DOI: 10.2390/biecoll-saga2013_5

In Pfeiffer and Essig (2013): Proceedings of the First International Workshop on Solutions for Automatic Gaze-Data Analysis 2013 (SAGA 2013). DOI: 10.2390/biecoll-saga2013_0

Using spatial statistics to investigate within-trial correlations of human gaze positions

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1 Introduction

The distribution of fixation locations can be interpreted as an intensity (density) function of an underlying spatial point process (Barthelmé, Trukenbrod, Engbert, & Wichmann, in press). In point process theory (Illian, Penttinen, Stoyan, & Stoyan, 2008), we analyze the point-to-point interactions to infer possible generating mechanisms. The pair correlation function (PCF) provides a mathematical measure of the statistical interaction of neighboring points (Law, Illian, Burslem, Gratzer, Gunatilleke, & Gunatilleke, 2009). Here we demonstrate that the inhomogeneous PCF can be used to analyze sequences of fixation locations recorded from human observers. The resulting PCF removes first-order heterogeneity induced by systematic variation of saliency within a given scene from second-order spatial statistics. Our results indicate significant spatial clustering at short length scales.

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2 Experiment

The present study explores the possibility to apply the *pair correlation function* (PCF), which provides a description of the distribution of distances between points, to the spatial analysis of fixation locations generated during single scanpaths. Our results are based on a reanalysis of scene-viewing data previously published by Mergenthaler and Engbert (2009).

Participants: We tested 24 students of the University of Potsdam (mean age: 23 years) with normal or corrected-to-normal vision. All participants received credit points for participation.

Stimulus material: Images consisted of twelve randomly selected, colored, natural landscape photographs presented across the entire screen (CRT display; Iiyama Vision Mater Pro 514; frame rate 100 Hz; resolution: 1024×768 pixels).

Task and procedure: Participants were instructed to position their head on a chinrest in front of a computer screen (viewing distance: 50 cm). Eye movements were recorded using a Eyelink II video-based eye-tracker (SR-Research, Osgoode/ON, Canada) with a sampling rate of 500 Hz. Each image was presented for 10 s. Participants were asked to freely explore each image. Between images, participants were engaged in a secondary fixation task for about 20 s.

Statistical analysis: Pair correlation functions (PCFs) were calculated in two steps. A detailed description of the underlying procedure can be found in Law et al. (2009).

First, we numerically estimated the intensity (or spatial density) of all fixations on a given image (across all participants). The intensity function was computed applying a 2D kernel density estimator (Baddeley & Turner, 2005; R Development Core Team, 2013). The estimated intensity $\hat{\lambda}(x,y)$ gives the density of all fixations, where dependence on position (x,y) indicates inhomogeneity.

Second, due to spatial inhomogeneity in the spatial distributions (see step one) we estimated the *inhomogeneous pair correlation function*. The inhomogeneous PCF $g_{inhom}(r)$ is a function of the distance r between points. The estimated inhomogenous PCF is a quantitative measure of spatial correlations between fixation locations, where the inhomogeneous spatial density $\hat{\lambda}(x,y)$ is taken into account.

The interpretation $g_{inhom}(r)$ is as follows: For distances r with $g_{inhom}(r) \approx 1$ fixation locations are statistically uncorrelated, while values of $g_{inhom}(r) > 1$ reveal spatial clustering at distance r, and values of $g_{inhom}(r) < 1$ reveal inhibition at distance r.

3 Results

Inhomogeneous pair correlation functions (PCFs) of the experimental data are shown in Figure 1. Gray lines depict PCFs of individual trials and reveal high variability between trials. The average PCF across all trials is plotted in red. The mean

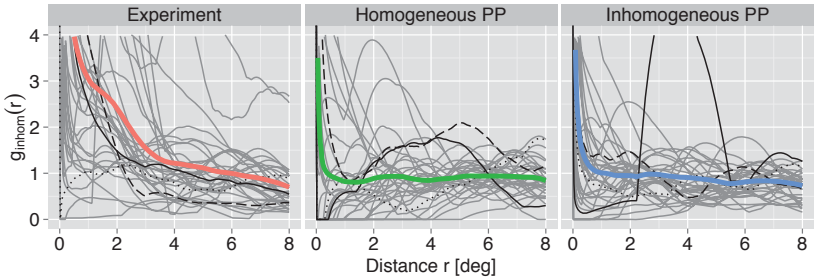

Fig. 1 Inhomogenous pair correlation function (PCF) for the experimental fixation sequences and surrogate fixation sequences. Surrogate fixation sequences were generated using a homogeneous and inhomogeneous Poisson process, respectively. Gray lines show PCFs of individual trials, colored lines the average PCF across all trials.

PCF indicates spatial clustering of fixations at small distances $r < 3^\circ$, while fixations at larger distances can be explained by the inhomogeneity of the spatial maps.

Next, we computed the PCFs for two surrogate data sets to test the validity of our statistical procedure. The surrogate data were selected to examine the null hypothesis of complete spatial randomness, both for a homogeneous Poisson process with constant intensity $\lambda(x,y) = \lambda_0$ (Fig. 1, central panel) and an inhomogeneous Poisson process with position-dependent intensity $\lambda(x,y)$ (Fig. 1, right panel). Analysis of our surrogate data reveal that both the homogeneous and inhomogeneous Poisson process give flat PCFs with $g_{inhom}(r) \approx 1$, which demonstrates the absence of clustering (with divergence at small scales being an artifact of numerical computations). We conclude that clustering in the experimental data is not a simple consequence of the inhomogeneous intensity.

4 Discussion and Further Work

Our analysis reveals that the pair correlation function (PCF) can be estimated for fixation locations from individual trials when normalized to the spatial density of all fixations. We observed strong clustering at small scales, i.e., at distances $r < 3^\circ$, reflecting a tendency of the eye to remain close to previously fixated regions. Finally, spatial statistics provide a number of useful tools to investigate the relation of fixation locations.

ACKNOWLEDGMENTS: This work was supported by Bundesministerium für Bildung und Forschung (BMBF, Bernstein Center for Computational Neuroscience Berlin, Project B3, Förderkennzeichen 01GQ1001F and 01GQ1001B to R.E. and F.A.W., respectively) and by Deutsche Forschungsgemeinschaft (DFG Research Unit 868, speaker: R.E.).

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