A Wall-Like Visualization for Spatio-Temporal Data

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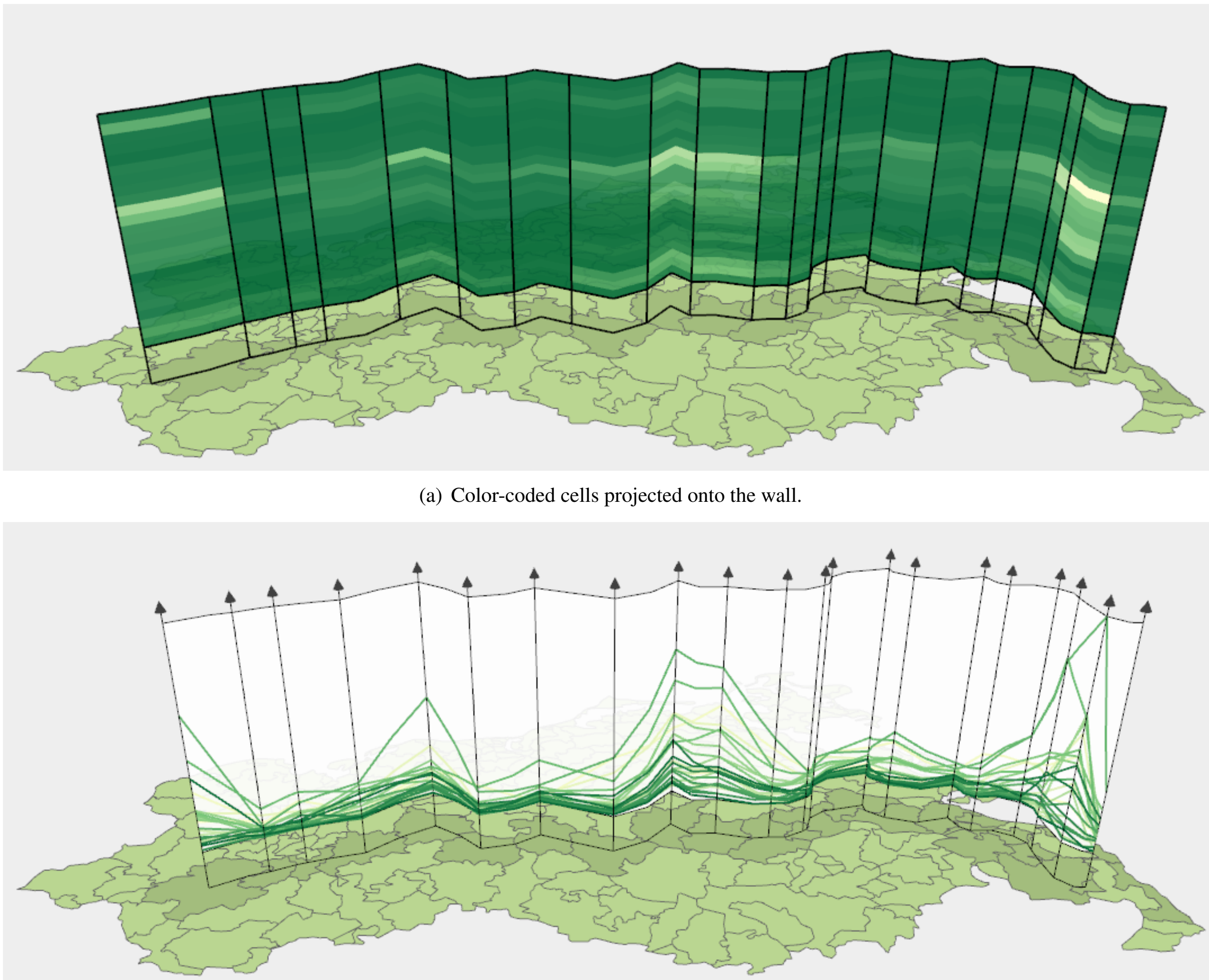

(a) Color-coded cells projected onto the wall.

(b) Parallel coordinates projected onto the wall.

Fig. 1. Cases of influenza for 24 months visualized along a selected path through space.

Abstract—Understanding how data evolves in space and time is an essential task in many application domains. Despite the numerous visual methods (e.g., showing the data on a map or plotting a time graph) that have been proposed to facilitate this task, the exploration of data with references to space and time still remains challenging. In this work, we present a novel concept for visualizing spatio-temporal data that refer to 2D geographical space and 1D linear time. The idea is to construct a non-planar slice – called the Great Wall of Space-Time – through the 3D (2D+1D) space-time continuum. Different visual representations can be projected onto the wall in order to display the data. We suggest using the wall's vertical extent to map the dimension of time and to color-code individual bricks within the wall. Alternatively, a parallel coordinates plot can be shown at the wall. Compared to existing approaches, the wall has the advantage that it shows a closed path through space with no gaps between the information-bearing pixels on the screen. Hence, our novel visualization has the potential to be a useful addition to the user's toolbox of techniques for exploring the spatial and temporal evolution of data.

Index Terms—Spatio-temporal data, visualization, interaction, space-time cube, slice.

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Interactive exploration and visual analysis of spatio-temporal data are relevant in many application domains [3]. A major challenge is to understand the interplay of space, time, and spatio-temporal data values.

In the past, several researchers have developed techniques that integrate space, time and data visually by embedding time-representing

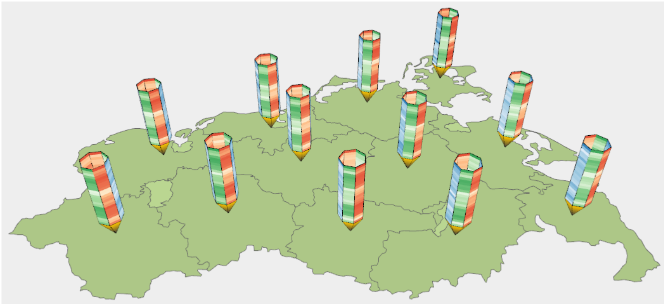


Fig. 2. Gaps between glyphs hamper relating the information displayed for the individual areas.

3D glyphs into a space-representing 2D map display [14, 12, 5]. This kind of representation has the advantage that spatial and temporal aspects are shown within a single image. However, it is difficult to mentally link the information displayed in one 3D glyph to the information of another 3D glyph. This is due to the fact that the glyphs are separated spatially, that is, there is empty space between them. Fig. 2 illustrates this problem.

To alleviate this difficulty, we propose a novel technique that avoids gaps in the visual representation of the data. Our solution is to create a non-planar slice through 3D space-time, which we call the *Great Wall of Space-Time*. The wall is constructed based on the properties of the spatial frame of reference. We provide interactive and automatic means to determine the wall's path through space. Once erected, the wall can be used to visualize spatio-temporal data in different ways. Here we demonstrate visual representations based on color-coding individual bricks in the wall and based on projecting parallel coordinates onto the wall. Appropriate interaction techniques have been integrated to support users in exploring the data.

In the next section, we will briefly describe the basics and related work. Section 2 is dedicated to the detailed introduction of our solution. This paper ends with a short summary in Section 3.

1 Basics and Related Work

We consider data that are defined as follows. The spatial dimension is composed of a set $\mathbf{A}$ of disjunct 2D geographical areas. The time dimension consists of a set $\mathbf{T}$ of discrete time-steps, where we assume a linear time model [2]. Space and time taken together define the domain in which spatio-temporal data have been collected. Our spatio-temporal data are stored as tuples of the form $(A, T, V_1, \ldots, V_n)$, where $A \in \mathbf{A}$ is a geographical area, $T \in \mathbf{T}$ is a time-step, and $V_i : 1 \leq i \leq n$ are the values measured at A and T. The challenge when visualizing such data is to integrate space, time, and data values.

In the visualization literature this challenges is dealt with in different ways. There are many techniques that focus either on the temporal aspect of the data [2] or on the spatial aspect of the data [9]. In order to combine these techniques, one can use multiple coordinated views [11], where multiple views show different aspects of the data, while the connection between space and time is realized via interactive brushing and linking [4].

A prominent example for the direct integration of space and time is the space-time cube [8]. There are several approaches that use the space-time cube as the underlying model for the visualization. One can distinguish between techniques that show collections of points in the space-time cube (e.g. [6, 7]) and techniques that embed time-representing glyphs into the space-time cube (e.g., [14, 12, 5]).

Our work is concerned with the latter class of techniques. Fig. 2 illustrates an example with glyphs embedded into a map display. A glyph visualizes the time dependency of the data of its associated area. By placing multiple glyphs on the map, the spatial dependency of the data can be communicated. However, due to the gaps between the glyphs, it can be difficult to understand how the data evolve in space.

2 Visualizing Spatio-Temporal Data as a Wall

Our idea is to provide a supplementary visualization that better supports the task of showing the spatial dependency while still maintaining the visibility of the temporal dependency of the data. Next we first provide a brief overview of our approach and then explain it in detail.

2.1 Solution Overview

Given the fact that we deal with discrete geographical areas in 2D space and discrete time-steps in 1D linear time, we can think of the data as a 3D space-time continuum. The basic idea of our approach is to visualize data values on a slice through such a 3D continuum. Slice representations have been used since the early years of visualization research, in particular in the realm of volume visualization.

In contrast to classic slicing-based visualization approaches, we do not consider a planar slice, but instead aim to create a meaningful topological path through space (see Fig. 3(a)). From the topological path, we create a geometrical path (in the x/y plane) based on the geographic characteristics of the spatial frame of reference. The geometrical path is extruded vertically (along the z-axis) to form a wall-like shape (see Fig. 3(b)). The wall is used to visualize the space- and time-dependent data. We map the dimension of time along the vertical extent of the wall and use color-coding to visualize individual data values (see Fig. 3(c)). Alternative visual encodings are possible as well, for example the projection of parallel coordinates onto the wall.

This general approach of constructing a wall for visualizing spatio-temporal data requires addressing the following aspects:

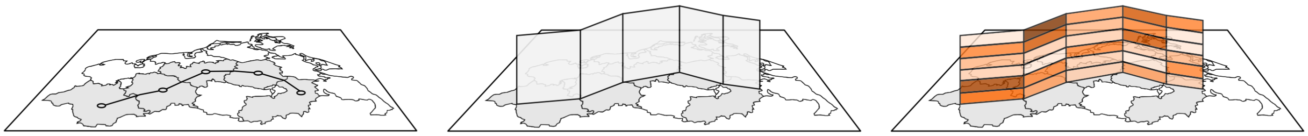
- **Meaningful topological path:** We must define what a "meaningful" topological path through space is. For this purpose, we consider the neighborhood graph induced by the partition of space into disjunct geographical areas.
- **Well-formed geometrical path:** The topological path has to be mapped to a geometrical representation. To this end, we consider the shapes of the geographical areas and make the geometrical path fit the areas' shapes.
- **Visual mapping:** We need an appropriate visual mapping of data values onto the wall. Here we rely on well-accepted conventions from the visualization literature.
- **3D occlusion:** Because the 3D approach inherently leads to occlusion, we need mechanisms to deal with it. Our solution provides 3D navigation and visual adaptation tools to let the user look around and through the wall.
- **Interactive exploration:** As we address exploratory analysis scenarios, all steps must be interactively steerable by the user. Where appropriate, automatic methods are integrated to assist the user.

Following the previously mentioned aspects, we will now describe our approach in detail. Next we take a look at the topological aspect followed by the geometrical aspect. Then we describe the visual mapping of data onto the wall and finally we explain the interactive techniques to address 3D occlusion and exploration.

2.2 Topological Considerations

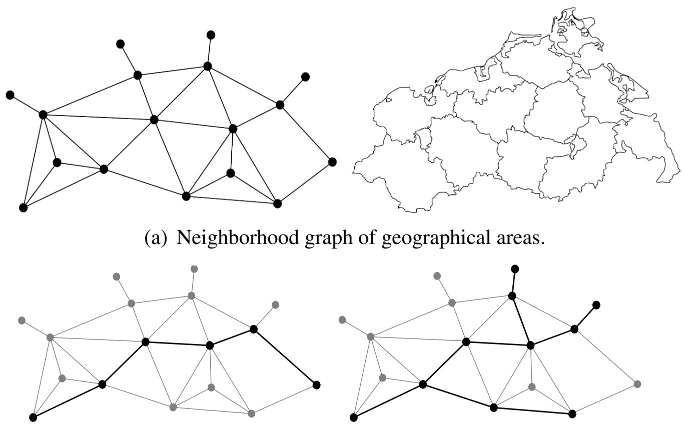
In order to construct the wall, we start with creating a topological path through space. This process is based on considering the neighborhood graph $G = (\mathbf{A}, \mathbf{N})$. The set of vertices of this graph corresponds to the set of geographical areas $\mathbf{A}$. The set of edges $\mathbf{N}$ describes the neighborhood relationships of the areas: If the areas $A \in \mathbf{A}$ and $B \in \mathbf{A}$ are neighbors, there is an undirected edge $(A, B) \in \mathbf{N}$. Note that special cases such as islands or areas with holes (area genus > 0) can be handled by inserting dummy edges into the neighborhood graph.

We define our topological path via a subset of areas $\mathbf{A}' \subset \mathbf{A}$ such that the subgraph G' induced by $\mathbf{A}'$ is connected. The connectedness criterion is required to create a wall without gaps. Further we impose the constraint that G' be an *acyclic path* through G. This constraint



(a) Specification of a path through space. (b) Construction of a wall. (c) Visualization of data at the wall.

Fig. 3. Basic idea of the Great Wall of Space-Time.



(a) Neighborhood graph of geographical areas.

(b) Acyclic path. (c) Acyclic subgraph.

Fig. 4. Topological aspects of the wall construction.

guarantees that the wall does not self-intersect. To allow for more flexibility in the construction of the wall, we can loosen this constraint by considering an *acyclic subgraph* instead of an *acyclic path*. Then it is possible to create branching topological paths through space. The different variants are illustrated in Fig. 4.

These topological considerations are the theoretical basis for the construction of the wall. In order to practically construct the wall, we need to provide means to specify the areas $\mathbf{A}'$ to be part of the topological path. To this end, we developed interactive, semiautomatic, and automatic mechanism that enable the user to construct walls dynamically at runtime.

Interactive construction Full control is provided by the interactive mechanism. The user can interactively define the path through space by successively selecting areas from the map. At all times, the mechanism offers only those areas for selection that lead to a well-defined continuation of the construction.

Semi-automatic construction If the map contains many areas, selecting them interactively can be cumbersome. For such cases, we provide a semiautomatic construction mechanism. The only selections to be made by the user are the start area and the end area of the wall to be constructed. The path in between the two selected areas is computed as the shortest path through the neighborhood graph. The computation can be based on the minimal number of areas in the path or on minimal edge weights (e.g., geographic distance between area centers).

Automatic construction The previous construction mechanisms operate on the topological characteristics of the geo-space, but they do not consider the spatio-temporal data. To further aid in the construction of the wall, we propose to construct the wall automatically based on trends in the data. Trends are often of interest when it comes to understanding how phenomena develop in space and time. To construct the wall along a trend, we apply a gradient descent starting either with an interactively selected area or with a minimum (or maximum) data value. Then we compare the data value of the starting area at time-step T_i to the data values of each of the neighbors at time-step T_{i+1}. The neighbor with the biggest increase (or decrease) is selected as the next area in the path. This mechanism is applied until no further areas can be added to the path.

2.3 Geometrical Considerations

With the previously described steps we have created an abstract topological path through space. In order to display a wall, we need to transform this abstract path into a geometrical representation. The geometrical path has to fulfill the following two requirements:

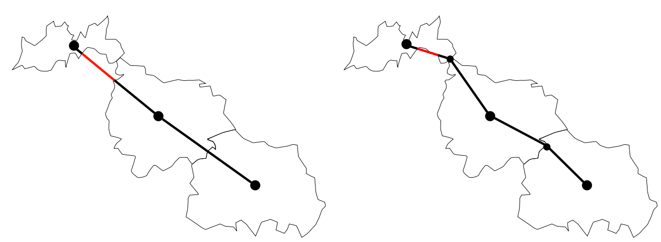
- **Inclusion:** The geometrical path should stay within the areas that make up the topological path. In other words, the geometrical path should not cross areas not belonging to the topological path.
- **Well-formedness** The geometrical path should be "well-shaped". Ideally, the geometrical path should be in the "center" of the area and be smooth with low curvature.

The difficulty is to fulfill these requirements given the arbitrary, often concave shapes of geographical areas. We identified different possible solutions that vary in their computational complexity and in the degree to which they fulfill the stated requirements.

Simple Geometry Construction The most basic solution is to assign an anchor point to each area and connect the anchor points to form the geometrical path. The anchor points can be computed based on the center of mass or the center of the largest inscribed circle, or they can be set manually for extraordinarily complex areas. Connecting the anchor points with straight line segments results in a geometrical path as shown in Fig. 5(a).

However, with this basic solution, parts of the geometrical path might be outside of the areas of the topological path (violation of the inclusion requirement). A simple way to alleviate, not to solve, this problem is to connect the anchor points via additional border points (see Fig. 5(b)). Border points can be defined as the center point of the border shared by two areas. If more than two areas are neighbors, the border point is trivially the point where the areas touch each other.

Using anchor points and border points we can create geometrical paths that are acceptable in many cases, while the computational costs are kept low. However, we cannot ensure fulfillment of the requirements stated before.



(a) (b)

Fig. 5. Simple construction of geometrical path (a) without and (b) with border points. Red segments indicate violation of the inclusion requirement.

Complex Geometry Construction To guarantee inclusion and well-formedness, methods need to be employed that are computationally more complex. We identified two methods that can be used for this purpose.

One is to compute the skeletons and derive the medial axes of the areas (see Ogniewicz & Kübler [10]) participating in the topological path. By connecting the medial axes one can obtain a geometrical path that is in the "center" of the areas. However, the geometrical path is not smooth, making it necessary to apply an additional smoothing step.

The second alternative is to utilize Abello & Gansner's [1] technique to compute a shortest smooth path between any two points on the boundary of arbitrary polygonal shapes. By successively computing such smooth paths between selected border points, one can construct a geometrical path with the desired features. This path is guaranteed to stay within the shapes of the areas, which meets our inclusion requirement, and the path is smooth, which meets our well-formedness requirement.

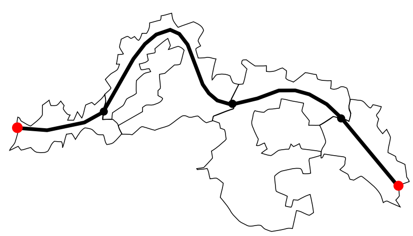


Fig. 6. Illustration of a geometrical path fulfilling the inclusion and well-formedness requirements.

Both complex methods generate better geometrical paths than the simple method (see Fig. 6). On the other hand, the computational as well as the implementation costs are much higher for the complex methods. For this reason, our prototype follows the simple method, which is sufficient for the purpose of demonstration. Using the geometrical path, we can now construct a wall and visualize data at the wall as described next.

2.4 Visualizing Data at the Wall

The geometrical path through the 2D map space is the reference for the spatial dependency in the data. In order to account for the time aspect of the data, we need to define a reference that serves for the temporal dependency. For this purpose, the geometrical path is extruded along the vertical z-axis, which is used to encode time. The result of the extrusion is a wall-like geometrical object at which visual representations of the data can be shown.

Our goal is to visualize the data such that there are no visual gaps between the areas along the wall. Therefore we decided for a color-coding of the wall. To visualize the data of the areas $\mathbf{A}' \subset \mathbf{A}$ along the wall for multiple time-steps $\mathbf{T}' \subset \mathbf{T}$ in the data, we subdivide the wall according to $\mathbf{A}'$ and $\mathbf{T}'$. By this subdivision we obtain a wall that consists of individual bricks (or cells), each of which is associated with a unique area A and time-step T. The bricks are then color-coded based on the data values stored for the individual areas and time-steps. For the color-coding, we rely on our previous work on task-driven color-coding [13]. Fig. 7(a) illustrates a color-coded wall with human health data. Green brick indicate low number of cases of influenza, whereas yellowish bricks stand for high values.

But colored bricks are not the only option for visualizing data. The wall can be considered a general projection surface that can show different visual representations with regard to the spatial and/or the temporal dependencies in the data. One alternative, for example, is to project a parallel-coordinates-like visualization onto the wall. Fig. 7(b) illustrates such a visual representation. We show a vertical axis per area and map a data variable to this axis. For each time-step we construct a polyline that connects the axes according to the underlying data values. Apparently, time-dependency of the data can no longer be mapped along the z-axis, because the vertical axes show the variable's value range. Therefore, we vary the saturation of the constructed polylines to indicate time. Of course, this works only with a limited number of time-steps.

The presented visual encodings demonstrate that the wall design can be useful to visualize temporal aspects of the data. But the wall is not limited to this purpose. Rather we see potential that a variety of goals can be achieved with the wall. One particular example is to compare the behavior of multiple attributes by attaching additional colored bricks to the wall.

2.5 Interaction

In order to explore the spatio-temporal data displayed at the wall the user must be provided with adequate interaction techniques. Our solution integrates classic 3D navigation, including free fly-through and orbit rotation, which allows the user to look at the wall from any perspective. 3D occlusion is addressed by providing the possibility to make the wall semi-transparent via alpha blending. Because the blending can have a negative impact on the perception of color-coded visualizations, we added a second option to temporarily resolve occlusions. The user can raise and lower the visualization at the wall much like raising and dropping a curtain. Raising the visualization leaves free space at the bottom of the wall (see Fig. 7), which is particularly useful to uncover the shapes of the areas contributing to the wall.

Because the wall's geometry depends on the shapes of the geographical areas, it can happen that some wall segments are rather small (then when the underlying area is small). Hence, the visual representation associated with small areas can be difficult to discern. To address this difficulty, users can apply an interactive cartographic lens, which temporarily distorts space to magnify smaller ares. The magnification affects both the map and the wall, which makes the data of smaller areas easier to explore.

On a more general level of interaction, our solution provides means to select the time range to be mapped to the wall and the attribute(s) to be visualized. The interactive (and semi/automatic) tools to select areas for the wall were already mentioned earlier. Further interactive adjustments of visualization parameters (e.g., task-driven color-coding) is supported via dedicated controls.

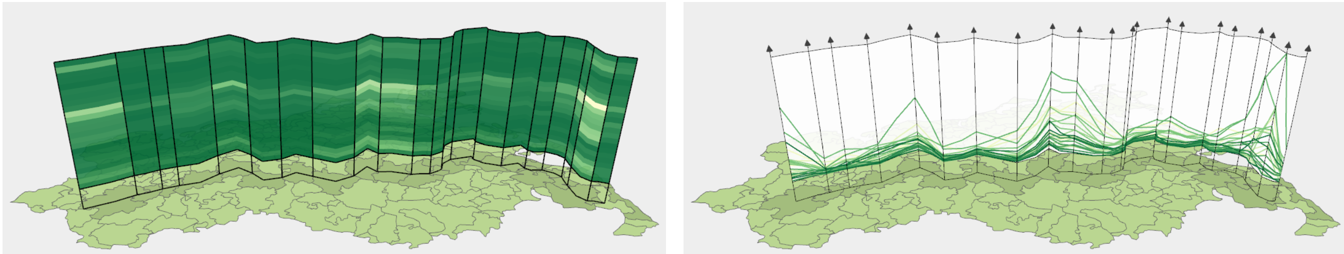
3 Summary

In summary, we presented a novel concept for visualizing spatio-temporal data. The visualization is based on the idea of creating a slice through space-time. The slicing corresponds to determining a path through the space dimension, whereas the time dimension is mapped along the vertical extent of the slice. The slice is used to construct (interactively or automatically) a 3D wall onto which the visualization of the data is projected. We have shown that the visual mapping of spatio-temporal data can be done by means of color-coding and parallel coordinates. The visualization is complemented with interaction techniques to navigate in 3D, to deal with occlusion and small areas, and to adjust visualization parameters.

Our novel solution avoids gaps in the visual representation, which potentially has a positive impact on interpreting the spatial dependency of the data in addition to the temporal evolution. On the other hand, the wall shows the spatial dependency only along the selected path, and so far, our implementation visualizes only one data variable. In this sense, we understand our technique as a complementary tool that has to work together with other techniques to support all aspects of exploratory analysis.

Here we presented just our initial ideas of using a wall for visualization. There are several things about this design that we have not yet explored in detail. In the future, we plan to investigate additional ways of specifying paths through space based on the underlying data. For that we have to look for data characteristics that can be exploited to define meaningful paths. Also in terms of the path geometry we plan to implement a better solution.

Given the vast body of available visualization techniques it makes sense to conduct a survey to find out which alternative visual representations can be mapped onto the wall. This survey can be structured



(a) Color-coded bricks.

(b) Parallel coordinates style.

Fig. 7. The Great Wall of Space-Time showing spatio-temporal data that consists of the number of cases of influenza per area and time-step.

along the different types of tasks that are relevant in exploratory analysis of spatio-temporal data.

Finally, we need to conduct studies to evaluate the novel concept. Although initial informal feedback about the design was positive, more detailed evaluation is needed to identify strong and weak parts of the concept. An additional aim of the studies should be to determine which visual encoding is suited given specific tasks and specific characteristics of the data.

Acknowledgments

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References

[1] J. Abello and E. R. Gansner. Short and Smooth Polygonal Paths. In *Proceedings of the Third Latin American Symposium on Theoretical Informatics (LATIN)*, volume 1380 of *Lecture Notes in Computer Science*, pages 151–162. Springer, 1998.

[2] W. Aigner, S. Miksch, H. Schumann, and C. Tominski. *Visualization of Time-Oriented Data*. Springer, 2011.

[3] G. Andrienko, N. Andrienko, U. Demšar, D. Dransch, J. Dykes, S. I. Fabrikant, M. Jern, M.-J. Kraak, H. Schumann, and C. Tominski. Space, Time and Visual Analytics. *International Journal of Geographical Information Science*, 24(10):1577–1600, 2010.

[4] A. Buja, J. A. McDonald, J. Michalak, and W. Stuetzle. Interactive Data Visualization using Focusing and Linking. In *Proceedings of the IEEE Visualization Conference (Vis)*, pages 156–163, Los Alamitos, CA, USA, 1991. IEEE Computer Society.

[5] C. Forlines and K. Wittenburg. Wakame: Sense Making of Multi-Dimensional Spatial-Temporal Data. In *Proceedings of the International Conference on Advanced Visual Interfaces (AVI)*, pages 33–40, New York, NY, USA, 2010. ACM Press.

[6] P. Gatalsky, N. Andrienko, and G. Andrienko. Interactive Analysis of Event Data Using Space-Time Cube. In *Proceedings of the International Conference Information Visualisation (IV)*, pages 145–152, Los Alamitos, CA, USA, 2004. IEEE Computer Society.

[7] T. Kapler and W. Wright. GeoTime Information Visualization. *Information Visualization*, 4(2):136–146, 2005.

[8] M.-J. Kraak. The Space-Time Cube Revisited from a Geovisualization Perspective. In *Proceedings of the 21st International Cartographic Conference (ICC)*, pages 1988–1995, Newcastle, UK, 2003. The International Cartographic Association (ICA).

[9] M.-J. Kraak and F. Ormeling. *Cartography: Visualization of Geospatial Data*. Pearson Education, Harlow, England, 2nd edition, 2003.

[10] R. Ogniewicz and O. Kübler. Hierarchic Voronoi Skeletons. *Pattern Recognition*, 28(3):343 – 359, 1995.

[11] J. Roberts. State of the Art: Coordinated Multiple Views in Exploratory Visualization. In *Proceedings of the International Conference on Coordinated and Multiple Views in Exploratory Visualization (CMV)*, pages 61–71, 2007.

[12] S. Thakur and A. J. Hanson. A 3D Visualization of Multiple Time Series on Maps. In *Proceedings of the International Conference Information Visualisation (IV)*, pages 336–343, Los Alamitos, CA, USA, 2010. IEEE Computer Society.

[13] C. Tominski, G. Fuchs, and H. Schumann. Task-Driven Color Coding. In *Proceedings of the International Conference on Information Visualisation (IV)*, pages 373–380. IEEE Computer Society, 2008.

[14] C. Tominski, P. Schulze-Wollgast, and H. Schumann. 3D Information Visualization for Time Dependent Data on Maps. In *Proceedings of the International Conference Information Visualisation (IV)*, pages 175–181. IEEE Computer Society, 2005.