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Visual exploration of eye movement data using the Space-Time-Cube

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Abstract. Eye movement recordings produce large quantities of spatio-temporal data, and are more and more frequently used as an aid to gain further insight into human thinking in usability studies in GIScience domain among others. After reviewing some common visualization methods for eye movement data, the limitations of these methods are discussed. This paper proposes an approach that enables the use of the Space-Time-Cube (STC) for representation of eye movement recordings. Via interactive functions in the STC, spatio-temporal patterns in eye movement data could be analyzed. A case study is presented according to proposed solutions for eye movement data analysis. Finally, the advantages and limitations of using the STC to visually analyze eye movement recordings are summarized and discussed.

Keywords: Eye movement analysis, Space-Time-Cube, Usability evaluation, Spatio-temporal data.

1 Introduction

Usability evaluations of visual repsentations have been drawing much attention in recent GIScience and visual analytics research [1, 2, 3, 4, 5]. The evaluations typically deal with user requirements, trying to find out how people solve spatial problems and what cognitive processes might be behind their actions. To be able to derive qualitative or quantitative measures of the user experience, a number of evaluation methods have been tested. Some examples for such methods can be listed as: focus group studies, interviews, direct observations, think-aloud protocols, retrospective think-aloud protocols, screen logging and eye movement recording and analysis. Recoding eye movements does not rely on self-reporting, therefore it can be considered an objective method and can enhance traditional performance tests, protocol analysis, and walk-through evaluations of a system [6].

Eye tracking research results in an enormous amount of highly detailed data. Typically a time stamp (temporal data) and gaze point location within the configured screen coordinate system (spatial data) is reported by the tracker. One of the challenges, as tackled by many researchers [2, 6, 7, 8, 9, 10] is how to process, manage, and use these continuous streams of data efficiently and effectively to support a usability evaluation.

Within the scope of this paper, the following questions are most relevant: Is it possible to analyze eye movement data using traditional spatio-temporal tools that have been used in spatial analysis domain? Can geo-visual analytics methods be used to improve the detection and comparison of possible spatio-temporal patterns in eye movement data? How can these methods be combined with typical eye movement analysis methods, such as gaze plots, density maps, AOI (area of interest) analysis and statistics? Do above ideas provide further insight into understanding and interpreting eye movement data? With above questions in mind, this paper tests an approach that combines typical eye movement analysis methods and the Space-Time-Cube (STC), which has been used in geography since its introduction by Hägerstrand in 1970 [11].

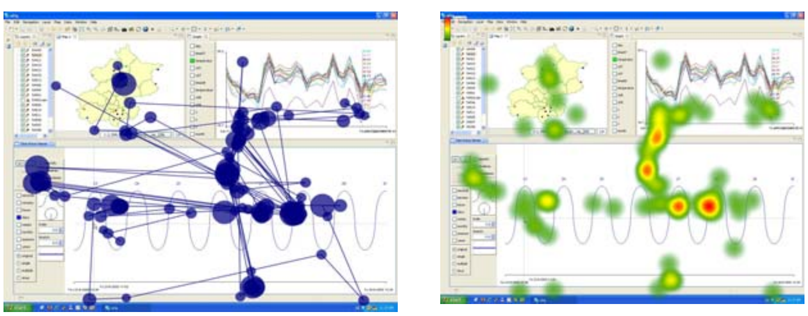
2 Eye movement data analysis and state-of-the-art in spatio-temporal geovisualization

Along with gradually maturing hardware technology to track eye movements, the applications (software) that utilize information derived from eye movements is also becoming more and more comprehensive. Eye movement recording and analysis may offer additional tools to enhance usability studies. Several research papers integrating usability studies and eye movement analysis have also been published in geovisualization domain [1, 2, 3, 12, 13] and appear to continue attracting attention. While clearly useful, processing, analyzing and interpreting data that is collected via eye tracking is still cumbersome and arduous. Can some developments in subfields of geo-visual analytics, such as the dynamic, interactive, 3D STC be helpful in making this easier? With this question in mind, some common methods for eye movement data processing and analysis, as well as some current spatio-temporal geovisualization methods will be discussed in the following sections.

2.1 Eye movement data analysis

Eye movement studies have been conducted long before computers were widely used. According to Jacob [14] such studies for basic psychological research existed already about 100 years ago, addressing a set of versatile questions; *e.g.*, it has been used when studying language comprehension and production [15], scene perception [15, 16], reading [17] or spatial reasoning [18]. Eye movement analysis has also been introduced and integrated into usability studies. Goldberg and Kotval [6] contend that performance and usability evaulations of spatial displays within information acquisition contexts, eye movement analysis has at least a 70 year long history. In geovisualization, using eye movement recording and analysis for evaluating the user performance can be considered both 'old' and 'new'. In this context, 'old' means that many typical evaluation studies supported by eye movement recording and analysis in other disciplines could also be used for geovisualization. Such studies exist, for example, in computer interface evaluation [6, 19, 20, 21, 22], human computer interaction (HCI) usability testing [7, 23, 24, 25] and cognitive processing [20, 26, 27]. Early eye movement studies in geovisualization were driven by cartographic research questions [3, 28]. 'New' refers to developments in technology that enable us to collect more data than ever before and new methods in geovisual analytics which enable us to design and visualize complex and dynamic processes. Eye tracking offers new promises and challenges in evaluating and analyzing the cognitive processes when people use these large, complex, often interactive data visualizations. However, eye movement data itself is typically very large.

To analyze and make use of the huge amounts of collected eye movement data efficiently, abundant research has been done (e.g., [8, 9, 10, 29, 30, 31, 32]). When dealing with traditional eye tracking data, several metrics are reported in usability studies, such as: fixation duration, gaze duration, area of interest (AOI) analysis, and scan path comparisons. These metrics are used to analyze the visual search processes of users as well as to establish the location of their overt attention. For instance, such metrics can be helpful to find out which part of the map attracts most attention at first glance, or what is the order of user gaze points while observing the map or solving tasks with it. These metrics can be represented as density maps, gaze plots and graphs. Fig. 1 shows an example of some common visualization methods used in representing eye movement data. On the left in Fig. 1, a gaze plot is shown which represents saccades, fixations and fixation durations plotted as a scan path. On the right, a density map can be seen which shows the average fixation duration of multiple users (density maps can also represent fixation counts). These representations provide a simple and direct static view of eye movement data and as such, they are included in most common eye tracking and analysis software.



(a) (b)

Fig. 1. Two common visualization methods used in visualizing eye movement data (screen view as background) produced in Tobii Studio. Left image shows a gaze plot, and the right image shows a fixation density map.

However, since eye movement datasets are almost always quite large, limitations of above visualization methods are obvious. Overlaps may cause misunderstanding of the data. For example, if viewer tries to identify the number of gaze points within a certain area this may not be possible, because larger fixations may occlude the smaller ones entirely. Furthermore, temporal information (such as the order of fixations on a scan path) is potentially lost at overlapping scan paths and this makes it difficult to establish when the fixation is directed to a certain area. For smaller data sets, design choices such as using transparency, or numbering the fixation points can partly solve the problem, but in large sets of data this approach may not be feasible.

When used as stimuli, highly interactive, multiple-link-view environments in common geovisualization software pose additional problems. Scrolling windows, pop-up dialogs, animated graphics, user-initiated object movements, and other navigation features leave the experimenter with technical challenges for studying and interpreting fixations [14]. Existing common solutions for these problems in most eye tracking and analysis software consist of updating the viewed stimuli according to the screen view, showing mouse clicks on the interface and allowing animation. However, to analyze the data in a linear, continuous order both in temporal and spatial context, the above solutions are not always sufficient. One example of such a problem is to identify and compare spatio-temporal patterns 'created' by differences among users. Another example relates to differences between the hypothetical and real situations. Can spatio-temporal geovisual analytical methods help solve these problems?

2.2 State-of-the-art in spatio-temporal geovisualization

There is abundant literature discussing spatio-temporal data visualization. Most solutions are based on three cartographic depiction modes: a single static map, multiple static maps (*i.e.*, "small multiple maps") and a map animation [33]. A single static map is the 'simplest' visualization solution for spatio-temporal data and most users are familiar with it. However, it is difficult to represent complex changes, as depicted in Fig. 1a where gaze points of different time stamps overlap with each other. Small multiple maps represent the temporal sequence by a spatial sequence of individual maps each representing a moment in time. This facilitates to find the difference between any two time points of interest. However, it is also a discrete representation of the dynamic process. The number of images is limited, so it is difficult to deal with long series. With map animation, users might catch the "trend of change" more easily. A user can control the speed of the animation, and "stop" at any moment in time. However, it is also easy for the viewer to neglect the actual time point that the change happened, and the user might have difficulty to fix attention on multiple changing items [1].

An alternative visual representation is the Space-Time-Cube (STC), which is the most prominent element in Hägerstrand's space-time model [34]. The STC combines time and space in a natural way. Time can be represented as continuous or discrete. The X and Y axes indicate the 2D space, while the time units along the Z-axis can be years, days, hours, etc. In the STC, the Space-Time-Path shows the object's trajectory through time and space.

The recent revival in the interest in the STC is due to the development of new technologies which makes data collection as well as creation and use of the cube much easier than before [35, 36, 37, 38, 39, 40, 41, 42]. Typical geovisualization characteristics like interaction, dynamic and alternative views are now also applicable to the STC, and made it part of an exploratory environment. Andrienko [36] and Gatalsy [39] linked the STC with dynamic map displays by simultaneous highlighting corresponding symbols, and applied temporal focusing with the STC. With support of rotating, panning, zooming in/out and similar functions, Johnson [43] and Forer [44] use the STC to display different snapshots along the time axis in a three-dimensional (3D) environment. Kraak [40] linked the STC with a 2D map view, video and attribute table to explore multi-variable, multi-media spatio-temporal data. Kraak and Madzudo [45] linked the STC with attribute graphs, such as bar charts and parallel coordinate plots (PCP) to interact with attribute patterns from both spatial and temporal perspectives. Another additional useful function is the option to move the 'base' map up and down along the time axis, which allows users to explore spatial distribution over time. Kraak [46] developed the STC in geovisualization environments further by intergrating Shneiderman's [47] viusal information seeking mantra (overview, zoom and filter, detail on demand) with the elementary spatial questions *where*, *what* and *when*. Another additonal function is the option to create paths with annotations [46]. Qualitative and quantitative information can be added as geo-tags to a path. This can supply extra multi-media detail within spatio-temporal context, such as pictures, videos, graphs, etc. and reduce the clutter in the STC view.

These progresses in research and development resulted in extending the functionality of the STC beyond its original design, and may supply more efficient ways to fully explore spatio-temporal data. Since eye movement data has both spatial and temporal characteristics, the next section will discuss whether it is possible to use the STC in eye movement data analysis and whether this helps solving some of the occlusion related problems with gaze plots and density maps.

3 Exploring eye movement data in a STC environment

A common approach to support problem solving with visualization is based on a combination of user tasks, a data framework and a visualization framework. With these 'constraints' in mind the next section will first discuss how the eye movement data can be represented by the STC, followed by an argumentation on how these representations can contribute to the understanding of the data, and help overcome some of the problems mentioned in the previous sections.

3.1 Eye movement data and spatio-temporal data modeling

Peuquet [48] distinguished three elements in spatio-temporal data: location, attribute and time (Fig. 2a). This data approach is widely accepted in geovisualization research. Eye movement data has similar characteristics, therefore it can be structured accordingly (Fig. 2a). The record's time stamp (or start time) for one gaze point corresponds to the time component in Peuquet's model; the X and Y of a gaze point (screen coordinates) represent the location component, and attributes could be for example validity, event data, gaze point content or AOI metadata. Hence, eye movement recordings have many similirties with spatio-temporal data and can be visualized as such. In an STC, the X, Y plane of the cube represents the user's screen view. The eye movement (Space-Time- Path) is along the Z axis. The movement's attributes can, for instance, be represented by the color, size (volume) of the path.

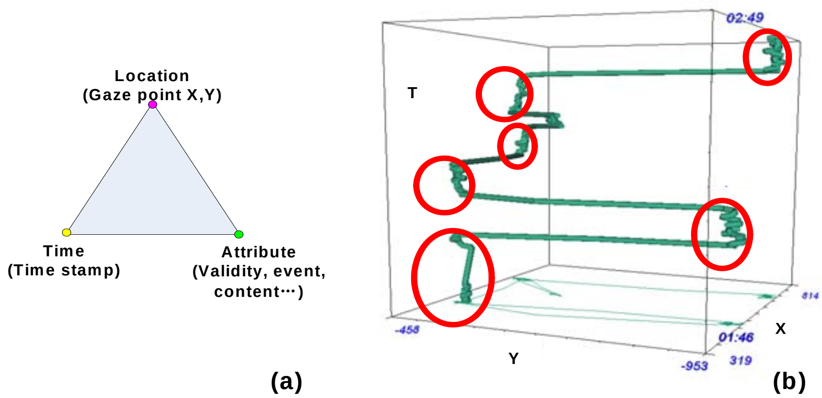


Fig. 2. (a) Eye movement data classified according to Peuquet's spatio-temporal model [48]; (b) a simple example of eye movement data in the STC.

Fig. 2b shows a simple example of eye movement data visualized in the STC. The trajectory of eye movements is displayed as Space-Time-Path (STP). It immediately reveals spatio-temporal patterns. The vertical 'lines' indicate (the ellipses in Fig. 2b) an eye fixation at a particular location. The fixations still include micro-movements as see in ellipses. This is not a surprise, because human eyes have continuous micro-saccadic movements and fixations are typically defined with temporal as well as spatial thresholds. In the STC, the fixation points can be easily identified by the approximate vertical line. The length of the approximate vertical line shows the duration of one fixation (fixation length). The horizontal lines indicate movements of eye (saccades). The slope of the line shows the speed of the eye movement. The Space-Time-Path can be projected on to a two-dimensional surface (screen view as background of the eye movement path), resulting in the familiar gaze plot representation with a scan path.

3.2 Solutions for visual analysis of eye movement data with STC

In comparison with visualizations presented in Section 2.1, the STC shows spatio-temporal patterns of eye movement data in a three-dimensional view equipped with dynamic and interactive functions. One advantage of the three dimensional view is that, overlaps (as shown in Fig.1 and Fig. 3a) can be avoided. In addition, the temporal order of the eye movement is revealed (*e.g.*, compare scan paths in Fig. 3a and 3c) and various spatio-temporal patterns in eye movements of multiple participants can be identified and compared.

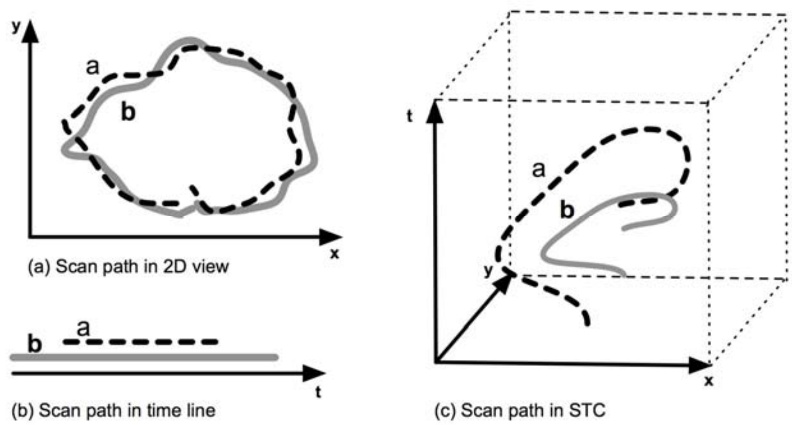


Fig. 3. Comparison of eye movements of two participants from different perspectives: (a) a 2D view shows the spatial pattern (potential overlap and no temporal order); (b) A timeline gives the temporal pattern only (no spatial information); (c) the STC reveals both spatial and temporal patterns.

Several functions supported by geovisualization could further extend the power of the STC for exploration of eye movement data. A moveable base map (screen view) along the T-axis could help discovering to what the participants were attending at a certain moment (Fig. 4a). Another flexible function of the STC is applying “the visual information seeking mantra” [47]. ‘Flexible’ here means that filter and zoom functions work on attribute, time and location in a flexible way. The attribute filter could help users to select the additional interesting attributes, for example, the validity of gaze point data, or the records of one participant for one particular task. Both the time instant and interval could be visualized, supported by a temporal zoom function (*i.e.*, zoom time in Fig. 4b). For example, a segment or a scene from a screen recording (which mark the steps of a task) could be defined this way. The zoom function could work on location as well (zoom location in Fig. 4b). Using this function, spatio-temporal patterns of multiple participants on a certain AOI could also be compared. Furthermore, it is possible to define the spatio-temporal zoom in the overview of the STC. For example, in Fig. 4c, the spatio-temporal behaviour of Participant 1 and Participant 2 over the same AOI could be compared.

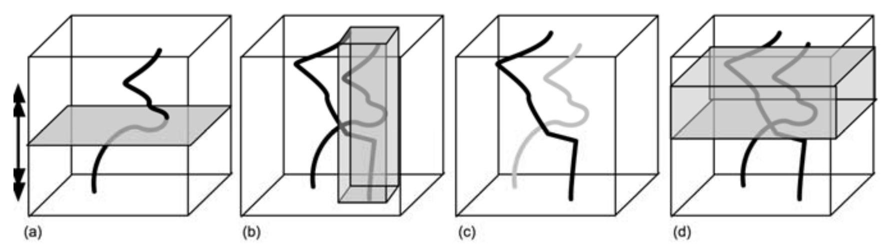


Fig. 4. Analytical functions in the STC (a) A moveable base map (screen view) along T-axis; (b) Spatial zoom; (c) Attribute filter; (d) Temporal zoom.

Fig. 5a shows another possible function in the STC *i.e.*, the annotations path. Additional multi-media information, such as video and images, or statistical results and notes (*e.g.*, interviews results) of the individual participants could be attached as annotations to the STP. During the analysis phase, annotations could be retrieved to access the detailed information with spatio-temporal content to further understand a participant's behavior. Fig. 5b and 5c shows a solution for analyzing the user behavior over a dynamic stimulus. In a geographic software environment, most frequently used functions are probably the spatial zoom in and zoom out. Understanding the geographic context is often very important for executing geographic tasks. In this case, the screen view after the spatial zooming could be projected back to the original scale. The x,y plan view adapts itself to the screen seen by the user. The time of the zooming operation could be shown with the Z axis. At this point, the scan path of the user could be reverted to the original scale, *i.e.*, overview scale, on the footprint map. Both spatial and temporal information of the zooming operations could be displayed. If dynamic view results in the non-geographic operations of a participant (*i.e.*, base map changes entirely) an optional solution could be showing the screen view along with the Z-axis or with STP.

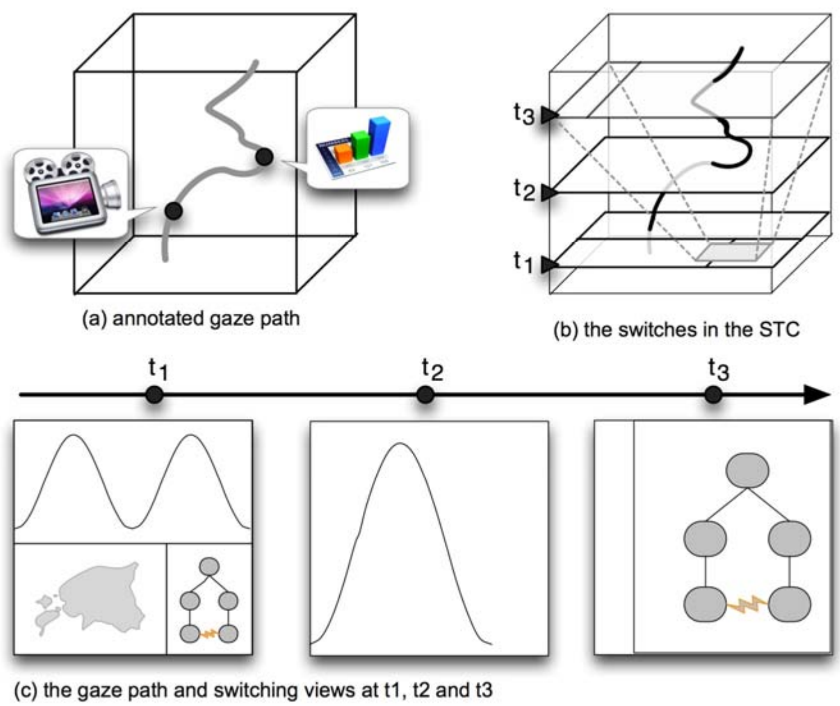


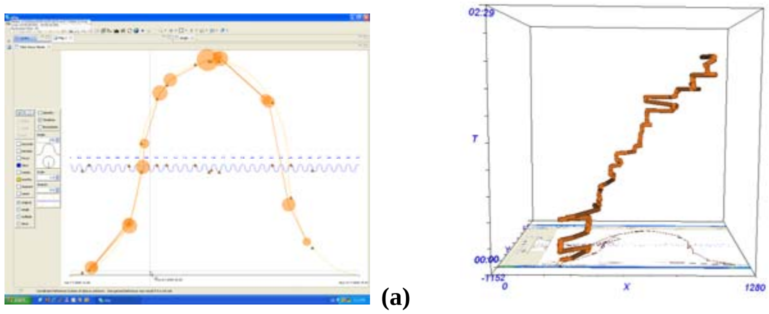
Fig. 5. Tracking the gaze path over a dynamic screen: (a) paths with annotations in times t1, t2 and t3; (b) user looks at overview screen (t1), zoom in on time wave (t2), and pan to graph (t3); (c) gaze path shown in the STC displaying the different screen views from (a) with the option to project them back into the original view.

4 Case study combining eye movement data and the STC

The eye movement data in this case study was collected for evaluating an experimental geovisual analytics system. The interface of the system is based on the coordinated multiple view approach and includes a 2D map, a line, graph and a representation for temporal data and the time wave [49]. The objective of the evaluation was to judge user's behavior in this environment and get insight into users' thought processes while working with the time wave. In this paper, the eye movement data collected for the evaluation study is used independently from the experiment's original goals. Here it serves as a test dataset to investigate whether a geovisual representation, namely the STC, can be used to improve the understanding of patterns observed in the data. Data collection was done in a controlled laboratory setting (GIVA's Eye Movement Lab [50]), that is equipped with an active, near-infrared enabled remote video eye tracker (Tobii X120). In this study, the tracker was configured to record at 60 Hz sampling rate. The fixation threshold value was set to 100 milliseconds. Screen resolution was set to 1280*1024 pixels and the system was calibrated for each participant. The data post-processing stage involved creating scenes, segments, and AOI visualizations. To create an STP of eye movements in the STC, the attributes TimeStamp, GazePointX and GazePointY were used.

The core of the geovisual analytcis system consists of uDig, an open source GIS software [51], with several dedicated plug-ins developed in-house such as, the time-wave and the STC. The STC functionality, which is most relevant in the scope of this paper, has been described in Section 3. Is it possible to use eye movement data to create STPs to visualize and qualitatively discover spatio-temporal patterns? Fig. 6 shows a comparison of a 'traditional' eye movement track represented in a gaze plot map overlaying a screen showing the time-wave (6a) and the same data in an STC. In Fig. 6a, it can be observed that the user's eyes followed the wave and stopped for a moment at the triangle points on the wave. These are the gaze points on the triangle and the scan path along the wave. However, the temporal order of gaze points cannot be determined in detail in this static image. Some scan paths that overlap can easily be misunderstood. In the STC view, as depicted in Fig. 6b, the trajectory does not follow the time wave straightforwardly, since it goes back and forth in places. This pattern cannot be derived from the 2D gaze plot map. The spatio-temporal pattern in the eye movement path is readily visible in the STC. The fixations can be identified by the approximate vertical section of the path. Thus, the STC visualization informs the viewer about the *when* and *how long* of the gaze behavior. In the experimental viewing environment, the STC is not the only available view; a 2D map is linked to the cube which gives the user the opportunity to follow the path in the cube and on the map at the same time, keeping control of the context view.

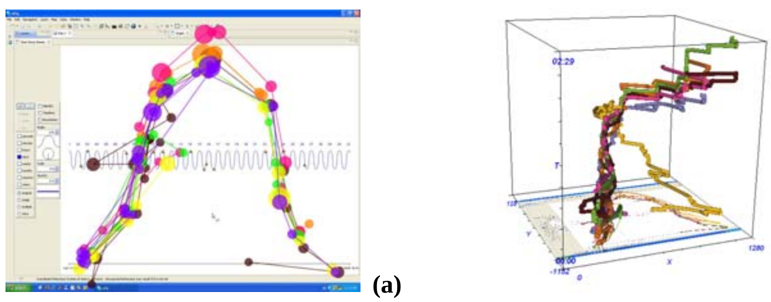
In Fig. 7, eye movement data for one particular task from a number of different participants is represented in the gaze plot and in the STC views. In the gaze plot all paths seem to be similar (Fig. 7a).



(a) (b)

Fig. 6. A comparison of a 'traditional' gaze plot representation of an eye movement recording (Tobii Studio) (a) with the same data in a STC (b).

From the STC (Fig. 7b) it can be concluded that this is not the case. One of the paths is clearly different from the others. This participant follows the wave right to left, while all the others went from left to right. The difference between participants' spatio-temporal patterns can be more easily distinguished in the STC visualization in comparison to 2D view where the 2D plot does not reveal the "odd case" as easily. The STC, in this case, offers a better visualization of spatio-temporal patterns, allowing a quick overview of the data, and in more detailed analysis. The STC can be combined with the other graphic representations with additional linked views.



(a) (b)

Fig. 7. Eye movement data for the same task performed by multiple participants shown as a gaze plot (a) and in the STC (b).

Fig. 8 illustrates a few additional visual analytics functions of the STC. The moveable base map can be seen in Fig. 8a. Fig. 8b shows the option to freely rotate the cube to get views from the different viewpoints. Users can switch on or off part of path above or below the map (Fig. 8b). In Fig. 8c, we see that a user can define AOIs represented as boxes in the STC to focus on a section of the path. A temporal selection has been added as shown in Fig. 8d. In this case, one is focusing on spatio-temporal patterns in the defined AOI within a certain time interval. The figure focuses on the fixations of participants in the defined AOI and in a certain time interval. With support of moveable base map feature, this AOI may be positioned directly on the context of stimulus.

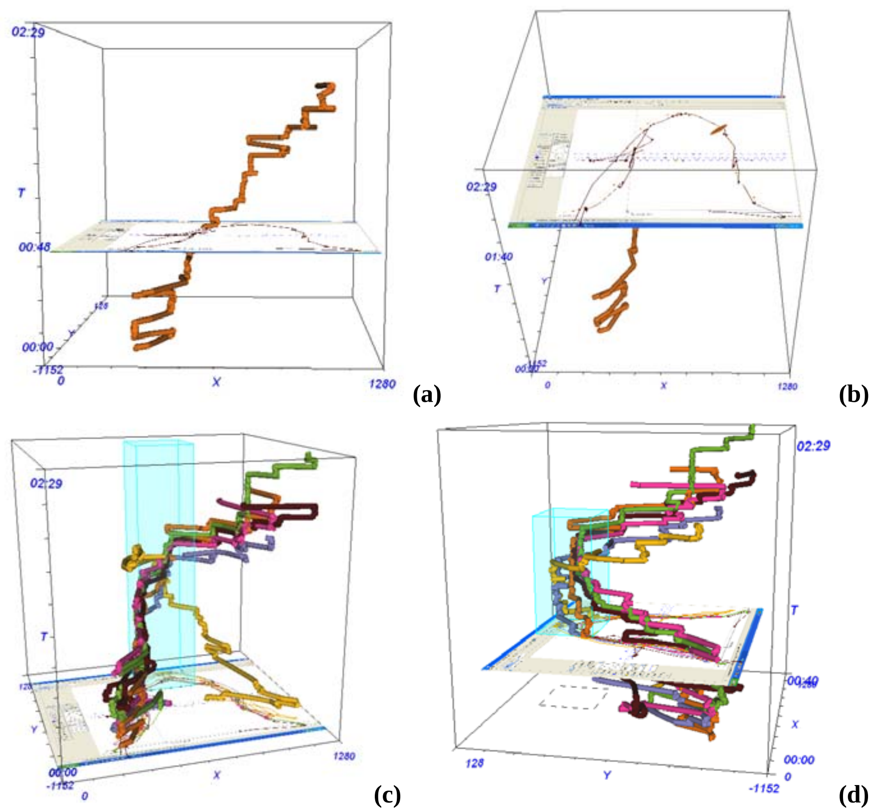


Fig. 8. A few additional visual analytics functions of the STC: (a) The moveable base map; (b) switching on or off the part of path above or below the map; (c) definition of the AOI (spatial selection) in STC; (d) temporal selection added to the previous spatial selection.

5 Discussion and conclusions

Recording and analysis of eye movements offer interesting opportunities to support user-experience studies, including evaluation of geovisualization systems. Current eye movement recording and analysis hardware and methods have come a long way since the first studies in 1960s [52]. However, even with today's more comfortable procedures, analysis stages are still cumbersome. Qualitative analysis of data is typically performed by visually inspecting gaze plots and density maps. Such representations are of course useful depending on the purpose [18], however, gaze plots typically suffer from massive overploting, and density maps offer only aggregate visualizations. Since the eye movement recordings essentially produce multivariate spatio-temporal data, geo-visual analytics methods that handle multivariate spatio-temporal data can be used to also analyze eye movement recordings. The STC is a 3D visualization method, which provides a combined view of time and space. While dynamic and interactive 3D visualizations may not be always easier to use for everyone, in particular novice users [18], patterns that can be discovered using the STC may offer new and/or a deeper understanding of eye movement data. These patterns will not be discovered as efficiently when spatial and temporal features are viewed separately, which makes the research on using the STC for eye movement analysis worthwhile. Exploration of eye movement data in the STC could also be useful for a quick overall understanding of the experiment, tasks and participant behavior. Many of the eye movement metrics integrated in usability studies (such as fixation and gaze durations, area of interest (AOI) analysis, and scan path comparisons) could be represented in modern STCs that allow multimedia integration, interactivity and dynamism. Furthermore, overlaps are avoided in the STC by extending the data onto the temporal dimension. At the same time, temporal order is visualized with the time dimension in the STC. Time-related questions regarding eye movements, such as *how long*, *how often*, *when* and *in what order* could be answered using these methods.

Developments in graphics processing, computer science and geovisualization domains provide even more opportunities for the use of the STC for eye movement analysis. Benefiting from these developments, several functions in recent STC software can help dealing with the difficulties in eye movement data analysis. For example, after an AOI is defined by a spatial zoom function, spatio-temporal behavior of a user's eye movement in this AOI could be explored further. A moveable base map along the time axis or a linked 2D view could offer more insight into the context of fixated regions. Dynamically changing the base map as the gaze plots are viewed in 3D space is potentially a great help with dynamic stimuli. Paths with annotations could provide useful information for user behavior analysis, such as videos, pictures and statistical graphs. Being able to change a view point in 3D space to explore complex data may provide additional insight into the complex multivariate data.

The use of the STC for visual analysis of eye movement data may complement statistical testing. To fully judge how useful these visualizations are, a good next step could be a usability study with experts working with eye tracking data. There are of course many other research questions that may follow up this study. For example, further visual inspection methods can be employed to study the spatio-temporal patterns found in eye movement data. Additionally, exploring the path annotations with qualitative analysis procedures could be taken into account. More importantly, to understand the thought processes better, not only *where* and *how long* but also *what* and *why* questions should be considered.

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