Shifted Maps: Revealing spatio-temporal topologies in movement data

Heike Otten*
University of Applied Sciences Potsdam

Lennart Hildebrand†
University of Applied Sciences Potsdam

Till Nagel‡
Mannheim University of Applied Sciences

Marian Dörk§
University of Applied Sciences Potsdam

Boris Müller¶
University of Applied Sciences Potsdam

Figure 1: The Shifted Maps visualization of individual movement data with its geospatial map view (a), and the three network layouts arranged by travel distance (b), duration of travel (c), and frequency of travels between places (d).

Abstract

We present a hybrid visualization technique that integrates maps into network visualizations to reveal and analyze diverse topologies in geospatial movement data. With the rise of GPS tracking in various contexts such as smartphones and vehicles there has been a drastic increase in geospatial data being collect for personal reflection and organizational optimization. The generated movement datasets contain both geographical and temporal information, from which rich relational information can be derived. Common map visualizations perform especially well in revealing basic spatial patterns, but pay less attention to more nuanced relational properties. In contrast, network visualizations represent the specific topological structure of a dataset through the visual connections of nodes and their positioning. So far there has been relatively little research on combining these two approaches. Shifted Maps aims to bring maps and network visualizations together as equals. The visualization of places shown as circular map extracts and movements between places shown as edges, can be analyzed in different network arrangements, which reveal spatial and temporal topologies of movement data. We implemented a web-based prototype and report on challenges and opportunities about a novel network layout of places gathered during a qualitative evaluation.

Keywords: Maps, Personal Visualization, Spatio-Temporal Data.

*e-mail: hi@heikeotten.de
†e-mail:hello@lennerd.com
‡e-mail:t.nagel@hs-mannheim.de
§e-mail:doerk@fh-potsdam.de
¶e-mail:boris.mueller@fh-potsdam.de

1 Introduction

Due to the increasing amount of collected movement data through small-scale mobile devices with tracking capabilities we witness a growing need for analyzing these spatio-temporal data sets. Visualizations help to reveal patterns, trends, and relationships inside this movement data. Whereas a plethora of specialized applications analyze movement data at scale, fewer visualizations focus on the perspective of the non-expert individuum and smaller datasets. A variety of personal visualizations [25] turn individually collected data into comprehensible information for personal analytics, that support self optimization. More recently, personal visualizations aim beyond the quantified self. They start supporting self-reflection, reminscing and sharing experiences with others [41]. We therefore aim to explore a novel visualization technique, with the goal to support a reflective use of individual movement data.

Many geovisualizations excel in revealing basic spatial patterns, as well as temporal trends, but fewer aim to support understanding relational properties. On the other hand, graph visualizations displaying items as nodes, and their connections as edges reveal the network structure of a dataset, but often do not adhere to geospatial distances. We strive to design a visualization merging maps and network visualizations in a balanced way to allow exploring and understanding important places and their relations based on tracked movement.

With Shifted Maps we present a visualization of individual movement data, which enables people to discover recurring patterns in long-term mobility traces. Rather than encouraging users to optimize their daily movements, they are invited to reflect on their relationship with different environments and their use of the urban space. In order to reveal diverse relationships between places, we developed a novel visualization consisting of networks of map extracts. We designed this technique to facilitate the representation of multiple correlations through nodes, while maintaining a reference to the spatial information through maps.

Our contribution is two-fold: The identification and discussion of a design space of network maps, and a prototype with different network arrangements visualizing real-world movement data, including the explanation of our design considerations in our iterative process.

In the following, we discuss related work on movement and network visualizations (Section 2), argue for the need of an hybrid approach (Section 3), and introduce the design, functionality, and implementation of the prototype (Section 4). After we describe its deployment at an exhibition, and the setup and results of a user study (Section 5), we summarize some of the lessons learned, and discuss general considerations in the area of network maps (Section 6).

2 Background

For several years already, the visualization community has investigated the viability of visualization to support casual data analysis [33]. With the recent surge of mass tracking of personal data, people increasingly need appropriate tools that help them analyze the data that pertains to their own behavior and immediate environment [8]. One particular thread of this research is visualizing personally relevant movement data. The default view of a popular service for logging one's movement [4] is a linear visualization of places connected through a timeline that represents the temporal length of trips and stays. Visualizations of personal data that aim to represent both time and space tend to portray a linear and to some extent imbalanced relationship between these two dimensions. For example, Move-O-Scope [3] represents the movements between places as aggregated traces on a map and additionally visualizes co-visitation patterns of selected places through flow diagrams. Visits [40] in turn focuses on temporal sequences of stays as map extracts that are placed along a timeline in order to visualize the relationship between time and space along a linear travelog. Our work really resonates with these efforts to help people explore their own movement along time and space, however, we aim to expand on the non-linear relationships between places emerging over time.

Revealing complex patterns in spatial data is one of the key aims of geovisualization [18]. The most iconic geovisualization of movement data is probably Minard's map of Napoleon's campaign in Russia [34] elegantly crafted to incorporate several dimensions in addition to space, such as time and temperature. At the most basic level though, movement data consists of at least the locations and times of the beginning and end of a trajectory with some or no intermediate data points; a spatio-temporal visualization may then simply consist of different time snapshots of spatial data shown sequentially. The connection between start and finish can be both a discrete origin/destination relation or the actual path between them with the spatial and temporal resolution differing in granularity [9]. Often such datasets also contain the amounts of flow intensity, be it the number of trips of a person, the sum of passengers per connection, or the volume of goods transported [21]. For a variety of data types and tasks many visualization approaches have already been proposed over the years [9]. For example, several techniques aim to visually integrate temporal with spatial properties [10], ranging from flow maps [21] to space-time cubes [30]. Alternatively, maps can also be accompanied by juxtaposed representations of additional data aspects to mitigate some of the occlusion and other visual problems [12, 44].

Besides enhancing maps that either serve as base layers or one view among several, the map's geographic space itself can be distorted by additional data dimensions. For example, geo-referenced networks such as metro maps are often distorted to show the many stations in the city center as well as the distant stations in the outskirts. Several techniques have been proposed such as lenses to highlight several areas on a map simultaneously [26, 39]. The transition from main map to focus area can be folded into a three-dimensional form [19], or treated as a discrete boundary by arranging the focus tiles along the map's edge [28]. While the strengths of these methods lie in the accuracy of the magnified focus points, they create a distorted or discontinuous space between them. Even though the resulting changes can cause misinterpretations [13], these and many related efforts demonstrate a growing interest in relaxing the strict spatial order of maps to reveal additional relationships in tempo-spatial data.

While map-based visualizations largely maintain the overall continuity of the geospatial space, geospatial networks drastically subvert the continuity of space and turn it into a discrete structure of nodes as places linked to each other. In fact, one of the founding papers on graph theory actually addresses a geographical problem (Euler's Seven Bridges of Königsberg, 1735). Instead of encoding additional data on top of maps, here the geospatial layout is left behind, and network visualizations are used to expose the relevant structure of a dataset to reveal patterns and solve problems. The resulting visualizations can maintain the geospatial topology to varying degrees. Geometric networks help to analyze certain graph properties, or visualize specific additional, extra-spatial data [43]. For instance, the amount of traffic on a road network can be mapped to the width of the edges of a graph representation. Visualizing geo-referenced networks as node-link diagrams can furthermore help to depict flows between bordering areas as graph layouts are reducing areas to nodes opening up space for additional information [15].

There has been a plethora of research on visualizing graphs and networks [20]. The most basic and probably most used network visualization is a node-link diagram, whose nodes are typically positioned by a force-directed layout algorithm. However, instead of generating the graph layout by an algorithm that reduces overlapping edges and node collisions, the positioning of nodes can also be based on semantics, for example, user-defined classes [38] or node-based similarities [17]. Viewers' general preferences can also inform the logic of automatic graph drawing to improve the perceived aesthetics of network visualizations [29]. For particularly large and dense graphs several techniques have been introduced that aggregate nodes based on their properties [42] or bundle paths with similar routes [24]. Another method to cope with large graphs while preserving access to clusters is Nodetrix, a hybrid network visualization technique that incorporates matrices into a node-link diagram [23]. Over the years, a diversity of layouts has been proposed, however, the viewer is seldom given the opportunity to shift between different arrangements. There has also not been much experimentation with the appearance of the nodes themselves and how they can reveal more detail about the entities they represent. While visualizations of social networks may feature people's profile images as nodes [22], there is great potential to encode additional information per node as glyphs, for example, to encode a given node's temporal development [27].

3 SHIFTING MAPS

Our visualization is loosely inspired by psychogeography. Similar to the French situationists in the 1950s, Shifted Maps aims to challenge universal maps [32] and emphasize the individual environmental perception. The situationists' psychogeography encompassed both studying the city through human perception as well as developing new ways of urban cartography [36]. To focus on the experience of the urban space, Guy Debord's "The Naked City" reassembles a subjective map of Paris as collage of neigborhoods connected by arrows that visualize routes between them [16]. Shifted Maps approaches an algorithmic modelling of mental maps [31] and aims to invite individuals to reflect on the relationship with their environment. Therefore, we suggest a visualization of individual movement data that surfaces not only spatial, but temporal and relational topologies.

While there is a wide range of geovisualization techniques for spatio-temporal data, the map has remained the underlying structure assuming the spatial rights, i.e., enforcing the positioning of visual elements [14]. Temporal and other data aspects are either superimposed or juxtaposed, but rarely is the overall basis for positioning data elements challenged by extra-spatial data dimensions. In contrast to the rigidness of maps, network visualizations offer flexible means to represent diverse topological aspects of movement data with a variety of techniques for arranging and aggregating graphs. However, the appearance of network visualizations can be relatively generic and arbitrary, with the essential elements being reduced to dots and lines, which often fail to reflect the personal nature of the data. We are interested in exploring the design space between maps and networks, to develop a representation of personal mobility that helps people explore their own particular spatio-temporal footprint.

3.1 Maps vs networks

Maps and networks are at opposing ends, when it comes to their use of visual variables, the interactions they afford, and the perspectives they provide on data. In the following, we briefly examine these differences in order to open up a design space for novel visualizations of spatio-temporal data.

While places on a map are typically fixed (according to a given projection technique), the nodes in a network layout are flexibly positioned based on a layout algorithm and the different weights of edges. Before any markers or trajectories are being rendered on a map, it is typically already filled with landmarks, streets, and topographic context. While these elements provide orientation and context, they often compete with the elements of interest. In contrast, a network visualization starts out empty and can be relatively sparse containing only a few elements depending on the visualized dataset. Both representation types support distinct types of proximity: the map is largely based on topography, i.e., the physical structure of the area, while the network's proximity is topology, i.e., the diverse connections and paths through among the nodes.

The viewer faces two very distinct affordance structures with regard to the manipulation of the view. While a map primarily allows for operations with global changes (zooming and panning), typical interaction techniques applied to graphs (selecting and dragging nodes), have more local impact on particular clusters of the network. It is typically possible to change the basis for a network layout, which would result in global changes to the display, but maybe a more typical operation is to manually move individual elements to see how they are connected to one another. This operation in turn would be confusing, if it was even possible on a map.

Maps and networks offer different perspectives on a given phenomenon, by privileging different types of relationships and interactions. Arguably, the relative density and contiguity of a map suggests that the view is comprehensive and fixed. In contrast, the sparsity and flexibility of a network's topology leaves room for changes of perspective or even the underlying data. While a typical map should work for as many people as possible, networks may not make sense without knowing the specific decisions influencing the selection of entities and how they are linked. In this way, a network representation may more easily be recognized as partial or personal than a map.

It is these contrasts between absolutes and relatives, between rigidness and flexibility that form the basis for a reconsideration of how personal movement data can be visualized in a hybrid representation.

3.2 Towards map networks

We seek to develop an alternative spatio-temporal representation of movement data in order explore a plurality of data relations and perspectives. By considering the intrinsic network structures in mobility traces we develop a new type of map visualization that reveals topologies of the personally experienced environment without hiding the topography of important places. We would like to explore spatial, temporal, and relational topologies in movement data and investigate how geographical and relational information can be visualized as equals. Based on above distinctions between maps and networks, we identify the following five design goals for "map networks":

1. **Integrate topography and topology.** Map networks should incorporate geographic information of personally meaningful places into the visualization of connections among them. Topographic differences should remain discernible among the main places in the topology.

2. **Support orientation and exploration.** Familiar landmarks should be immediately visible in the visualization, while possibly unexpected relations should be revealed to encourage exploration.

3. **Explore diverse relationships.** The links among the places should be explorable based on alternative relationship types, such as spatial and temporal proximity as well as the frequency of trips between them.

4. **Shift between perspectives.** In order to compare various views on the data, it should be possible to enable shifting between map and different network arrangements in order to make use of both strengths and reveal new relationships in movement data. The visualization should also allow for zooming to explore the map network at varying levels of aggregation.

5. **Reveal details** The visualization should provide an overview of various relationships, but also reveal detailed information about individual places.

With the idea of map networks we aim to bridge the gap between maps and networks. While the strength of maps is to quickly identify places and orient oneself, networks do especially well in revealing diverse relationships between nodes. We plan to explore how the layout of spatio-temporal network visualizations can be used for other information than the geographical position, without excluding the geographical aspects. Introducing geographic information into networks raises new challenges for the design of meaningful arrangements. We aim to explore the potentials of spatio-temporal network arrangements and investigate if force-directed layouts are appropriate and if the geographic position needs to influence the network to support readability.

4 Shifted Maps

To explore the idea of map networks, we have designed Shifted Maps, a hybrid visualization technique implemented as a web-based prototype that represents personal movement data as networks of places. The visualization allows people to visualize their own movement data, with the intention to reveal prolific places and explore diverse relational patterns among them. In the following we describe the main decisions that went into the design and development of Shifted Maps and provide a scenario-based walkthrough.

4.1 Place markers

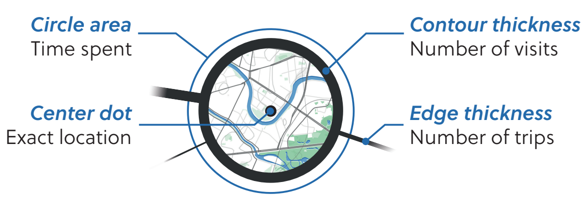

Figure 2: Illustration of marker representing one visited place, and the visual encodings of different properties.

The basic element of the visualization are place markers that represent places acting as nodes in a network spanning the movements of one person (see Fig. 2). The main idea is to focus topographic detail around the places that a person visits often, freeing up space between these markers to encode different topological aspects of spatio-temporal connectivity and experiment with alternative arrangements.

Each place marker is a map extract showing a visited place with the area of the circle corresponding to the time spent there, and the thickness of the contour indicating the number of visits to this place. Into the circle area a map is embedded that spans the vicinity of the given place(s). To aid initial orientation the visual design of the map tile features names for districts and landmarks. To further distinguish different place markers and provide sufficient topographic detail, the map cut-out features colored areas for parks, rivers and lakes as well as main roads and street names.

The circle is centered around the location of its place with a dot in the center signifying its exact position. In order to give a general impression of the surroundings, the map extract shows a small area around its respective place with a diameter of 200 meters. We experimented with various spatial spans, but settled with this distance as it reflects a typical sight line in an urban environment. Places with a long durations are shown bigger and with more map details, in order to gain visual importance and function as a reference point in the network. With this we aim to support recognizing and memorizing personally significant places.

All place markers are ordered by size in the view, resulting in bigger places shown in front of smaller ones. This guarantees their guidance function even if many places have been visited in close vicinity and overlap in the visualization. To facilitate orientation in an unfamiliar part of the place network, each place marker has a label displaying its name per hover, or its address if the name is not available in the data source. Overlapping places are clustered and merged into one circle in order to reduce visual clutter, and enhance readability. The spatial scope of map extracts embedded in the markers representing clusters are enlarged and the single dot representing an exact place is hidden. Their tooltip labels present the name of the major place while making a hint to the number of consolidated places through a supplementary text sequence. Places and clustered places are connected by straight lines, whose line thickness indicates the frequency of trips. As clusters are treated as one aggregated place, connections from multiple places within a cluster to a place outside the cluster are bundled into one connection. Connections among places inside the cluster are omitted.

4.2 Four arrangements

We have devised four distinct layouts for place networks each emphasizing a different spatio-temporal aspect in personal movement data.

Geospatial Map. To provide a general overview and orientation, a conventional map is shown in the background with the places positioned at their exact geographic locations. This view corresponds to existing visualizations that superimpose connections on top of a map. In the map view, the connection lines correspond to the beeline between the places. This arrangement aims to enhance initial orientation and to ease recognizing visited places.

However, the resulting network of places connected by trips can be arranged in alternative ways while keeping selective geographic references present through the map extracts. As illustrated in Fig. 3, we propose three different network arrangements in order to reveal and compare spatial, temporal, and relational aspects of personal movement: travel distance, travel time, and trip frequency. The positioning of the places and the length of the connections vary between these views. To facilitate a better comparability and ease gradual switching between the views, the visual encoding of the place markers and the stroke width of the connection lines remain the same throughout all arrangements. For the same reason, clusters are always based on the geographic proximity of places, even if a network arrangements is activated. The labels and units displayed along the connections indicate the current arrangement.

Travel distance. The first relational view is similar to the conventional map, however, as the network is arranged according to the distance traveled between the visited places (see Fig. 3a). In contrast to the beeline (which is the basis for the edges in the map view), these distances may be longer, as most means of transport do not follow a direct line. If a route has been traveled several times the average distance is used to determine the length of a connection.

Travel time. The second arrangement is defined by the duration of trips between the places (see Fig. 3b). Especially when the connection is traveled by public transport or foot, the time it takes to get from one place to another tends to be more decisive than the geographic distance. Therefore places with a larger travel distance are positioned further apart, while places with a faster connection move closer together. For example, a connection with a short distance, but a long travel duration, might have been taken by foot, with a relatively slow mode of transport, or was accompanied by traffic jams.

Trip frequency. The number of trips among places defines the arrangement in the third layout (see Fig. 3c). Places linked by more frequent connections move closer to each other, while places with less frequent connections move further apart. As a result, seldom visited places tend to move to the edges, while often visited places

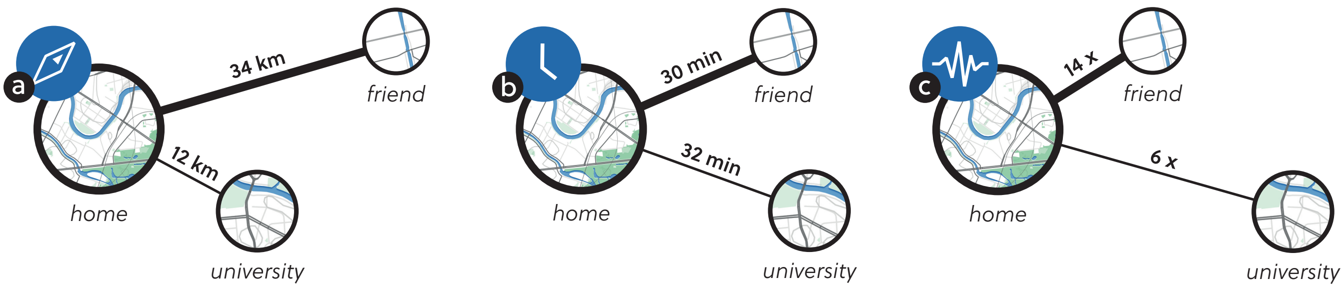

Figure 3: Three arrangements of personal places represent different aspects of relationships among places according to (a) travel distance, (b) average travel time, and (c) frequency of trips—each resulting in different proximities and thus layouts.

congregate in one or more centers. Especially this arrangement might give clues about personally relevant relationships between the places despite their distances and travel times.

While the map provides a precise representation of geospatial distance, the network arrangements are only 'informed' by the different types of edge weights. This has the effect that the ratios between different edge lengths are not always exact, but that the layouts offer different kinds of spatio-temporal groupings.

4.3 Interacting with Shifted Maps

The design of the interaction techniques follow Shneiderman's classic information-seeking mantra "Overview first, zoom and filter, then details on demand" [37].

To give an overview the prototype starts with the map arrangement, which is most familiar to the user and enables an understanding of the spatial context. Zooming and panning allows investigating the geographic space and selecting areas of interest. As these interaction mechanism are used in online maps and mobile map applications people are already accustomed to them [35]. We deploy these interactions not only in the map arrangement but also in the network arrangements, in order to maintain continuity and comparability between the four views.

A small timeline in the top left panel shows the overall time span of the data set. Additionally, it enables temporal filtering, as it acts as a time-range slider, making it possible to compare shorter spans, or follow the growth of the network over time.

The top left panel furthermore contains three buttons to switch through the different arrangements, each showing a simple icon symbolizing its network layout. After selecting one of the three network arrangements, zooming and panning allows visual adaptation of the network. Zooming in not only increases the level of detail inside the map extracts, but also disaggregates clusters to show more individual places and connections (see Fig. 4). In this way, zooming increases the granularity of the network. Panning permits a free exploration of the network in all zoom levels.

The circles allow two levels of interaction to give more detailed information about a visited place: Hovering over a circle reveals its label and also brings the respective circle to the foreground. A more detailed place view containing geographic, temporal and relational information is triggered through clicking on a circle. The place circle is shown at the highest zoom level presenting the direct environment of a place, in order to enable an examination of the spatial surrounding, as visible when visiting the respective place (Fig. 5). To provide detailed temporal information rings around the place circle reveal the exact duration of stay for four selected days. Additionally, for individual days connection details, e.g. which other places have been visited before and after the focused place, are shown.

4.4 Implementation

We implemented Shifted Maps as a JavaScript-based application[1] that is publicly available on the web[2].

The movement data is collected via the Moves [4] smartphone application for iPhone and Android, which tracks movement via GPS, acceleration, and vibration sensors[3]. It automatically distinguishes between places and the movement between these places and enables the user to add names to visited locations by using the Facebook Location API or by manually entering them. Via the Moves API, we are able to request detailed summaries of user's

[1]The code is licensed under GNU General Public License and can be accessed at `https://github.com/anonymized/shifted-maps`.

[2]`http://www.shifted-maps.com`

[3]Moves is defunct since August 2018. We are currently investigating movement tracking apps with a comparable feature set.

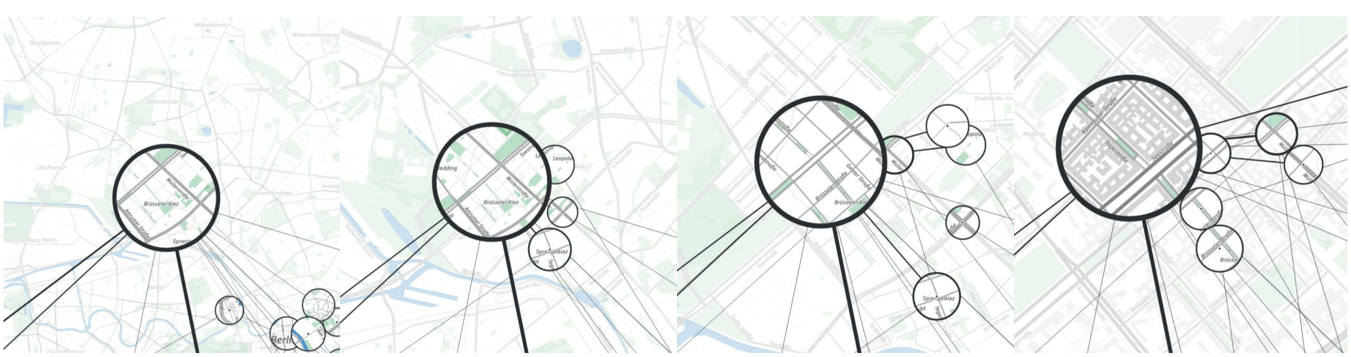

Figure 4: A place cluster dissolves when zooming in, with more and more individual places appearing (from left to right). Clusters are calculated based on the proximity of places in the map arrangement, but stay the same in the network arrangements.

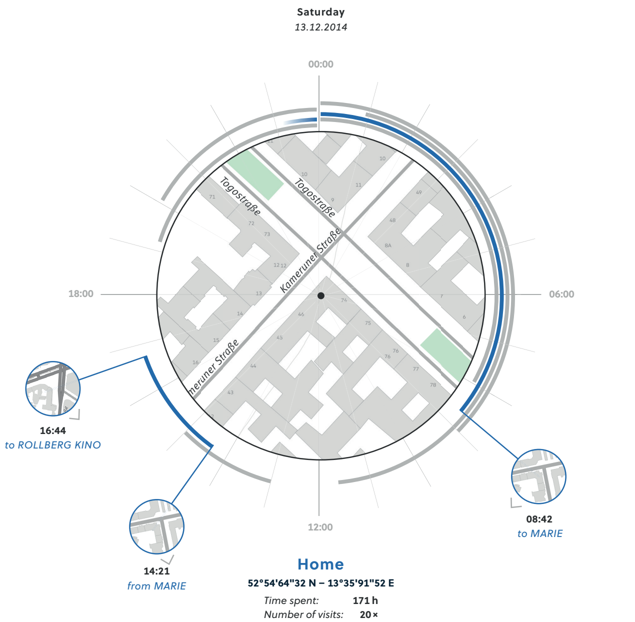

Figure 5: When clicking on a circle, a more detailed place view is revelead, giving more information about duration of stays and connections to other places.

daily movements. The API also features a dedicated page for authorizing our visualization prototype, which let users grant access to their movement data by using the smartphone app as an auth key generator. Our application can be used with both the visitor's own as well as an anonymized demo dataset. This way the visualization can be tried out even by users who do not have a Moves-based dataset.

The map extracts and background map are requested from the tiles provider Mapbox [2], which enables us to customize and optimize the map layout for the use case of our visualization, especially the integration of small map extracts. The maps are integrated via the Leaflet library [1], which provides established interaction techniques to manipulate the view of the map. Places, which are not labelled by the user in the Moves app, are reverse-geocoded with the Mapbox geocoding API.

For connecting to the Moves API we use a Node.js [5] based server-side application, which transforms and filters the movement data and passes a transformed movement stream to the front end. To be able to add new features during the design process easily and to get better modularity and maintenance, we decided to build the client-side application with React [6] and redux [7], while d3 [11] is mainly used for its scale and force-directed graph algorithms.

Creating an interactive application for the web adds the advantage to make prototypes accessible to a great number of users. On the other hand the application must be able to display very heterogenous datasets, as these can vary in both data size and spatial area. These needs become particularly apparent in the implementation of the force-directed graph and place clusters. To control the network edge lengths when calculating the graph layout, we use linear scales provided by d3. These scales have an input and output range and are able to map values from one range to another. The input range is filled with the minimum and maximum travel distance, duration and frequency, depending on the selected arrangement, while the output range uses the minimum and maximum edge lengths from the initial map arrangement. This way we are able to map travel properties to their corresponding edge lengths, without risking the comparability when switching between the four arrangements. As many people tend to have many connections with small frequencies, we try to prevent large diversions of the places by simply minimizing the maximum edge length when the frequency arrangement is active. We removed this modification of the maxium edge length, as we realized, that the three network arrangements would have been more difficult to compare. After the evaluation (see Section 5), we added a subtle force to every node towards their origin. This way, we ease the orientation for the users as places are not moved too far away from their original position on the map (Fig. 7). Place clusters are created by comparing all places ordered by the time the person spends there and calculating the beeline distances between them. If places overlap by at least 40 percent of their area, they are grouped into clusters. This threshold was defined with the aim to reduce visual clutter yet keep as many distinct places as possible. To reduce the number of calculations places that are already clustered are not compared to other places again. The clusters are recomputed when the user changes the time span filter or zooms into or out of the visualization, but stay the same when the user navigates through the different arrangements.

4.5 Walk-through

In the following, we illustrate the functionality of Shifted Maps by describing a walk-through of a persona. Anna is 27 years old, lives in Berlin, and studies in Potsdam. She likes to track her personal movements using her mobile phone. From time to time she examines her data using visualizations like Shifted Maps, in order to get insights into her movement patterns.

Fig. 6 shows Anna's movement data of about three months and 100 visited places. Anna starts exploring her movement network in the map arrangement (see Fig. 1b and 6a). The visualization highlights several places in the Berlin area, as well as the connections between them. The main places Anna has visited are her home and her friend Paul's place in Berlin, as well as her university in Potsdam. Consequently the most frequent connections also lie between these places, though some routes show stopovers at the train stations in Berlin and Potsdam. Anna has also visited a number of

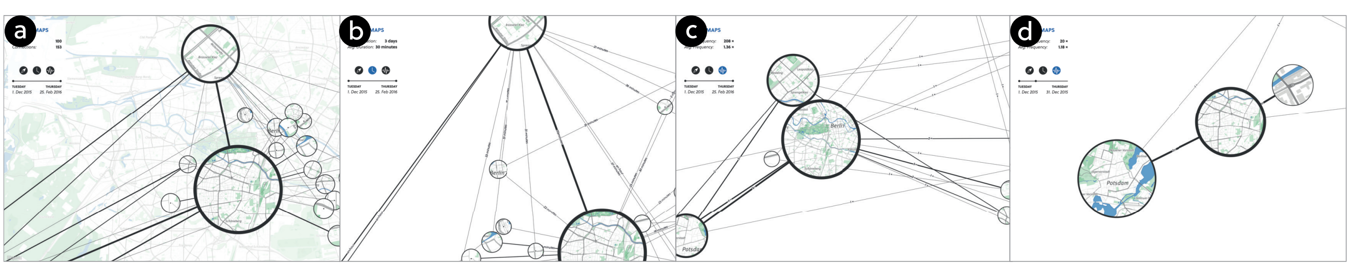

Figure 6: Walk-through of Anna: First she explores her movement data in the map arrangement (a). She then switches to travel time arrangement and zooms in a bit (b), and finally explores her visited places in the travel frequency arrangement (c). After she selects a single month on the time slider, the data is filtered and only places she visited in that time span are shown (d).

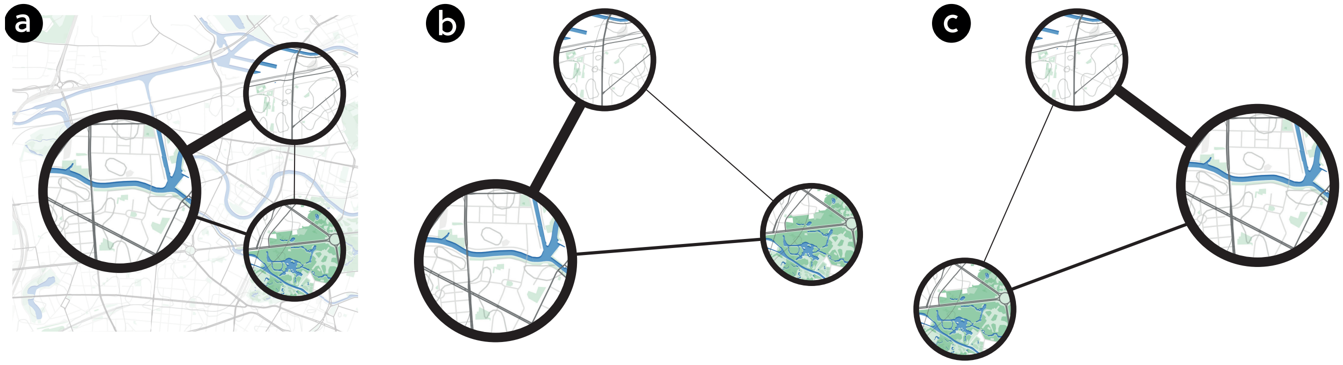

Figure 7: The geographic position of places (a) influences the algorithm of the network arrangement (b) to enhance readability. (c) shows network without geographic force.

places in the east of Berlin, where she spent significantly less time.

To analyze the relationships between the places she visited, Anna compares her movement network in the different arrangements. The travel distance arrangement (Fig. 1b) reveals only minor changes in the network. However, Anna can observe that her home and Paul's place diverge from each other as her bus makes a big detour between these places and the traveled distance is consequently longer. She compares this layout to the travel time arrangement (Fig. 6b), which emphasizes the temporal distance between the places. In this arrangement the university and her home move closer, resulting from the fast train connection, while Paul's place is pushed away, due to the slower travel speed. Similarly, other visited places in the east of Berlin move further away, as the temporal distance in Anna's movement data is relatively longer than the geographical distance, as she often cycles within Berlin. Finally, Anna explores her data in the travel-frequency arrangement (Fig. 6c), where the visualization emphasizes the frequent connections between her home, the university, and Paul's place by moving them closer to each other. In parallel seldom visited places diverge.

Through the time slider, Anna can now focus on a shorter time span (Fig. 6d). She remembered, that she spent less time at Paul's place in this month. As a result the circle of Paul's place gets smaller, while other places, like a school in Berlin, become relatively larger. As the connection between university, home and the school is now relatively more frequent, this also influences the layout of the frequency arrangement by moving these places closer to each other.

5 Evaluation

To investigate the potential of map networks for analyzing personal movement data, we carried out evaluations of the Shifted Maps visualization in three different stages: During an initial, formative study we tested the general comprehensibility of our concept and the interaction techniques. Second, we gathered feedback in the context of a week-long exhibition, where we were able to address a broader audience. And third, we conducted a qualitative user study to better understand the perception of map networks.

Each evaluation step informed the subsequent design and refinement of the visualization. In the following we will describe the settings, our observations and the feedback we received from people, and discuss some of the insights people had.

5.1 Formative study and exhibition feedback

As our visualization suggested a novel abstract combination of map and network, it was important to us to get feedback at an early stage, in order to identify challenges and opportunities and target them throughout the design process.

First, we evaluated an early interactive prototype during a formative study with three participants (aged 24-27, one female, two male) each with their own movement dataset of about two weeks. The participants were asked to visually explore their own data using the provided visualization. During this study, we observed that the users understood the general concept of the visualization and its interaction techniques. However, dissolving clusters and the frequency arrangement caused problems of comprehension, which might have been due to inaccuracies in the graph layout algorithm. As a result we implemented a force-directed algorithm (as described in Section 4.4) to improve the layout.

Second, we gathered feedback during a week-long exhibition about visualizations of various urban datasets, which gave us the possibility to accumulate thoughts and impressions on the prototype in a casual atmosphere and with a broad audience from visualization novices to experts. The exhibition was open to the public and attracted 150 visitors to the gallery space; about 30-50 persons were visiting the exhibition per day during the subsequent week. The authors of the project were present, explained the visualization, and answered questions about its concept and functionality. Generally, visitors enjoyed exploring the visualization and started interpreting the sample dataset, like making assumptions on the person's frequent movement between university and home, as well as seldom visited places, like bars. Several visitors also loaded their own movement data into the visualization and explained their movements to other visitors, which lead to more engagement with the prototype. During this exhibition we also noticed that the transition between the map and the network arrangements initially confused some of the visitors, though the general concept was understood after some explanations and further interactions with the prototype. Visitors typically watched others interacting with the visualization before trying it out themselves. This as well as chatting with other people in the social space of an exhibition might have helped understanding parts of the network views. After the feedback from the formative study, we removed the clustering for prototype shown at the exhibition and all circles were shown at any time. In lower zoom levels places overlapped in the map arrangement, but became visible when switching to the network arrangement due to the forces in the layout algorithm. This sudden appearance of places confused several users. To address these findings we developed the current cluster method, which is based on the map arrangement and stays the same in the network arrangements. This method was in place for the qualitative user study.

5.2 Qualitative user study

After we have addressed a few minor problems and refined the visualization, we carried out a user study to gain a deeper understanding of how people would use the visualization and what patterns they would recognize. Since we introduced map extracts in networks, we were especially interested in gaining a deeper understanding about their effect on the understanding of a movement network. Additionally, the qualitative user study enabled us to observe more deeply the functionality of zooming and panning interactions applied to networks.

5.2.1 Set-up

This study consisted of three parts: a pre-study interview, a set of tasks and questions to be carried out with the prototype, and a post-study interview. The utilized prototype contained all functionalities except the detailed place view. The visualization was available both with a demo dataset as well as the participants' own movement dataset. The sample dataset consisted of a single person's anonymized movement data. As it was crucial to us to compare the perception of an unfamiliar dataset with a personal dataset, we also showed each participant their own personal movement data. The order of the two datasets were randomized. The moderators were part of the research team, audio recordings were taken during the interviews and usage of the visualization, and video recordings were captured of the screen as well.

5.2.2 Participants

The study was carried out with nine participants (aged 20-59, three female, six male). Six of the participants were recruited from the design department of our university, two were students from other fields, and one was employed in a non-related field. A short interview was conducted before the study to assess the participants' experience with map services and personal tracking. All participants previously tracked their movements using the Moves app. The participants can be categorized in two groups: one group (three participants) tracked their movements exclusively for the study for one to two weeks and normally do not use tracking apps; the other group (six participants) already tracked their movements before (ranging from two months up to two years), with many additionally using other tracking services like fitness apps.

5.2.3 Tasks and procedure

The test was carried out at a desktop computer in separated conference rooms of the research lab and an office, and a brief explanation of the context of the study was given. During the pre-study interview, participants were asked about their background, the usage of tracking and map services, as well as to self-assess their ability to read maps. Throughout the whole study the participants were asked to think aloud, aiming to gather insights on impressions and expectations about the prototype.

For the main part of the study participants were asked to only describe the visualization in order to check the general understanding of the visual elements and the user interface. Afterwards they were able to freely explore the prototype and the interactions, accompanied by several questions about expectations and comprehension, like "Which interactions do you expect?" or "How do you orient yourself within the visualization?" Half of the participants started with their own dataset, the other half with the sample dataset. After exploring the first dataset all remaining questions by the participants were answered and undiscovered functions were explained. Next, participants were asked to explore and describe the remaining dataset; here we paid particular attention on how participants oriented themselves.

After the tasks were completed we conducted a follow-up interview in which we inquired insights gathered by the participants while exploring the data. We requested their opinions on the prototype and suggestions for improvement. An average session lasted about 50 minutes including pre- and post study interview.

5.2.4 Observations

The main visual elements, round map extracts and lines between them were identified as visited places and traveled routes by all participants. Only one participant initially had problems understanding the meaning of the lines. Participants interpreted the size of the circles as the places' importance (2 participants), frequency of visits (3 participants), or time spent there (4 participants). Most participants (6 participants) did not recognize any meaning in the contour of the circles. In most cases, participants first recognized their home as the biggest circle. After exploring several places with a longer duration of stay, they started exploring connections within these, then discovered smaller, seldom visited places and how they are connected.

The network can be explored in different arrangements. However, some of the users did not expect this interaction, as they at first did not notice the user interface elements to switch, or struggled understanding the icons for the three different arrangements. The new network layout was initially confusing for some of the participants. Though after comparing the different network arrangements, participants noticed that places are no longer located at their geographic position but placed according to their relationships based on travel distance, time, or frequency. After discovering the different arrangements most of the participants switched from one arrangement to another, observed changes in the network, and compared the position of single places. Through the comparison some participants' attention was attracted by smaller, so far unnoticed places, which enabled discoveries such as interesting locations that might be worthwhile to be visited more often. One participant (P8) also suggested to further support the comparison of single places by highlighting or fixing them. The different scope of the participants' datasets and their radius of movement caused greatly varying networks. In some cases the network algorithm caused overlapping circles in the network arrangement, which irritated the participants and negatively affected their understanding of the arrangement. When one of the network arrangements was activated, several participants were unsure how to get back to the default map arrangement. The time slider was understood by most of the participants but rarely used when exploring the visualization.

Generally, participants expected to apply typical map interactions like panning and zooming to navigate with the visualization and used these techniques without problems. As the prototype did not provide the common plus and minus buttons for zooming in and out, these were missed by the participants. Most participants also anticipated to interact with the map extracts and revealed that clicking on them caused further zooming in and dissolving clusters. The prototype used during this user test did not contain the detail view. However, participants stated that they would have expected to get more information about a place. "I would now like to know when exactly I was here, the time and the date would be nice." (P9) Similarly, some participants wished for more information about the connections after clicking on them. Participants suggested "displaying information about the places which are connected by a line" (P1) or even "getting to a connected place, when clicking on one of the lines" (P4).

When comparing the participants' thoughts and impressions on their own dataset and the sample dataset, we observed that the description of the sample data was considerably more abstract. Two of the participants struggled with imprecise personal data from the Moves app, which also affected their general trust in the visualization. In order to make sense of the sample datasets, participants tended to hover over the places in order to read the labels. In contrast, when exploring their own movements, they used the map extracts, particularly in bigger circles, to reassign places in their own data. While most participants developed questions about their own data, they seemed to explore the sample data more aimlessly.

When asked about ways of orienting in the map, the majority of participants stated that bigger places are identified through the map extracts. Street and district names as well as parks and lakes supported the recognition of the places. As the extracts for smaller places were significantly less expressive, participants used the labels to identify them. Five out of nine participants declared that the visualization would not work without the map extracts. However, even participants which did not orient themselves primarily through the map extracts, but through the labels, described that the map extracts helped them reassigning places.

All participants were asked to rate their trust in the visualization on a scale from one to five. In average the participants rated the visualization 4.1, though it can be observed that participants with imprecise personal movement data rated the visualization lower. During the post-study interview participants explained their thoughts and impressions on the visualization. Most participants enjoyed exploring their movement data, including those participants who tracked their movement data primarily for the user study. Half of the participants stated that they would like to use the visualization on a regular basis. Those participants were especially interested in observing their movements in longer time intervals ranging from once per month to once per year in order have a significant amount of movement data and rediscover places they already forgot. Several participants also mentioned that they enjoyed the simple aesthetics of the visualization. While some participants wished there was more information about the places and the connections between them, participants generally appreciated the visualization.

6 Discussion

Regarding our concept of networks in maps, our goal was to put geographical and relational information on an equal footing and design a visualization that makes these information equally accessible. Generally the feedback from our studies suggests that our prototype offered an accessible approach of combining maps and networks. However, the verbal feedback during the studies revealed specific issues of the prototype as well as more general challenges and potentials for the combination of maps and networks. In the following we will discuss these briefly.

Visualizing individual movement data. Throughout the evaluation of Shifted Maps, we observed that the engagement with the visualization was much higher when users explored their own data. Users quickly discoverd important places and seem to use them for orientation, while their attention shifted towards smaller places. These observations might indicate that a familar datasets, like personal data, serve particularly well to explore new visualization techniques. More than discovering unknown overall patterns in their own data, users rediscovered places they visited less often. Plus, they seemed to seek confirmation for known movement behaviours and showed them to others. While the novelity of the visualization technique seemed to encourage users to try out the application, start a conversation, and discuss the results during an exhibition, the visualization might still profit from an improved sharing functionality to enable sharing memories in a non face-to-face situation.

Introducing a new technique. Since the combination of maps and networks is a rather novel type of visualization for most people, the level of abstraction from the initial map arrangement to the network arrangement was high. As a result, some participants initially struggled with understanding the new placement of map extracts but understood the general concept after further exploration. Nevertheless, this observation indicates the necessity of a carefully phrased and designed introduction when a new and abstract visualization concept is implemented. Elements of storytelling as well as a legend on how to read the visualization might offer better guidance and enable a quick start into exploration. To improve this kind of introduction to map networks, we designed an explanatory video which automatically starts when people visit the web-based prototype. Furthermore, we observed that animations and slow transitions between different network arrangements and zoom levels enabled the participants to follow the action, which made it easier to rediscover places.

A geospatial ordering. Once the participants explored the network arrangements, some of them were confused by the layout of the places. Due to a missing geographical influence in the graph layout algorithm of the tested prototype, it was possible that the position of a place varies greatly from its initial position on the map. Especially when a general geospatial order of significant places was disrupted—place A is below B, even though A is North of B—the alternative arrangements would be challenging. Thus, we implemented an additional force pulling the place markers towards their original location in order to ease spatial understandability, and to allow people to focus more on the relationships between places (Fig. 7).

Place clustering. Throughout the design process, we iteratively tested clustering as a way to enhance the readability, especially of more complex networks. In the first prototype, clusters were calculated based on node proximity in the network, which caused the groups to re-cluster in the different network arrangements. As a result, places were hard to keep an eye on as they might have been part of a new cluster. Thus, in the second version of the prototype we decided to leave out the clustering and show individual place circles in all arrangements. However, the large amount of circles caused visual clutter and also negatively affected comparability of several places' relationship in the different arrangements. Finally, we implemented a clustering algorithm based on geographic positions in such a way that clusters stay the same throughout the different network arrangements but gradually dissolve when zooming in. We observed during the user study that participants subsequently had fewer problems re-finding places. This leads us to believe that it is important to cluster places in order to reduce visual clutter. However, when switching between different arrangements the clustering basis should be maintained to ensure a certain level of continuity.

7 Conclusion

As more people collect individual movement data, there is an increasing demand for adequate tools to analyze spatio-temporal data. Existing geovisualizations already reveal spatial patterns and temporal trends, however, these efforts could be taken further by analyzing relationships, as often visualized through networks.

In this paper, we introduced the concept of map networks: the integration of map extracts into networks in order represent correlations through nodes. We realized this concept in the Shifted Maps visualization, which supports the analysis of spatial, temporal, and relational topologies in personal movement data. The visualization fosters the comparison of different relationships between places in a network on a map and three extra-spatial network arrangements. It reveals more detailed information through interactions like zooming and panning as well as temporal filtering.

Results from our iterative evaluation suggests that map extracts provide a visual guidance, which supports the identification of places in different arrangements. They also enhance the perception of unknown datasets, as the map extracts give additional information about the places and might reflect known urban structures.

As expected for a visualization designed for personal movement data, participants in our study had a much higher interest in investing time and effort to understand a novel technique if the visualized data was their own. An interesting future direction might be to investigate whether this holds true when the data is about different movements yet still of a topic a person has an interest in (e.g., visited places of a famous person such as Goethe's Italian Journey or Darwin's Voyage of the Beagle). How does personal interest or relevance influence the analysis of spatio-temporal data?

With our discussion of challenges and potentials of combining maps with networks we laid a foundation for a design space of network maps. The design and implementation of Shifted Maps and our lessons learned contribute to a better understanding of that area. While the visitors as well as the study participants had a diverse set of ideas and issues in regard to the visualization, we see our prototype as a good demonstration of a functional map network. One of our major contribution lies in the two important lessons we learned on the path towards a hybrid visualization: The importance of some geographical factor influencing the network layouts, as well as a geo-spatial based clustering in the network arrangements.

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