EMHMM: Eye Movement Analysis with Hidden Markov Models and Its Applications in Cognitive Research

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Keywords: EMHMM; eye movement; hidden Markov model

Significance of the Method

In many daily life activities, eye movements provide strong clues about underlying cognitive processes. For example, patients with cognitive deficits have atypical eye movement patterns. Users with different experiences show different eye movement behavior in viewing websites. Thus, eye movement has become an important measure in the broad research fields in cognitive science.

Recent research has reported substantial individual differences in eye movements during cognitive tasks. Nevertheless, most of the current analysis methods do not adequately reflect these individual differences. Also, they focus on spatial information (fixation locations), whereas temporal information (transitions among fixation locations) is typically overlooked. The most common method has been the use of predefined regions of interests (ROIs) on the stimuli. However, predefined ROIs are often subject to experimenter bias and inconsistency across studies. To address these problems, Caldara and Miellet (2011) proposed to directly perform by-pixel statistical tests on fixation heat maps (where fixations are smoothed with a Gaussian function) to determine the regions with significant difference between conditions. Nevertheless, these regions are often irregularly shaped and difficult to interpret. Also, fixation maps at different times only show the transition of overall fixation distribution and do not provide information about transitions between regions. Another method (Jack et al., 2009) is to define ROIs as regions formed by running the k-means clustering algorithm on significantly fixated regions of a fixation map. However, this approach assumes that all ROIs are circular and the same size, and the number of ROIs must be preset by the experimenter.

Thus, we have developed a novel eye movement data analysis method, Eye Movement analysis with Hidden Markov Models (EMHMM; Chuk, Chan, & Hsiao, 2014), which summarizes each individual's eye movement pattern using a hidden Markov model (HMM; a type of machine learning model for time series data), including person-specific ROIs and transition probabilities among the ROIs. Individual HMMs can be clustered according to similarities to discover common patterns (Fig. 1a), and the similarity between an individual pattern and a common pattern can be quantitatively assessed through estimating the likelihood of the individual's data being generated by the common pattern HMM. This similarity measure then can be used to examine associations between eye movement patterns and other cognitive measures (Fig. 1b & 1c). We have applied this method to face recognition research and made discoveries thus far not revealed by other methods, including how eye movements are associated with recognition performance, cognitive abilities (Chan, Chan, Lee, & Hsiao, 2018), cultural differences (Chuk, Crookes, et al., 2017), memory encoding/retrieval (Chuk, Chan, & Hsiao, 2017), sleep loss (Zhang, Chan, Lau, & Hsiao, 2019), and activations in brain regions important for top-down attention control (Chan et al., 2016). We have also recently developed new methodologies for more complex cognitive tasks, including using switching HMMs for tasks involving cognitive state changes (Chuk, Chan, Shimojo, & Hsiao, 2016), and using the machine learning algorithm co-clustering for tasks involving stimuli with different feature layouts (Hsiao, Chan, Du, & Chan, 2019).

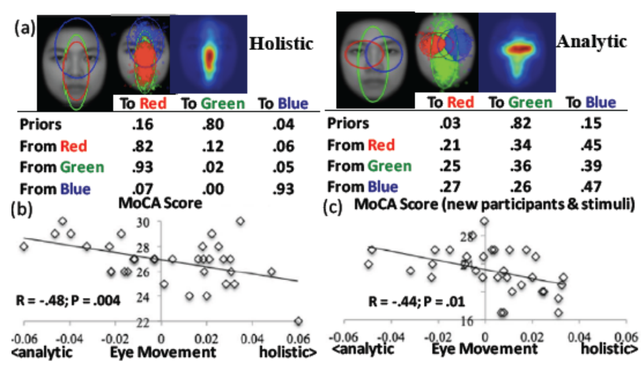

Fig. 1: (a) Analytic and holistic patterns in face recognition (Chan et al., 2018). Ellipses show ROIs as 2-D Gaussian emissions. The table shows transition probabilities among the ROIs. Priors show the probabilities that a fixation sequence starts from the ellipse. (b) In older adults, the more holistic the pattern, the lower the cognitive status (by MoCA), and (c) this correlation was replicated with new participants viewing new face images using the representative HMMs in (b).

In short, the EMHMM methodology will allow us to summarize, quantitatively assess, and compare individual eye movement patterns across stimuli and tasks, and examine how they are associated with other cognitive measures. It will lead to innovative findings not revealed by any existing methods with a lasting impact on how eye tracking is used for understanding cognition across disciplines. The Matlab Toolbox for EMHMM is available at http://visal.cs.cityu.edu.hk/research/emhmm/.

Structure and Activities

This half-day tutorial consists of 2 sessions:

1. Introduction to EMHMM and Its Applications: We will first introduce current methods in eye movement data analysis to illustrate the advantages of the EMHMM method. We will then introduce how we can apply EMHMM to research on face recognition, reading, cultural difference, ageing, sleep, information systems, decision making, scene perception, and video viewing. In the end we will provide a short demo in which attendees can come to perform a face recognition task with eye tracking, and get a personalized EMHMM report on site.

2. Tutorial and Hands-on Experience: We will first present an EMHMM simulation study (Chan & Hsiao, 2018) and provide recommendations for using EMHMM in cognitive research. We will then provide an EMHMM Matlab Toolbox tutorial with sample data for attendees to practice using the toolbox on their own laptops. We will have at least one laptop available onsite for attendees who do not have access to Matlab. Attendees may also bring their own data and ask questions on site.

Credentials of the Tutorial Organizers

The tutorial organizers have been developing the EMHMM method for 7 years. Since the first paper/talk presented at the Annual Meeting of the Cognitive Science Society (Chuk, Chan, & Hsiao, 2013), they have published 6 journal papers (including *Cognition* and *Sleep*) and 23 conference/invited presentations (including VSS and ICIS) using this method with collaborators from the UK, the US, Germany, and Australia, etc. on various topics.

Janet Hsiao is a world-leading expert in using eye tracking and computational modeling methods to understand human cognition. She has published in several high-profile cognitive science journals including *Psychological Science* and *Cognition*. She is currently an Associate Editor for *Cognitive Science*, and has been served on the Program Committee for the annual meetings of the Cognitive Science Society since 2016.

Antoni Chan is a world-leading expert in probabilistic models for time series data analysis and pattern recognition. He has published in several high-profile machine learning and computer vision journals, including *IEEE Trans. on Pattern Analysis and Machine Intelligence* and the *Journal of Machine Learning Research*. He is currently a Senior Area Editor for *IEEE Signal Processing Letters*, and served as an Area Chair for ICCV'15, '17, and '19.

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