be difficult because of the design. The opinion of the participants partly coincided with hypothesis in table 3.

Q1.3 *What do you think about patterns in STC? Can we use them for data representation with depth cues? Does it make sense on overview or on zoom level?*

As an alternative, but uncommon visual variable the patterns were applied on the shaded space-time paths (Figure 2-3). In a first reaction the participant came with strongly negative recommendations. They unanimously suggested not to use patterns. Despite the immediate negative reaction several interesting comments and suggestion were made. If patterns were to be used they should stick to the path so they could follow the rotation of the cube, however this might change the perception of the pattern and people might ‘get lost’. The participants also came with the argument the dashed lines might be confused with broken or interrupted trajectories, in other words the design of the patterns is very critical. Answering the ethnicity question would be virtually impossible and the results were in line with the hypothesis in table 3.

Q2. *What are the quantitative visual variables that can effectively visualize different income groups on overview level considering the data complexity? And on zoom level?*

Q2.1 *How effective is value to display the different income groups?*

The map on the touch screen represented four the income groups by color value ordered from light to dark blue (see figure 2-4). The participants remarked that the data complexity was the major factor influencing the success of the use of any visual variables. In case of value the overlap between trajectories complicated a proper perception of the four group categories represented by color value. There proved to be insufficient difference between colors and participants found difficult to distinguish the income groups visually. Because of this, color value was considered a less effective visual variable even on zoom level. It was suggested to convert the quantitative data scale into a qualitative data scale to be able to use a color scheme. For instance to use light red, red, light blue, dark blue and distinguish between poorest and richest groups. The outcome of the discussion was different from the hypothesis in table 3.

Q2.2 *What is the effect if we add depth cues to the representation on overview level? At the zoom level?*

The 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 2-5). They advised not to use this depth cue under the current circumstances, neither on overview nor on zoom level. The income related question could not be answered, and hypothesis was partly rejected.

Q2.3 *What do you think about size visual variable in STC? Can we use it for representation with depth cues? Does it make sense on overview or on zoom level?*

The last visual variable discussed was size (see Figure 2-6). The participants commented that the differentiation in size among the individual path was not big enough to judge. They suggested to use it in combination with the qualitative color scheme as suggested above. The participants did not have a different opinion for the zoom level. The question regarding the income groups was difficult to answer. And the hypothesis was rejected.

Discussion, conclusion and future work

The involvement of domain experts from the start of the project has resulted in a realistic case based scenario. The experts from human geography did not have much experience with STC, but while using it they saw new opportunities because they were able to look at their data from a different perspective. In their eagerness to explore they complaint about the lack of analytical functionality. This was seen as a compliment because it proved the experts saw benefit of working with the STC. In establishing a workflow for the use case, their actions were linked to the steps in Shneiderman's mantra. This was then linked to a cartographic design approach with some hypothesis on the use of the visual variables in combination with depth cues in the STC.

The hypotheses on the use of the visual variables in the STC have been formulated based on the cartographic design theory. Special attention was given to the depth cues. The use of visual variables was somehow limited by what the STC could represent with this amount of data, and also design that software would make possible. The hypothesis formulated for each level of the visualization strategies also required different design. The main question here was how much limited was STC content in design when playing with different levels of Shneiderman's mantra. And the evaluation session conducted on it certainly provided answer on this question.

A focus group interview has been set up to evaluate the hypotheses on the visual variables. The participants were all geovisualization experts. The discussions revealed some expected results in relation to the application of color. However, the combination of visual variables with depth cues was not recommended in the context of the use case. A surprising result was the recommendation to convert the quantitative data scale into qualitative data scale to be able to profit from the strength of color as visual variable. It was also observed that the complexity of the data did put constraint on the use of the variables. A combination of analytical functionality with the design solution was recommended as practical to answer the question of the domain experts.

As a result of the project it is now possible to execute more used case based experiments with other datasets. This experiment will be conducted, to be able to draw some more definite conclusions about the use of the STC.

Acknowledgement

I would like to thank research partners from University of Tartu for their cooperation for this research project. Thanks to all participants of focus group interview for their interesting discussions. Also, thanks to Bas Retsios for software development and Dr. Corné van Elzaker for his assistance during the focus group discussion.

References

Ahas, R. Aasa, A. Silm, S. and Tiru, M. (2007) Mobile Positioning Data in Tourism Studies and Monitoring: Case Study in Tartu, Estonia. *Information and Communication Technologies in Tourism*. Ed. Sigala, M. Mich, L. and Murphy, J., Springer Vienna. 3, pp. 119-128.

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.

Andrienko, G. and Andrienko, N. (2011) Dynamic Time Transformations for Visualizing Multiple Trajectories in Interactive Space-Time Cube. *International Cartographic Conference (ICC 2011)*. France, Paris.

Bertin, J. (1967) *Semiologie graphique : les diagrammes, les réseaux, les cartes*. Paris etc., Mouton ; Gauthier-Villars.

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) *Timing Space and Spacing Time: Human activity and time geography*. London, E. Arnold.

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

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.

Dykes, J. A. and Mountain, D. M. (2003) "Seeking structure in records of spatio - temporal behaviour: visualization issues, efforts and applications." *Computational statistics and data analysis*. Elsevier, 43, pp. 581-603.

Gatalsky, P. Andrienko, N. and Andrienko, G. (2004) Interactive analysis of event data using space - time cube. *Proceedings of the 8th international conference on information visualisation*, IEEE Computer Society.

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

Hägerstrand, T. (1970) "What about people in Regional Science?" *Papers in Regional Science*. 24, 1, pp. 6-21.

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

Huisman, O. and Forer, P. (1998) Computational agents and urban life spaces: a preliminary realisation of the time-geography of student lifestyles. *Proceedings of the 3rd International Conference on GeoComputation*. University of Bristol, United Kingdom, Sept. 1998.

Kjellin, A. Pettersson, L. W. Seipel, S. and Lind, M. (2010 a) "Evaluating 2D and 3D visualizations of spatiotemporal information." *ACM Transactions on Applied Perception*. 7, 3, pp. 1-23.

Kjellin, A. Pettersson, L. W. Seipel, S. and Lind, M. (2010 b) "Different levels of 3D: An evaluation of visualized discrete spatiotemporal data in space-time cubes." *Information Visualization*. 9, pp. 152 -164.

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

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

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.

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

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

Lenntorp, B. (1976) Paths in Space-Time Environments: A Time Geographic Study of Movement Possibilities of individuals. *Lund Studies in Geography B*. Ed. Gleerup, Lund, Human Geography, pp.

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

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

Miller, H. J. (1999) "Measuring space-time accessibility benefeits within transportation networks: basic theory and computational procedures " *Geographical analysis*. 31, 1, pp. 1-26.

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

Morgan, D. J. (2010) *A visual time-geographic approach to the crime mapping*. PhD thesis, Florida state university.

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*. Boston, MA.

Parkes, D. N. and Thrift, N. J. (1980) *Times, spaces and places : a chronographic perspective*. Chichester, Wiley & Sons.

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. Chen, J. Lengerich, E. Meyer, H. and MacEachren, A. (2005) Combining Usability Techniques to Design Geovisualization Tools for Epidemiology. *Proceedings, AutoCarto 2005*. Las Vegas, NV.

Robinson, A. H. (1995) *Elements of cartography*. New York, Wiley & Sons.

Shneiderman, B. (1996) The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations. *Proceedings of the 1996 IEEE Symposium on Visual Languages*. USA, IEEE Computer Society Washington.

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.

Thrift, N. (1977) *An introduction to time geography*. Norwich, University of East Anglia, Geo Books.

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. (2006) 3D contour perception for flow visualization. *Proceedings of the 3rd symposium on Applied perception in graphics and visualization*. Boston, Massachusetts, ACM.

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.