SEQIT: Visualizing Sequences of Interest in Eye Tracking Data

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Abstract— Eye tracking is becoming widely used in HCI and many other fields to study user behaviour. Eye tracking data explains user attention pattern in great details and is often large in volume. This complex nature makes analyzing it a challenge. Various visualizations have been designed to aid the data analysis, but none of them focuses sequential patterns in eye gaze, which can reveal insights in user behaviours. SEQIT is a visualization system designed for sequence analysis of eye tracking data. Using defined areas of interest (AOI), SEQIT aggregates fixations into AOI visits and presents sequences of AOI visits in a timeline. SEQIT supports comparison between multiple sequences and exploration of sequence patterns associated with user characteristics. The interface of SEQIT is cleanly designed, fast, and responsive.

✦

1 INTRODUCTION

Eye trackers are increasingly present in academic research and commercial applications [1]. Researchers in human-computer interaction use eye tracking to study the usability of computer interfaces, as it can provide data that describe user behaviour and reveal usability problems that traditional methods might have missed [18]. It has also been used in various medical exams, e.g., for detecting schizophrenia [10], and in developmental psychology to study the perceptual and cognitive abilities of children [8].

Analyzing eye tracking data often involves examining a set of quantitative metrics, including fixation count, saccade amplitude, pupil size, etc. While statistical analysis is suitable for generating these metrics, visualization techniques can reveal spatial-temporal patterns and trends in the data that can then be verified through statistical testing [1]. Thus, the tasks performed on eye tracking visualizations include understanding overall distribution of fixations and identifying sequential patterns of user's eye movement. To draw conclusions about the behaviours of a group of users requires comparing the patterns and finding common ones among users. There has not been a tool that supports these analyses.

In this paper, I present SEQIT, a visualization system that facilitates discovery and analysis of sequences of interest (SEQIT) in eye tracking data. This system focuses on finding sequence patterns that correlate with certain user characteristics in the eye gaze dataset. The system leverages areas of interest (AOI) defined on the interface and aggregates fixation sequences into AOI visit sequences.

Eye tracking datasets are often large in volume: an HCI experiment often involves tens of participants and hundreds of trials, which result in hundreds of thousands of fixations [1]. On a standard desktop monitor with high definition resolution, the design of SEQIT can support visualizing around one hundred sequences at a time and comparing around ten user characteristic attributes.

I begin with a survey of related work in eye tracking visualization and sequence analysis in Section 2. Next in Section 3, I describe the task and data abstractions in designing the visualization. In Section 4, I propose the solution, and the resulting system is presented in Section 4. Finally, I discuss the strengths and weaknesses of the system and future work in Section 7, and Section 8 summarizes the contributions of this work.

2 RELATED WORK

Because of its spatial and temporal properties, eye tracking data is often analyzed through visualization, and there is a wide range of visualization tools that support different aspect of the anlaysis. Sequence analyses of eye gaze have also been done through statistical testing and visualizations.

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2.1 Eye Tracking Visualization

Two traditional approaches are plotting the scan path and the heatmap of fixations. Scan path suffer from visual clutter easily as the amount of data visualized increases; heatmap is visually appealing, but it lacks temporal information associated with each fixation [19]. The temporal information, in terms of the sequence of user's eye movement, can often reveal insights such as the efficiency of the arrangement of elements in the interface and user's strategies when processing the visual information [18].

Both ISeeCube [13] and the EyeC [20] present the AOI sequence in the form of scarf plots in a timeline, which SEQIT also shares but uses with added purposes.

There has been an increasing number of eye-tracking visualizations developed in recent years [1]. Blascheck et al. surveyed the field and found that many of the systems lack the support for interactive analysis [1]. They classified these systems according to a set of categories: SEQIT is both point- and AOI-based and facilitates interactive spatial-temporal analysis with multiple comparisons – there is no existing system that falls into this set of categories.

2.2 Eye Gaze Sequence Analysis and Visualization

Researchers have made a number of attempts at identifying patterns in eye gaze sequences. West et al.'s eyePatterns tool extract patterns in the AOI sequence using text processing techniques. The tool analyzes two types of sequences: expanded and collapsed. In the expanded sequences, each element in the AOI sequence is associated with a fixation, whereas in the collapsed sequence, consecutive fixations within the same AOI are "collapsed" into one element in the AOI sequence. This collapsing technique inspired the concept of AOI visits in SEQIT, which is described later in Section 4.1. The shortcoming of eyePatterns tool is the removal of durations. Fixation durations are not considered when forming the sequence, so the significance of each fixation are equalized regardless of its duration. The number of fixations that collapsed into one element in the collapsed sequence is also ignored in the analysis.

Statistical analyses using sequential pattern mining have identified, in AOI sequences, patterns that are different between user groups defined by their cognitive abilities and task groups defined by task difficulty [22]. These analyses also do not take into account temporal information, such as durations and temporal position of the pattern within the trial.

Transitions between AOIs are sequence patterns of length two, and there are various form of visualization that encodes transition frequencies. Blascheck et al., Holmqvist et al., Tory et al. all visualize transition between AOIs with arrows [2, 9, 23]. They encodes the frequency of transitions with the width of the arrow. None of these systems support sequence patterns longer than two.

Sequence patterns with length longer than two have been visualized in tree structures, where each branch of the tree represents a sequence pattern [20]. Tsang et al. encodes the frequency of the pattern as the size of the node [24]. This tree representation is the only known
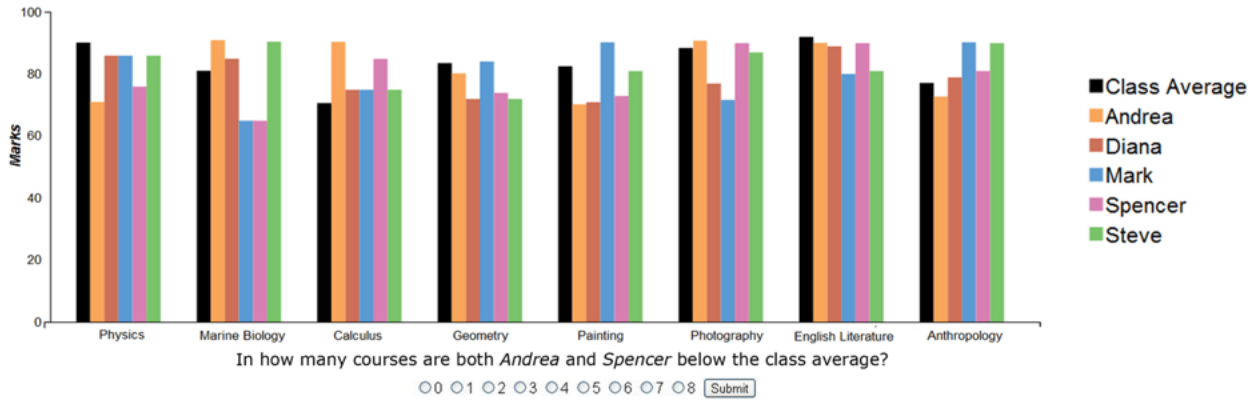
Fig. 1. An example of the task given in the experiment [5]. Eye tracking data from this experiment is used in this paper to illustrate SEQIT.

visualization of sequences, but these implementations also lack the temporal information such as duration as the statistical analyses of sequences do.

3 TASK AND DATA ABSTRACTIONS

This system is designed to support exploring sequence patterns in eye gaze. Any sequences of interest are generally unknown *a priori*, so the task is to explore and discover the patterns. Sequences of interest are those that uncover user behaviours, either in general or associated with certain groups of users. Thus, another task is to find correlations between sequence patterns and user characteristics.

As a full analysis tool, it also provides the opportunity for general inspection of the data, in terms of data quality and overall trend. Low data quality in eye tracking may be present in the form of missing data and/or offset in the fixation coordinates resulted from incorrect calibration of the eye tracker. Overall trend concerns with the distribution of fixations, the length of the trials, etc.

Eye tracking data can be abstracted as time-series data with spatial properties. Each fixation occurs in a time interval and at a spatial location. Two consecutive fixations are linked by a saccade, which is a rapid movement of the eye.

In interface analyses with eye tracking, meaningful regions in the visual stimulus are often defined as areas of interest (AOI) to assist the analysis of the interface by providing the semantics to the spatial locations of the fixations.

Task and data abstractions are summarized in Table 2.

3.1 Example Data

In this paper, I use the dataset from an experiment conducted with eye tracking as the example [5]. There are 62 participants in the study, each participant performed 80 tasks. In each task, participants were asked to answer a question based on the information presented in a bar chart (Figure 1). User characteristic data recorded in this experiment include three cognitive ability measures: perceptual speed, verbal working memory, and visual working memory. Each measure is a quantitative value computed from the respective cognitive test. There are five AOIs defined on the interface (Figure 2).

4 SOLUTION

SEQIT uses aggregation and linked multiform views among other visualization idioms. Eye tracking data is presented in multiform views: individual fixations are shown only as details on demand; for overview, I choose to reduce the complexity by aggregating fixations. The views in the interface are connected by linked highlighting and shared colour encoding, and I use interactive components to support exploration and discovery of sequence patterns. The solution is summarized in Table 2.

4.1 AOI Visits

AOI visits are derived from the aggregation of fixations. Successive fixations within the same AOI are grouped as an AOI visit. The du-
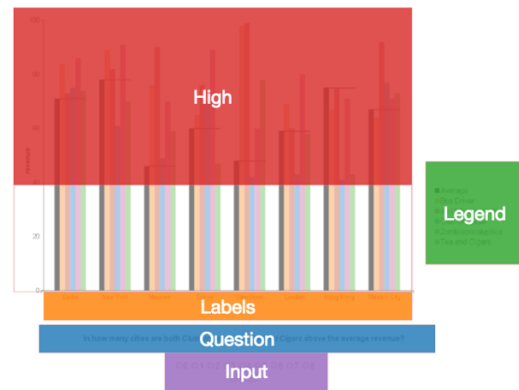

Fig. 2. Five AOIs are defined on the interface in the example dataset.

Table 1. Examples of AOI visit. Each row represents a fixation point in the data. The first five data points correspond to two AOI visits.

Timestamp	Fixation AOI	Fixation Duration	AOI Visit	AOI Visit Duration
0	Question	200		
200	Question	250	Question	650
450	Question	200		
650	Legend	350	Legend	600
1000	Legend	250		
1250	Label	300	...	...

ration of the AOI visit is the summed durations of individual fixations in the AOI visit. Table 1 gives an example of the relation between fixation and AOI visit. Each AOI is assigned a colour to be applied consistently throughout the interface for representing the AOI.

4.2 Interface Panels

SEQIT consists of four closely connected panels: the review panel, the timeline panel, the user characteristics panel, and the sequence tool panel.

4.2.1 Review Panel

The review panel contains the visual stimulus as the background and overlays additional data. The visual stimulus in the example dataset is a screenshot of the visualization task given to the experiment participants (Figure 1). Data that can be displayed on top of the visual stimulus include fixations and saccades, a heatmap of fixations, and regions of the AOIs. The visual stimulus background provides the spatial context for the overlaid data to allow easy reference.

Table 2. System analysis based on the framework by Munzner [14].

System	SEQIT
What: Data	Time-series data with spatial property.
What: Derived	Aggregation of time-series data according to spatial semantic.
Why: Task	Inspect data and explore to discover sequences of interests.
How: Encode	Timeline with stacked bar charts. Color by spatial semantic.
How: Facet	Multiform with linked coloring and highlighting.
How: Reduce	Filtering.
Scale	User characteristics column: ten. Timeline rows: one hundred.

4.2.2 Timeline Panel

The timeline panel shows the eye-tracking data in the form of sequences of AOI visits. The panel shows the data of one task in the experiment at a time, and the eye gaze sequence of each participant is displayed as a row in the timeline panel. Each sequence is visually encoded in a series of horizontally stacked bars to represent the AOI visits, with the length of each bar denoting the duration of that AOI visit, and its colour corresponding to the AOI of the visit. Thus, the timeline panel contains multiple rows of AOI visit sequences, aligned on the left at trial start time.

When users hover over a row in the timeline, a fisheye distortion is applied to zoom into this particular row, and the colours of other rows are faded out to further highlight the selected row. At the same time, the fixations and saccades associated with the selected trial are drawn in the review panel on top of the visual stimulus.

The timeline can be presented in two time scales: absolute and relative. In absolute time scale, the actual times of the trials are mapped consistently across all of the rows, so that the total length of a bar represents the total duration of the trial. In relative time scale, the proportion of trial completed acts as the time scale, under which all bars are of the same length and aligned at the rightmost point, which denotes 100% of trial completed.

4.2.3 User Characteristics Panel

The user characteristics panel presents the cognitive ability measures of the participants. Each measure form a bar chart, with the bar for a participant aligned with the corresponding row in the timeline. The bar chart of each measure can be sorted by its value, and the ordering of the rows in the timeline is updated accordingly at the same time. Sorting allows users of SEQIT to find correlations between user characteristics as well as between any user characteristic and sequence patterns in the timeline.

4.2.4 Sequence Tool Panel

Using the sequence tool, users can create sequence patterns and visualize the occurrences of these patterns on the timeline. After clicking on the "New sequence" button, users can select an AOI in the review panel to form a sequence pattern. Created sequences are saved in a list in this panel.

4.3 Interface Interactions

The four panels are connected through linked highlighting. When users hovering over the region of an AOI in the review panel, the region is highlighted and labeled, while in the timeline view, every bar that represents a visit to this AOI is also highlighted. Similarly, in the sequence tool panel, when users hovering over a saved sequence pattern, any occurrence of such pattern is highlighted in the timeline view.

5 IMPLEMENTATION

The visualization is implemented as a web application. It is written in HTML, CSS, and Javascript, and I built it with a number of Javscript libraries. D3.js [4] is the core library for drawing geometric components and applying animated transition on various actions. The fisheye distortion effect in the timeline panel and user characteristics panel is implemented with D3's fisheye plugin. The animation for sorting the timeline rows is inspired by Mike Bostock's sortable bar chart example [3]. The heatmap of fixations is created with Heatmap.js [25]. The

tooltips used in SEQIT are those from d3.tip [17]. The toggle buttons are Bootstrap Toggle [11]. The user characteristics icons are from the Font Awesome icon library [6]. The overall layout in the application is built with the responsive bootstrap framework [16].

There are two main SVG objects, one forms the review panel and the other combines both the user characteristics panel and the timeline panel. I used D3.js to draw the individual components such as the fixation points and the saccades in the review panel, the AOI visits in the timeline panel, and the bar charts in the user characteristics panel. The actions of the buttons and controls are implemented in Javascript with the help of jQuery [12].

I designed and implemented the algorithms and the logics behind the linked highlighting described in Section 4.3. I also wrote scripts in python to transform data outputted from the eye tracker to JSON format to be read as input by SEQIT, and once it is read, I store the data in structures that allow easy and efficient access.

6 RESULTS

Figure 3 shows SEQIT in action. The review panel is in the upper-left portion of the interface. The visual stimulus, in this case a screenshot of the experiment task, is shown as the background. A toggle in the top-right corner of the review panel shows and hides the heatmap.

Below the review panel is the sequence tool panel, which displays sequence patterns that are created. The sequences are colored based on the AOI colours. The "New sequence" button is located in the top-right corner of the sequence tool panel. Hovering over any created pattern highlights the occurrences of the pattern in the timeline (Figure 5).

To the right of these two panels is the user characteristics panel. The three cognitive ability measures in the dataset are presented as bar charts in the three columns. Sorting controls are located in the header of each column, clicking on which would toggle between ascending and descending sort by each measure, and the state of the toggle would change to reflect the current sorting behaviour.

To the right of the user characteristics panel is the timeline panel, where each row is aligned with the bar of the user's characteristics. The AOI visit sequences are presented as stacked bars according to the description in Section 4.2.2. A legend for the AOI colour coding is positioned at the top of the timeline panel, and a toggle for switching between absolute and relative time scale is to the right of the legend in the top-right corner of the timeline panel. Figure 3 shows the timeline in absolute time scale, and Figure 4 shows it in relative scale.

The fisheye distortion when users hovering over the timeline is depicted in Figure 4, where rows that are not selected are faded out, and the review panel shows the fixations and the saccades associated with the selected trial.

6.1 Scenarios of Use

Jim is a HCI researcher who just conducted a user study for his newly designed user interface, measured the cognitive abilities of the participants, and collected eye tracking data while the participants were performing tasks on the interface. He has exported the data from the eye tracker, transformed it to the format supported by SEQIT, and loaded it into the system.

6.2 Scenario 1: Data Inspection

Jim first takes a holistic look at the timeline view. In a number of rows, he finds large white spaces among the otherwise colourful AOI visits. These white spaces indicate gaps in the fixation data. He then hovers over these rows individually and examine the fixation and saccade plots shown in the review panel. He notes down any trials with potentially low data quality for future crosschecking with other trials performed by those users.

6.3 Scenario 2: Overall Trends

Jim sorts the user characteristic and the timeline panels by each of the cognitive ability measures he recorded in the study. He did not see any noticeable correlations between any pair of the measures, but he will confirm this observation later through statistical analysis.
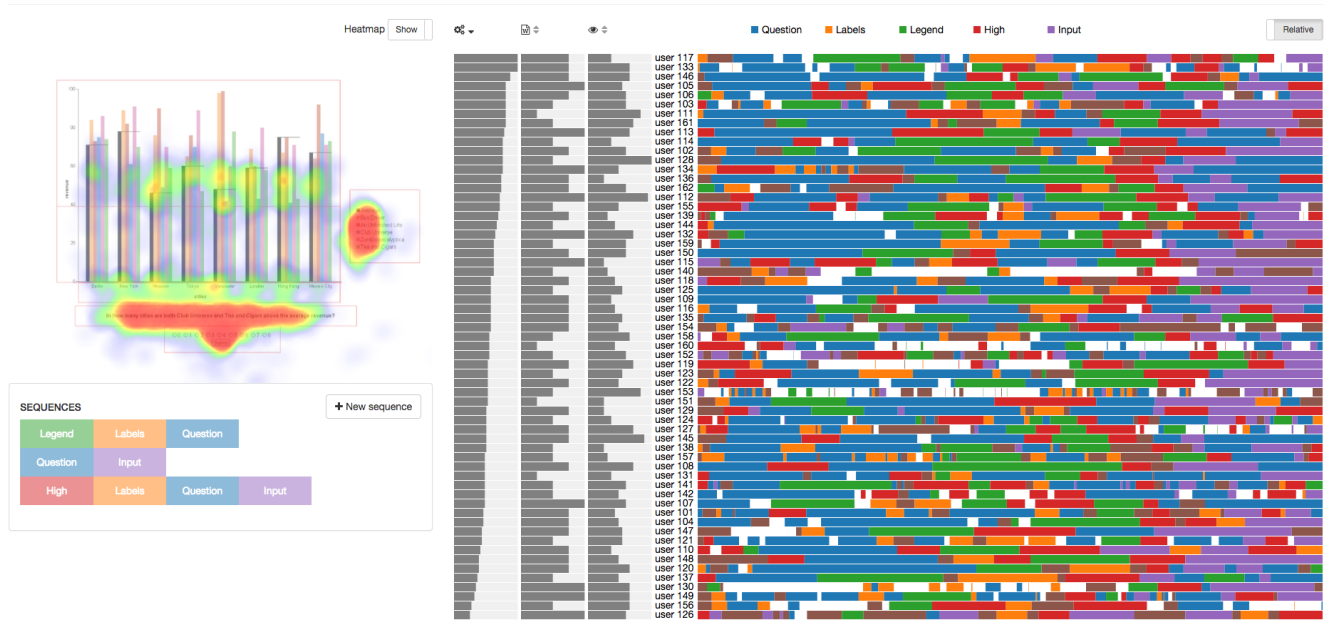
Fig. 3. SEQIT, with heatmap toggled on, timeline in relative scale and sorted by perceptual speed. The review panel is in the top-left corder, below which is the sequence tool, and to their right are the user characteristics panel and the timeline panel.
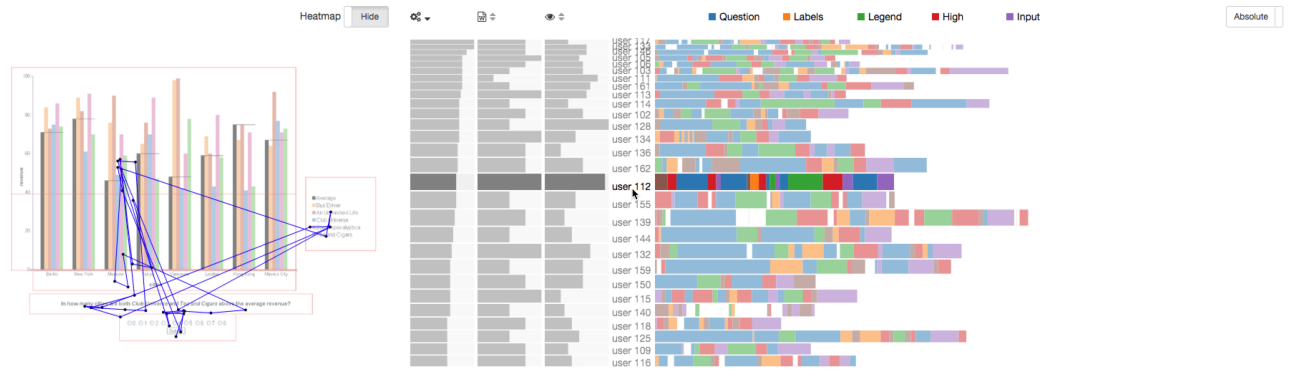

Fig. 4. Fisheye distortion is applied when users hover over a row in the timeline, which is in absolute time scale in this figure. Timeline rows that are not hovered are faded out. The fixations and saccades from the trial represented by the hovered row are displayed in the review panel.
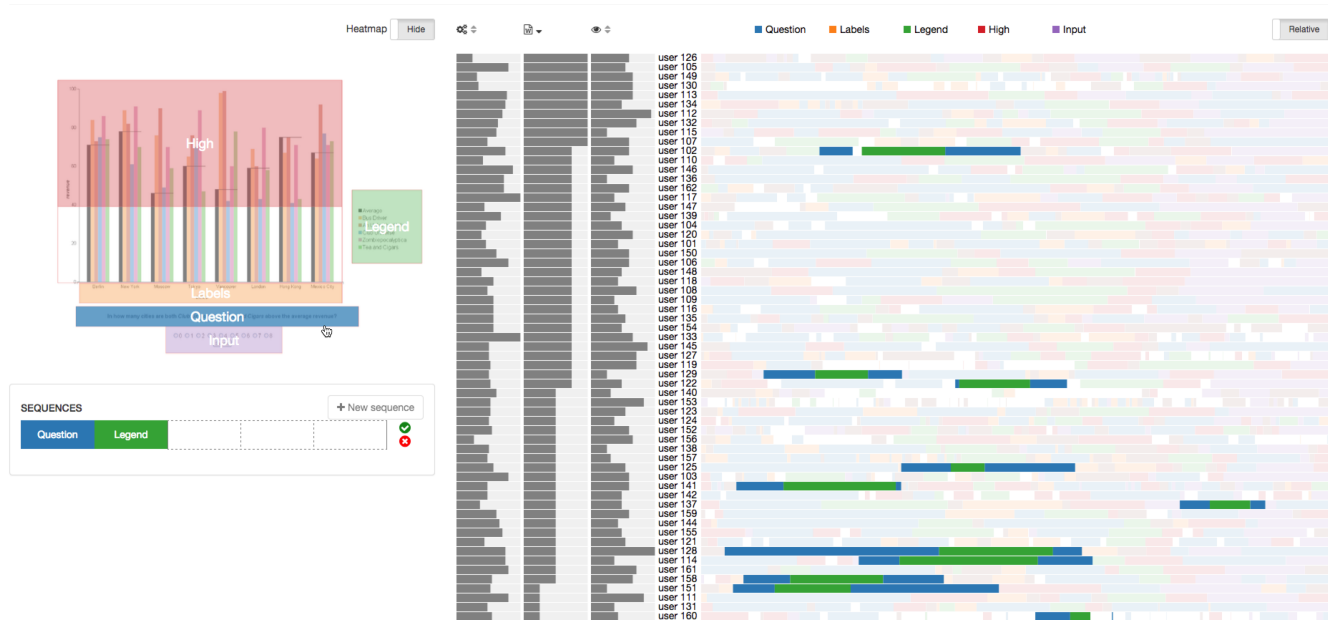
Fig. 5. Sequence pattern creation process. Two AOIs, Question and Legend, have been added to the sequence pattern, as shown in the sequence tool panel in the bottom-right corner. The cursor is hovering over the Question AOI, so every occurrence of the pattern Question-Legend-Question is highlighted in the timeline panel. Note the uneven distribution of the pattern towards the lower half of the timeline that is associated with participants with low verbal working memory capacity.

He sets the timeline to absolute scale and looks to see if the length of the sequences is correlated with any of the user characteristics. He noticed that users with high perceptual speed tend to finish the task faster than those with low perceptual speed.

Then, he sets the timeline to relative scale, hovers over each AOI in the review panel, and examines visits to this AOI in the timeline in terms of location, duration, and frequency to understand the user behaviour in general. He tries sorting the timeline by each user characteristic to see if there are any trends related to these measures.

6.4 Scenario 3: Sequence Pattern Discovery

Jim wants to explore some patterns in the AOI visit sequences, so he goes to the sequence tool panel. After pressing the "New sequence" button, he clicks on the Question AOI, the Legend AOI, and again the Question AOI in the review panel sequentially to define the pattern, which is being added to the list of patterns in the sequence tool panel (Figure 5). At each step during this process, he examines the occurrences of the pattern he has created thus far in the timeline. Finally, he clicks on the green checkmark button to complete the creation of this pattern.

He repeats this process to create a number of other sequence patterns. He sorts the timeline by each user characteristic and hovers over each pattern to look for trend in the occurrences of these patterns in terms of location, duration, and frequency. He finds that the Question-Legend-Question pattern occur more frequently for users with low verbal working memory capacity, so he notes it down for future analysis across all tasks in the experiment.

7 DISCUSSION AND FUTURE WORK

SEQIT aims to aid the exploration and analysis of eye tracking data, which is often large in volume, so the system employs the "overview first, then details-on-demand" mantra [21] as well as focus+context idioms. SEQIT presents the eye tracking data in both the fixation level as well as the aggregated AOI-visit level. The system supports tasks in different stages of the analysis workflow, while giving the flexibility of controls to various parameters.

The interface is carefully laid out and elements nicely align with each other to produce a clean design overall. The web application is built with the bootstrap framework, so layout of the content is adapted to the screen size – most of the features are fully functional on a mobile device. Navigations are clear and easy to use, and icons are used whenever possible to increase the recognizability of the controls. The colours that represent the AOIs are distinct and used consistently across the interface.

Currently, there are certain limitations to the system. First, it supports analysis of only one task at a time, so users cannot compare trends across all tasks. Second, the AOIs must be pre-defined and loaded into the system, that is, dynamic defining AOI is not yet possible. Third, more detailed information can be encoded into the timeline rows to take advantage of the fisheye zooming, which might have a relatively low utility value in the current stage.

For future work, I will resolve the limitations described above among other improvements. I will add the support for comparison across multiple tasks, in which the timeline panel will show all of the tasks performed by one user or a condensed representation of every task by each users. Custom AOIs can be dynamically defined by selecting any regions in the review panel. I will design and implement easy-to-use export tools to save any findings made in SEQIT. Details of the interface can be further fine-tuned, for example, I will add a time axis to the timeline and tooltips for the user characteristic icons, and I will try lowering the saturation in the AOI colours used in the timeline to improve its visual appearance. The style of the saccade can be optimized for easy tracing based on the results in two comparison studies [7, 15].

Developing this visualization allows me to understand my data in a much clearer way. By laying down the sequences in a timeline, I am able to see the gaps and the mix of short and long fixations in the sequences. These findings force me to rethink the process of eye tracking data analyses in the future.

8 CONCLUSIONS

I presented a visualization system, named SEQIT, for sequence analysis of eye tracking data. It supports tasks at various stages of data analysis: the timeline gives an overview of the AOI visits, the sequence tool supports defining and visualizing specific sequence patterns, and the review panel shows the fixations and saccades of the

selected trial. The interface is cleanly designed, fast, responsive, and easy to use. The system offers various controls, such as a toggle to display the time-series data in different scales. Users can perform the intended task of discovering sequences of interests easily in SEQIT. SEQIT with the example dataset is open sourced[1] and available for viewing online[2]; a number of sequences of interest have already been discovered through the use of SEQIT.

ACKNOWLEDGMENTS

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