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

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ABSTRACT

Evaluating the effectiveness of the visual design of an interface is an important yet challenging problem. In this paper, we introduce The VERP (Visualization of Eye movements with Recurrence Plots) Explorer, a 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. We find that the recurrence plots are characterized square recurrence plot "motifs". At a higher level, we introduce the idea that these square motifs are part of a pattern of "visual micro-foraging" in which the searcher searches for a relevant information patch, then spends effort trying to understand the patch well enough to extract the search question answer, repeating the process as necessary. The analysis also reveals unexpected distractors in the design.

Author Keywords

Visualization, HCI theory, visual search, eye-movements, recurrence plots, motifs, quantified recurrence analysis (QRA), sequential behavior, time series, information foraging theory, visual micro-foraging.

VISUAL-COGNITIVE INTERACTION

Cognitive interaction with visual displays drives many interactive human-computer systems; yet, designing and engineering such systems can be problematic. General principles can be applied in generating the display, but it is difficult to understand the details of how the principles affect actual user behavior. Adding to the difficulty, a principle may be right in general, but defeated by particulars of a given case. Better methods for understanding how well a visual-cognitive design is working would be helpful.

Fortunately, eye movements afford a window into sequential visual-cognitive interactions. But eye movements are at a different behavioral level from the design decisions being addressed, requiring anecdotal use of observations or questionable aggregation methods. This paper proposes a set of analytical methods that may help with this problem, especially the specific problem of visual search. Our methods have two main goals: (1) to raise the level of the behavioral characterization for the designer so that she may more easily understand the good and bad characteristics of a prototype visual design for a given system, and (2) to package the methods into an integrated tool, The VERP (Visualization of Eye Movements using Recurrence Plots) Explorer, so as to make them easy and rapid to use. In order to accomplish these purposes we characterize the sequential behavior of eye movements using recurrence plots (rp's), motifs (rp patterns), and recurrence quantification analysis (RQA). Our analysis leads us to the proposal that visual search can be additionally characterized at an even higher level, by a variety of information foraging theory we term visual micro-foraging, for which we propose visualizations and micro-foraging quantification metrics. As an illustration of their use, we apply these methods to the analysis of designs for emergency medical checklists for hospital operating rooms.

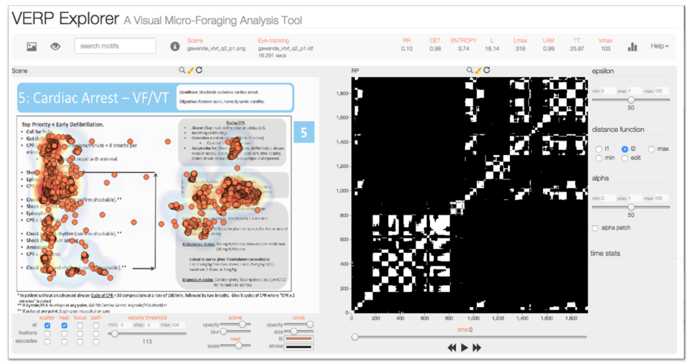

Figure 1. The VERP Explorer interface.

Eye Movements

Eye movements afford a window into visual-cognitive interactions. Eye movements are part of the brain's strategy to trade time-resolution for bandwidth. Spatially, the high bandwidth part of the eye, the fovea, covers only a very small portion, from the center of the visual field out to about 1 deg, of eccentricity. In this small region, the eye is densely packed with the cones required for color vision and high resolution. From about $1 \sim 5$ deg, the mixed cones and rods of the parafovea, provide resolution too low for reading 12 pt text, but enough cones remain for limited color [23]. Beyond 5 deg is the periphery, consisting predominantly of rods that can detect large, high-contrast features and motion. If we combine the field for the two eyes, the periphery extends about 130 deg high and 200 deg wide and consists of low spatial frequency blobs. Neglecting the specialized eye movements for image stabilization and pursuit, dynamically, the small, high-resolution portion of the eye jerks and pauses across the visual field, assembling an integrated view of the world gleaned during the pauses at a time resolution of about three samples per second. This implies that there are about 150,000-200,000 eye-movements per day every day for life, requiring that eye-movements be metabolically very cheap. The eye is constantly moving, sampling from the visual field to build up a percept or to attend to areas of high information content, such as moving objects. The successions of eye movements extract interpretations from high-information features like sharp corners and gestalt continuity. As objects are examined, their locations become visually indexed so that search time to relocate them is reduced. As a result, objects may form a spatial external working memory indexed relative to large, low spatial frequency, blobby features. Eye movements are under competing control of the task, the attraction of unknown high-contrast blobby elements, and a continuous monitoring for movement or change. The upshot is that eye-movements tend to track the sequential attention of the user giving important clues into the detail of visual-cognitive interaction, but the clues are not always straight-forward to interpret.

Visualizing Eye Movements

Advances in eye-tracking capability and practicality has brought increased interest in developing better visual analysis methods for eye-movement data [4]. There are several standard techniques for visualizing eye-tracking data, including heat maps, focus maps, and gaze plots (scan paths) [21].

Heat map visualizations are widely used for displaying aggregated patterns of eye movements. However, they suffer from over saturation when the underlying data is dense. Heat maps can also be misleading if the color map isnt chosen carefully [6]. Related to heat maps are focus maps. A focus map is an image mask that shows the underlying stimulus image at eye-tracking points. The degree of visibility at a particular stimulus region is proportional to the density of the tracking points at that region. Missing from heat maps and focus maps is a temporal view of the data. Understanding temporal patterns in eye tracking is important as they change not only by the visual stimulus but also by the task [38]. Animated heat maps and gaze plots are widely used to visualize the time ordering in eye tracking data. Animations may, however, cognitively overload viewers trying to grasp the temporal context [34].

Understanding differences and similarities in eye movements across subjects is an important goal in eye-tracking studies. However, basic configurations of heat maps and gaze plots suffer from visual clutter when the underlying eye tracking data is dense [4]. Prior work uses several techniques to reduce visual clutter and support multi-subject comparisons. Raschke *et al.* [31] introduce a parallel scan-path visualization to facilitate the comparison of eye-tracking data across users. Earlier research also applies the space-time cube visualization to eye movement trajectories [26, 25]. Originally proposed for geographic movement analysis [16, 24], the space-time cube visualization treats time as the thirdspatialdimension, enabling static visualizations of multiple eye-movement trajectories in 3D. Reducing visual complexity often requires aggregating and sampling the data, while introducing simpler abstract representations without losing the original data context. Burch *et al.* introduce saccade plots that combine a heat map and a graph-based matrix representation for aggregated movement directions [9]. Experts often capture semantics of eye movements by tagging areas of interest (AOIs) on the stimulus image and associating them with fixations. This also reduces the cognitive complexity as the experts care more about what the viewers look at than where they look at. Prior research borrows from text visualization techniques to visualize AOIs. Tsang *et al.* [33] applies the WordTree visualization [36] to AOI tags concatenated based on their order in eye-movement trajectories. Similar to ThemeRiver [19], AOI Rivers [8] visualizes fixation frequencies of AOIs as flow maps. While the spatial context is accessible only indirectly, the flow map visualization reduces the visual clutter that would be otherwise caused by use of gaze plots. The VERP Explorer couples several of the standard eye-tracking visualizations above, including heat maps, focus maps, gaze plots, with recurrence plots and other new visualizations through interaction.

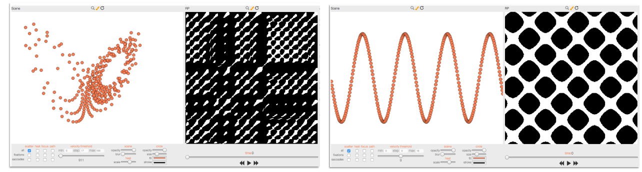

Figure 2. (Left) Recurrence plot of the Lorenz function—projected into the plane. (Right) Recurrence plot a sine wave.

Recurrence Plots

Recurrence plots are a type of non-linear analysis that has been used in the study of dynamical systems and other areas [13, 28]. Figure 2 shows the recurrence plots for the Lorentz (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 start with the first data value (e.g., the value of a time-varying function at time zero or the first eye-tracking position) f_1 and compare it to all the other values in the sequence, including itself. If the distance between the two compared values is within some small distance then we put a 1 at that position in the matrix, otherwise a 0.

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

Coloring all of the one-cells white and the zero-cells white, we get the recurrence plot.

Recurrence plots are particularly good at picking up periodic and semi-periodic sequences. The recurrence graph of a sine wave shown in Figure 2 (), for example, exhibits strong periodic behavior in the recurrence plot shown on the right. Recently recurrence plots have recently been applied to eye movements [1] for natural scene viewing. In this paper, we

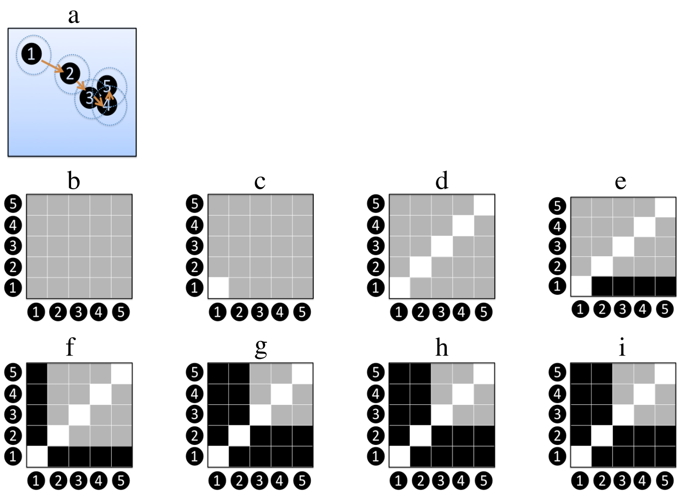

Figure 3. Construction of a recurrence plot.

integrate previous techniques of eye-movement and recursion plot analysis into an interactive tool, simplifying exploratory analysis. We use the tool to study visual search, which to our knowledge has not been studied in this way. We find a higher level organization for the behavior revealed by the eye movements and to propose visualization of this behavior.

Figure 3 shows in more detail how a recurrence graph for eye movements is constructed. We start with a *s*cene Figure 3a representing a set of eye-movements plotted over the (static) scene in the field of view of the participants. The small circle outside of the eye fixation location indicates the 1 to 2 deg fovea (we shall use 1.5 in our illustration) around the point of regard. For our purposes, one eye fixation overlapping the circle of another will be considered as the same point of regard. That is, $\epsilon =$ diameter of the fovea $= 2 \times 1.5deg = 3deg$.

Given a sequence of eye movements, we draw circles around each fixation point to indicate the 1.5 deg foveal area in which a person could read the text. To construct the recurrence plot Figure 3i of Figure 3a, we start with a blank matrix Figure 3b whose cells are the width of the foveal area. Eye fixation 1 is within its own circle so cell (1, 1) is white (Figure 3c). Likewise, all other fixations fall within their own circles, so the diagonal (i, j) is white (Figure 3d). No other fixations falls within the circle of fixation 1, so the rest of row 1 is black Figure 3e.

Since the matrix is symmetric, the rest of column 1 is black as well (Figure 3f).

Fixation 2 is also not quite in any other fixations circle, therefore, except for the cell (2, 2) on the diagonal, its row and column are black (Figure 3g).

Fixation 3 is in the circle of both fixation 4 and fixation 5, so cells (3, 4) and (3, 5) are white, by symmetry, so are cells (4, 3) and (5, 3) (Figure 3h). Finally, fixation 4 is in the circle of fixation, so (4, 5) and (5, 4) are white (Figure 3i).

DESIGN OF THE VERP EXPLORER

Our primary goals for developing the VERP Explorer were to first to provide an interactive tool for applying recurrence-based analysis, integrating it with other eye movement techniques, and second to use these methods to get a higher order representation of the analyzed behavior, especially in regard to visual search. Figure 1 shows a screenshot for the VERP Explorer tool. In the tool eye movement data are plotted twice: in the scene view on the left and in the recurrence plot view on the right. Both views are coordinated through brushing and linking. We now discuss the design of visual representations and interaction techniques in the VERP Explorer to support these goals.

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. While all the three methods primarily encode eye-movement positions and are typically overlaid on the stimulus scene, they have complementary strengths.

*H*eat maps and *f*ocus maps are two related standard visualization 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 drawing semi-opaque disks centered at eye-tracking positions. The disks are filled with a color gradient and their opacity is modulated (decreased) with the distance from the disk center (Figure 4). By painting eye-movement point densities, heat maps obscure, however, the areas of attention when overlaid on the stimulus image. Focus maps visually invert heat maps to enable the visibility of the areas of viewer attention. To create a focus 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 visualize eye movements indirectly, facilitating visual aggregation. On the other hand, *scatter plots* provide a discrete view by representing eye-movement positions directly. The VERP Explorer creates scatter plot views by drawing each eye tracking position as a circular node in the plane (Figure 4). Scatter plots are useful for seeing patterns and outliers in eye-movements, while enabling the inspection of individual eye-movement positions. We also use the scatter plot view for the timeline animation, as it provides a discrete representation of the tracking positions.

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

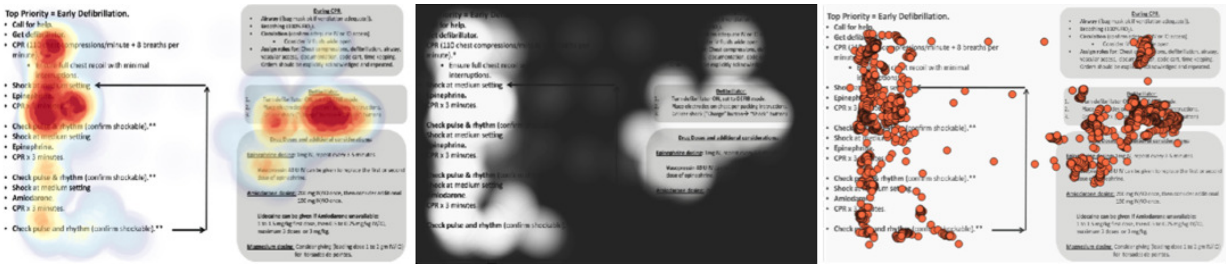

Figure 4. Three spatial eye-tracking visualizations from the VERP Explorer: Heat map (left), focus map (middle), and scatter plot (right).

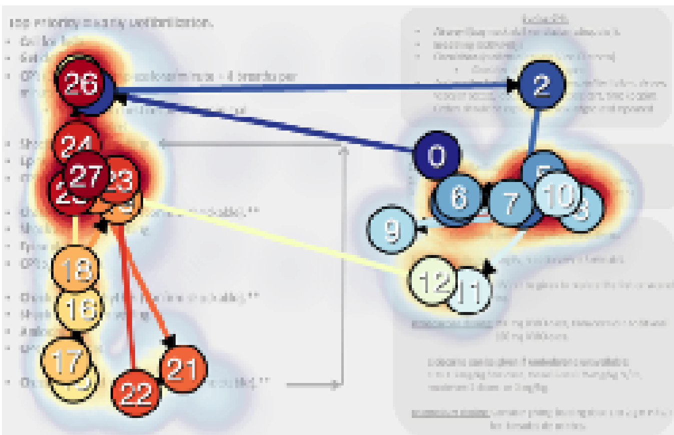

Figure 5. Scan path.

red [18] (Figure 5). We generate the fixation clusters using the velocity-threshold fixation (I-VT) algorithm [32]. I-VT is a fast and robust algorithm for identifying fixations and saccades based on their point-to-point velocities. I-VT operates under the assumption that low-velocity eye movements correspond to fixations, while high velocities to saccade. We now describe the algorithm briefly. See [32] for a detailed, comparative discussion of fixation identification algorithms. Using I-VT, we compute clusters of fixations in three steps. We first 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 (our default value is 300/s). If the points velocity is below the threshold, it becomes a fixation point, otherwise it is considered a saccade points. The VERP Explorer lets users interactively modify the velocity threshold using a sliding bar. In the final step, we gather consecutive fixation points into identical clusters and compute associated measures such as the cluster centroid and duration. We set the minimum cluster size to twenty. Clusters with fewer than twenty fixation points are discarded.

Alpha Patches

Visual clutter is often a concern in eye tracking data visualization. We introduce α-patches, α-shapes [14] of fixation points, to provide a cleaner view of underlying eye-movement locations. α-patches enable users to visualize fixated regions as filled polygonal patches. Figure 6 shows α-shapes of a point set with varying α values.

Figure 6. Alpha patches with increasing alpha values from left to right.

The α-shape is a generalization of the convex hull of a point set [14]. The primary advantage of α-shapes over the convex hull is that α-shapes can recover disconnected, non-convex spaces with holes. Specifically, for a given real parameter $\alpha \in [0, \infty)$, α-balls are balls of radius α centered at the points in P. The α shape of P is then the union of the convex hulls of the points whose α-balls intersect. The VERP Explorer enables users to automatically create shapes of eye-movement positions, which we call α-patches.

We now discuss our algorithm for deriving patches. Given an eye tracking point set (e.g., fixations) and an value, we generate the shape 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 α distance. The union of the extracted triangles is known as the α-complex of the point set. In the final step, we determine the boundary of the α-complex and draw them as simple closed polygons.

In our implementation, we create the Delaunay triangulation once and extract α-complexes for varying—user determined—α values as needed.

Interaction Techniques

The visualizations we have described are interactive, giving rise to a number active 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 view 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.

The ability to interactively aggregate, sample and filter data is key to exploring and untangling complex datasets. The VERP Explorer enables to users dynamically change the visualization and analysis parameters.

Epsilon Filtering. Epsilon filtering enables users to explore custom ranges of epsilon values for recurrence plots. These changes are also reflected in measures calculated. Users can also select different distance measures. 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 and the edit distance.

Alpha Filtering. Similar to epsilon filtering, alpha filtering The VERP Explorer allows users to change the α parameter of the α-shapes dynamically. This enables creation of a multi-scale, coarse-to-fine, view of the underlying eye-tracking data.

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

Timeline Animation. While the scan path visualization provides an aggregate 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 in the scatterplot view. Users can set the speed of the animation or manually control it by dragging the animation sliders handle.

Motif Search. Recurrence plots facilitate pattern-based analysis of time varying data. One of the motivations of the current work is to relate behavioral eye-movement patterns to visual design through recurrence patterns. The VERP Explorer enables users to search for predefined patterns through the recurrence plot (Figure 7). Currently users can search diagonal, vertical, and horizontal structures, which are important in recurrence-based analysis. Search results are highlighted in the scatter plot view as well as the recurrence plot view. Note that the pattern search excludes the main diagonal of recurrence plots from the search.

Recurrence Quantification Analysis

Developing quantitative metrics expressing features of recurrence plots is one way in which we can compare groups of subjects, trials, tasks, or visual situations and is called Recurrence Quantification Analysis (RQA). Several measures have been proposed in the general recurrence plot literature. An-

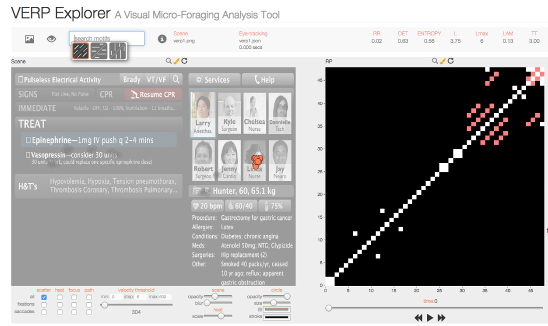

Figure 7. Diagonal pattern search result in the VERP Explorer. .

derson [1] selected a set a set of measures likely to be useful for eye movements. We implemented Anderson's set in VERP. These include:

Recurrence Rate (RR). This is the percentage of cells in the recurrence plot that are white. It measures how many of the visual positions in the scene are looked at more than once. In general recurrence plots, this metric is strongly affected by the value chosen for ϵ. But since we have a natural way of setting epsilon as equal to the foveal diameter projected onto the display, this metric has more physical meaning.

$$RR = \frac{1}{N(N-1)} \sum_{i \neq j} R(i,j)$$

Determinism (DET). This is the proportion of recurrent points forming diagonal lines. The metric picks up repeated scan patterns.

$$DET = \frac{\sum_{\ell=\ell_{min}}^{N-1} \ell H(\ell)}{\sum_{i \neq j} R(i,j)}$$

Average Diagonal Line Length (L). This is meant to pick up the average length of repeated scan paths.

$$L = \frac{\sum_{\ell=\ell_{\min}}^{N-1} \ell H(\ell)}{\sum_{\ell=\ell_{\min}}^{N-1} H(\ell)}$$

Maximum Diagonal Line Length (Lmax).

Entropy (ENTR). Shannon entropy based on diagonal line histograms.

$$ENTR = \sum_{\ell=\ell_{\min}}^{N-1} p(\ell) \ln p(\ell)$$

Laminar Phases (LAM). Analogous to DET, but uses vertical lengths.

$$LAM = \frac{\sum_{v=v_{min}}^{N-1} vH(v)}{\sum_{i \neq j} R(i,j)}$$

Trapping Time (TT). Trapping Time is the average length of the vertical recurrence structures.

$$TT = \frac{\sum_{v=v_{\min}}^{N-1} vH(v)}{\sum_{v=v_{\min}}^{N-1} H(v)}$$

Implementation

The VERP Explorer is a web-based application and can be accessed at [*anonymized for blind submission*]. We implemented The VERP Explorer in JavaScript using D3 [7] and AngularJS [2] libraries. The source code along with example datasets are also available at [*anonymized for blind submission*].

ILLUSTRATION OF USE: VISUAL SEARCH IN EMERGENCY MEDICAL CHECKLISTS

We now describe a task designed to serve both as an illustration of the use of the VERP Explorer and a pilot shakedown test as part of VERP's development. As an illustration of the use of the VERP Explorer for exploring a cognitive-visual task, we will use the task of designing visual displays for emergency medical checklists. In U.S. hospitals, estimates range in excess of 100,000 deaths per year associated with preventable harm, and serious complications may be ten to twenty times more common [22]. In general, these incidents are not caused by lack of skill, but rather by the complexity of the task. Checklists have the opportunity for tremendous impact by helping doctors manage cognitive complexity [15]. Checklist use improves performance in aviation [5, 12, 10] and medicine from surgery to intensive care and crisis response [3, 15, 17, 20, 27, 30, 39].

However, checklists are not a panacea. Checklists have been criticized for adding delay, attentional load, and complexity [15, 37], slowing down crucial medical procedures. As Verdaasdonk *et al.* [35] 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.

Comparing Two Checklist Formats

For our illustration, we want to compare two formats for checklists (Figure **??**). The first format is from the World Health Organization and is an example of current best practice [22]. The second is a dynamic format for which the current checklist step is enlarged and more distant steps shrunk or hidden[11].

Participants, who were medical doctors, were seated in a chair at a fixed distance of approximately 2' from a 22" monitor with a 1680 1050 pixel resolution. After reading a question, they pressed the spacebar in order to show the aid. Once they found the answer, they said the answer aloud, and pressed the spacebar again to advance to the next question. The experiment measured response time for answers as the interval between spacebar presses. Each session was videotaped, and a SMI RED eye-tracker captured participants eye movements. This eye-tracker requires no restraint or equipment to be worn, and is accurate to approximately 0.5 to 1 deg of arc. For our illustration, we will select only data pertaining to

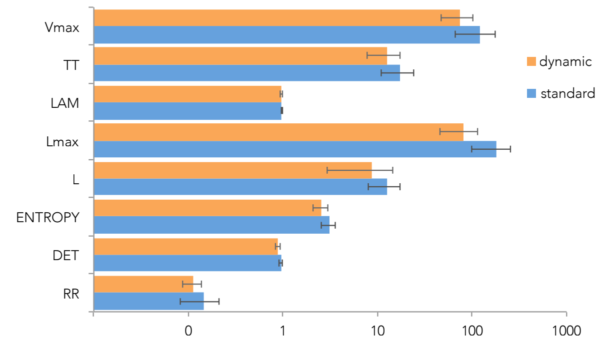

Figure 8. RQA measures: standard vs. dynamic.

the question: *What is the correct dose of atropine?* We will only consider data from five participants and two checklist formats giving us 10 eye-tracker sessions. Using this illustrative data, we now seek show how The VERP Explorer can help the designer to discover more insight about the structure of the checklist task and how successful the proposed design is.

Figure 9 shows the comparison between the standard checklist and our intended improvement. To establish that that the two formats result in different search times, we compute that the average search time for the dynamic format is 32% faster than the standard format. Now we use VERP to gain additional insight.

Recurrance Plots and Motifs. VERP outputs from the eye movements of five doctors are plotted in Figure 11. They are arranged, within format, in order from the fastest trials to the slowest trials. The first thing to notice is that the recurrence plots consist mainly of square patterns with some vertical and horizontal lines. The patterns look nothing like the patterns in Figures [xx fig2] and [xxfig3]. This leads us to our first conclusion. *Eye movements exhibit very different patterns than the semi-periodic function applications investigated in the earlier literature.* We recall the square pattern from Figure 3. These 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 exampled, 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. It should be noted that the recurrence plots have been normalized to the number of eye movements. This means that recurrence plots to tasks that were accomplished more quickly will have fewer eye movements and thus the image will appear relatively magnified, exaggerating the scatter on faster tasks.

Our second conclusion is that *It would be helpful to formalize more the patterns identified from the recurrence plot and build up catalog of these patterns.* Recurrence plots often contain pattern elements that are identifiable building blocks

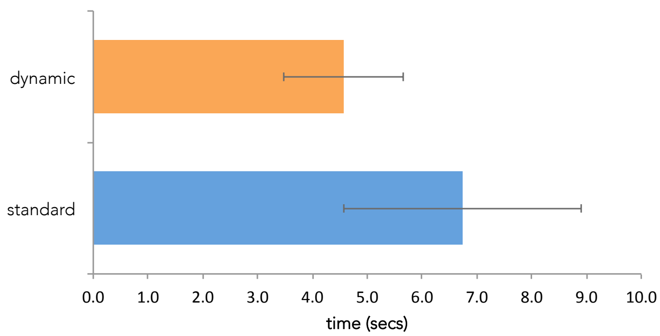

Figure 9. Standard vs. improved times.

of the recurrence plot and the behavior it expresses. Inspection of the eye movement rp's for our visual search task leads us to here propose the following patterns, which we will call textual visual search *m*otifs. [xx We applied our implementation of the RQA analysis suggested by [xx Anderson 2013] (see [xx Fig 8]). The differences between the metrics for the faster and slower format were modest, although there were some differences, particularly for Vmax and L. Our third conclusion follows is that since the rp patterns are so different, that is that motifs should be developed taking this into account and that there is an opportunity to develop RQA at several levels. We propose three levels [xx See Fig xx]. At Level 1, the Immediate Level, we are concerned with local patterns that could be detected with a template that looks at a cell and it's immediate neighbors:

Glance NowStudy Later. These present as horizontal lines (above the diagonal). The eyes come back to study something they noted briefly before.

Study NowRefer Later. These present as vertical lines (above the diagonal). The eyes study something when it is first encountered, then glance back at it later.

Study Square. The dominant motif in the recurrence plot of Figure 3 is a study square. It appears in Figure 3 as a consequence of multiple fixation points of regard in close proximity. The larger the square, the more fixation points, the more intensity is indicated the study.

At Level 2, the Extended Level, we are concerned with how our Level 1 mosaics function as components for a higher level pattern. The Level 2 motifs we have discovered are larger scale versions of the Study Square pattern.

On-Diagonal Extended Study Square. This pattern extends out from the diagonal an indefinite distance. The square indicates a cluster of eye movements in a fixed space, for example trying to extract and act on information on dosage or reading ingredients on a food label.

Off-Diagonal Extended Study Square. Again, the square indicates a cluster of eye movements in a fixed space, for example trying to extract and act on information on dosage or reading ingredients on a food label. These motifs are likely to indicate a distraction or a difficult search.

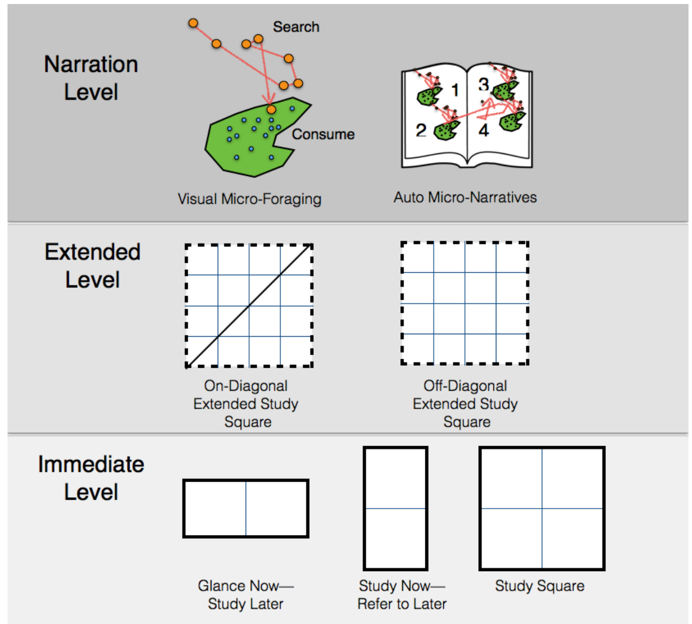

Figure 10. Motifs.

But the most interesting level of motif we have seen is at Level 3, which we have called the Narration Level. Level 3 is high enough that the patterns relate to the terms of the task. So far, we have been considering eye movements individually, but the square motif in our recurrence plots suggests that they interact in groups: a sequence of saccades to a position on the checklist followed by a set of fixations around that area (see [xx Fig FF]) Notice that the square motif appears regardless of the order of the fixation within the cluster. This pattern is similar to the patterns found in information foraging theory [29].

Visual Micro-Foraging

According to information foraging theory, the organism is trying to maximize the rate of information gain, R, which is equal to the ratio of net information gain, U, divided by the time spent T in foraging.

$$R = \frac{U}{T} = \frac{U_f - (C_s + C_h)}{T_s + T_h}$$

In the model, the net information gain U is obtained by subtracting the cost of foraging search, C_f, and handling, C_h, from the total foraging information gain, U_f. Similarly, the time spent in foraging is equal to the total time spent in searching, T_s, and handling, T_h.

The pattern can readily be seen in Figure **??**a. The first panel shows a set of saccades to find a promising patch (search costs, which is then intensively studied Figure **??**b with fixations to extract the needed information (handling costs). This approach transforms the way we look at the data. The scene can be treated as consisting of information patches. The search costs are the saccades to find the patch. Handling

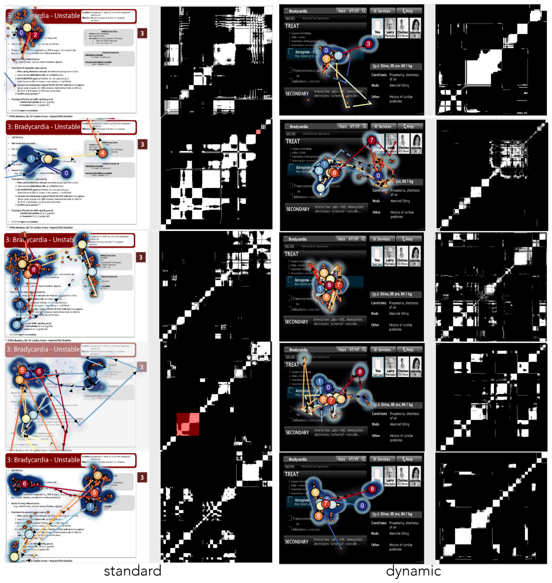

Figure 11. Information Foraging analysis for ten cases. Left pair of columns shows eye movements and recurrence plots for Standard emergency checklist arranged from fastest on top to slowest. Right pair of columns shows Dynamic checklist. Information patchees are automatically detected and numbered. generally there are more of them and they are less organized for slower trials.

costs are the costs associated with actually reading and understanding the information. Information Foraging Theory suggests two ways to improve the efficiency of acquiring knowledge from the checklists [29]: between-patch enrichment and within-patch enrichment. Between-patch enrichment means improving the search to make the desired information easier to find. This has been done in the case of the Dynamic checklist format by dynamically hiding or minimizing items not immediate to the currently relevant item in the checklist and using the space to make the relevant item larger. Within-patch enrichment means making the desired information easier to assimilate. An example in the Dynamic format, drug dosage information follows a rigid format to make it faster to extract the currently need information. Chernovs Marginal Utility Theorem [**?**] says that whether we do between or within patch enrichment, that the time the information searcher spends in a patch should be shortened. Our fourth conclusion is that at the higher level, *visual search is a kind of micro-foraging*.

We can use VERP to identify patches automatically. First, we separate search saccades from fixations using the angular velocity threshold of 300 degrees/sec. We then collapse consecutive fixations into clusters (**??**). Each fixation cluster forms a patch and we number the patches from 0 (the starting position of the eye) upwards. To show the searches, we draw a line following the saccades.

From[xx Fig 10?] it is evident that the smaller information patches, whose construction we have just described, are part of larger patches. To depict these, we use heat maps. The effect of this analysis is to create an automatically generated micro-narrative in pictures of what the participant paid attention to. There seems to be a general correlation to

Verbal Micro-Narratives

We can go even further with this idea by noting the words under the heat map. For the fastest trial of the Standard checklist format in [xx fig10?], the words show what the graphic shows: the participant quickly located the concept, the sets of words in a patch are similar. The participant quickly found the patch and spent most of her time trying to understand the content.

1. …Airway (accesses and…
   …Breathing (100% Get transcutaneous…
   …Atropine (1.5…
2. …for help…
   …transcutaneous pacer…
   …atropine (1.5 ms IV; may…
3. …transcutaneous pacer…
   …atropine (1.5 ms IV; may…
   …stimulation if laparoscopy…

On the other hand, for the slowest time (Fig 10), each set of words in the patches below is quite different, because the participant is lost in the search part. The sequence of concepts to which the participant responds and the visual representation of the sequence of information patches searched form a micro-narrative at a behavioral level above the eye movement and recurrence plot levels. This enables us to quickly characterize the participants behavior.

1. …Calcium channel…
   …-Calcium chloride…
2. …Increase the milliamperes…
3. …Consider expert consultation…
4. …Airway (accesses and…
   …Breathing (100% …
5. …Beta blocker overdo…
   …Overdose…
6. …Give Atropine…

It's almost like having an automatically-generated think-aloud protocol of what the participant was thinking. Our fifth conclusion, therefore is that *It is possible to make tools that translate eye movements into verbal sequences that narrate the searcher's journey.*

Gremlins

We have concentrated on the general patterns in the eye movements, but since the eyes are controlled both in reaction to visual stimuli as well as cognitively in service of a goal, we also are able to use the VERP Explorer to discover unexpected effects–we call them *gremlins*. Such was the case with these analyses. In four out of five of the Dynamic format screen shots in Figure 11, 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 individualan important element of disciplined coordination to prevent errors. It did not occur to the designers of this format that the high contrast of the picture to the dark background would draw the eye, thereby interfering with the acquisition of information in the checklist, although this is particular gremlin becomes obvious and visible once it is pointed out. Thus the displays of VERP can be useful for pointing out issues that no-one thought to ask. In general, the Dynamic format was the better compared format of the two and so tested as in Figure 9. But this general success masked a gremlin within the design.

CONCLUSION

Evaluating the effectiveness of the visual design of an interface is an important yet challenging problem. The analysis of eye movements has been recognized as an important technique for this problem, but eye movements are usually at a lower level than the behavior the designer needs to analyze, and eye movements can be complex to interpret. This paper proposes a set of analytical methods that may help with this problem, especially the specific problem of visual search. Our methods have two main goals: (1) to raise the level of the behavioral characterization for the designer so that she may more easily understand the good and bad characteristics of a prototype visual design for a given system, and (2) to package the methods into an integrated tool, The VERP Explorer has integrated and extended methods for the eye movement analysis of visual-cognitive interfaces, especially involving visual search. We illustrated its use eye movement data on doctors acquiring information from emergency medical checklists.

We believe our contributions to be the following. (1) an implemented visualization tool that integrates recurrence analysis and eye movement analysis, especially for visual search, (2) a proposal for organizing and quantifying patterns in the eye movement representations (”mosaics”) above the level of a sequential set of movements, (3)a new, automatic method of generating visualizations of search based on to applying information foraging theory to the eye movement analysis and computed visualization of examples, and (4) a proposal for automatic generation of a sort of verbal narrative generated by the search.

Together these proposals address our goals. With respect to raising the level of analysis, these methods let us move above the level of individual eye movements to immediate patterns, extended patterns, and narrative patterns. With these techniques we can explicate what happens during the visual interaction. With respect to an integrated tool, we have demonstrated a working system that integrates these capabilities, allowing the user to brush back and forth from scene-based to recurrence plot based representations, for example.

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