The VERP Explorer: A Tool for Exploring Eye Movements of Visual-Cognitive Tasks Using Recurrence Plots

Çağatay Demiralp, Jesse Cirimele, Jeffrey Heer and Stuart K. Card

Abstract Eye movement based analysis is becoming ever prevalent across domains with the commoditization of eye tracking hardware. Eye tracking datasets are, however, often complex and difficult to interpret and map to higher-level visual-cognitive behavior. Practitioners using eye tracking need tools to explore, characterize and quantify patterned structures in eye movements. In this paper, we introduce the VERP (Visualization of Eye movements with Recurrence Plots) Explorer, an interactive visual analysis tool for exploring eye movements during visual-cognitive tasks. The VERP Explorer couples conventional visualizations of eye movements with recurrence plots that reveal patterns of revisitation over time. We apply the VERP Explorer to the domain of medical checklist design, analyzing eye movements of doctors searching for information in checklists under time pressure.

1 Introduction

Eye tracking has been increasingly popular in diverse application areas ranging from neuroscience to marketing due to reduced cost and improved quality in data collection. What makes eye tracking attractive in such a wide range of domains is that eye movements often provide an objective signature for visual-cognitive behavior by tracking the sequential attention of users. However, understanding eye movement trajectories is not straightforward. Practitioners in application domains need tools that facilitate not just the interactive exploration of eye movements but also the qualitative and quantitative characterization of patterned structures in eye movements that can be associated with higher-level behavior.

We introduce the VERP (Visualization of Eye movements with Recurrence Plots) Explorer to support the interactive visual and quantitative analysis of eye movements. The

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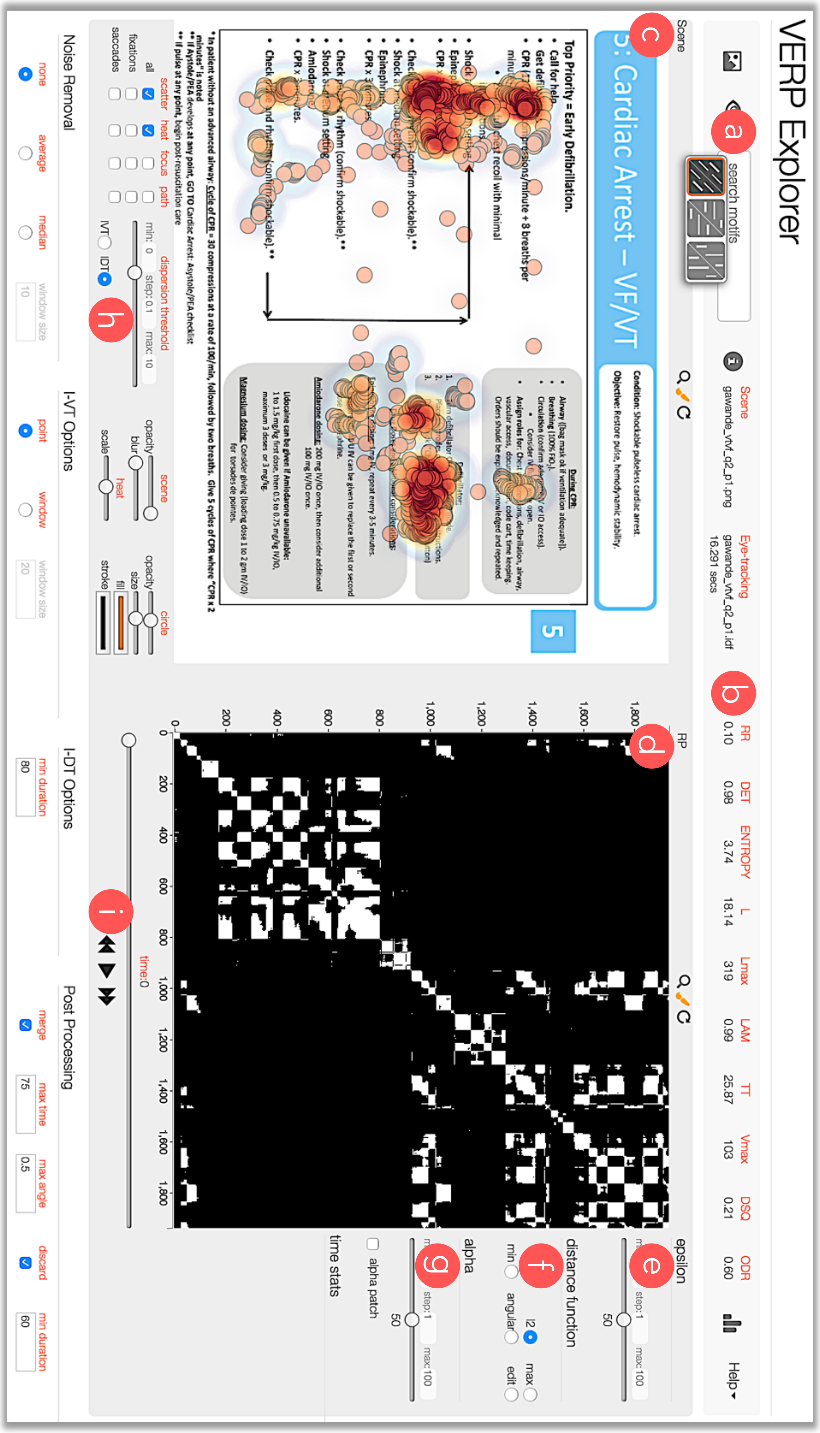
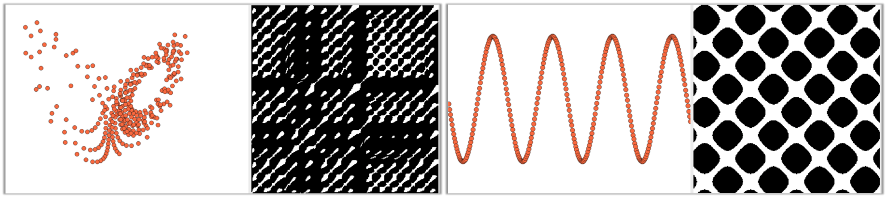


Fig. 1: The VERP Explorer interface has two main views: the scene view (c) and the recurrence plot view (d). The VERP Explorer combines spatial eye movement visualizations with recurrence plots to support the visual and quantitative analysis of eye movements. (See Section 2 for descriptions of the interface elements labeled above.)



Lorenz

Sine

Fig. 2: Recurrence plots of the Lorenz function (left)—projected into the plane—and the sine function (right).

VERP Explorer integrates recurrence plots and recurrence based analysis with several spatial eye movement visualizations such as scatter plots, heat maps, gaze plots and alpha patches. We apply the VERP Explorer to evaluate medical checklist designs based on eye movements of doctors searching for information in the checklists to answer a question.

1.1 Visualizing Eye Movements

Advances in eye tracking technology have made eye movement data collection more practical than ever, increasing the need for developing better visual analysis methods [4]. There are several standard techniques for visualizing eye tracking data including heat maps, focus maps, and gaze plots (scan paths). Understanding differences and similarities in eye movements across subjects is an important goal in eye tracking studies. Earlier research introduces several techniques to reduce visual clutter and support multi-subject comparisons (e.g., [8, 24, 25, 30]). Experts often capture semantics of eye movements by tagging areas of interest (AOIs) on the stimulus and associating them with fixations. Typically borrowing from the text visualization literature (e.g, [19, 35]), prior work also proposes visualization techniques to support AOI-based analysis (e.g., [7, 33]).

1.2 Recurrence Plots

Recurrence plots originate from the study of dynamical systems and were introduced for visual analysis of trajectories [14, 27]. Figure 2 shows the recurrence plots for the Lorenz (left) and sine (right) functions. Notice that the Lorenz function is a multidimensional function parametrized by time. To obtain the matrix $[r_{ij}]$ that is the basis for a recurrence plot, we compare each data value f_i (e.g., the eye tracking sample or value of a time-varying function at time figures/fig$c.pdf$) to all the other values in the sequence, including itself. If the distance d_{ij} between the two compared values is within some small distance ε, then we put a 1 at that position in the matrix, otherwise a 0. Formally,

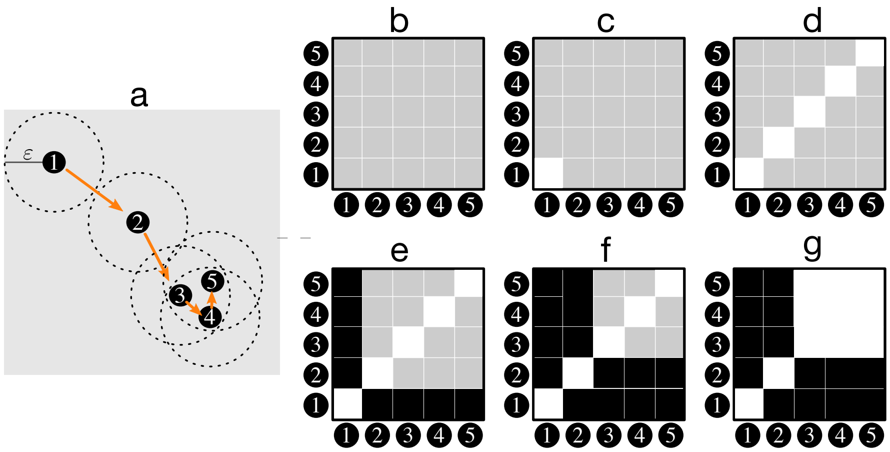


Fig. 3: Construction of a recurrence plot for the eye movements shown in (a). The radius of dotted circles around the points is ε. For every pair of points, we put 1 (white) in the corresponding matrix entry if they are within ε distance (i.e., their dotted circles intersect), otherwise we enter 0 (black).

$$r_{ij} = \begin{cases} 1 & \text{if } d_{ij} \leq \varepsilon \\ 0 & \text{otherwise} \end{cases}$$

Recurrence plots are essentially thresholded self similarity matrices, where what constitutes to be similar is regulated through choices of the distance measure and the epsilon threshold. The VERP Explorer enables users to create recurrences plots of raw eye movements with ability to dynamically change the values of these two parameters.

Figure 3 illustrates how a recurrence graph for eye movements (Figure 3a) is constructed. The dotted circles represent the ε-distance regions around the locations of eye movements. To analyze a visual text search task, for example, we would set ε to be 1.5°, as the radius of the foveal circle in which a person can read the text is about 1.5° [23]. To construct the recurrence plot Figure 3g of the eye movements shown in Figure 3a, we start with a blank matrix Figure 3b. Eye movement 1 is within its own circle so cell (1, 1) is white (Figure 3c). Likewise, all other eye movements fall within their own circles, so the diagonal (i, i) is white (Figure 3d). No other eye movement falls within the circle of eye movement 1, so the rest of row 1 is black Figure 3e. Since the distance metric used is symmetric, the rest of column 1 is black as well (Figure 3f). Eye movement 2 is also not quite in any other eye movement's circle, therefore, except for the cell (2, 2) on the diagonal, its row and column are black (Figure 3f). Eye movement 3 is in the circles of eye movements 4 and 5, so cells (3, 4) and (3, 5) are white, by symmetry, so are cells (4, 3) and (5, 3). Finally, eye movement 4 is in the circle of eye movement 5, so (4, 5) and (5, 4) are also white (Figure 3g).

Recurrence plots are particularly good at characterizing periodic and semi-periodic sequences in a time series. The recurrence graph of a sine wave shown in Figure 2, for example, exhibits strong periodic behavior.

Prior work applies recurrence plots to analysis of speaker-listener eye movement coordination [11, 31] and characterization of eye movements in viewing scenes [1, 37]. Facilitating both visual (qualitative) and quantitative analysis is a powerful feature of recurrence plots. Recurrence quantification analysis (RQA) [28] uses scalar descriptors such as Recurrence Rate, Entropy, Determinism, etc. to quantify different recurrence patterns. Anderson *et al.* [1] apply RQA to characterize the type of the stimulus scene viewed, finding RQA measures to be sensitive to differences between scene types (e.g., indoor vs. outdoor). Building on this work, Wu *et al.* find that differences in eye movement patterns as quantified by RQA correspond to scene complexity and clutter [37].

To our knowledge, our work is among the first to study the goal-oriented task of visual search using recurrence plots of eye movements. The VERP Explorer simplifies exploratory analysis by integrating spatial eye tracking visualizations with recurrence plots and quantified recurrence analysis.

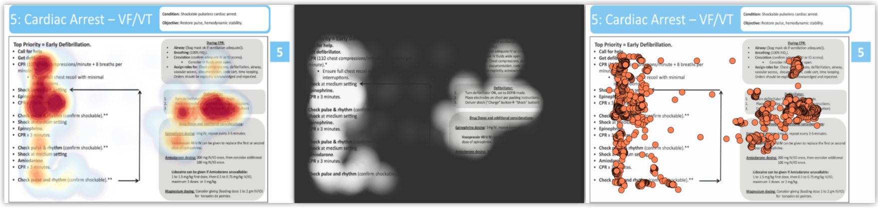
2 Design of The VERP Explorer

The goal of the VERP Explorer is to support the interactive visual analysis of eye movements using recurrence plots. To this end, the VERP Explorer couples several spatial eye movement visualizations with recurrence plots through brushing and linking (Figure1). The VERP Explorer is a web based application implemented in JavaScript with help of D3 [6], AngularJS [2] and heatmap.js [21] libraries. The source code and a deployed copy of the VERP Explorer can be accessed at `https://www.github.com/uwdata/verp/`.

We now briefly discuss the visualizations and interactions that the VERP Explorer supports.

2.1 Heat Maps, Focus Maps, and Scatter Plots

The VERP Explorer enables users to visualize eye tracking positions as heat maps, focus maps, and scatter plots. The three have complementary strengths. *Heat maps* and *focus maps* are two related standard techniques that are useful for providing a synaptic view of eye movements aggregated over time and subjects. The VERP Explorer creates the heat map visualizations by using a Gaussian (radial) blur function with a color gradient (Figure 4). Users can interactively change the maximum value used for normalizing the heat maps. This enables a dynamic adjustment of the color gradient sensitivity. By painting eye movement point densities, heat maps obscure, however, the areas of attention when overlaid on the stimulus image.



Heat map Focus map Scatter plot

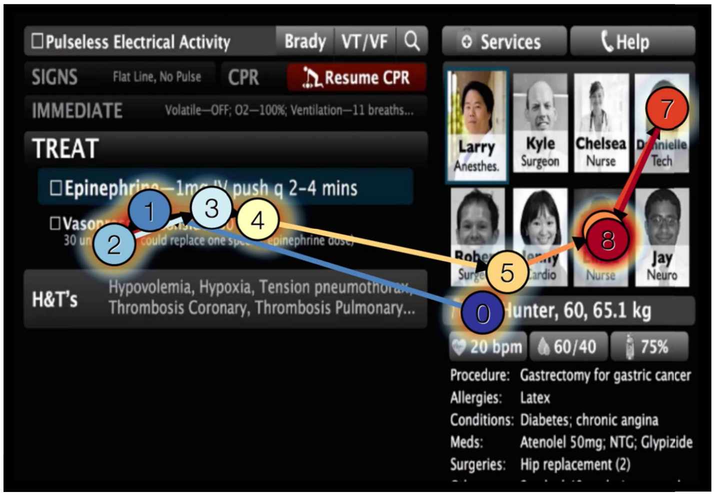
Fig. 4: Three spatial eye tracking visualizations from the VERP Explorer: Heat map (left), focus map (middle), and scatter plot (right). The three visualizations have complementary advantages. Heat maps and focus maps are particularly useful for providing a continuous aggregate view of eye movements and their negative space. Scatter plots directly encode eye movements (as circular nodes here), enabling the exploration of eye tracking datasets at the level of individual eye movements.

Focus maps visually "invert" heat maps to enable the visibility of the areas of viewer attention. To create a focus map, we first create a uniform image (mask) that has the same size as the underlying stimulus image. We then vary the opacity at each pixel inversely proportional to the opacity of the corresponding heat map pixel. Focus maps are essentially negative space representations, visualizing the negative space of the corresponding heat maps (Figure 4).

Heat maps and focus maps support visual aggregation while visualizing eye movements indirectly. On the other hand, *scatter plots* provide a discrete view by representing eye movement positions directly, enabling the inspection of patterns and outliers at the level of individual eye movements. The VERP Explorer creates scatter plot views by drawing each eye tracking position as a circular node in the plane (Figure 4).

2.2 Scan Paths

In their basic, static configuration, neither heat maps nor focus maps convey the temporal order of eye movements. The VERP Explorer uses scan paths (gaze plots) to provide an aggregate temporal view of eye movements. It creates scan path views by drawing circles centered at the centroids of fixation clusters and connecting two consecutive clusters with arrows. The VERP Explorer numbers the nodes sequentially. It also encodes the temporal order of fixations by coloring the nodes and the arrows using a color map ranging from dark blue to red [18] (Figure 5).



Procedure: Gastrectomy for gastric cancer
Allergies: Latex
Conditions: Diabetes; chronic angina
Meds: Atenolel 50mg; NTG; Glypizide
Surgeries: Hip replacement (2)

Fig. 5: Scan path visualization of fixation points. The VERP Explorer uses text, shape, and color to encode the temporal order of fixations. It sequentially numbers the nodes that represents fixation clusters, puts an arrow between consecutive nodes, and colors the nodes and the arrows using a color map ranging from dark blue to red.

2.2.1 Identifying Fixations and Saccades

Note that the VERP Explorer does not assume the eye tracking points are already classified. It provides two different methods for identifying fixations and saccades; velocity-threshold identification (I-VT) and dispersion-threshold identification (I-FT) [32]. I-VT and I-DT are both fast, threshold based algorithms for classifying eye movements into fixations and saccades. I-VT identifies fixations and saccades based on a threshold on point-to-point velocities of eye movements. On other hand, I-DT identifies them using a threshold on spatial dispersion of eye movements. We briefly discuss below our implementation of these two algorithms. See [32] for a comparative discussion of fixation-saccade identification algorithms.

I-VT operates under the assumption that low-velocity eye movements correspond to fixations and high velocities to saccades. Using I-VT, we compute clusters of fixations in three steps. First, we calculate point-to-point velocities for each tracking point. Note that velocities can be computed using spatial or angular distance between consecutive points. We use angular velocities if the head position is provided in the tracking data. We then classify each point as a fixation or saccade using a velocity threshold. If the points velocity is below the threshold, it becomes a fixation point, otherwise it is considered a saccade points. In the final step, we gather consecutive fixation points into clusters (gaze regions).

Due to their low velocities, consecutive fixations have smaller dispersion than consecutive saccadic eye movements. I-DT aims to directly detect fixation clusters using a dispersion threshold on eye tracking points in a moving window. We start by placing the

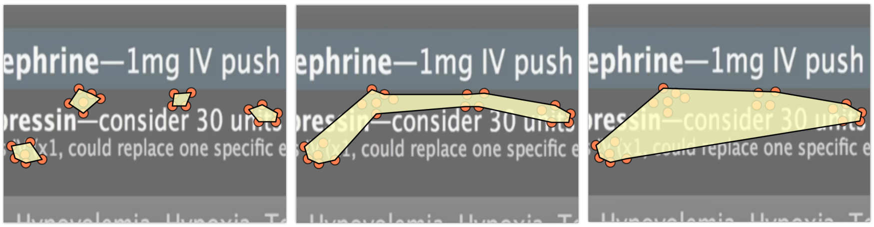


Fig. 6: Four alpha patches with increasing α values from left to right. Notice that, when α is sufficiently large, the alpha patch is the convex hull of the points (right).

window at the first eye tracking point, spanning a minimum number of points. We then compute the dispersion of the points in the window by adding the width and the height of the bounding box of the points. If the dispersion is above a threshold, the window does not represent a fixation cluster, and we move the window one point to the right. If the dispersion is below the dispersion threshold, the window represents a fixation cluster. In this case, we expand the window to the right as far as its dispersion is below the threshold. We designate the points in the final expanded window as a fixation cluster. We then move the beginning of the window to the point excluded from the last fixation cluster and reset the window size to the minimum number of points. We repeat the above process by moving the window to the right until all the eye tracking points are processed.

For both algorithms, the VERP Explorer computes measures such as centroid, geometric median, and duration for each found fixation cluster. More importantly, the VERP Explorer enables users to dynamically modify the velocity and dispersion thresholds or tune the parameters of the algorithms (Figure 1h), while viewing the changing scan path visualizations interactively.

2.3 Alpha Patches

Visual clutter is often a concern in analysis of eye tracking data. We introduce *alpha patches*, alpha shapes [15] of eye movements, to provide a cleaner view of eye tracking positions through filled polygonal patches.

The alpha shape is a generalization of the convex hull of a point set [15]. Unlike the convex hull, the alpha shape can recover disconnected, non-convex spaces with holes. Crucially, it provides a control over the specificity of the polygonal approximation of the underlying points through a parameter $\alpha \in [0,\infty)$ (Figure 6). The VERP Explorer enables users to automatically create alpha patches of fixations with a dynamic control over the α parameter (Figure 1g).

Given an eye tracking point set (e.g., fixations) and an alpha value, we generate the alpha patch for the point set in three steps. First, we create the Delaunay triangulation of the set. Note that the boundary of the Delaunay triangulation is the convex hull of the points in the set. Second, we extract from the Delaunay triangulation the triangles whose vertices are within the alpha distance. The union of the extracted triangles is known as the alpha complex of the point set. In the final step, we determine the boundary of the alpha complex and draw them as simple closed polygons. In our implementation, we create the Delaunay triangulation once and extract alpha complexes for varying—user determined—alpha values as needed.

2.4 Interaction Techniques

The visualizations we have described are interactive, giving rise to a number of exploration techniques:

Zooming & Panning: The VERP Explorer provides zooming and panning interactions on all of the visualizations that it generates. Both zooming and panning are forms of dynamic visual filtering and essential for exploring dense eye movement datasets.

Brushing & Linking: We use brushing & linking in the VERP Explorer to coordinate the scatter plot of the eye tracking data with the recurrence plot view. This is the main mechanism that allows users to inspect recurrence space and spatial eye movements simultaneously. Brushing over a location on the scene highlights all the corresponding entries in the recurrence view. Conversely, brushing on the recurrence plot highlights corresponding eye movement positions represented as circular scatter plot nodes. Brushing regions can be resized or moved using mouse as well as keyboard.

Epsilon Filtering: Epsilon filtering enables the interactive exploration of epsilon values for recurrence plots (Figure 1e). Users can also select different distance measures (Figure 1f). We provide the Euclidean (L_2-Norm), the city block (L_1-Norm), the maximum (L_∞-Norm) and the minimum of the absolute differences along data dimensions. In addition to these general distance measures, users can select eye movement specific distances, including the angular distance and edit distance (to be used if eye movements are associated with textual tags).

Alpha Filtering: Similar to epsilon filtering, alpha filtering allows users to dynamically change the α parameter of the alpha patches. This enables a control over the precision of the polygonal representation for the underlying eye movements (Figure 1g).

Dynamic Fixation-Saccade Classification: The VERP Explorer also enables users to change the threshold for fixation-saccade classification dynamically. This is particularly useful when angular velocity calculations are not possible or reliable (Figure 1h).

Motif Search and Quantification: Recurrence plots facilitate pattern-based analysis of time varying data. One of the motivations of the current work is to help relate behavioral eye movement patterns to visual design through recurrence patterns. The VERP Explorer computes (Figure 1b) several recurrence quantification measures such as Recurrence Rate (RR) and Determinism (DET), Entropy (ENTROPY), etc. (See [28] for detailed discussion of recurrence quantification measures.) In addition, VERP Explorer enables the search for predefined, arbitrary patterns in the recurrence plots (Figure 1a). Currently users can search for diagonal, vertical and horizontal recurrence structures.

Timeline Animation: While the scan path visualization provides an aggregated temporal view of the eye movement, it is desirable to be able to directly examine the timeline of the complete data. The VERP Explorer enables users to animate the appearance of eye tracking points using the scatter plot visualization (Figure 1i).

3 Illustration of Use: Visual Search in Emergency Medical Checklists

The purpose of visualization is to ease and amplify the work of cognition by re-coding information so as to exploit the perceptual abilities of the eye. To design for the eye, we have principles at a general level—the principles of perception, the gestalt laws, etc.—but to gain more insight, we need to understand the lower-level mechanisms forming these principles. Insights and models derived from lower-level empirical data can inform higher-level visual design principles [13]. Fortunately, eye movements often track the sequential attention of the user, affording a unique window into visual-cognitive interactions. Analyzing eye movement patterns can therefore provide useful insights into the effectiveness of a visual design.

To illustrate the use of the VERP Explorer for exploring a cognitive-visual task, we use the task of designing visual displays for emergency medical checklists. In U.S. hospitals, it is estimated that medical errors cause in excess of 100,000 deaths per year, half of which are thought to be preventable [22]. Checklist use has been found to improve performance in aviation [5, 9, 12] and medicine from surgery to intensive care and crisis response [3, 16, 17, 20, 26, 29, 38]. However, checklists have been criticized for adding delay, attentional load, and complexity [16, 36], slowing down crucial medical procedures. As Verdaasdonk *et al.* [34] put it, “Time governs willingness and compliance in the use of checklists.” It would therefore be desirable to improve the speed (and accuracy) with which aids can be used.

3.1 Comparing Two Checklist Formats

We compare two checklist designs. The first design is from the World Health Organization (“Standard”) and is an example of current best practice [22]. The second is a dynamic format (“Dynamic”) for which the current checklist step is enlarged and more distant steps shrunk or hidden [10]. For purposes of the illustration, we consider data only from five participants (doctors) collected while they were searching the checklist to answer a single question: *What is the correct dose of atropine?* We used an eye tracker that is accurate to approximately 0.5 deg to 1 deg of arc.

To start, we compute the average time to answer the question with each checklist format. The result is that the Dynamic checklist format is 32% faster than the Standard format. But we would like more insight into why. We therefore analyze the eye movement data with the VERP Explorer. We load the image of the checklist and the eye movement data files into the VERP Explorer. At this point, the many controls of the VERP Explorer allow us to tailor an analysis to our interests.

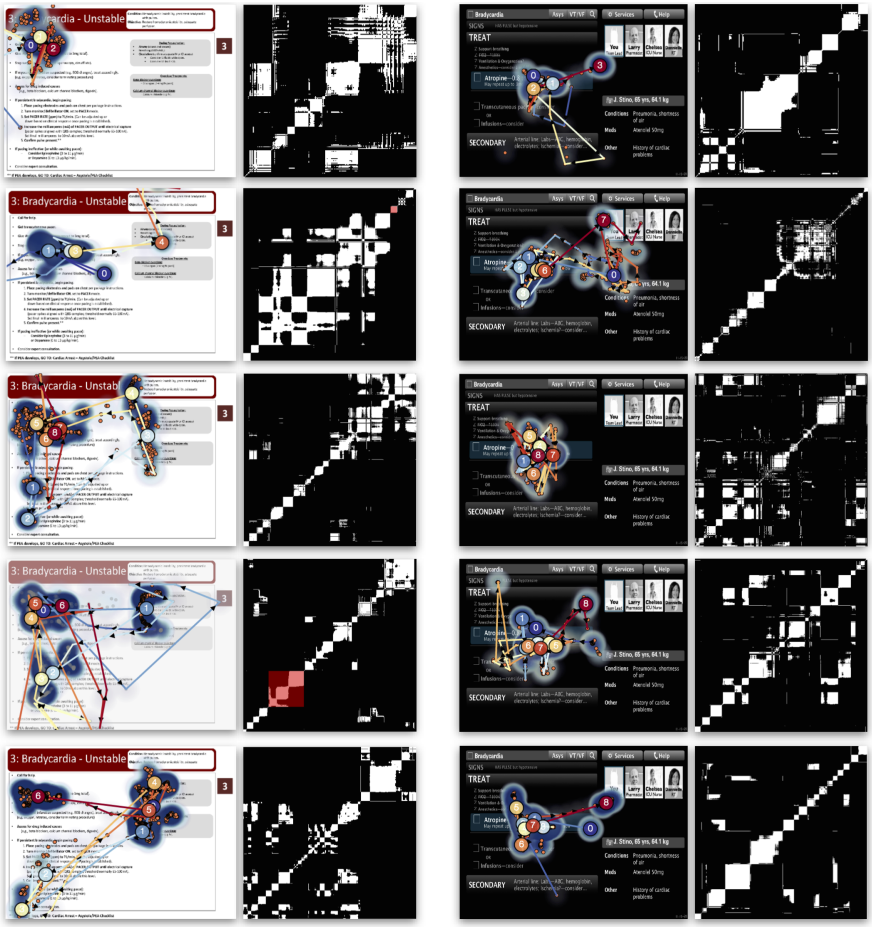


Fig. 7: Analysis eye movements of five participants using two checklist designs. Left pair of columns shows eye movements along with gaze plots and recurrence plots for Standard emergency checklist. Right pair of columns shows Dynamic checklist. Both are arranged from fastest on top to slowest. Generally there are more of them and they are less organized for slower trials.

Figure 7 shows the screenshots from the VERP Explorer for the eye movements of the five doctors. They are arranged in order from the fastest trials to the slowest trials for each format.

Study Squares: The first thing to notice is that the eye movements for searching through text exhibit very different recurrence patterns than the semi-periodic function applications in Figure 2 investigated in the earlier literature. The recurrence plots of visual text search consist mainly of square patterns (*Study Squares*) comprised mainly of fixations, separated by subsequences of saccades on the diagonal.

To this basic patterns are added off-diagonal lines and squares representing regressive re-viewing of previously seen parts of the display (i.e., cycles). The Study Squares come about as in Figure 3 from a group of eye fixation points in close proximity, that is, exhibiting locality of reference. The more intensively some part of the scene is looked at, the larger the size of the square. Some squares have a checkerboard character, indicating that the doctor shifted her gaze to another part of the scene and then back. Searches taking more time often appear more scattered, reflecting the disorganization of the search. The brushing tools provided with VERP allow us to discover where square motifs on the recurrence plot are located in the scene.

Inadvertent Detractors: We have concentrated on the general patterns in the eye movement, but since the eyes are controlled both in reaction to visual stimuli as well as cognitively in service of a goal, we also discover unexpected details. Such was the case with these analyses. In four out of five of the Dynamic format screen shots in Figure 7, the eye has been attracted to the pictures of doctors attending. This features was included in the format, because it is often the case that attending medical personnel do not know each others names, which in turn makes it difficult to address direct requests to a named individual—an important element of disciplined coordination to prevent requesting participant from thinking some task has been done, whereas no one actually accepted responsibility for doing it. It did not occur to the designers of this format that the high contrast of the picture to the dark background would interfere with the acquisition of information in the checklist by inadvertently attracting the eye, although this is obvious once it is pointed out. This is a type of problem that can remain invisible and decrease user performance despite a basically sound design. The VERP Explorer enabled us to find this problem easily.

4 Discussion and Conclusion

Eye movement based analysis provides a unique opportunity for evaluating the effectiveness of a visual design. Eye movements are, however, lower-level manifestations of visual-cognitive interactions that need to be mapped to the behavior the designer usually needs.

We developed the VERP Explorer to support interactive visual and quantitative analysis of eye tracking datasets using recurrence plots. The VERP Explorer is an open source web application available at *https://www.github.com/uwdata/verp/*. We applied it in comparing medical checklist designs based on eye movements of doctors searching for information in the checklists. We focused on visual search task and characterize eye movements of visual search through recurrence plots and other visualizations provided by the VERP Explorer.

Eye tracking hardware is becoming a commodity with ever expanding range of applications. To better utilize the increasingly ubiquitous eye tracking data, we need tools to better map patterned structures of eye movements to visual-cognitive behavior in application domains. The VERP Explorer is a contribution to our toolbox for that end.

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