Cluttered centres: interaction between eccentricity and clutter in attracting visual attention of readers of a 16th century map

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***Abstract*—The study of the history of cognitive processes is essential to understand the co-evolution of humans and artefacts. In the current pioneer eye tracking experiment we used a complex and colorful early map as stimulus. We analyzed eye movements of 28 novice map readers. Our results suggests interaction between bottom-up (i.e. visual clutter) and top-down (eccentricity) cognitive processes in viewing patterns. These research findings represent a novel direction in studying the history of cognitive data visualizations and could be considered in directing contemporary design of user interfaces.**

I. Introduction

Spatial information is traditionally communicated graphically by maps. Although an ancient practice, we still know very little how these superb visualization tools are actually used by humans. Cognitive cartography is the application of the cognitive science approach in the cartographic design process to develop cognitively relevant and salient graphical displays, which can be used intuitively and effectively.

While today cartographic design principles (e.g. visual hierarchy based on figure-ground separation) are generally known by everybody interested in graphical user interfaces (GUI), these are typically reflections of conventions derived from practices which were accepted and followed by makers of maps, diagrams or infographics (see also [1]). Although the first attempts to study cognitive processes from visual information acquisition to spatial decision making and behavior go back to the late 19th century the first century of research resulted in limited empirical knowledge on visualization [2].Only in the past decades became empirical research on aspects of the use of graphic devices affordable.

A. Cognitive cartographic research with eye tracking

The first cartographic experiments applying eye-tracking technology in the 1970s used simple dot maps as stimuli. Maps are very popular in cognitive research (e.g. [3], [4]) and this is due to their growing importance in the development of spatial thinking in modern societies. Maps are a paradigmatic visual interface where spatial and object information must be arranged and read in graphical layers. Even the simplest map consists of a background and a topic, resulting in a complex visualization. Visual complexity depends partly on the structure of the data base, which can be highly sophisticated already in the case of the common reference maps with dozens or even hundreds of different object categories. The graphical representation of multiple categories is a great challenge and a complicated task for the designer. This is especially true in the era of Big Spatial Data with ubiquitous, interactive, virtual or augmented graphical displays in apparently any field of human field. As recent research evidence suggest the design process makes the visual communication of information more effective and easier to comprehend by the reader [3]. This is why the study of the cognitive aspects of graphical design is a pressing task not only for geovisualization, but for cognitive infocommunication in general [5].

By the 21st century the technology has developed and both eye-tracking devices and softwares became available for various research topics relating to map use. As an unobtrusive technology eye tracking is perhaps the most popular research method to study processes in human visuo-spatial processes. The advantage of the technology is not only its affordability but also the fact that monitoring the human gaze can be done under almost natural conditions. Eye tracking metrics analysis should be interpreted in a consistent cognitive theory and fixation data should be related to specific inference tasks to link visual attention to cognitive processes.

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The first eye tracking device and visualization software in the field of geovisualization was developed by Z. G. Török and Bérces in 2013. Using an DIY eye tracking glass and the "Map Reader" software the first experiments compared the usability of thematic maps, visualizations generated by common GIS softwares [6]. In the following year the empiric research was continued with another eye tracking glass.

B. *Towards a history of visualization?*

The new series of experiments were designed by Z. G. Török in the framework of historical geovisualization. This novel direction of cognitive cartographic research was initially proposed to make researchers able to answer usability questions relating to old maps. Despite the common belief that more accurate representations were better and, consequently, they were used by contemporaries is not supported by historical evidence (see e.g. [7], [8]).

If old maps were evaluated not according to modern criteria, perhaps we should consider them as visual tools and study them as graphic displays using modern technology. The hypothesis we wanted to test by our eye tracking experiment was that if better maps were actually easier to read, in other words, they were more effective communication tools than their rivals.

For our pilot study we designed a test combining eye tracking and spatial inference tasks. As test subjects were to look at two similar cartographic images, to lower the effect of their mental combination between the two test images a third map was included and shown for the participants. This paper presents the preliminary analysis of the gaze tracking data recorded during this intermediate sessions and gives us insights into structures appealing visual attention of users', and in more general sense map reading strategies of novice readers.

The test stimulus was the 1528 Lazarus map, the first printed cartographical representation of Hungary. The map was based on the manuscript of the clerk Lazarus, which was edited and prepared for publication by humanists in Vienna, and was printed in the workshop of Peter Apian in Ingolstadt. Today this important document is preserved in a single copy in the collection of the Széchenyi National Library, Budapest. The Lazarus map is relevant for study as it represents an early form of modern cartographic visualization [9]. This map was chosen not only for its historical significance, but also for its unusual, standing format and its confusing orientation, which makes it unfamiliar even for modern Hungarian readers (i.e. the Kingdom of Hungary was conveniently represented in landscape format as the country is more extended on the West-East axis than on the South-North axis). The map lacks conventional elements of modern maps, e.g. there is no legend, title or marginal information which could suggest common map reading strategies. On the other hand, the study of this printed map offers insights into early modern cartographic design practices. The woodcut with stereotype labels is highly complex graphics, moreover, it was colored by hand according to contemporary conventions and political colouring was added according to an explanatory note. These characteristics made this geographical image especially suitable for our pilot study and to analyze eye tracking metrics with visual models based on perceptual salience.

To quantify the clutter on this map, we used the saliency based model by Rosenholz et al. was used [4], which has been validated with meaningful displays. This feature congestion model of visual clutter proposes a new interpretation of the concept. According to Rosenholz et al [4] visual clutter is greater when a new item is more difficult to add to the display. Their statistical saliency model is based on a feature space (color hue, color value etc.), where distractors are compared with the target in the scene. In our intermediate experiment eye tracking measurement data was recorded during free exploration of the Lazarus map by test subjects and we suppose that the analysis of data reflects bottom-up, that is stimulus driven cognitive processes, most importantly visual attention.

II. Methods

A. *Participants*

28 volunteers participated in the study ($n_{female} = 18$). Their age varied between 19 and 23 years, and all of them were geography or geoscience bachelor students at Eötvös Loránd University. All of the participants had normal or corrected to normal vision, and reported no color blindness. The experiment met the ethical principles of the Nuremberg code and the Declaration of Helsinki. An informed consent was collected from all participants prior to the experiments. Test subjects could registrate using an online interface for the test, which took place at the eye track lab at the Department of Cartography and Geoinformatics.

B. *Procedure*

Participants were seated in an armchair in a dimly lit room in front of a 19" LCD screen with refresh rate of 60Hz and resolution of 1024 X 768 px. The distance between their eyes and the screen varied between 40 and 60 cm. Participants were wearing an eye tracking glasses [10], which was a custom made tool consisting of a USB 2.0 compatible webcam, IR diode. Eye tracking signals were recorded with MapReader, a sofware developed for cartographic eyetracking experiments [10]. Recording was done with 5 Hz sampling frequency.

The experiment consisted of viewing 3 maps with different tasks. In one they had to carry out directed exploration, in another they had to explore the map in an undirected fashion. In both of these tasks, they had to answer related questions after the exploration and learning phase. A third map was inserted in between the above two tasks. Here participants had no instructions only to look at the map and explore it on their own. This part was inserted to investigate the incidental exploration of a historical visualization by means of eye tracking trajectories. This first map of Hungary, with Latin title "Tabula Hungarie", also known as the Lazarus' map was chosen as stimulus. Participants were allowed to explore this map for ~ 1 min, after which interlude the experimenter started the next

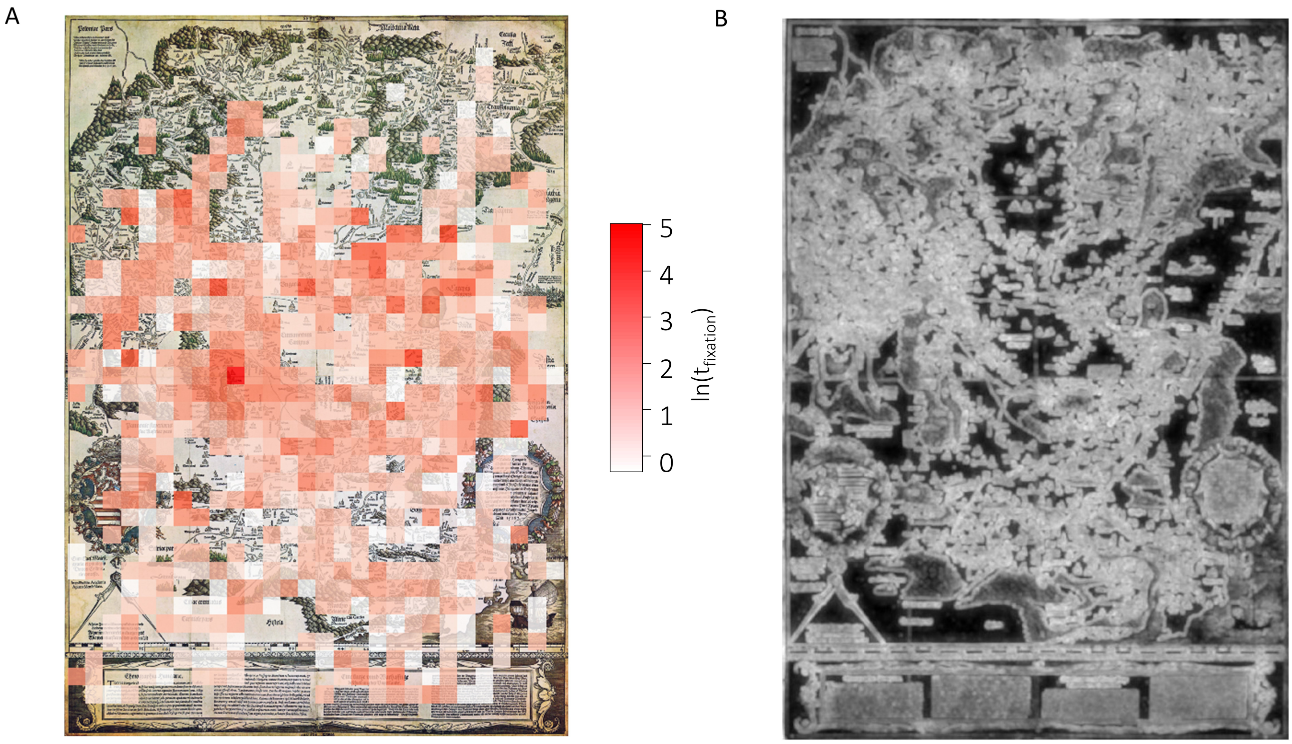

Fig. 1. Aggregated fixations in the 20 X 20 bins (A) and the Feature Congestion map of the graphic (B). It can be seen that many extremeties of the map have not been looked at by the participants in such a short exposure. This is likely due to the high clutter of this historic visualization.

task with a new map. Test subjects were not informed about the details of this map, and we supposed that they had no previous knowledge about it, which could influence their visual exploration.

C. Data Analysis

In the current analysis we analyzed the effects of visual clutter and eccentricity on fixation times. First, to warrant the same looking time for all participants, we took only datapoints where all participants were recorded. This left the first 336 samples of fixation to analyze. Fixations were calculated after rejecting trajectories outside of the map and eyeblinks. Instead of the raw fixation coordinates, we summarized fixations in 20 X 20 px bins. This strategy was followed to minimise the effect of tracking uncertainty and to smooth the pixel-by-pixel measure of visual clutter. Visual clutter was quantified by calculating Feature Congestion for the Lazarus map using Visual clutter, a toolset designed in Matlab [4]. Clutter was also summarized in 20 X 20 px bins (see Fig. 1). Eccentricity was calculated by taking the Euclidean distance of each bin from the center of the picture. Since fixation times followed a left skewed distribution, we performed the statistical analysis on log transformed fixation times. Analysis was done in R [11] using the lme4 package [12].

III. Results

We used mixed effects modeling to explicitly model the effect of factors on the population and on individual level.

Our factors of interest were:

- (1) *Eccentricty* of image area,

- (2) *Visual clutter* quantified by Feature congestion,

In the mixed effects modeling all these were handled as continous variables without any transformation applied to the variables.

We specified the fixed effects in our mixed effects model by adding the factors of interest (*Eccentricity* and *Visual clutter*) along with their interactions to the model. Being the fixed factors, these effects were modelled on the population level. On the subject level, we modeled included all within-subject random terms justified by the design in our model [13], that is coefficients were estimated for all participants, Eccentricity, Visual clutter and the interaction combinations. Participant Id was modeled as random intercept, while the other factors were estimated with correlated random slopes.

A general mixed effects model can be expressed in matrix notation as:

$$Y = X\beta + Zb + \varepsilon$$

Here X and Z are the design matrices, β is the fixed effect coefficient and b is the random coefficient matrix and ϵ is the residual. In our case, we estimated separate intercepts for each J subjects, therefore $j = 1, 2, ..., J$. Based on this, when partitioned to each level, the above formula can be written as:

$$\begin{bmatrix} \mathbf{Y_1} \\ \mathbf{Y_2} \\ \vdots \\ \mathbf{Y_J} \end{bmatrix} = \begin{bmatrix} \mathbf{X_1} & \mathbf{Z_1} & 0 & \dots & 0 & 0 \\ \mathbf{X_2} & 0 & \mathbf{Z_2} & \dots & 0 & 0 \\ \vdots & & & \dots & & \\ \mathbf{X_J} & 0 & 0 & \dots & 0 & \mathbf{Z_J} \end{bmatrix} \begin{bmatrix} \beta \\ b_1 \\ b_2 \\ \vdots \\ b_J \end{bmatrix} + \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \vdots \\ \epsilon_J \end{bmatrix}$$

Where Y_j is a $n_j * 1$ matrix containing the log Fixation times of subject j, X_j and Z_j are $n_j * 4$ design matrices and ϵ_j is the residual matrix of size $n_j * 1$. Writing them in explicit form, we have:

$$\mathbf{Y_j} = \begin{bmatrix} y_{1j} \\ y_{2j} \\ \vdots \\ y_{n_j j} \end{bmatrix},$$

$$\mathbf{X_j} = \mathbf{Z_j} = \begin{bmatrix} 1 & x_{1j} & z_{1j} & xz_{1j} \\ 1 & x_{2j} & z_{2j} & xz_{2j} \\ \vdots & \vdots & & \\ 1 & x_{n_j j} & z_{n_j j} & xz_{n_j j} \end{bmatrix},$$

$$\text{and} \quad \epsilon_j = \begin{bmatrix} \epsilon_{1j} \\ \epsilon_{2j} \\ \vdots \\ \epsilon_{n_j j} \end{bmatrix} |\epsilon_{n_j j} \; N(0, \sigma^2)$$

Where y_{ij} is the ith measured log transformed fixation time ($i = 1..n_j$), x_{ij} is the *Eccentricity*, z_{ij} is the *Visual clutter*.

$$\beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix}, b_j = \begin{bmatrix} u_{0j} \\ u_{1j} \\ u_{2j} \\ u_{3j} \end{bmatrix}$$

We estimated correlated random slopes and intercepts. The random slope and intercept model had better fit than a simple linear model without random terms (model_linear: df = 5, AIC = 3033.9; model_mixed: df = 15, AIC = 3022.1; $\chi^2(19) = 31.798$, $p < .001$).

Wald chisquare tests (type 3) were used to test the fixed effects, which showed a significant effect of Visual clutter ($\chi^2(1) = 6.31$, p = .01) and an interaction between Visual clutter and Eccentricity ($\chi^2(1) = 4.10$, p = .04). The positive coefficient indicates that the effect of Visual clutter means that participants tended to look more at the areas which were more cluttered. The interaction effect further clarifies this by showing, that there is an interaction between Eccentricity and Visual clutter: Participants watched cluttered parts of the map longer only in the center (see Fig 2). On more extreme positions of the map Fixations were more likely detected on non-cluttered areas. Importantly, we did not find significant effect of Eccentricity (p = .15), indicating that Eccentricity in itself does not define Fixation times.

TABLE I. Summary of fixed effects in the mixed effects model

Dependent variable:	*Estimate (SE)*	χ^2 *(df)*
Visual clutter	1.418	6.31*
	(0.565)	(1)
Eccentricity	0.045	2.03
	(0.032)	(1)
Visual clutter:Eccentricity	−0.113	4.10*
	(0.056)	(1)
Intercept	0.702	5.33*
	(0.304)	(1)
Observations	1,079	
Log Likelihood	−1,504.502	
Akaike Inf. Crit.	3,039.004	
Bayesian Inf. Crit.	3,113.761	

Note: *p<0.05

IV. Discussion

In our pilot experiment to study historical visualization methods we used a complex and colorful image of an 1528 country map as a stimulus. The analysis of eye tracking data, more specifically duration of fixations during free exploration revealed interaction between bottom-up (i.e. visual clutter) and top-down (eccentricity) cognitive processes in the view patterns of novice readers. Summarizing our results, we have found that people spent more time looking at more cluttered areas, but this effect was in interaction with eccentricity. That is farther away from the visual center the effect flips and fixations more often fell on less cluttered areas during the first minute of looking at a novel graphic. These preliminary results should be validated by other visual stimuli in the future and may suggest tacit knowledge about foveated display design five centuries ago. Further studies should also investigate whether this interaction effect is specific to maps or is common to all data visualizations.

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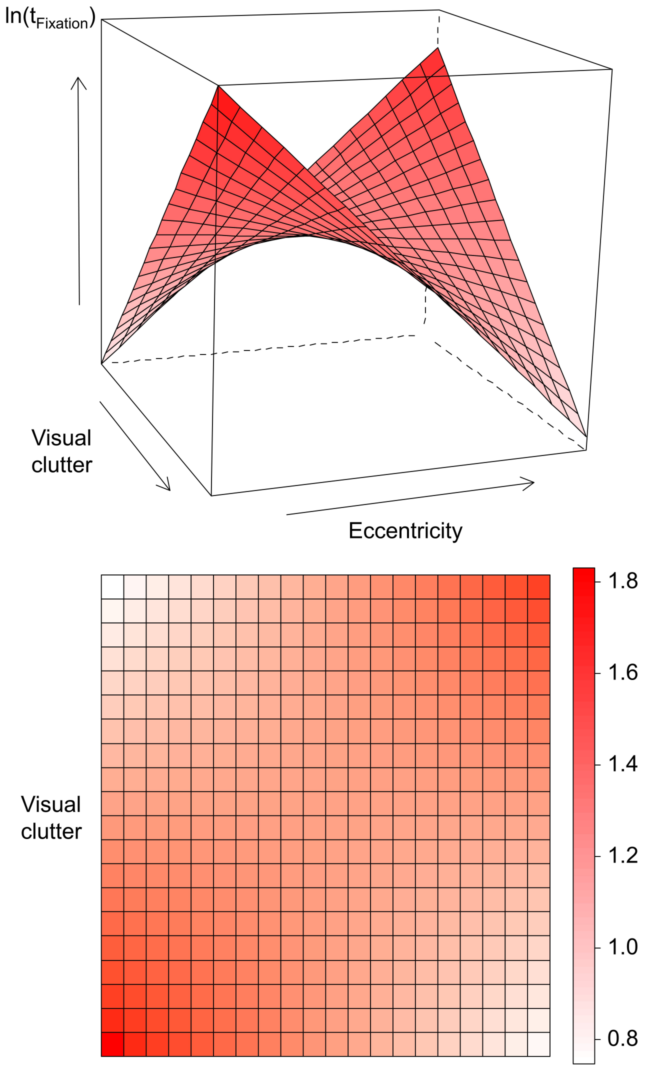

Fig. 2. Visualization of the interaction effect from the mixed effects model. At lower eccentricities higher clutter is correlated with longer fixation times, while in higher eccentricities the relationship is the opposite.

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