Spot-Tracking Lens: A Zoomable User Interface for Animated Bubble Charts

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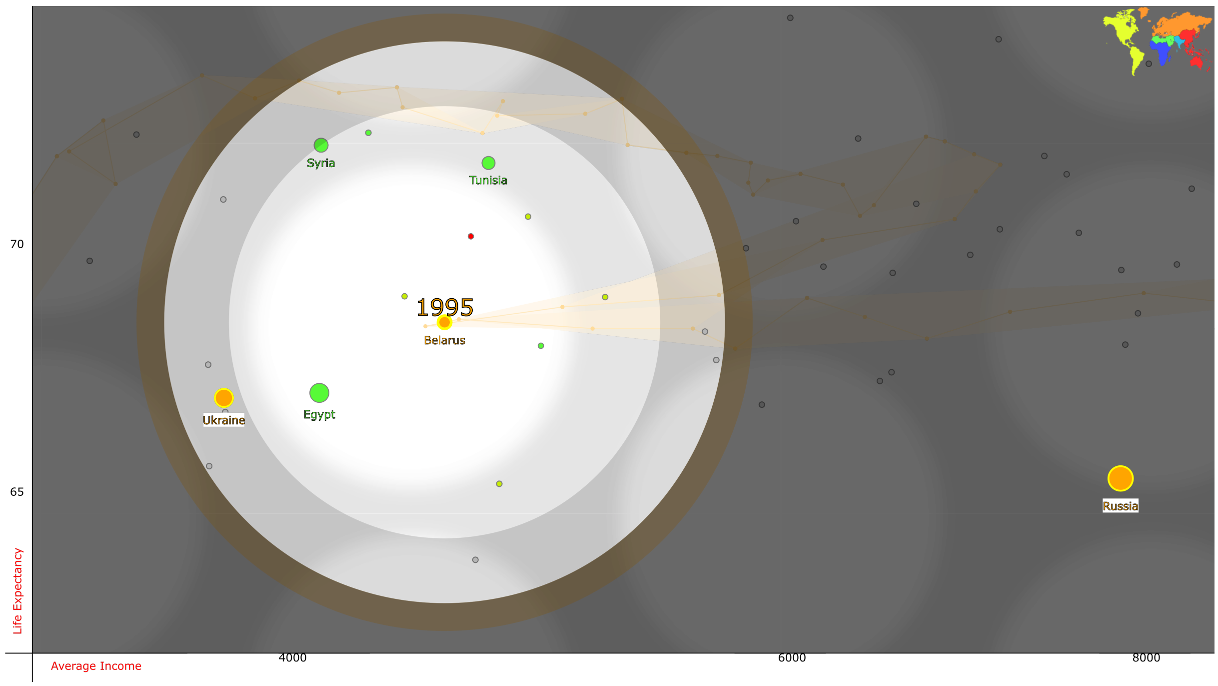

Figure 1: A screenshot of the spot-tracking lens. The lens is following Belarus in the year 1995. Egypt, Syria, and Tunisia are automatically labeled since they move faster than Belarus. Ukraine and Russia are tracked. They are visible even when they go out of the spotlight. The color coding of countries is the same as in Gapminder[1], in which countries from the same geographic region share the same color. The world map on the top right corner provides a legend of the colors.

Abstract

Zoomable user interfaces are widely used in static visualizations and have many benefits. However, they are not well supported in animated visualizations due to problems such as change blindness and information overload. We propose the spot-tracking lens, a new zoomable user interface for animated bubble charts, to tackle these problems. It couples zooming with automatic panning and provides a rich set of auxiliary techniques to enhance its effectiveness. Our preliminary user studies suggested that, besides allowing users to examine detail information, it can be an engaging approach to exploratory analysis for dynamic data.

Keywords: Animation; Zooming; Panning; Highlighting; Bubble Chart; Labeling

1 Introduction

Zoomable user interfaces [6, 7, 23] are widely used in information visualization systems. They allow users to magnify the view and thus see more details. Zooming brings many benefits to visualization: it allows users to examine the context of an interesting object by zooming in the area where the object resides; labels overcrowded in the original view can be displayed without overlaps after zooming in; it allows users to focus on a local area and thus reduce their cognitive load.

In spite of these benefits, zooming is not as well supported in animated visualizations as it is in static visualizations due to several challenges. First, objects are typically moving rather than staying still during an animation. Therefore, zooming has to be tightly coupled with panning for users to track objects of interest. Manual panning requires a lot of user effort to intensively follow moving objects, while automatic panning may cause difficulties for users to perceive the absolute speeds of objects in the view when the camera is moving unpredictably. In addition, users may lose their orientation with a frequently moving camera. Therefore, techniques helping users sense the speeds of objects while maintaining orientation need to be developed, which is critical to facilitate zooming coupled with automatic panning. Second, even after zooming in, multiple objects moving in varying speeds in the view can still cause huge cognitive loads on users. Users are prevented from effectively gaining insights from the data due to the change blindness problem [22]. Therefore, new interaction techniques based on the dynamic features of animation need to be developed to reduce change blindness so that users can enjoy the full benefits of zooming in an animated

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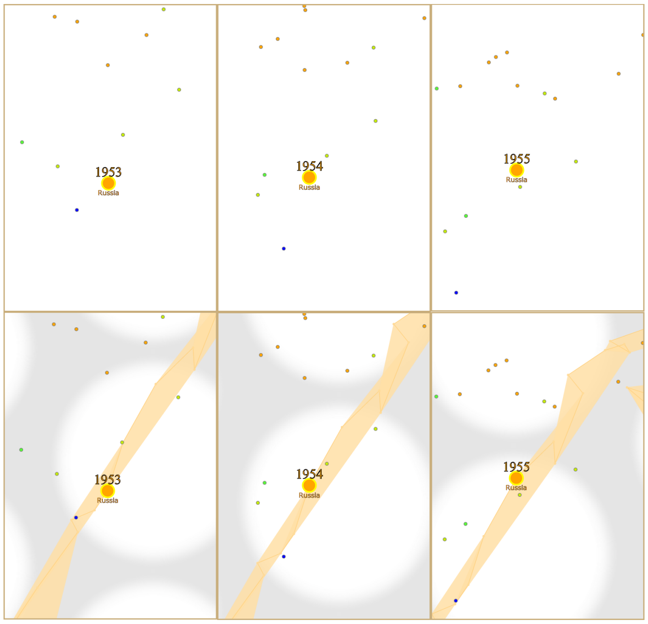


Figure 2: The frame of reference. Top row: screenshots of an animation showing a focal object moving from 1953 to 1955. No reference frame is used. Bottom row: screenshots of the same animation with a reference frame. It is easier to sense the movement of the focal object in the bottom view.

visualization.

Toward this goal, we present the spot-tracking lens (see Figure 1), a new zoomable user interface implemented on animated bubble charts. It is designed to effectively conduct the following tasks: (1) to zoom in and track a moving focal object with automatic panning. No manual panning is needed; (2) to sense the speeds and directions of the objects in the global data space from the zoomed view during the animation; (3) to capture significant dynamic events related to the moving objects in the immediate context of the focal object; and (4) to examine and follow up on the varying relationship between the focal object and its neighbors. The tasks are addressed through the following techniques:

- To support task 1, we design a moving and tracking lens providing an ego-centric view following a focal object. It couples zooming with two distinct automatic panning techniques. The stepwise panning simulates a user manually panning the view to track the focal object; and the continuous panning smoothly follows the focal object, mimicking a long shot in movies.
- To support task 2, we use a frame of reference which enhances the perception of the speeds and directions of moving objects in the zoomed view. A frame of reference generation technique has been proposed (Figure 2).
- To support task 3, we propose several task-oriented automatic labeling techniques. The labeled objects can direct user attention to significant events in the focal area during an animation.
- To support task 4, we add a novel spotlight to the tracking lens. It greatly augments users' capabilities to track a moving focal object and examine its immediate context. With the spotlight, users can keep their attention focused on the immediate context of the focal object, while perceptually sensing a set of objects of interest outside the immediate context (Figures 1 and 3).
- Furthermore, we propose to use scrolling to interactively control an animated bubble chart. It allows users to seamlessly switch among automatic playing, stepwise animation, slow forward/backward, and pausing, so as to improve the efficiency of analysis with animated bubble charts.

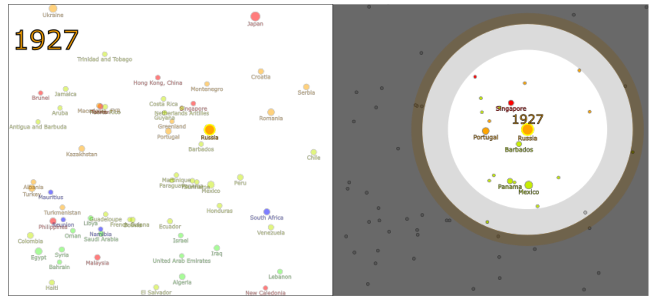


Figure 3: The spotlight. Left: A screenshot of an animation. Non-focal objects and their labels are semi-transparent. Right: The same animation with the spotlight turned on. Automatic labeling is turned on for highlighting fast moving objects near the focal object.

Preliminary user studies have been conducted to evaluate the effectiveness of the spot-tracking lens. The studies showed that the interface can effectively conduct the aforementioned target tasks. Moreover, we noticed an unpredicted benefit of the lens: since it allows users to pleasantly follow a focal object and observe significant events happing around it, the new tool greatly promotes ego-centric visual exploration, where users gain many interrelated, detail-rich insights around a focal object. Such long chains of insights are beneficial for sense making and reasoning. Therefore, this spot-tracking lens lends itself a potentially useful tool to promote exploratory visual analytics of dynamic data.

2 Related Work

Animated visualization is an important approach to analyzing temporal data since human vision is sensitive to changes and movements. Hans Rosling presented the animated bubble chart in his TED 2006 talk [26], where each bubble represented a country and its *x* position, *y* position, size, and color represented attributes of the country. The bubbles were animated to reveal changes in attributes over time. Rosling's talk invoked a lot of interest in animated visualization. Later, InfoCanvas [20] used moving entities to encode time series data. StreamIT [2] used animation to illustrate the impact of newly arrived objects to the clustering structure of existing objects in streaming data. Visual Sedimentation [14] presented animated displays that imitated real-world sedimentation processes to represent data streams. GraphDiaries [4] used staged animations and complementary small multiples to help users understand changes between individual time stamps in dynamic networks.

However, recent studies reported that although animated visualization is enjoyable and exciting [9, 25, 28], it can be problematic in supporting analysis tasks. For example, Robertson et al. [25] presented a user study comparing the animated bubble chart, small multiples, and traces for presenting and analyzing temporal data. The results showed that the animated bubble chart was the least effective in analysis. There are several reasons for this phenomenon. First, a large number of moving objects clutter the screen and tracking them at the same time is beyond the cognitive capabilities of ordinary users. Robertson et al. pointed out that users can be confused by having too many data objects moving in the display in their user study [25]. Farrugia and Quigley also addressed that, when conducting analysis in animation, users can easily get lost when too many data objects are moving on the screen [9]. Second, the complex manner of movement in animation may lead to change blindness [12], where users miss important temporal patterns [22, 30]. Change blindness can seriously harm the effectiveness of visual exploration in animated visualizations.

Clearly, a Zoomable User Interface (ZUI) can be a solution to the first problem by allowing users to focus on a smaller set of moving objects in a less cluttered display. There exist many examples of

ZUIs. Cockburn et al. [7] presented a survey which discussed design issues of ZUIs and summarized existing zooming applications, toolkits, and models, among other categories of interfaces supporting both focused and contextual views. Pad++ [6] was a toolkit that allows users to control where they look on a vast data surface by panning and zooming. Pocket PhotoMesa [18] used a ZUI to allow users to explore large image collections on small devices. PolyZoom [17] is a recent ZUI for multiscale and multifocus exploration in 2D visual spaces.

Zooming is often coupled with panning through automatic algorithms. For example, Jark van Wijk et al. [29] discussed how to support smooth animations from one view to another by automatically coupling panning and zooming. The speed-dependent automatic zooming [15] automatically changed the zoom level according to the panning speed. The spacetree application [24] automatically panned a view when users selected a different focal node in a tree visualization. Our approach uses automatic panning to track a moving focal object in a zoomed view, which is a scenario different from the existing examples. In existing approaches to visualizing moving objects, researchers have noticed that objects of interest may run out of the zoomed view and called it the "off-view" problem. Existing solutions, such as Canyon [16] and Halo [5], have been focused on providing location awareness of interesting objects off the view without panning the view. By panning the view following a moving focal object, our approach provides an "object-centric" solution rather than the existing "location-centric" solution, which distinguishes our approach from existing approaches.

Many suggestions have been given in the literature on how to reduce change blindness in animations. Examples include ensuring that time intervals between different scenes are long enough, limiting the number of changes through filtering and other interactions, and keeping users oriented with additional visual indicators [27]. Many of these ideas have been used in our design. In particular, our approach allows users to flexibly control the animation speed, automatically labels the most important objects while suppressing the visual representations of the other objects, provides a spotlight to guide users to follow a focal object and its immediate context, and uses a reference frame to keep users oriented.

In most animation systems, analysts control the animation by widgets such as buttons and time sliders. Since these widgets are usually far away from the focal area, interacting with them interrupts users from watching the focal area. Archambault et al. [3] found in a user study that subjects rarely used the play controls, even though using them could reduce the analysis time. In addition, it is difficult to display a time slider that is long enough for precise speed control. Kondo and Collins [19] attached a timeline to the trajectory of a focal object, making play control more tangible. However, this technique only applies to touch screens. We propose a different approach to control animation with scrolling. Scrolling techniques have been used in story telling websites to control the slides playing speed [11]. Our approach is among the first efforts to control animated data visualizations using scrolling.

3 The Spot-Tracking Lens

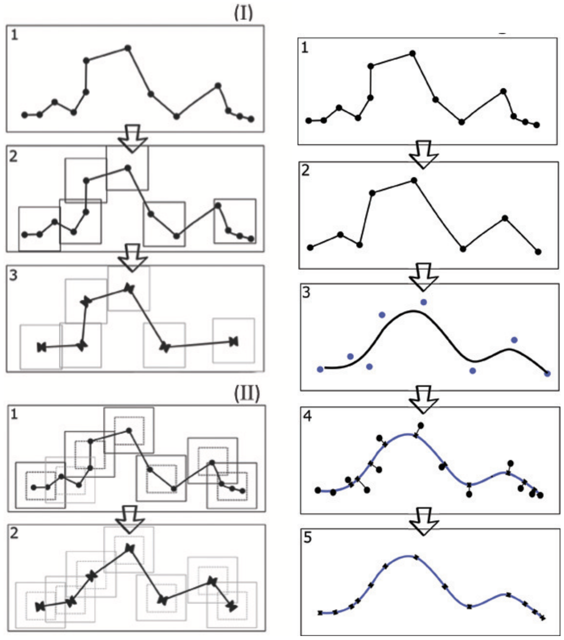
The spot-tracking lens works as follows: (1) Activation: After users select a focal object from the overview animation (the animated bubble chart without zooming), they can use the + key to zoom in. The animation is paused and a frame of reference and a spotlight is added to the visualization. (2) Analysis: The users either set an automatic play mode or use scrolling to resume the animation. During the animation, the camera roughly follows the movement of the focal object automatically through automatic panning. The frame of reference helps the users sense the direction and speed of the focal object and other objects in the view. The spotlight highlights the focal object and its immediate context so that the users can effectively perceive interesting objects in this region and monitor their dynamically changing relationships with the focal object. If dynamic labeling is turned on, only the labels of the most salient objects, such as the ones that are the closest to the focal object, are displayed. The users can use scrolling to control the animation, such as moving slowly forward/backward to search interesting events and then pausing to examine the detail. (3) Adjustment: At any time during the animation, users can change the zoom level using the + or -key or set another object as the focal object by clicking it or searching it by name from a search box. In the following sections, we present these techniques in more detail.

3.1 Automatic Panning

Three different automatic panning strategies have been explored. In our original approach, the camera is tied to the focal object and thus the focal object is always centered in the view. It is easy to observe the dynamic relationships between the moving objects and the focal object. However, this simple approach makes the camera "shake" intensively when the trajectory of the focal object is not smooth. Consequently, the unpredictable panning makes sensing the speeds and directions of the objects extremely difficult. To conquer the problem, we develop two automatic panning methods to move the camera positions smartly so that the resulting camera path is smooth and stable: Stepwise panning simulates the drag-and-drop panning effect in manual panning; and continuous panning allows the camera to smoothly follow the focal object without jitter. These two automatic panning algorithms are implemented in three steps: (1) find a sequence of view center positions according to the full trajectory of the focal object and the zoom level; (2) determine the starting time and end time of panning when the view center moves from one position to the next position; and (3) interpolate the real motion path of the camera between the two positions with smooth transitions.

Stepwise Panning: We adopt a strategy for stable camera motion which pans the camera only when the focal object is about to move out of a current camera viewport. Each camera position is computed to cover as many subsequent focal object positions along the trajectory as possible. This strategy mostly simulates the drag-and-drop panning operation when a user manually traces a moving object. When a focal object makes a sequence of small movements around the view center, camera panning is not triggered to follow such shaking variations so no extra cognitive load is imposed on users. Figure 4a shows the implementation of this method: First, create a sequence of bounding boxes (I-2) along the focal object trajectory (I-1) to cover all the focal object positions. Each box has the same size as the size of the zoomed view. The box is computed to cover as many focal object positions as possible. Second, the centers of the bounding boxes are computed to decide the camera positions along the animation (I-3). This method is further optimized so that users can examine the context of the focal object better. In detail, the bounding boxes (II-1) are set to be smaller than the size of the camera view. With this approach each frame of the animation ensures a minimum distance between the focal object and the view boundary (II-2). Panning starts when the focal object leaves the last position in the current view and ends when it reaches the first position in the next view.

Continuous panning: Continuous panning follows the focal object in a smooth long shot, akin to a camera following a runner in a race in movie recording. Figure 4b illustrates our method for determining the view center positions. First, to reduce jitters, the focal object trajectory (Figure 4b-1) is simplified to a trajectory with less joints (Figure 4b-2) using the Douglas-Peucker algorithm [13]. To preserve more details in a larger zoom level, the tolerance parameter of this algorithm is associated with the zoom level and maps to approximately 100 screen pixels in the zoomed view. Second, joints in the simplified trajectory are used as control points (Figure 4b-3) to create a B-spline curve [8] . Third, for each focal object



(a) Stepwise panning (b) Continuous panning

Figure 4: Illustration of view center trajectory generation.

position, we calculate its closest point on the curve (Figure 4b-4). These points are used as the view center positions (Figure 4b-5). To avoid jitters, the order of the view centers on the curve is kept as the same as the order of the focal object positions. Whenever the focal object moves to a new position, the view center also moves to the corresponding nearest point on the curve. In this way, the focal object is usually close to the view center and the panning is smoothed.

Discussion: Different automatic panning techniques work better on different focal object trajectory types. When the focal object is rambling within a small area, the stepwise panning works better since it leads to very few panning operations. On the other hand, continuous panning is preferred when the focal object is moving quickly along a roughly smooth path, as continuous panning inherits the nature of the object's movement and causes less jump and jitter. In our current system, users can choose one of the two techniques to fit their needs. Automatically choosing and switching panning techniques during animation remain as future work.

3.2 Frame of Reference

When automatic panning is conducted, users have difficulties in interpreting the movements of the objects in the zoomed view due to the combination of camera panning and object movements. For example, when the camera quickly moves upward following the focal object, the users may feel that other objects moving slower than the focal object in the same direction are moving downward. To address this issue, we introduce a frame of reference. When we sit in a train, we know the train is moving forward when we see the landscape outside the window is moving backward. The landscape plays a role as the **frame of reference**. Similarly, we provide a frame of reference which is static in the whole domain. It is displayed as the background of the zoomed view to help users sense the speed and direction of the moving objects. This background should be designed so that it is non-distracting to avoid adding visual noise to the animation. In our prototype, we design and combine two types of backgrounds as the frame of reference. One is a silhouette of the focal object trajectory and the other is a texture with symmetric patterns (see Figure 1).

In our initial design, we used the focal object trajectory as the background. As a reference, it is always visible in the zoomed view and provides additional information such as the trend of how the focal object moves. However, a raw trajectory itself can be cluttered lines and be visually complex and distracting. Therefore, we now use a colored silhouette of the trajectory as a reference, which captures the outline of the trajectory. It is less cluttered and distracting while still preserving the mobility trends of the focal object. The silhouette is created using the following algorithm: Starting from N = 1, create a convex hull to cover all the positions numbered from N to N+M along the focal object trajectory (where M is a positive integer). A smaller M preserves more details of the trajectory variation, which is preferred when the zoom level is large. This process is repeated by increasing N until all the points on the trajectory are covered. Then, we combine all the convex hulls to form the trajectory silhouette. The shape of the silhouette reveals the temporal trend of the focal object. For example, the silhouette is slim and smooth when the focal object is moving consistently toward a direction. The silhouette is semi-transparent, which makes it easy to observe but not distracting.

We use the silhouette together with a texture of symmetric patterns (see the background circles in Figure 1) as the frame of reference. The symmetric patterns improve the situation awareness of users so that the movement of the objects is immediately perceived. Here the size of the circles in the texture indicates the zoom level.

3.3 The Spotlight

In stage arts, a spotlight is often shed on a focal character and moves synchronously with her. The characters in the dark do not attract attention unless they get close to the focal character. The spotlight follows the focal character to illustrate an ego-centric story around her: at times, other characters run into the spotlight to meet her or she approaches and leaves other characters. We design a spotlight in the spot-tracking lens. As shown in Figure 3, the spotlight is always centered on the focal object, highlighting its immediate neighborhood as a focal area. During the animation, the spotlight moves synchronously with the focal object, emphasizing its neighbor domain, attracting user attention to the object and its context, and allowing users to examine details in the focal area.

There are two ways to get attention: let the focus be more attractive, or let everything else be less attractive. Both strategies are used in the spotlight. To make the focal object more attractive, it is highlighted by a time stamp displayed above it. To make objects far away from the focal object less attractive, the area outside of the spotlight is covered by a semi-transparent dark gray mask. The objects in this area are shown as small, dark circles, which are not attractive in the dark gray background. Their labels are also turned off. We further deliberately design the coloring of the spotlight. Inspired by five tone shading [21], a basic technique in painting for drawing how lighting effects an object, several tones are used in the spotlight to make it look realistic. A light gray middle tone area provides a transition between the spotlight area and its surrounding context. Outside the middle tone, a thin darker shadow area enhances the spotlight's boundary. It also indicates the boundary of the region where the objects are readable with their original labels, sizes, and colors. Finally, we slightly decorate the shadow using the hue of the focal object.

Users can interactively turn off/on the spotlight or adjust its size and the transparency of the dark gray mask outside it. They can also change the appearance of objects inside/outside the spotlight by toggling color (colorful or grey) and size (varying sized or small circles).

The assumption underlying the spotlight design is that objects outside of the focal area are unimportant since they are far away from the focal object. However, in the dynamic environment, an object can move close to the focal object in one moment and far away in the next. In this situation, users may keep a long term interest in it. For example, they may want to check if the object comes close to the focal object again or compare the overall movement of the object with that of the focal object in a longer time sequence. To support this need, a tracking interaction is provided where users can click an object in the view to highlight it. Highlighted objects are always displayed with labels and are never degraded and masked. Therefore, they are easily seen in the dark background when they move out of the focal area (Figure 1). When they move out of the zoomed view, they are displayed as half circles hanging on the boundary of the view, inspired by the off-view object display solution proposed in Halo [5] and Canyon [16].

3.4 Selective Labeling

Labels provide important semantic information in visualizations [10]. In animated visualizations, manual labeling approaches may require intensive human efforts since insights and relevant objects may change over time. The "label all" strategy may cause clutter even in a magnified view. We propose a new labeling strategy called selective labeling. It automatically labels or de-labels objects of interest or objects that are no longer of interest during the animation based on pre-defined user tasks. The selective labeling is implemented as: (1) at each moment, calculate an importance value for each object in the view and rank them from high to low; (2) label the top N objects (N is set by users to show more or fewer labels).

We now present how to automatically label objects that are the nearest to the focal object. Note that we can observe objects passing by the focal object during their movement. Users often consider them as close to the objects and want to identify them. It is different from static visualization where only static positions need to be considered. We propose the following algorithm to determine the importance values of objects according to such closeness:

Considering two objects p and s, whose locations at time step 1 are s_1, p_1 and whose locations at time step 2 are s_2 and p_2, we interpolate their moving path between the two time steps. The minimum distance between them can then be computed as

$$\min_{d\in[0,1]} \| (\vec{p_1} * d + \vec{p_2} * (1-d)) - (\vec{s_1} * d + \vec{s_2} * (1-d)) \| \quad (1)$$

where d ($0 < d < 1$) is the time between the two steps. The average minimum distance between an object and the focal object in the time window is the importance value to be used in the selective labeling algorithm.

The importance value can also be defined in different ways to support different tasks. For example, using the moving speeds of the objects as the importance values can capture objects that are moving fast. They are changing dramatically and are thus worth the attention of users. An object can be labeled prior to a fast movement to prepare users to capture volatile patterns.

3.5 Scrolling

Unlike watching a movie, exploratory analyses require full control of the playing speed. The spot-tracking lens is implemented in a webpage and uses scrolling to control a virtual timeline of the animation, inspired by the parallax scrolling websites [11]. Users can scroll the mouse wheel to drive the animation and the scrolling speed determines the animation speed. For example, users can slowly scroll the wheel up or down to move the animation slowly forward or backward to capture volatile patterns. They can also pause the scrolling to pause the animation so that they can check labels or highlight interesting objects. With scrolling, users can easily change the animation speed without the penalty of being interrupted by switching their attention to adjust a slider. Users can also drag the scroll bar to jump to a certain position of the timeline, click the left/right mouse button to move forward/backward stepwise, or start an auto-play mode by clicking a function key.

4 Spotlight User Study

The spotlight combined with a zoomed view tracking a focal object is an important technique in the spot-tracking lens to achieve our goal of improving animated bubble charts. A user study has been conducted to evaluate its effectiveness in helping users follow a focal object and examine its immediate context by comparing it with a benchmark technique. In Gapminder World [1], the state-of-art animated bubble chart prototype, the focal objects are displayed in dense colors and all other objects are semi-transparent. This approach was used as the benchmark technique. Our hypotheses were: (1) The spotlight allows users to examine a focal object and its immediate context more easily, especially when the object is moving in the view. (2) The spotlight allows users to examine a moving focal object and its immediate context more easily when there are distant objects moving in the view. (3) The spotlight allows users to track a small set of distant focal objects more easily while still focusing on a moving focal object.

To control distracting variables, animation videos were used in this user study. They were recorded from two systems. Both systems provided a zoomed view of an animated bubble chart with automatic panning. All objects in both systems are represented by colorful, varying sized bubbles with labels. The focal object was highlighted by a thin yellow halo and was opaque. The test system casted a spotlight on the focal object while the benchmark system displayed non-focal objects and their labels semi-transparently (alpha was set to 0.5. See Figure 3 on the left). The background color was white and no frames of reference were used in both systems.

A subset of a world wealth and health dataset downloaded from Gapminder [1] was used in this study. It contains data about 200 countries since 1900. The populations of the countries were mapped to the bubble size. Life expectancy was mapped to the y axis in a linear scale and average income was mapped to the x axis in a logarithmic scale. Countries are grouped into 6 geographical regions: Asia and Pacific, Sub-Saharan Africa, Middle East and North Africa, South Asia, America, Europe and Central Asia. The regions were represented by the color of the bubbles.

Eighteen graduate students majoring in Computer Science participated in this study through an online survey and a within-subjects design was used. Five videos were embedded in the survey with a question under each of them. Each video lasted about 30 seconds, including two 8-second sections separated by a 15-second black screen. The two sections recorded an animation generated by the benchmark system and the test system, respectively. The two animations in the same video had the same focal object(s), time period, animation speed, view centers, panning path and speed, and zoom level. The impact of the order of the animations to the study results was ignored since the subjects could repeat a video as many times as possible before they answered the question and only user preference data was collected.

Two videos were used for evaluating the first hypothesis: the "fixed" video showed a focal object fixed in the center of the display during the animation; and the "moving" video showed a focal object moving in the view. Two videos were used to evaluate the second hypothesis: the "cluttered" video showed a moving focal object with a lot of distant objects moving in the view; the "sparse" videos showed a moving focal object with only a few distant objects moving in the view. When the subjects watched the four videos, they were asked to speak out the first letter of the country closest to the focal country in every year. Instead of the whole name, just saying the first letter made the task easier for non-native English speakers. The purpose of this task was to force the subjects to follow the focal object and pay attention to its immediate context. In the "multi-tracking" video evaluating the third hypothesis, four secondary focal objects were highlighted by thin yellow halos and dense colors and moving around in the view. The subjects were asked to track them while paying attention to the moving fo-

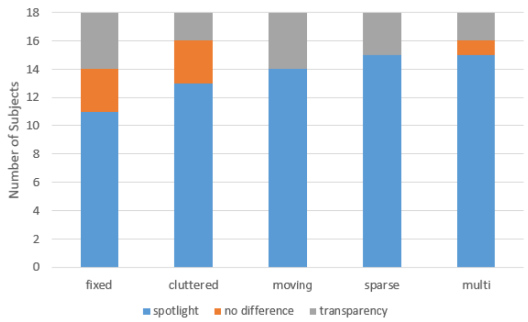


Figure 5: Videos preferred in the spotlight user study.

cal object. For each video, the subjects were asked to select the video section that allowed them to conduct the task more easily or indicate no difference.

Study results are shown in Figure 5. The spotlight was preferred by more subjects than the benchmark technique in all the scenarios and all the hypotheses were supported. The difference was the biggest in the multi-tracking scenario (15 vs 2). Even when the focal area was fixed in the center of the view, the spotlight was still preferred (11 vs 4). We notice that when there were more objects moving outside the spotlight, the number of subjects preferring the spotlight dropped from 15 to 13. It suggests that it is beneficial to mute the distant objects (displaying them as small, gray circles) in the spot-tracking lens (they were not muted in this experiment).

5 Open-Ended User Study for Spot-Tracking Lens

In this preliminary user study, we investigated how the spot-tracking lens changed the subjects' visual exploration strategies and the types of insights they captured in analysis. We also recorded several cases generated by the subjects to illustrate the utility of this zoomable user interface. Two systems were used in this study: one was Gapminder World (Gapminder for short) [1] as the benchmark; the other was the spot-tracking lens interface presented in this paper. We wondered whether our interface could provide an alternative perspective in the exploration of time series data.

Four master students with visualization background participated in this user study. They were divided into two groups and the subjects in the same group were familiar with each other. Each group was asked to have teamwork to explore world history after 1900 using the systems. They spent one hour on each system, with a break of at least one hour between the two sessions. The two sessions were conducted in the same day. One group used Gapminder first and the other used the spot-tracking lens first. The instructor trained the subjects on how to use the system before each session. She observed all the sessions and video recorded them. The subjects were told that insights about the relationships among multiple countries were more valuable than insights about single countries, since the latter can be easily captured by static displays.

First, we present two stories captured by the subjects.

The story around Germany: Subject group A investigated the dataset by setting Germany as the focal object (see Figure 6). They turned on the selective labeling to highlight countries close to Germany and ran the animation starting from World War II. They found that after World War II, Germany surpassed many western European countries in both x and y axes within a 20 year period. Figure 6 shows a snapshot of the animation after Germany surpassed France and Belgium. After this time period, Germany maintained its rapid progress and surpassed the United Kingdom. Then, the subjects noticed that Japan came into the race and joined Germany's neighborhood. They noticed that Japan had been the only Asian country (red bubble) in this neighborhood until 1980, when many more red bubbles appeared in the neighborhood (see Figure 6). They argued that Asia had its biggest leap at that time according to this observation.

The story around India:Subject group B selected India as the focal object (see Figure 7) and enabled automatic labeling for fast moving objects. In the zoomed view they were able to read the names of fast moving countries in India's neighborhood. They saw countries such as China and Vietnam during World War II. These names made sense to them since they were the World War II participants. After World War II, they were surprised to see that India experienced a slight drop in 1946 while most other countries around it were quickly recovering from the war. They also noticed that Pakistan had a similar experience. They suspected that it might be relevant to the Partition of India and Pakistan in 1947.

We now discuss the observations from the study:

- Leaps: Gapminder users captured large leaps of big countries easily. They also captured several small countries when they were leaping to a sparse area, but they did not notice leaps occurring in cluttered areas. Spot-tracking lens users captured leaping countries when they were in the view, even in cluttered areas. They were able to capture small leaps such as the one mentioned in the India story. Such leaps are not noticeable in either Gapminder or static displays.
- Inter-country relationships: It was noticed that subjects observed many more inter-country relationship insights in the spot-tracking lens. With Gapminder, the comparison often relied on the subjects' pre-knowledge of a country's history. The subjects had to add trails for two countries to examine their relationships.
- Maintaining attention: As shown in the Germany story, spot-tracking lens users were able to keep their interest in a country longer and discover many insights about it. It was also observed that the subjects jumped to a focal object after finding interesting insights about it when exploring another focal object. The exploration patterns in Gapminder were quite different. The subjects more often followed the mode of generating a hypothesis based on pre-knowledge - verifying the hypothesis using animation - and then generating another hypothesis based on other pre-knowledge. The difference suggested that the spot-tracking lens may be a useful technique for ego-centric visual explorations and progressive visual explorations.

The leap discovery observation confirmed that the spot-tracking lens helps users examine fine details during animation as expected. We did not anticipate the advantages the spot-tracking lens provides in finding inter-country relationships and supporting ego-centric and progressive visual explorations. It hints that the spot-tracking lens may be an engaging and inspiring approach in exploratory analysis of dynamic data, which needs to be investigated in future user studies.

After the subjects finished both sections, preferences and feedback were collected from them. All subjects agreed that the spot-tracking lens and Gapminder were designed for different tasks and they should work together to get more insights. The subjects all gave positive feedback to the visualization design of the spot-tracking lens. They commented that its trajectory silhouette background looked good and was informative; they could read labels easily in the spot-tracking lens; its design was artistic; and it provided the flexibility to go back and forth and control speed through scrolling.

6 Conclusion

In this paper, we propose the spot-tracking lens, a new zoomable user interface for animated bubble charts. It couples zooming with automatic panning and a set of novel techniques, such as frames of reference, spotlight, and selective labeling. It not only allows users to enjoy the expected benefits of zooming, such as focusing on focal objects and their context, examining details and labels in a less cluttered view, but also brings additional benefits into animated vi-

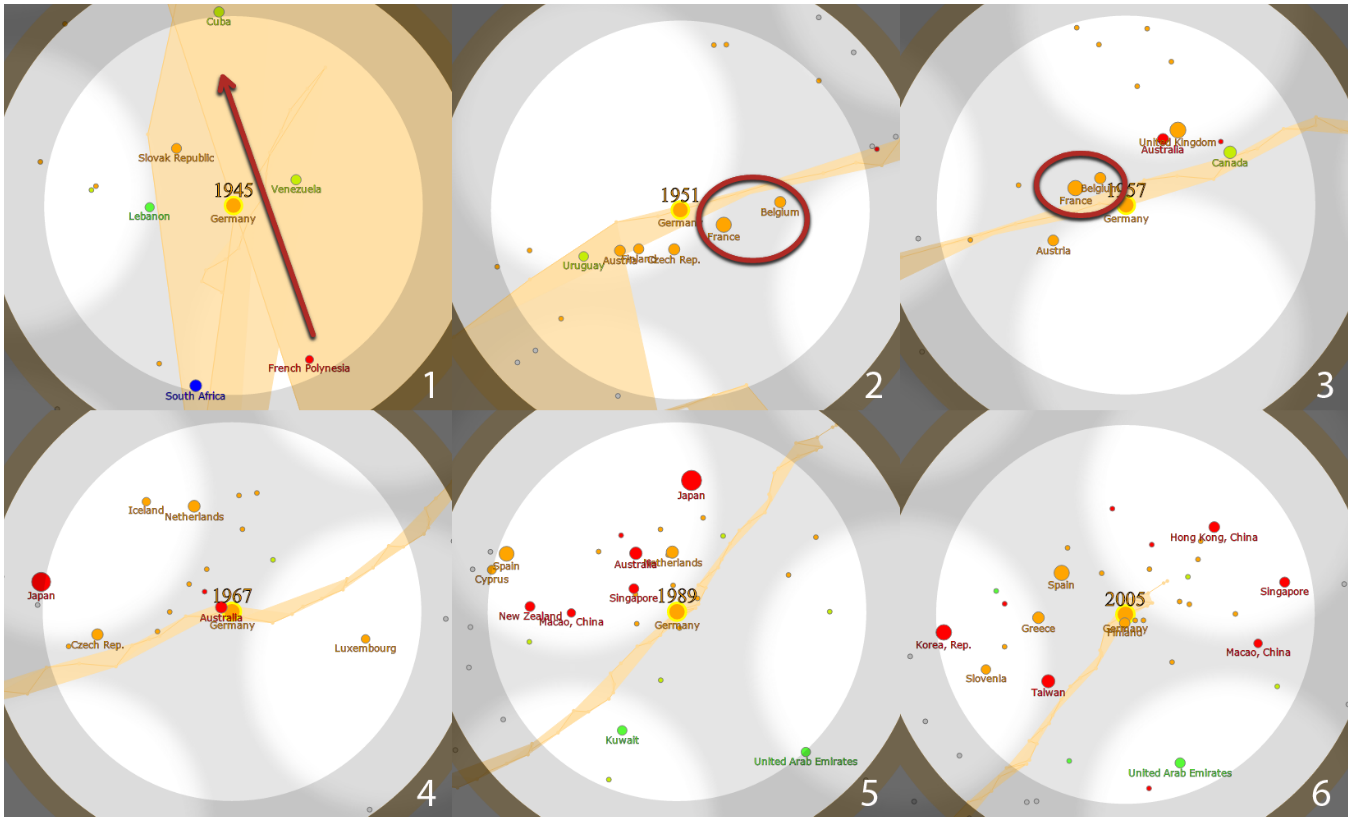


Figure 6: The journey of Germany after World War II. 1: Germany recovers from WWII in 1945 quickly. 2 and 3. Germany quickly surpasses other European countries such as France and Belgium. 4. In 1967, Japan moves forward to join Germany's neighborhood. 5. More red bubbles (Asian countries) join Germany's neighborhood in 1989. Meanwhile, Germany retreats a little bit as the result of reunification. 6. Red bubbles continue their progress in surpassing Germany.

sualization. Our preliminary user study suggested that it can be an engaging user interface for ego-centric, progressive visual exploration of dynamic data. Our exploration also reveals that interactions, such as zooming, face new challenges in animated visualization that are not encountered in traditional static visualizations. It is an under-explored research area where new efforts can be challenging yet productive. We argue that new techniques developed in this area may help solve the dilemma that animated visualization is fun and exciting, but less effective than static visualization in supporting analysis tasks. After a complete set of interactions are developed in the future, animated visualization may fully reveal its effectiveness and efficiency in analysis tasks.

The spot-tracking lens still has its limitations as a zoomable user interface. First, users are limited to a small focal area in the zoomed view and thus they do not get a full picture of the dataset. This problem can be addressed by coordinating the zoomed view with an overview to form an overview + detail view interface [7]. Second, in the current implementation, users can only track one focal object at a time, which is not suitable for tasks where multiple focal objects need to be compared. This problem can be leveraged by multifocus zooming techniques such as PolyZoom [17] or distortion techniques where multiple foci can be examined. Third, the spot-tracking lens requires users to manually adjust the zoom level. Since the density of objects in the zoomed view varies over time, the screen space can be used more efficiently if the zoom level can be automatically adjusted to maintain a desired object density in the view. This problem can be addressed by coupling both automatic zooming and automatic panning. In the future, we would like to work on the aforementioned improvements as well as developing new zoomable user interfaces for other animated visualizations such as dynamic graph visualization.

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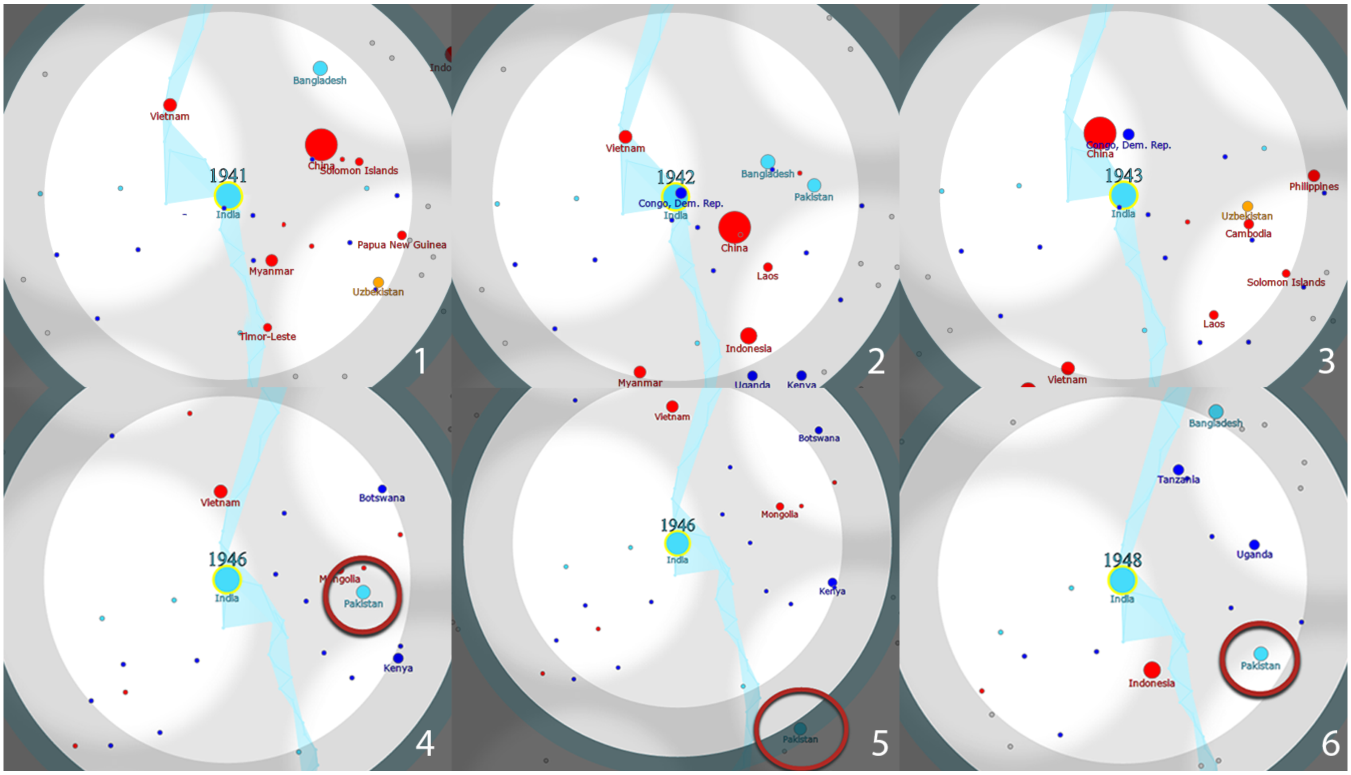

Figure 7: The journey of India around its independence. 1, 2, and 3. Asian countries such as China, Vietnam, the Philippines, and Indonesia are in an unstable status as they are involved in World War II. India is relatively stable. 4, 5, and 6. In 1946, countries like Vietnam are recovering from the War. India, on the contrary, drops slightly but soon recovers by 1948. Meanwhile, Pakistan also drops and recovers synchronously.

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