Visual Analysis of Eye Movements by Hierarchical Filter Wheels

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***Abstract*—The visual exploration of spatio-temporal eye movement data is challenging, especially if we are interested in the movement patterns of a large number of study participants. For example, if popular visualization techniques like heat maps or gaze plots are used, we may lose the temporal information or get lost in visual clutter. To address these issues, we propose an approach for filtering saccadic eye movement data called hierarchical filter wheels, which employs a radial representation of saccade information. It supports the analysis of sequences of saccades by filtering them with respect to direction and length. The focus of our approach is a fast initial analysis of data from eye tracking studies without the need of defining areas of interest (AOIs) or other preprocessing of the data. The hierarchical filters are interactively generated on users' demand by creating a hierarchy of multiple filter wheels each filtering one element of the sequence. We use a bubble tree layout to represent the generated filter hierarchy. The node positions in our layout directly represent the spatial properties of the filter criteria allowing an intuitive incremental generation and understanding of filter hierarchies. We illustrate the approach by applying it to eye movement data formerly recorded in an eye tracking study investigating the readability of different node-link tree diagrams. We further demonstrate how the hierarchical filter wheels can be used in combination with gaze plots.**

I. INTRODUCTION

Eye tracking has emerged as an important evaluation strategy [1], [2], [3], in particular, to observe visual attention and visual task solution strategies of data analysts using visualizations or visual analytics techniques [4]. While recording vast amounts of spatio-temporal eye movement data is no issue any more, the analysis and visualization of it shows up as challenging tasks [5], [6]. Typically, the data consists of trajectories from eye movement data of several participants. If we try to visually analyze such data by traditional techniques such as heat maps [7] or gaze plots [8], we soon reach a situation where we are not able to visually explore the temporal aspect in the data or get confronted with visual clutter caused by many link crossings and overlaps [9]. Existing visualization techniques typically have to deal with issues of visual scalability in the form of overplotting and visual clutter.

In this paper, we describe an approach—called *hierarchical filter wheels*—for filtering saccades or sequences of them in eye movement data to reduce the amount of displayed data. Our approach allows us to filter saccades with respect to direction and length; especially the length of saccades is a common metric for analyzing eye tracking data [2]. Furthermore, concatenating multiple filter wheels in a filter hierarchy enables us to filter sequences of saccades. Our implementation allows the interactive construction of the filter wheel hierarchy, with the filtered data being simultaneously updated and displayed.

The filter wheels integrate different saccade information in a radial representation. Furthermore, by using a bubble tree layout [10], [11], [12], we allow the user to interactively build filter hierarchies in a spatial orientation-preserving and intuitive way. The positions of the nodes in the layout correspond to the filter properties under exploration. Our method is designed for a fast initial analysis of the eye movement data to detect areas of interest (AOIs) or interesting movement patterns.

We applied our approach to eye movement data from a formerly conducted eye tracking experiment in which people had to locate the least common ancestor of highlighted leaf nodes in tree diagrams [13]. This data consists of eye movement data from a larger group of participants. With our filtering technique, we are able to find common sequential patterns in the eye movements as we demonstrate in our case study.

II. RELATED WORK

Different attempts have been made to visually represent eye movement data, as recently surveyed by Blascheck et al. [6]. For example, an attention map [7] shows the areas of visual attention as a color-coded scalar field. However, this approach aggregates over the study participants and time. Moreover, saccadic information cannot be explored by such maps since only the eye fixations are typically used to generate the visualization.

Gaze plots [8], in contrast, show the saccadic eye movements in an unaggregated fashion; but by plotting each single trajectory, such plots typically suffer from visual clutter [9], in particular, when the task to be solved in the study is of long duration and when a large group of people participates in the study. Although gaze plots might be used with appropriate interaction techniques to filter the gazes, there exists no filtering approach that would take sequences of saccades into account. Panagiotidis et al. [14] presented the edge analyzer for visually filtering links in graph data. However, the approach neither works for sequences of relations in a graph nor was it applied to saccadic eye movements.

The eSeeTrack system [15] allows the analysis of eye movement data by showing the sequential order of visited AOIs but ignores the sequential saccadic information. Furthermore, eSeeTrack also exploits a tree representation but not in a bubble tree layout [10], [11], [12] as in our approach.

Burch et al. [16] developed saccade plots in which the stimulus is shown in the center of the visualization as context information, optionally overlaid by an attention map or gaze plot, while using curved arcs or pixel-based triangular matrices surrounding the plot for an uncluttered view on the saccade data. Although this concept has some benefits, the saccade data is split into x- and y-coordinates, making it hard to analyze the saccades with respect to length and orientation, which is important to analyze eye movement data. Moreover, other data dimensions such as the temporal component or information about participants and fixation durations are hard to visually analyze with saccade plots. Furthermore, the data cannot be filtered for saccade sequences.

Andrienko et al. [5] assessed existing techniques from geo spatial visual analytics for their applicability for eye movement data. Among the useful candidates, we did not find any that would be capable of applying filtering techniques to saccadic data in a way as we provide in this work.

III. DATA MODEL AND VISUALIZATION

We model eye movement data recorded during eye tracking studies as a set of $m \in \mathbb{N}$ trajectories, one for each study participant. A single trajectory T consists of a finite sequence of fixation points $p_i \in \mathbb{R}^2$ from the two-dimensional plane (where the stimulus is displayed), i.e.,

$$T := \{p_1 \longrightarrow p_2 \longrightarrow \ldots \longrightarrow p_n\} .$$

It should be noted that the trajectories T_j are typically of different length.

Each fixation p_i is accompanied by two timestamps t_i^e and t_i^l, i.e., the time the eye enters this point and the time the eye leaves it again. The time between these timestamps is considered the fixation duration. The vector v_i between two consecutive points p_i and p_{i+1} is the saccade. The saccade is a rapid eye movement from one point to the next, where in general no attention is paid and no information is gathered.

Consequently, each vector v_i has a length and an orientation, which we will use as the basis for our design of the hierarchical filter wheels (Section IV). Furthermore, with an increasing number of such vectors, the probability of similar vectors increases, which we denote by the saccade frequency.

The trajectory data alone, recorded during eye movement studies, already consists of a vast amount of data which is worth to be analyzed with a suitable visualization and filtering technique. The analysis of saccade sequences with additional data attached—such as orientations, lengths, participants, or temporal aspects—is even more difficult; we want to address this problem with our new visualization technique. Line-based diagrams are typically used to directly represent spatio-temporal eye movement trajectories. Such a visualization is referred to as gaze plot and shows the inherent orientations and lengths of the saccades (Figure 1). However, it makes the visual exploration of data with a large number of saccades difficult due to overplotting issues (Figures 3 (a), 3 (c), and 3 (e)). Our filtering approach reduces the data displayed with such a visualization to allow a better exploration of the data. It supports the search for specific characteristics and patterns in saccadic eye movement data and is especially aimed at analyzing saccade sequences. For this, we enable the user to build a hierarchy of filters that highlight only those saccade sequences that match the filter sequence.

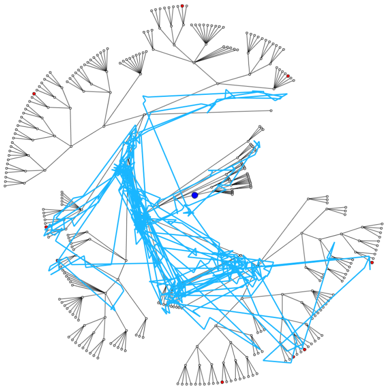


Fig. 1. Gaze plot for the eye tracking data of a single participant. The gaze plot is drawn over the stimulus, in this case a radial tree diagram.

IV. HIERARCHICAL FILTER WHEELS

Figure 2 shows an image of our implementation of the approach. On the left, we can see the stimulus from the eye tracking study overlaid with a gaze plot illustrating the eye movements of the study participants. When many participants took part in the study and the task was of long duration, the gaze plot soon gets unreadable due to overplotting and visual clutter. On the positive side, the gaze plot representation of the spatio-temporal data still serves as a good overview where zoom and filter operations can be applied and finally details on demand can be requested [17].

The diagram on the right shows the hierarchical filter wheel with several saccade sequences already selected. Every leaf node in the filter wheel corresponds to one selected saccade sequence and is identified with a unique color. We can easily see that saccade sequences following different patterns can be inspected. The filtered patterns are highlighted in the gaze plot on the stimulus with the respective color from the filter wheel. This helps analyze the saccade sequences while simultaneously seeing the spatial information, i.e., in which regions of the stimulus the saccade sequences start and where they end.

A. Saccade Direction and Length

Typically, the direction and length of saccades are of interest. While gaze plots implicitly represent these properties, it is difficult to extract the distribution of directions and lengths from such plots since the saccades occur at different positions. The first element of our approach is therefore a visualization that provides this information.

To this end, we plot the directions and length of saccades on a polar coordinates system (Figure 3), in which the angle

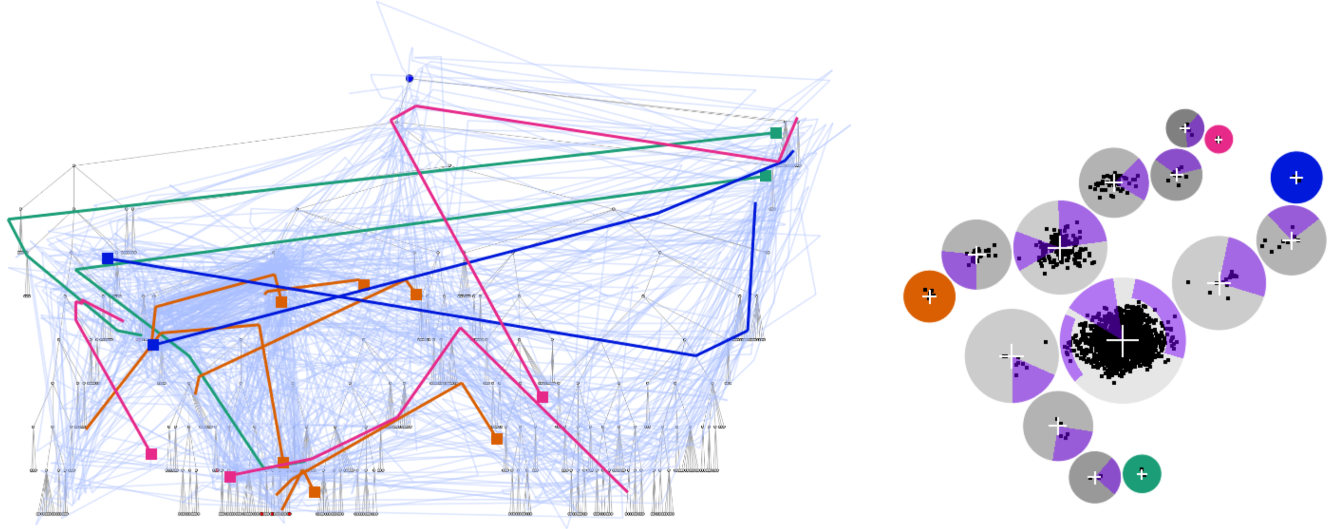


Fig. 2. Our analysis environment consists of a gaze plot (light blue) overlaid on top of the stimulus (left) and the hierarchical filter wheel (right), already constructed to filter four different types of saccade sequences. The interactive filtering for saccade sequences defines the shape of a bubble tree layout where the orientation of single saccades in the sequences is preserved. Each leaf node in the filter wheel corresponds to one type of saccade sequence and has its own color. These sequences are marked with the respective color in the gaze plot.

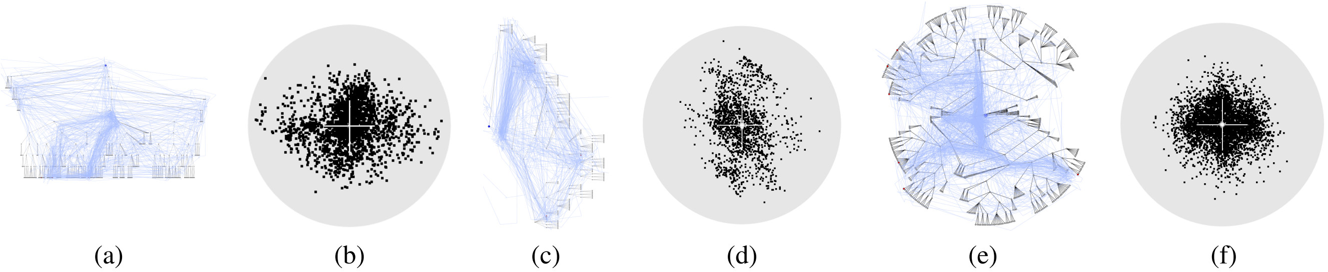


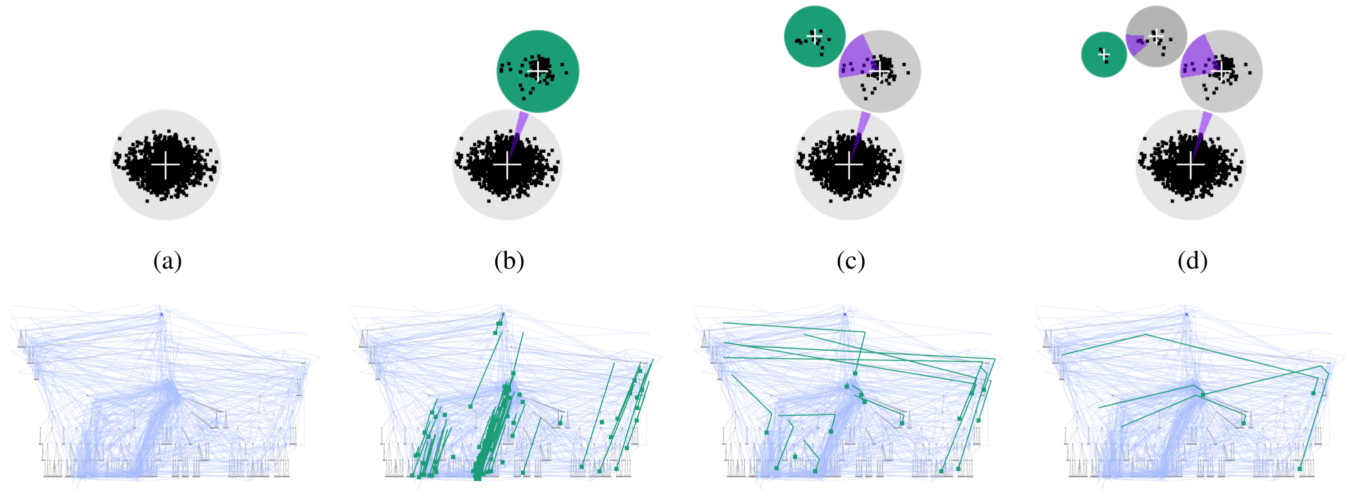
Fig. 3. Plot of saccade direction and length inside filter wheels. The saccades are plotted on a polar coordinate system to ease the analysis of direction and length. This example shows eye tracking data for 3 different stimuli and their gaze plots (a, c, e) along with the respective plots inside the filter wheel (b, d, e).

represents the direction and the radius the length of the saccade. The lengths of the saccades are normalized with the maximum possible length in the stimulus, i.e., a point on the border of the plot represents a saccade with the length corresponding to the diagonal of the stimulus. Such a radial visualization allows an intuitive perception of directions. To reduce overdraw, we just show the respective points instead of lines in the plot. Furthermore, since short saccades typically dominate, we use the square root of the length in the plot to better utilize the provided space. This non-linear mapping is no issue because it is not required to see the absolute length in the plot. As Figure 3 shows, these plots allow us to recognize the distribution of lengths and directions, e.g., the saccades for the stimuli with a radial tree layout (Figures 3 (e) and 3 (f)) exhibit a more equal distribution of directions than the saccades for the other stimuli. Furthermore, the traditional tree layouts (Figures 3 (a) – 3 (d)) exhibit more saccades with a length near the maximum.

These radial plots of saccade direction and length are shown inside our filter wheels to support the filter creation (Figure 2).

B. Hierarchical Filter

Our approach is based on the concatenation of filter wheels, resulting in a hierarchical filter structure (Figure 4). Each filter wheel defines a range of direction and length. Only saccades lying inside this range are selected. The defined range is marked in the filter wheel (purple sectors). In this context, an important aspect is that the filter wheel is not passing the saccades fulfilling the filter range to the next filter wheel, but the subsequent saccades in the trajectory are passed. This means that with every new level in the hierarchy the length of the resulting sequence is increased. Figure 4 exemplifies this. With only one filter wheel (besides the root), single saccades with the defined direction and length are highlighted (Figure 4 (b)). With three concatenated filter wheels, sequences of three saccades are highlighted (Figure 4 (d)). It has to be noted that the starting points of the saccade sequences shown in the gaze plot are marked with small squares to indicate where the sequences start and end. Inside the filter wheels, plots for the saccades fulfilling the defined filter ranges are shown. Again, we do not show the saccades fulfilling the previous filter step but the subsequent saccades in the sequence.


(a) (b) (c) (d)

(e) (f) (g) (h)

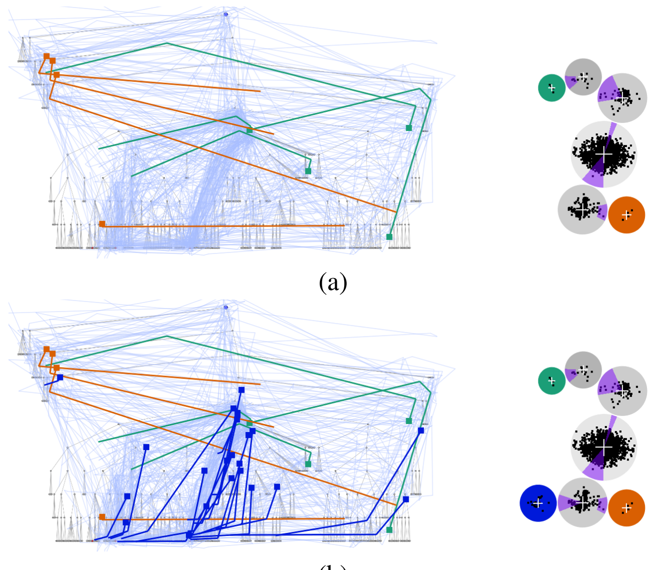
Fig. 4. Creation of a hierarchical filter. (a) No filters are defined initially; only the root filter wheel exists and shows the plot of all saccades. (e) Saccades are not highlighted in the respective gaze plot. (b) Adding a filter wheel to the root highlights saccades of the respective direction (f). (c) The filter depth is increased and only sequences of two saccades with the respective directions are highlighted (g). (d) The next level in the filter hierarchy reduces the number of highlighted saccades further. In this example, also the length is restricted and only longer saccades are selected.

A closer look at the example shows the effect of the different filter settings. The first filter wheel (Figure 4 (b)) defines a narrow directional range. The result is that the highlighted saccades are quite parallel to each other (Figure 4 (f)). The second filter wheel defines a rather large directional range (Figure 4 (c)). We can see that the second segment of the highlighted sequences varies more in direction than the first (Figure 4 (g)). So far, both filter wheels only restricted the direction of the saccades. The third filter wheel (Figure 4 (d)) now restricts the saccades in their length. Only longer saccades are selected. This results in a similar length of the third segment of the highlighted sequences (Figure 4 (h)).

The created filter hierarchy is shown with a bubble tree layout. With every level in the hierarchy, the size of the wheels decreases. Furthermore, deeper levels in the hierarchy are indicated with a darker shade of gray . A special property of our layout is that the position of the nodes/wheels directly represents the directional range of the filter: the position of a concatenated wheel corresponds to the mean of the selected directional range. This allows an intuitive creation and understanding of filter hierarchies. To extend the filter structure, the user selects a wheel and can then drag the newly added wheel around the parent wheel to define the directional range of the filter.

C. Multiple Sequences

If the user creates a filter hierarchy with multiple leaf nodes, saccade sequences corresponding to the different subtrees are highlighted simultaneously (Figure 5). Every subtree, i.e., path from the root node to a leaf node in the filter hierarchy, defines a sequence of saccades that have to lie in the defined range of direction and length. Hence, it is possible to simultaneously highlight different motion patterns in the data.


(a)

(b)

Fig. 5. Saccade sequences resulting from multiple subtrees in the hierarchy are displayed together. The leaf nodes of these subtrees are marked with different colors. These colors are used to highlight the corresponding saccade sequences in the gaze plot. (a) More filter wheels are added to the hierarchy from the previous example (Figure 4 (d)). The saccade sequences fulfilling the new filter criteria are highlighted in orange. (b) Another filter wheel increases the set of highlighted saccade sequences (dark blue).

The leaf nodes are displayed with different colors and the saccade sequences corresponding to the respective subtree are also highlighted with this color. For this purpose, we have adapted a qualitative colormap for categorical data from ColorBrewer [18]. We slightly changed the colors so that they have a higher contrast to the light blue color of the gaze plots. This allows an easy identification and comparison of different motion patterns in the data.

V. CASE STUDY

We demonstrate our filtering approach with eye movement data formerly recorded in an eye tracking study by Burch et al. [13], who made the data publicly available [19]. The dataset consists of the eye tracking data of 38 participants. Different tree layouts were used as stimuli.

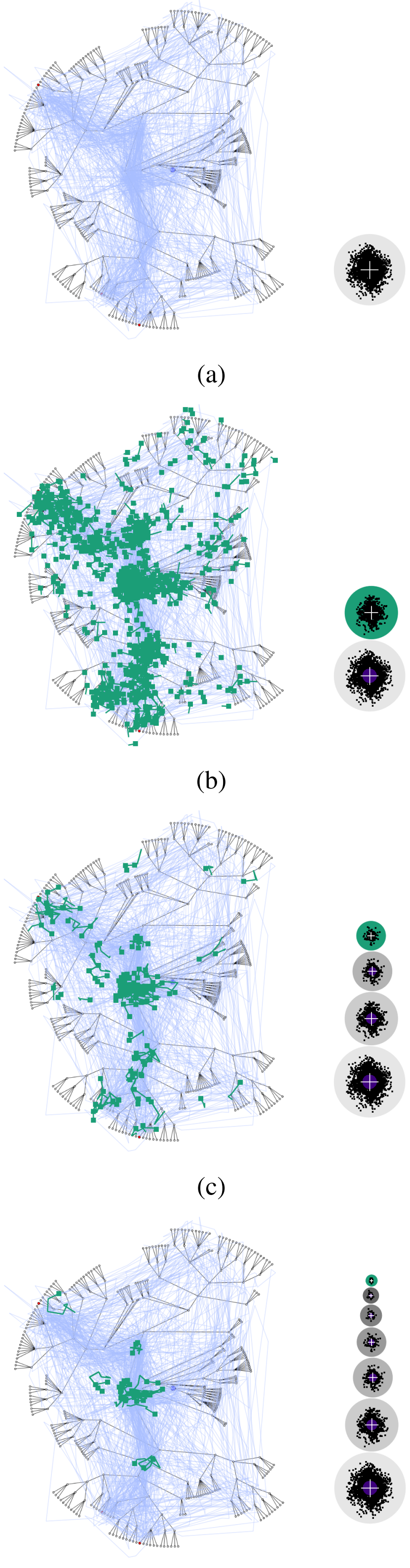
First, we analyze the data for a radial tree layout with respect to the length of the saccades. Many of the saccades in this dataset are located on the path between the red points at the boundary of the radial layout and the blue point at the center (Figure 6 (a)). If we select only short saccades (Figure 6 (b)), in this example equal or below 20 percent of the maximum saccade length, we can see that there are clusters of such short saccades in the previous mentioned area of high saccade density. However, there are also short saccades in other parts of the stimulus. Next, we extend the filter wheel to select sequences of three short saccades (Figure 6 (c)). The number of highlighted saccades is strongly reduced, but most of the previously seen clusters still exist. Even longer sequences of short length are only present for a small number of trajectories (Figure 6 (d)). Now, a large cluster remains in the center area. These longer sequences of short saccades can be an indication of searching behavior, mainly occurring near the blue point at the center.

In the second example, we look at the dataset for a traditional tree layout. The gaze plot for this dataset (Figure 7 (a)) shows much visual clutter, it is hard to see individual saccades. However, structures are visible, resulting from the overplotting of the semi-transparent lines, e.g., the shape of “7” is visible (marked black). Since the gaze plots for multiple participants are simultaneously displayed, this can be an indication for a common search strategy of the participants. However, it is not clear from the gaze plot how many saccades really lie inside this shape and if there are multiple saccade sequences that form the visible structure. We therefore create filters with respective directions (Figure 7 (b)). The result shows only a few saccade sequences lying in the shape.

We have so far only filtered in one direction. However, the shape could also result from saccades starting at the bottom and going in upward direction. We therefore create a second filter sequence (Figure 7 (c)), resulting in many more highlighted saccades in the respective area. This combination of directions seems to be quite common in the dataset.

The created filter hierarchy can be reused for other data, e.g., we can apply it to the data of a single user for the same stimulus (Figure 7 (d)). It is visible that two of the saccade sequences of this participant also lie in the respective area.

It is even more interesting to apply the filter hierarchy to a different dataset (Figure 7 (e)) to analyze if specific patterns and sequences from one dataset also occur in other datasets. In this case, there are many saccades with the respective combination of directions in the second dataset. A reason for this are the similar tree layouts used in both examples as stimuli and that the saccade direction is strongly influenced by the tree layout.

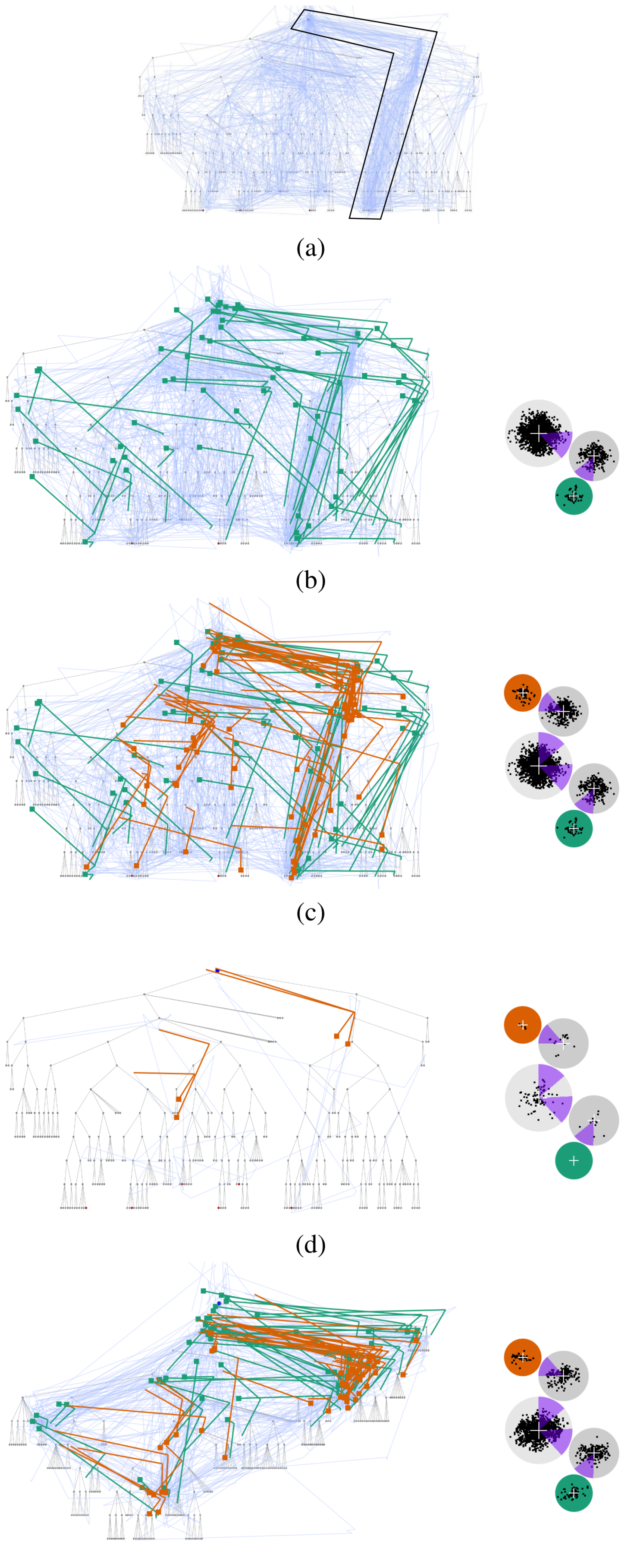

(a)

(b)

(c)

(d)

Fig. 6. Analyzing saccade length in the case study. (a) Overview of the dataset, no saccades are filtered. (b) Saccades are filtered only with respect to their length. In this case, only short saccades are selected. (c) Now, sequences of only three short saccades are selected. (d) The filter wheel is further extended and selects now only sequences of six short saccades.


(a)

(b)

(c)

(d)

(e)

Fig. 7. Analyzing directional patterns in the case study. (a) In this dataset, a larger amount of saccades induce the shape of “7” in the gaze plot (marked black). (b) Saccade sequences following this shape in downward direction are highlighted. (c) Saccade sequences following this shape in upward direction are additionally highlighted. (d) The previously defined filter is applied to the data of a single user. (e) The previously defined filter is applied to another dataset.

The two examples demonstrated how the data from eye tracking studies with several participants can be filtered and analyzed with respect to the length and direction of saccades. This allows us to identify possible search strategies of the participants or other common eye movement patterns. The intuitive layout of the filter wheels and the interactive brushing-and-linking approach allow a fast initial analysis of the data. We do not incorporate positional information or AOIs but rather see our method as a tool to identify respective AOIs or other interesting patterns that can then be further investigated.

VI. CONCLUSION AND FUTURE WORK

We presented a filtering approach for eye tracking data that supports the analysis of saccade sequences and is designed to be combined with typical visualizations for eye tracking data like gaze plots. The user can define the saccade sequences of interest by combining multiple filter wheels in a hierarchy. The resulting sequences are then highlighted with different colors in the visualization of the eye tracking data. Our visual representation of the filter wheel hierarchy is based on a bubble tree layout. The user is further supported by plots of saccade direction and length inside the filter wheels. The use case shows that our visualization can be used to search for common eye movement sequences in study data with a large number of participants.

However, our approach has a number of limitations. Our filtering approach is currently very restrictive by focusing only on subsequent saccades in the data. If a single saccade in the sequence does not fulfill the criteria, the full sequence is rejected. Fuzzy filtering could help find further interesting patterns. Furthermore, the bubble tree layout has scalability issues for long sequences. Modifications of the layout or suitable interaction methods could address this issue. Besides resolving these limitations, it could also be interesting for future work to apply our approach to data for dynamic stimuli, e.g., videos. Furthermore, our filter wheels could be extended to incorporate further information of interest, e.g., fixation duration or AOI information. Respective information could be displayed inside the filter wheels or with color coding in the gaze plot.

ACKNOWLEDGMENT

This work was funded by Deutsche Forschungsgemeinschaft (DFG) within project WE 2836/4-1.

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