Data assimilation in dynamical cognitive models

Bayesian parameter estimation for dynamical models of eye-movement control using Markov Chain Monte Carlo techniques

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In Short

- We study parameter inference for cognitive models [1] of eye-movement control during reading
- For the class of dynamical cognitive models being investigated a likelihood function can be computed numerically for experimental data sets
- Using adaptive Markov Chain Monte Carlo (MCMC) techniques, we implement a Bayesian approach for model parameter inference
- We will compare exact likelihood computations with synthetic and approximative likelihood methods to increase computational efficiency
- In perspective, this approach might be exploited for real-time gaze prediction in everyday tasks (e.g. driving, human-machine interaction)

In cognitive modeling, we investigate mathematical and computational approaches to explain human behavior by a set of basic assumptions on principles of information processing of mind and brain. In this approach, model fitting and comparison are becoming more and more important due to increasingly complex models and the existence of competing modeling approaches. This is particularly important in the case of dynamical cognitive models, where parameter identification and model comparison must be based on time-ordered data (time series).

The focus of the current project is on dynamical models of eye-movement control during reading. Eye-movement control is an important area of cognitive modeling, since the eyes are both sensory and motor systems and, therefore, are among the best experimental measures of ongoing cognition. We will investigate a prominent dynamical model that generates sequences of eye movements during text reading [1].

Since high-acuity visual perception is limited to the very center of the visual field (the fovea) and visual information processing is only efficient if the eye is stationary, our visual system has to apply a discrete sampling strategy. The eye performs a rapid sequence of fast eye movements (saccades, about 3-4 times per second) to minimize flight time, while information processing is done during fixations (average duration 200 ms). In reading, approximately one fixation is generated per word, however, there is statistical variability depending on word length and word difficulty. Even during reading of simple texts, only 50% of all saccades move the gaze from one word to the next (see Fig. 1). Frequently, refixations of the same word, skippings, and regression (saccades that go against reading direction) are observed.

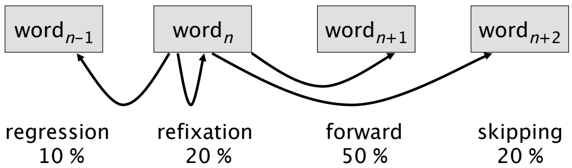

Figure 1: *Saccades during reading. Only about 50% of the saccades during reading move the eye from word n to $n+1$. Other types of saccades are skippings, refixations, and regressions.*

The SWIFT model [1] is a dynamical model that generates all types of saccades from a theoretically coherent framework using a temporally-evolving neural activation field (Fig. 2). The model combines well-established cognitive assumptions on sensorimotor processing, attention, and word recognition with neurophysiological plausibility (e.g. partial independence of spatial and temporal control of saccades).

Experimental data are available in the form of fixation sequences from eye-tracking experiments. We developed a procedure for the computation of the likelihood function of the model given a set of model parameter values and an experimental data set (∼20,000 fixations). The likelihood function is fundamental for the implementation of a Bayesian approach to parameter inference. Since we work with time-ordered data (fixation sequences), this framework is called data assimilation.

In the Bayesian approach, we are using stochastic simulations to sample model parameter values from the posterior probability distribution. In a pilot study, we investigated this approach for a less complex model of eye-movement control during scene viewing [2]. Using standard Markov Chain Monte Carlo (MCMC) techniques, we demonstrated the viability of this approach for cognitive models.

The necessary computations for the SWIFT model are qualitatively similar, however, the SWIFT model uses stochastic internal (latent) states that need to be approximated in the numerical computation of

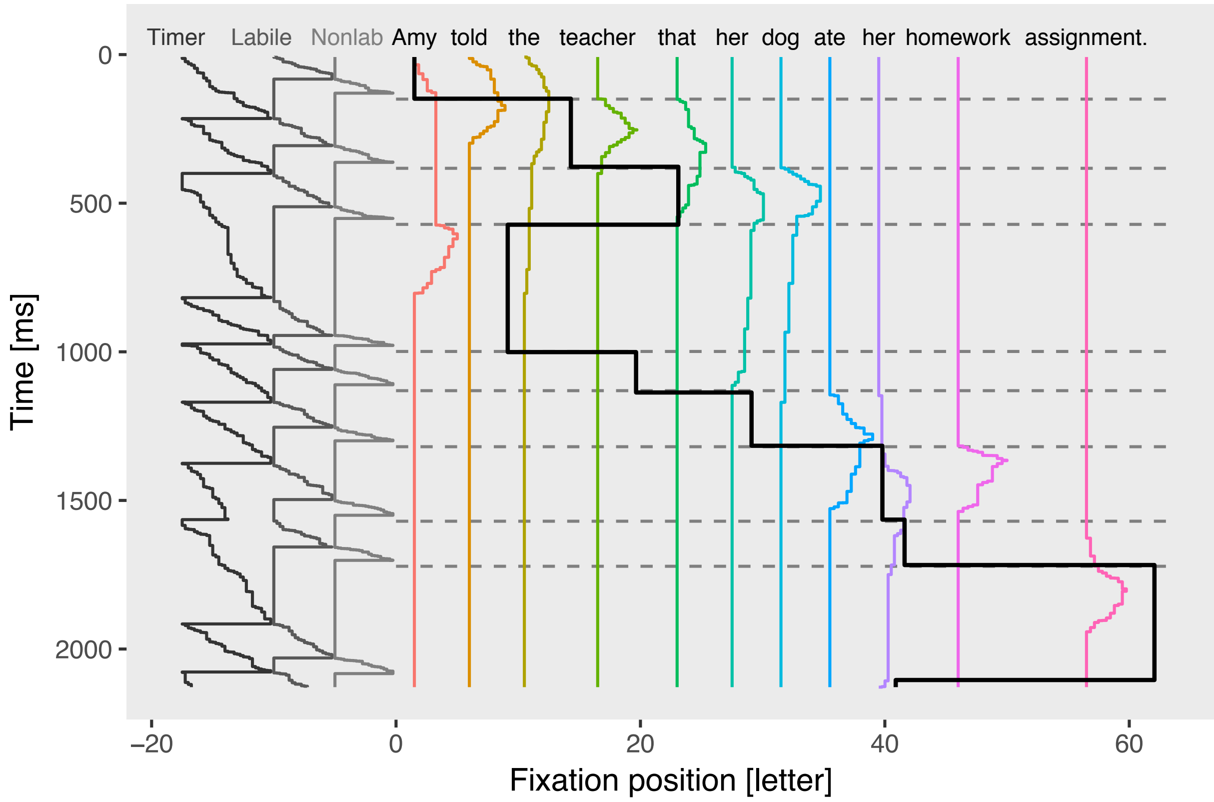

Figure 2: *SWIFT model. Visualization of a simulated gaze trajectory from the SWIFT model of eye-movement control during reading. The three curves on the left part (grey) represent internal processes of saccade programming, while the right curves (colors) indicate word recognition processes during the reading process.*

the likelihood function. Since the log-likelihood function is composed of the sum of statistically independent likelihoods for single experimental fixation sequences (~ 200), the numerical calculations can be implemented via parallel computations.

An important challenge for model parameter inference in cognitive modeling is the fact that statistical random effects are observed due to inter-individual differences (e.g., reading span of experimental participants) and text material (e.g., text genre). The Bayesian approach will be able to account for both of these random effects simultaneously using hierarchical priors on the model parameters.

Due to the complexity of the posterior distributions and high dimensionality of the parameter space we aim to explore different sampling strategies within the MCMC framework. To increase numerical efficiency, we will investigate the use of synthetic likelihoods and approximate Bayesian computations (ABC).

In perspective, our approach to model identification for individual observers could be used to implement real-time gaze prediction on the basis of mobile eye-tracking devices. An important application is the surveillance of human-machine interaction or driving.

WWW

https://www.sfb1294.de/research/research-area-b/b03/

More Information

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[2] H.H. Schütt, L.O.M. Rothkegel, H.A. Trukenbrod, S. Reich, F.A. Wichmann, & R. Engbert, *Psychol. Rev.* **124**(4), 505–524 (2017). doi:10.1037/rev0000068

Project Partners

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