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REFEREED PAPER

Towards 4D Cartography – Four-dimensional Dynamic Maps for Understanding Spatio-temporal Correlations in Lightning Events

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While graphic variables in 2D maps have been extensively investigated, 4D cartography is still a widely unexplored field. In this paper, we investigate the usefulness of 4D maps (three spatial dimensions plus time) for cartographically illustrating spatio-temporal environmental phenomena. The presented approach focuses mostly on explorative research rather than on enhancement and extension of existing methods and principles. The user study described in the paper shows that 4D cartography is not a well-explored research area and that many experienced map users try to apply their knowledge from 2D maps to 4D dynamic visualisations. Thus, in order to foster the discussion within the community, we formulated several basic research questions for the area of 4D cartography, which range from methods for representing time in 4D visualisations and understanding the temporal context to finding generic methods to achieve optimized temporal generalisation and a consistent definition of graphical variables for 3D and 4D.

Keywords: 4D cartography, spatio-temporal maps, dynamic maps, Digital Earth, user study, lightning events

INTRODUCTION

In the broad research area of Digital Earth, cartographic representations of geospatial phenomena play an increasingly important role (Craglia *et al.*, 2012). Even though cartographic principles and variables (Bertin, 1974) are extensively explored and their perceptive impact is well-documented (e.g. Garlandini and Fabrikant, 2009), 4D representation (three spatial dimensions plus time) of time-varying phenomena, i.e. thematic 4D mapping, is still widely untouched.

This is particularly surprising as the fast rise of Google Earth since 2005 has revolutionized the Geographic Information (GI) domain through making 3D geo-information available to non-experienced users and thus through fostering the idea of map-based information systems on the Web. This is probably due to the fact that Google Earth is mostly used to view quasi-static content such as satellite imagery, 3D city models or a variety of points of interest.

In contrast to static information, the learning effect, i.e. cognitive knowledge creation by understanding a spatio-temporal process, is more complex for time-varying phenomena. It can be optimized by dual coding methods (Dransch, 1997) such as varying graphical variables like colour, shape, intensity or the *z*-value extrusion. In effect, the understanding of spatio-temporal processes such as lightning events can be fostered by conveying facts like flash densities via multiple channels. The sections on ‘Description of base data’ and ‘Cartographic representation of flashes’ show how we have exploited this concept in our research.

Bertin’s visual variables for 2D data portrayal have been developed from decades of professional experience and have been interpreted as a fundamental consensus at Bertin’s cartographic lab (Morita, 2011; Palsky, 2011). Textbooks on thematic cartography can also be viewed as post-hoc academic reflections trying to provide order and structure to the explosion of thematic mapping that happened in the middle of the twentieth century with symbolisation systems and map-type taxonomies.

A comparable technology-driven development is happening right now in the field of 3D/4D and animated mapping,

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fuelled by widely available deluge of temporal data and the software and hardware tools to render them in arbitrary ways. This appears to apply especially for thematic portrayal of 4D data in map-like environments. Little is known though for the case of thematic data as not even essential research questions have been exhaustively collected, let alone structured. The presented work tries to accompany thematic data portrayal with explorative empirical work to contribute to the general task facing cartography.

It has been shown that dynamic 3D visualisations can potentially have considerable advantages versus 2D approaches in effectively conveying spatial content (Engin *et al.*, 2009; Jobst and Germanichs, 2007). The main goal of our research is to examine how 4D representations can foster the understanding of natural phenomena. Furthermore, we show that 4D maps are a useful method for visualizing dynamic environmental processes in an intuitive manner.

In this paper, we investigate the usefulness of 4D maps for dynamically displaying thematic information. In particular, we focus on lightning events out of several reasons: (1) this paper aims to discuss 4D thematic maps rather than topographic ones, which have partly been investigated in previous work (Brooks and Whalley, 2005; Häberling *et al.*, 2008); (2) flashes are natural candidates for 3D (+time) representation as they would only be visible as points or icons in 2D maps; and (3) 3D can be useful in lightning event analysis in terms of dynamic analytics, whereas 2D flash densities would rather be used for descriptive statistics.

It shall be mentioned that the presented approach focuses mostly on explorative research rather than on enhancement and extension of existing methods and principles. This is due to the fact that thematic 4D cartography is not a widely-developed research area and thus hardly represented in current literature (the section on 'Related work') – particularly usability is still an underestimated aspect in GI research. There are some approaches to representing cartographic information in 3D, but they mostly do not take the dynamic presentation of temporal variations into account. Furthermore, the presented research focuses on 4D cartography rather than on lightning research.

This paper is structured as follows. This introduction is followed by a section on related work in the area of 4D cartography to present time-varying phenomena. The section on '4D cartography: methods and realisation' presents the motivational background and the interface design of our application. Thereafter, the section on 'Research challenges: visualizing flashes in 4D' points out the research challenges, which we have been dealing with, before section on 'Empirical user study' discusses the performed user study. Finally, the section on 'Conclusion and future research avenues' concludes the paper with an outlook on future research avenues.

RELATED WORK

In the early 1990s, researchers developed new strategies to represent geographic time series data contrasting their traditional representation as statistical diagrams (Monmonier, 1990). It has been found that users perceive information derived from spatio-temporal data faster from animated than from static maps (Koussoulakou and Kraak, 1992), which brought up a variety of studies in this field regarding animation techniques and visualisation criteria (e.g., Acevedo and Masuoka, 1997, van Wijk, 2002). An overview of spatio-temporal data visualisation methods has been presented by Andrienko *et al.* (2003) and Aigner *et al.* (2007).

With the rise of spatio-temporal data acquisition and storage, institutions and researchers have been trying to cope with questions of storing, updating and visualizing 3D and 4D data in several fields for some time now. Examples comprise the National Mapping Agencies (Capstick *et al.*, 2007), database researchers (Ankerst *et al.*, 1999), 3D city models (Jahnke *et al.*, 2011), dynamic visualisations of spatio-temporal environmental processes (Resch *et al.*, 2010) or pipeline and utility network engineering (Du *et al.*, 2006; Döner *et al.*, 2010, Balogun *et al.*, 2011).

The fields of 3D city semiotics (e.g. Jobst *et al.*, 2008), mountain cartography (Brooks and Whalley, 2005; Häberling *et al.*, 2008) or landscape visualisation (Kettunen *et al* 2009) have indeed identified several reliable mappings of graphical variations as expressive depictions even with interactions, but remain close to tangible objects on the Earth's surface. There, graphical depth-cues (Buchroithner *et al.*, 2000) need not be dual-coded. Strategies for freeing some graphical variables for other data are stylisation/non-photorealistic rendering, which lessens strain on texture and lighting conflicts (e.g. Buchholz *et al.*, 2005; Zanola *et al.*, 2009), or using different means of 3D illusion (Dickmann, 2010). For the recurring problem of dealing with object occlusion due to dynamic viewing angles, minimization strategies were proposed by Chaudhuri and Shen (2012) and Huang *et al.* (2012).

Although the visualisation of time series data in 2D and 3D has been a focus of research for several years, it shows shortcomings particularly concerning user impressions and interaction. For instance, the navigation of 4D interactive maps is not yet completely studied. Accordingly, the minimum set of navigation controls needed to explore time series data and the most suitable controls for map users have not been identified yet. Beyond that, it is not yet proven if 4D representation can help understanding dynamic real-world phenomena. Likewise, the influence of the visualisation complexity, varying from simple abstraction to photorealistic representation of the spatio-temporal phenomenon, on the user regarding the comprehensibility of the map has not been extensively studied.

4D CARTOGRAPHY: METHODS AND REALISATION

Before discussing the actual research challenges and outcomes, this section presents general requirements and backgrounds in designing 4D maps, and illustrates some methodological and technical details of our practical realisation.

Methods: cognitive aspects in 4D cartography

Cognitive processes – like understanding the contents of a map – are automatic to a great degree (Jobst and Germanichs, 2007). Still, regarding and comprehending a thematic map requires significant cognitive and perceptive capabilities. Depending on how profound these capabilities have been 'learned' by a person, we can observe differences in time consumption and efficiency in understanding a map.

The learning effect – and thus the efficiency in viewing a map – can be optimized by dual coding methods, for instance by varying graphical variables such as colour, shape or intensity. In effect, the understanding of spatio-temporal can be fostered by conveying facts such as flash densities in lightning events via multiple channels.

However, efficiency will be drastically reduced if too much information is presented at once and if too much sensual input is available, as this prevents new knowledge creation resulting from information overflow, in which an input cannot be processed before the next stimulus arrives (Kluwe and Schulze, 1994). As the human brain will discard unprocessed information in this situation, it is vitally important to account for map semiotics in the design process, in particular the pragmatics, but also semantics and syntactics. This especially applies to 3D environments, which are cognitively considerably more demanding than 2D environments.

In consequence, perception and cognition of 3D maps, i.e. readability and objective possibility to interpret spatial content, can be considered a psychological bridge between highly simplified abstracted 2D maps and reality (Burt, 1995). Even though 2D maps may be sufficient for conveying simple matters, and they offer geometrically correct topographic representations, they drastically simplify reality and thus do not account for the highly complex capabilities of human spatial cognition.

On the downside, 3D representations of real-world scenes are by definition distorted due to a number of factors such as spherical perspective, topographic irregularities, hidden objects, scale-dependent feature presentation or geometric inconsistencies arising from the use of different Spatial Reference Systems. Despite these shortcomings, 3D cartographic representations account for the complex human perception of the world better than 2D representations.

Realisation: 4D interface design

The advantages of cartographic 3D representations of real-world phenomena are the basis for the design of a 4D interface (3D + time) for presenting lightning events in an interactive spatio-temporal application. According to Jobst and Germanichs (2007), the technical design of the user interface is still a central quality aspect in cartographic products. This requirement is increasingly gaining importance through the widespread use of digital user interfaces on mobile phones and computer screens, which offer new and more dynamic ways of presenting geospatial information (dynamic interaction, scale-based data sub-selection, graphical presentation of geographic features, on-demand data visualisation, etc.).

The interface of the presented 4D visualisation application (see the section on 'User study' for screenshots) is divided into two parts: the viewport, which occupies a major part of the screen, and the top panel in the upper area of the screen. The top panel is used for time navigation – it allows for directly navigating to any month of the year (by clicking on a month) – as well as launching and stopping the visualisation process. Furthermore, it displays information about the visible phenomenon such as a time slider, a timestamp and the legend.

The viewport is kept free from any kind of textual information and serves solely for visualizing spatio-temporal lightning events. The entire scene is rendered in 3D as this is the most realistic way to illustrate a real-world phenomenon on the Earth's surface. Beyond that, this representation is well established and widely spread through applications like Google Earth, Bing Maps 3D or NASA World Wind. Accordingly, various common means of user interaction in 3D scenes like panning (in a drag-and-drop fashion), zooming (using the mouse or the keyboard) and rotating around all three spatial axes x–y–z (using the mouse or the keyboard) are supported by the application.

Regarding general cartographic design decisions, the map's base colour is chosen rather dark as this intuitively conveys the typical weather conditions during thunderstorms. Additionally, a dynamic cloud layer was added to emphasize these perceptions. Owing to performance issues, the cloud is visualized as a 2D noise plane instead of a more photorealistic visualisation in 3D.

From a technical viewpoint, the application is based on the open-source software Processing (Fry and Casey, 2012), a Java-based toolkit for 2D and 3D visualisations. It utilizes the Open Graphics Library renderer and is therefore well suited for high-performance rendering of spatio-temporal phenomena.

The interface of the application is shown in the section on 'User study' to illustrate the different graphical implementations (photo-realistic versus straight lines) and to illustrate the 3D extrusion of flash densities.

RESEARCH CHALLENGES: VISUALIZING FLASHES IN 4D

After having discussed general critical aspects of 4D visualisation in the section on '4D cartography: methods and realisation', this section pinpoints concrete challenges in intuitively visualizing lightning events as a spatio-temporal process. After a brief description of the visualized base data, three main challenges are discussed: (1) finding an expressive graphical representation of flashes; (2) determining the optimal graphical representation for flash densities; and (3) developing innovative and intuitive ways to cartographically illustrate spatio-temporal phenomena as dynamic processes.

Description of base data

The data used in this study comprise all *lightning events* (20,260 flashes) from the year 2003 in the Austrian state of Salzburg by courtesy of ALDIS (Austrian Lightning Detection and Information System, http://www.aldis.at). The events are stored in a simple text-based point data collection represented by the three attributes latitude, longitude and a timestamp. The geographical position actually represents the centre of an ellipse with a major semi-axis of about one kilometre. This ellipse characterizes the Gaussian-shaped probability of the actual location of a lightning event (Neuwirth *et al.*, 2012). The timestamp represents the exact time when a lightning event occurred with a temporal accuracy of 1 second.

Furthermore, pre-calculated *flash density* information is used to illustrate the spatial distribution and occurrence of the flashes. For different experiments, this density layer can be displayed in two different aggregation granularities – hourly and daily. The density information is visualized by 3D points which vary in colour and height to emphasize areas with different flash intensities. Finally, a *shaded relief* based on the Shuttle Radar Topography Mission C-band radar data is used to visualize the regional topography of the Alps. The Shuttle Radar Topography Mission layer mainly serves for spatial orientation purposes.

Cartographic representation of flashes

A central challenge in the presented research was to find an expressive graphical representation of flashes in the application. 'Expressive' in this case means that the goals of the survey (see the section on 'Empirical user study') could be achieved in the best possible and most efficient way, according to the ISO standard 9241 on ergonomics of human system interaction – i.e. usability and user experience.

During the design process, it was decided to implement two different representations: (1) a pseudo photo-realistic one, which should convey a quasi-realistic presentation of lightning events; and (2) a simple one (straight lines with decreasing opacity from a flash's centre), which should presumably help to identify the origin and the destination of a flash.

Another fundamental design decision was to show flashes always in white colour instead of colouring them according to the cumulated density of lightning strikes on the ground. This decision was taken to comply with the requirement of adequate information density (see the section on 'Methods: cognitive aspects in 4D cartography') and to preserve the quasi-realistic impression of the application and thus not to confuse users by adding another level of complexity. In consequence, this means that changes in the cumulated flash density can only be recognized by the density pixels' colour and height.

The empirical user study dedicatedly asked the test persons, which way of representing flashes helped them more in accomplishing the required tasks, which in simplified terms was to understand different properties of thunderstorm events. The user study is presented in the section on 'Empirical user study'.

Expressive cartographic representation of flash densities

Displays of densities always face pragmatic as well as epistemic problems. Densities are, by their very nature, averages over a certain area. As this area approaches zero, a density depiction transforms into a scatter plot. Pragmatically speaking, a recurring problem is to choose a useful classification and a matching kernel size to compute the density surface from the population of individual events. For lightning densities, the classification into five classes and the decision to use a dual colour ramp was informed by lightning researchers. While, technically, a density surface was created, actually a mosaic of colour-coded raster cells was produced. The raster cells were dynamically elevated according to incoming lightning events (Figure 3). This brings the advantage of making use of the degrees of freedom an interactive environment offers:

1. From directly above, the mosaic is equivalent to a traditional, classified density map.
2. As the user changes their elevation viewpoint angle, a 3D surface emerges, showing the 'hills and valleys' of lightning intensity.
3. As the elevation angle becomes more acute, the gaps between the mosaic-cells allow inspection of the topography again.
4. At elevation of zero, the view transforms naturally into a cross section of the intensity, surface, equivalent to a histogram across the current viewshed.

These transformations of diagram and map type are naturally deducible from the graphical encoding and truly allow for exploration of the data space directly in the map. No linked views, harsh cuts in encoding or conscious user decision are needed. We conjectured this technique to not only foster the understanding of the subject at hand, but even more to enhance the understanding of what aggregate density measures mean and how they relate to actual events in time and space.

Presentation as a process visualisation

A central motivation for the presented research was to find innovative and intuitive ways to cartographically illustrate spatio-temporal phenomena as dynamic processes.

Regarding thunderstorm events, two basic types of processes are visualized using our approach. Firstly, the spatial movement of a thunderstorm over time is presented in three spatial dimensions – including 3D navigation – to foster understanding of the natural phenomenon. Secondly, the time-dependent process of increasing flash densities (cumulated densities over a whole year) is visualized. It shall be mentioned that different temporal resolutions were used to visualize the two processes: hourly for illustrating the spatial movement and daily for displaying cumulated flash densities over a whole year.

These types of process illustration require the integration of three spatial dimensions with the visualisation of a temporal development. In the presented research, the third spatial dimension (*z*-axis) contains the cumulated lightning densities. Using extrusion in *z*-direction together with colour coding according to the legend, we tried to comply with the dual coding approach mentioned in the section on 'Introduction'. Like this, it is easier for the user to comprehend the increasing development in the cumulated densities and thus to understand the spatio-temporal process.

EMPIRICAL USER STUDY

To verify the hypotheses discussed in the section on 'Research challenges: visualizing flashes in 4D', we carried out a user study involving 20 participants. Before answering the questions, the test persons could make themselves familiar with the application in terms of interaction, navigation, controls, the time slider, the presented meta-information and the map interface itself. The questionnaire

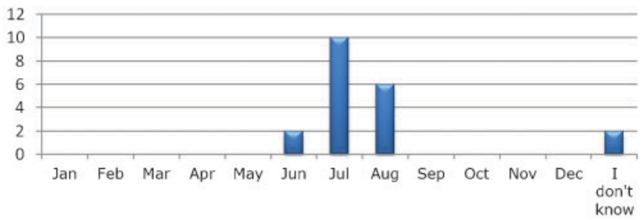

Figure 1. Answer distribution: month with most flashes

comprised eight questions – four closed, two hybrid and two open questions.

This section presents the results of the user study. The result discussion and interpretation for each question are done in the section on 'User study' separately for every question, whereas an overall discussion and conclusion for the survey are presented in the section on 'Conclusions from the user study'.

User study

Question 1 asked about the experience level of the participants. The test persons indicated their experience on a four-point scale (only single answers were allowed) as follows: 'Expert' – 55%, 'Experienced' – 35%, 'Some Experience' – 10%, and 'No Experience' – 0%.

The high concentration of experienced test persons results from consciously preferring participants with more than no experience in using digital maps. This was done out of two reasons: firstly to avoid navigation problems and issues with understanding the complexity if combined 3D-spatial, temporal and thematic contents, and secondly to receive accurate and advanced feedback from a cartographic and user interaction viewpoint.

Question 2 was the first thematic question in that participants were asked in which month of the year the most flashes occurred. Only single answers were allowed. Figure 1 shows a bar chart of the answers.

The right answer to question 2 would be 'July', whereby four months throughout the year show outstanding amounts of flashes: May (3375), June (5734), July (6552) and August (4337) – the month with the fifth highest concentration is March (158), which is by magnitudes lower than the first four ones. From the answer distribution, we can see a clear focus on these 3 months.

A central aspect in the interpretation of the answers to question 2 is how the test persons perceived the density and the accumulation of lightning events. From the answers and free-text comments of the participants, we conclude that a few extremely intensive days are attributed higher contribution to a month's sum than more days with fewer flashes in average. For instance, July includes 4 days with an extraordinarily high number of flashes (876–1541), but all in all there are only 16 days, in which lightning events occurred. In contrast, there were 26 such days in June, 20 in August and 19 in May.

A second reason for the fact that most test persons answered question 2 with 'July' or 'August' results from a practical observation during the survey. As the first 4 months of the time series (January–April) only contained 6 days with lightning events, the first third of the year is passing by quickly in the animation. In consequence, most people were still exploring the application (map interface, navigation, switch between flash representations, etc.), while May had already been displayed. Despite the possibility for temporal navigation using the time slider in the header bar, most participants have not replayed the month of May. This may have resulted from personal experiences with lightning events in that most test persons thought already before watching the animation that the most intense months would be June, July or August.

In conclusion, it can be stated that the daily aggregation of flashes is not optimal for the task of identifying the month of most lightning events. Daily aggregation has been chosen to find an adequate trade-off between a reasonable number of flashes per time step (flashes should still be individually visible) and the overall duration of the animation (displaying all flashes over a whole year). This issue will be discussed in more detail in the section on 'Conclusion and future research avenues'.

Question 3 asked whether participants could see a correlation between lightning strikes (flash density) and topography (mountains versus valleys). Most participants (85%) could clearly recognize the correlation that there is higher density of lightning strikes on mountains. Considering the answers to question 4 (perception of 3D representation) and question 7 (helpfulness of the 3D representation), we conclude that the 3D representation was helpful for the test persons to understand these topographic correlations – even though we are aware of the fact that this knowledge may also be considered extended general knowledge.

Question 4 asked how the participants subjectively perceived the 3D representation of lightning events. This was asked in a hybrid question in four pre-defined categories ('Clarifying', 'Stimulating Curiosity', 'Confusing', 'Fostering Process Understanding') plus the possibility for free-text comments. The participants could check multiple categories in their answer. Figure 2 diagrammatically illustrates the participants' answers. Most test persons found that the animation was clarifying and stimulating curiosity.

The free-text comments for question 4 (representing the 'Other' part in the diagram right above) contained mostly remarks about the visualisation itself – it was perceived 'entertaining', 'nice-looking', but also 'slightly overloaded' and 'cognitively challenging'.

Question 5 asked how the extrusion of the cumulated lightning densities helped the participants in identifying dynamic changes in the densities. The participants were offered four possibilities for answering: 'Very much', 'Rather more', 'Rather less' and 'Not at all'. Figure 3 shows a screenshot of the application illustrating the 3D extrusion of the flash densities. Pixels are elevated from the ground proportionally to their value and coloured according to the legend.

Figure 4 diagrammatically depicts the answers given to question 5. 65% found that the 3D extrusion of the lightning densities was very helpful or rather helpful, 40% that it was rather less helpful and 5% that it was not helpful at all.

Question 6 asked, which type of portraying the flashes helped the participants more in understanding the map's dynamic content, i.e. the spatio-temporally varying phenom-

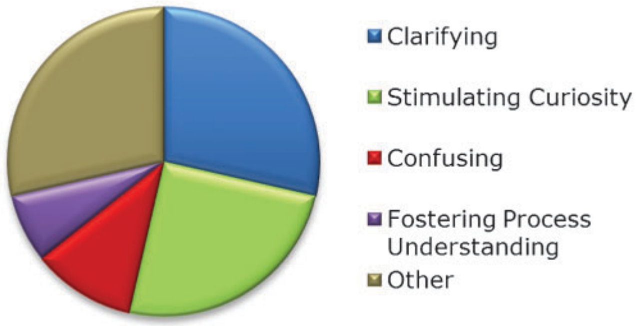

Figure 2. Participants' perception of the 3D representation of lightning events

enon of thunderstorm events. Most participants (60%) found the pseudo-photorealistic illustration more helpful because it conveyed a more realistic view of lightning events. Only 10% thought that the straight lines were more helpful, 30% considered the two presentations equally helpful. Figure 5 shows a screenshot of both lightning representations – pseudo-photorealistic (left) and straight lines (right).

Question 7 asked how the 3D representation of thunderstorm events helped the participants in understanding a dynamic natural phenomenon. Pre-defined answering possibilities were that the 3D representation was…

- …helpful in understanding the dynamic nature of thunderstorms.
- …providing a helpful different cartographic perspective on dynamic phenomena.
- …helpful in identifying topographical correlations.
- …engaging.
- …helpful in identifying the spatial context of the study area.
- …none of the above.
- … Other *(please enter text into the box below)*

Figure 6 illustrates the statistical distribution of the answers for question 7, for which multiple answers were allowed.

From the above diagram, it can be seen that most test persons perceived the 4D visualisation as being helpful to understand a dynamic natural phenomenon, to identify topographic correlations and to identify the particular spatial context in the presented application. Furthermore, most participants found that the visualisation provided a useful alternative cartographic perspective on dynamic phenomena in comparison to previous 2D-based approaches. Also, some persons indicated that the 4D representation of lightning

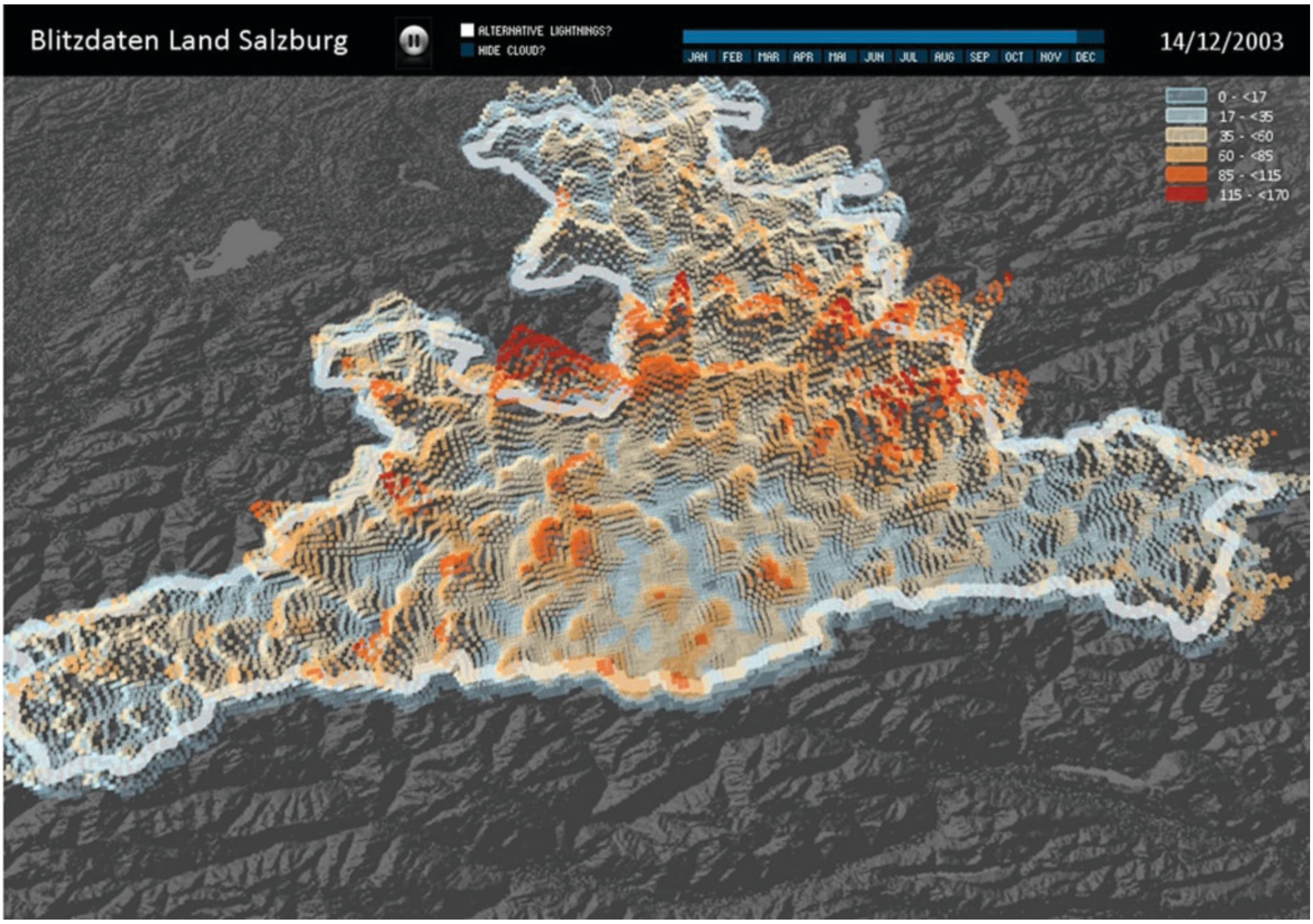

Figure 3. 3D extrusion and colouring of the pixels according to their value

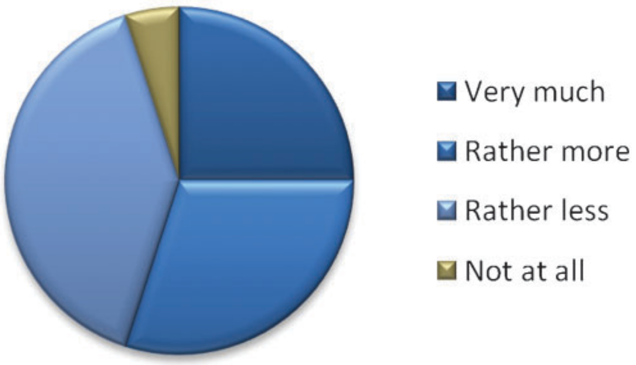

Figure 4. Helpfulness of extruding cumulated lightning densities for identifying dynamic changes in the densities

events was engaging in that it was subjectively pleasing to use the application.

The free-text comments (representing the 'Other' option) mainly contained statements on improving the visualisation by using a more detailed terrain model, by integrating a satellite image to identify natural features, and by adding 3D city models. All in all, the 20 participants provided 46 answers, meaning that each test person chose 2.3 answering possibilities in average.

Question 8 finally asked the participants, in which direction thunderstorms in the presented area predominantly travel. Therefore, the test persons could switch to a temporal granularity of 1 hour for displaying the flashes and the densities. The question was consciously conceived in a very open manner without giving hints of pre-defined answers in order to understand people's perception of a geographical area. The authors expected different kinds of answers such as 'west to east', 'left to right', 'upward' or 'along the mountains'. Surprisingly, most test persons (95%) answered with 'west to east' or 'east direction', which presumes geographical knowledge even without knowing the presented area of interest. This finding complies with the fact that many participants consider themselves experts or at least experienced in using digital maps (see **question 1**).

Conclusions from the user study

From the results of the user study presented in the previous sub-section, it can be seen that the cartographic 4D representation of dynamic natural phenomena is considered *helpful for understanding spatio-temporal processes*. Yet, some test persons – particularly those with a strong background in 2D cartography – are reluctant versus adopting new visualisation methods. This may result from the fact that previous research in cartography has not predominantly focused on visualizing dynamic processes and time series data.

From the free-text feedback, it is striking that many participants gave suggestions on visually optimizing the interface and the dynamic map, but *nearly no propositions were given on how to improve the cartographic visualisation of spatio-temporal processes*. This probably results from the fact that many test persons tried to apply their knowledge of static 2D maps to cartographic representations of 4D phenomena.

The mentioned *suggestions on the visualisation* included minor modifications of the navigation (a button for switching on/off the overlay, additional panning possibilities, a button for adapting the speed of the animation, etc.) and visual adaptations (alternative illustrations of extruded accumulated densities, colouring flashes according to the density pixel they are hitting, information presentation on several scales, choice of different colour ramps, etc.).

In conclusion, we can see that the perception of cartographically presented information is still very conservative, and new and innovative approaches towards depicting spatio-temporal phenomena in dynamic map interfaces are still to be found. The section on 'Conclusion and future research avenues' now discusses potential future research avenues in this area.

CONCLUSION AND FUTURE RESEARCH AVENUES

In the broad research area of Digital Earth, cartographic representations of geospatial phenomena play an increasingly important role (Craglia *et al.*, 2012). Even though cartographic principles and variables (Bertin, 1974) are

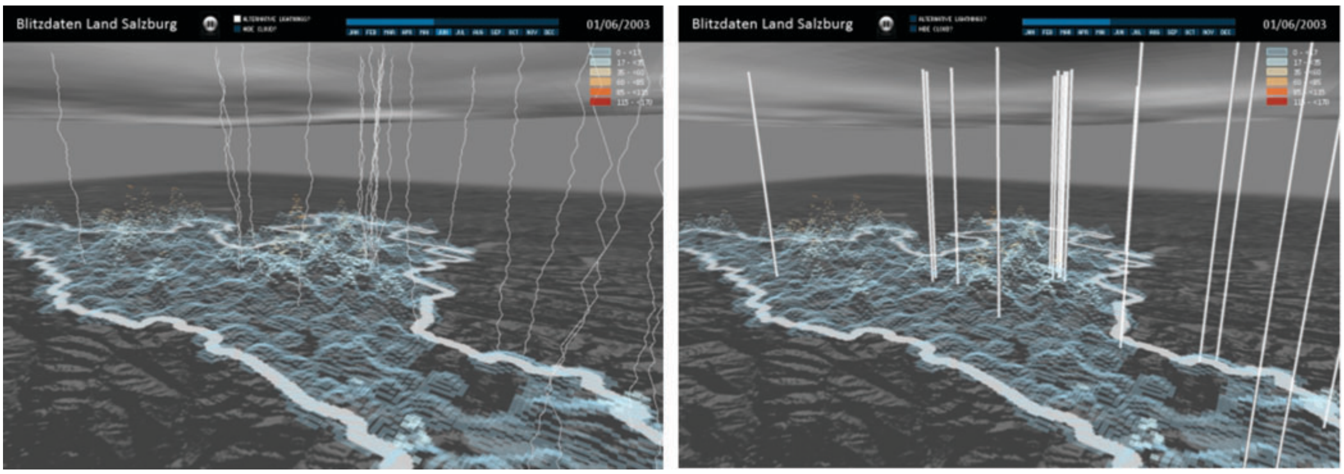

Figure 5. Different lightning representations – pseudo photo-realistic (left) and straight lines (right)

Figure 6. How the 3D representation of thunderstorm events helped the participants in understanding a dynamic natural phenomenon

extensively explored and their perceptive impact is well documented (e.g. Garlandini and Fabrikant, 2009), 4D representation (three spatial dimensions plus time) of time-varying phenomena, i.e. thematic 4D mapping, is still widely untouched.

In this paper, we investigated the usefulness of 4D maps (three spatial dimensions plus time) for cartographically illustrating spatio-temporal phenomena. The presented approach focuses mostly on explorative research rather than on enhancement and extension of existing methods and principles.

In our research, we demonstrated that 4D cartographic representations can help to understand dynamic spatio-temporal phenomena. The user study showed that 4D cartography is not a broadly investigated research area and that many experienced map users try to apply their knowledge from 2D maps to 4D dynamic visualisations – which does mostly not include the integration of increasingly important usability guidelines. Thus, in order to foster the discussion within the GI/cartography community, we formulated several basic research questions for the area of 4D cartography.

Future research avenues

One central future research question, which arose in the course of our study, is how to **represent time in 4D visualisations** other than using the traditional method of a compressed time axis. Current approaches mostly focus on temporal animations as a time series of static maps, each of which representing a single point in time (sequence of states), or on indicating movements in single static maps, e.g. by the use of arrows or flow lines. In this area it will be important to find out more about the cognitive and perceptive processes that determine how humans actually perceive time in 4D processes. This in turn will also determine which ways can be found for alternative representations of the time dimension.

A tightly coupled issue is how we can foster the understanding of the **temporal context** in dynamic 4D maps, i.e. how to optimize a viewer's perception of a spatio-temporal cartographic development. In case of the presented research on lightning events, this could potentially be achieved by small 2D maps, which are generated per month and lined up as a screen overlay. Another method could be the integration of diagrams (histograms, statistics, etc.) to display dynamic developments. However, we consider these ways non-innovative methods that rely on current state of the art and do not introduce a new paradigm of representing the temporal dimension.

A general question is to find methods for defining **optimized temporal generalisation**. So far, this has only been achieved on a per-application basis as the temporal granularity strongly depends on the data, the application and the goals or tasks the user wants to achieve. For example, a 10-minute aggregation interval might be suitable to identify movement directions of a weather front, but a 4-week aggregation interval might be useful for detecting monthly changes in flash densities. This problem seems to be of generic nature and needs to be parameterized to be solvable.

A fundamental question is to identify reliable expressive relationships between thematic data structures and graphical depiction. Although reams of possible graphical variations have been identified for 4D maps, a true mapping to the **thematic expressivity** is still missing. The visual variables for the 2D case of Bertin are a subset of all thinkable and technically modifiable graphical variables; namely the subset that allows reliable mappings from data to visual depiction. The extant literature often mixes the concepts, diluting both. Especially in computer screen 3D environments, for instance, size, colour, texture and lighting effects must interact to provide illusions of depth. This is related to the profound inverse optics problem as it is also encountered in 2D maps (Reimer, 2011), which puts severe limits on the expressive capabilities of many graphical modifications to actually achieve dual coding.

Further open questions include the definition of graphical variables for 3D and 4D, optimized dynamic colouring strategies (cf. 'dual coding' as mentioned in the section on 'Introduction') and the development of guidelines for user experience design in 3D/4D cartographic applications.

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