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

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Cog Sci Tutorial, July 24 2019
Outline

• **Introduction to EMHMM and Its Applications**
  – EMHMM: Face recognition + other examples
  – EMHMM with co-clustering: Scene perception
  – EMSHMM (Switching HMM): Preference decision making

• **Demo + Break:**
  – Face recognition task + personalized report

• **Tutorial and Hands-on Experience**
  – Simulation study
  – EMHMM toolbox tutorial
  – Hands-on experience/demo
Background

- Eye movement reflects underlying cognitive processes.

(Hsiao & Cottrell, 2008)

(Coutrot, Hsiao, & Chan, 2018)
Background

- Substantial individual differences in eye movements can indicate differences in strategy or cognitive style.

Website viewing (Eckhardt et al., 2013)

Face recognition (Kelly et al., 2011)
Eye Movement Analysis

• Most of the current eye movement analysis methods Do not adequately reflect individual differences:
  – **Regions of Interest** (ROI) (e.g. Barton et al. 2006; Goldberg & Helfman, 2010)
    Problem: ROIs are inconsistent across studies; it does not reflect individual difference in ROI choices
  – **Heat map** approach (iMap, Caldara & Miellet, 2011)
    Problems: Difference maps can be hard to interpret; it does not handle transition information between ROIs

![Correct Trials](image1)

![Incorrect Trials](image2)

![Difference](image3)
Eye Movement analysis with Hidden Markov Models (EMHMM)

- **EMHMM** (Chuk, Chan, & Hsiao, 2014) summarizes a person’s eye movement pattern using personalized ROIs and transitions among the ROIs.

The ellipses show the ROIs as 2-D Gaussian emissions; number of ROIs is automatically determined using Bayesian methods.

The prior values indicate the probabilities that a fixation sequence starts from the ellipses.

The transition probabilities indicate the probabilities of observing a particular transition.

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EMHMM: Clustering

- A data-driven approach to discover common strategies:
  - Representative HMMs of common strategies
  - Log likelihood measures to quantify eye movement pattern similarities

Example of EMHMM Clustering

- 34 young and 34 older adults performed a face recognition task.

- We clustered individual HMMs into 2 groups.

Example of EMHMM Clustering: age difference

- More older adults adopted holistic patterns while more young adults adopted analytic patterns, $X(2) = 4.77, p = .03$ (Chi-square test)
Example of EMHMMM Clustering: Traditional group comparison vs. EMHMMM

- Individual differences are obscured in direct group comparisons

Traditional Age group comparison

- a) Older adults group
- b) Young adults group
- c) Difference (Old – Young)

HMM subgroup comparison

- d) Holistic pattern group
- e) Analytic pattern group
- f) Difference (Holistic – Analytic)
Example of Similarity Measures

• We can quantify the similarity of a participant’s eye movement pattern to a common strategy using log-likelihood measures.

• E.g., Examine the correlation between the similarity and performance.

• EMHMM is particularly suitable for examining the link between eye movement patterns and other measures.

EMHMM Summary

Feature 1: Generate Individual HMMs
- Personalized regions of interest (ROIs)
- Transition probabilities among the ROIs

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EMHMM Summary

Feature 2: Discover Common Patterns through Clustering

Individuals’ HMMs

Representative HMMs of the clusters

Group A (S1, S2)

Group B (S3, S4)

VHEM Clustering Algorithm

Holistic Pattern Analytic Pattern

(Chuk, Chan, & Hsiao, 2014)

(Coviello, Chan, Lanckriet. JMLR, 2014)
EMHMM Summary

Feature 3: Quantify Similarity between Patterns (Using Data Log-Likelihoods)

Feature 1: Generate Individual HMMs
Feature 2: Discover Common Patterns among Individuals through Clustering
Feature 3: Quantify Similarity between Patterns Using Machine Learning Methods
Feature 4: Use the Similarity Measure to Examine the Relationship between Eye Movement Patterns and Other Measures

Other features:
- FREE & EASY to use!!
- Built on MATLAB

Suitable for eye movements in viewing any types of visual stimuli (images, videos, etc.).

To Red
To Green
To Blue

Priors

From Red

From Green

From Blue

More Information & Free Download:

Summarize an individual's gaze pattern in an HMM -
- Personalized ROIs,
- Transition probabilities

Example Similarity to Holistic Pattern:

r = -.48, p = .004
EMHMM Summary

Feature 4:
Use the Similarity Measure to Examine the Relationship between Eye Movement Patterns and Other Measures

![Graph showing the relationship between MoCA (Cognitive Assessment) and Similarity to Holistic Pattern, with correlation coefficient r = -0.48, p = 0.004]
EMHMM: Face Recognition

- Face learning vs. face recognition
- Eye movement & cognitive ability
- Insomnia and facial expression recognition
Face learning vs. face recognition

- **Scan path theory**: Eye movements produced during learning have to be repeated during recognition for the recognition to be successful (Noton & Stark, 1971a; 1971b).
  - Yes: Eye movements during recognition resembled those generated during learning (e.g., Laeng and Teodorescu, 2002: Caldara et al., 2010)
  - No: An exact repetition of eye movements during learning was not necessary for successful recognition (Henderson et al., 2005)
  - Problem: It was unclear how to quantitatively measure eye movement pattern similarity.

- **Is the similarity between eye movement patterns in face learning and recognition related to recognition performance?**

Face learning vs. face recognition: EMHMM Clustering

- ROI with fixation duration (ROID)
- Each participant had 2 models (for learning and recognition phase respectively). We clustered all models to discover common patterns.
Face learning vs. face recognition

Results

• About 40% of the participants used different patterns between face learning and recognition ($\chi^2(1) = 2.08, p = .15$)

<table>
<thead>
<tr>
<th>Pattern switch</th>
<th>recognition phase</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>same</td>
<td>different</td>
</tr>
<tr>
<td><strong>learning</strong></td>
<td>holistic</td>
<td>18</td>
</tr>
<tr>
<td><strong>phase</strong></td>
<td>analytic</td>
<td>11</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>29</td>
<td>19</td>
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</tbody>
</table>

• Participants who used same or different patterns between learning and recognition did not differ significantly in recognition performance, $t(46) = .36, p = .72$.

• Participants who used analytic patterns had better recognition performance than those using holistic patterns (Learning phase pattern, $t(46) = 2.24, p = .03$; Recognition phase pattern, $t(46) = 3.13, p = .003$)

EMHMM: Face Recognition

- Face learning vs. face recognition
- Eye movement & cognitive ability
- Insomnia and facial expression recognition
Eye movement & cognitive ability

• Do eye movement patterns in face recognition reflect cognitive ability? We examined cognitive decline in older adults.

• 34 young and 34 older adults recognized 20 learned faces among 20 new faces.

• Older adults’ cognitive ability was assessed by the Montreal Cognitive Assessment (MoCA) Hong Kong version (Wong et al., 2009)

Eye movement & cognitive ability: EMHMM Clustering

- Cluster all individual HMMs into 2 clusters
Eye movement & cognitive ability: Correlations

- In older adults, the lower the cognitive ability (by MoCA), the higher the H-A scale:

  \[ R = -0.48, P = 0.004 \]
Eye movement & cognitive ability: Correlations

• The relationship between H-A scale and cognitive ability (MoCA score) was replicated in new older adult participants (n = 38) viewing new face images using the old representative holistic and analytic HMMs.

\[ R = -.44, \ p = 0.01 \]

• This result suggests the possibility of using eye movements as an easily deployable screening assessment for cognitive decline in older adults.
Eye movement & cognitive ability: Correlations

- H-A scale was particularly correlated with executive and visual attention functions.

<table>
<thead>
<tr>
<th></th>
<th>Correlation with H-A Scale</th>
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<tbody>
<tr>
<td></td>
<td>r</td>
</tr>
<tr>
<td>1. General Cognitive assessment (MoCA)</td>
<td>-.44</td>
</tr>
<tr>
<td>2. Executive Planning (TOL; Total moves)</td>
<td>.36</td>
</tr>
<tr>
<td>3. Visual Attention (TMT)</td>
<td>.37</td>
</tr>
<tr>
<td>4. Working Memory</td>
<td></td>
</tr>
<tr>
<td>- Verbal 2-back</td>
<td>-.35</td>
</tr>
<tr>
<td>- Spatial 2-back</td>
<td>-.35</td>
</tr>
<tr>
<td>5. Verbal Memory (CAVLT)</td>
<td>-.17</td>
</tr>
<tr>
<td>6. Verbal Fluency (CVFT)</td>
<td>-.15</td>
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</tbody>
</table>

Eye movement & cognitive ability: Brain activation

- fMRI study with healthy young adults (Chan et al., 2016): Holistic patterns were associated with lower activation in areas important for top-down control of visual attention including the frontal eye field and intraparietal sulcus.

EMHMM: Face Recognition

- Face learning vs. face recognition
- Eye movement & cognitive ability
- Insomnia and facial expression recognition
Insomnia and facial expression recognition

• Individuals with insomnia have disturbed perception of facial expressions – could it be due to impaired attention control?

• 23 individuals with insomnia and 23 controls, performed a facial expression recognition task with happy, sad, fearful, and angry faces.

Insomnia and facial expression recognition: Insomnia vs. control

- Individuals with insomnia were more likely to misidentify angry faces as fearful.

![Responses towards Angry Faces](chart.png)
Insomnia and facial expression recognition: EMHMM Clustering

- Cluster individual HMMs into 2 groups:

- Individuals adopting eyes–mouth patterns (accuracy: 84.5% ± 0.091) were more accurate to recognize angry faces than those adopting nose–mouth patterns (accuracy: 72.6% ± 0.150), $t(44) = 3.078$, $p = .004$
Insomnia and facial expression recognition: Insomnia vs. control

- Most individuals with insomnia adopted the nose-mouth pattern whereas most controls adopted the eyes-mouth pattern, $X(1) = 4.39, p = .036$

<table>
<thead>
<tr>
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<th>Control (n = 23)</th>
<th>Insomnia (n = 23)</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>Eyes-mouth patterns</td>
<td>13 (56.5% control)</td>
<td>6 (26.1% insomnia)</td>
<td>19</td>
</tr>
<tr>
<td>Nose-mouth patterns</td>
<td>10 (43.5% control)</td>
<td>17 (73.9% insomnia)</td>
<td>27</td>
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- The compromised emotion perception in individuals with insomnia may be related to impaired visual attention control as reflected in eye movement pattern.

EMHMM: Other examples

- Eye movements when watching documentary videos (Zheng, Ye, & Hsiao, Cog Sci 2019):

**Distributed Strategy**

<table>
<thead>
<tr>
<th>Distributed</th>
<th>To Red</th>
<th>To Green</th>
<th>To Blue</th>
<th>To Pink</th>
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</thead>
<tbody>
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<td>0.00</td>
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<tr>
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<td>From Green</td>
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<td>0.08</td>
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**Centralized Strategy**

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<tbody>
<tr>
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<td>0.44</td>
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<td>0.00</td>
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<tr>
<td>From Red</td>
<td>0.91</td>
<td>0.08</td>
<td>0.01</td>
<td>0.00</td>
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<td>From Green</td>
<td>0.18</td>
<td>0.78</td>
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<td>0.39</td>
<td>0.44</td>
<td>0.00</td>
</tr>
<tr>
<td>From Pink</td>
<td>0.03</td>
<td>0.04</td>
<td>0.00</td>
<td>0.93</td>
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**Friday July 26th, 10:20 am-12:00 pm, Paper Session 23 Thinking**

[Student Travel Grant Award]

EMHMM: Other examples

- Eye fixations on individual words/musical segments during reading (Li, Chung, Yip, Chan, & Hsiao, ICMPC15/ESCOM10, 2018)

### English short words (2 – 3 letters)

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**Top-focus pattern**

**Bottom-focus pattern**
Outline

• Introduction to EMHMM and Its Applications
  – EMHMM: Face recognition + other examples
  – EMHMM with co-clustering: Scene perception
  – EMSHMM (Switching HMM): Preference decision making

• Demo + Break:
  – Face recognition task + personalized report

• Tutorial and Hands-on Experience
  – Simulation study
  – EMHMM toolbox tutorial
  – Hands-on experience/demo
EMHMM with co-clustering

• How to summarize a general eye movement strategy in tasks where stimuli’s feature layouts differ significantly (e.g., scene perception, visual search, reading etc.)?

• **EMHMM with co-clustering**: 1 stimulus 1 model; use co-clustering to discover participants using the same pattern across stimuli.
EMHMM with co-clustering: Scene perception clustering

- 61 Asian participants viewed 150 natural and 150 urban scene images and rated their preference (1 to 5), followed by a surprise foreground object recognition task.

Explorative pattern (37 participants)

Focused pattern (24 participants)
EMHMM with co-clustering: Scene perception preliminary findings

• Previous research reported that Asians showed explorative whereas Caucasians showed focused patterns (Chua, Boland, & Nisbett, 2005). Our participants were all Asians.

• Explorativ pattern was associated with better foreground object recognition performance.

• Focused pattern was associated with faster responses in the congruent condition of the flanker task and higher preference ratings of the scenes.

Friday July 26th, 13:00-14:30, Poster Session 2
Outline

• Introduction to EMHMM and Its Applications
  – EMHMM: Face recognition + other examples
  – EMHMM with co-clustering: Scene perception
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EMSHMM (Switching HMM)

- For analyzing eye movements in cognitive tasks involving cognitive state changes (e.g., decision making).
- A switching hidden Markov model (SHMM) to capture a participant’s cognitive state transitions, with eye movement patterns during each cognitive state being summarized using a regular HMM.
EMSHMM (Switching HMM): Clustering results

• 24 participants, 60 trials of preference decisions between 2 faces.
• We clustered individual models into 2 groups according to cognitive state transitions; here shows resulting preference-biased period HMMs:

  Group A: higher probability to stay at the chosen side and switch less between 2 sides

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<thead>
<tr>
<th>Group A</th>
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<th>Chosen</th>
<th>Not-chosen</th>
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<tbody>
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<td></td>
<td></td>
<td>0.50</td>
<td>0.50</td>
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<tr>
<td>Prior</td>
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<td>0.83</td>
<td>0.17</td>
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<tr>
<td>Chosen</td>
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  Group B

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<td>0.54</td>
<td>0.46</td>
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<tr>
<td>Prior</td>
<td></td>
<td>0.71</td>
<td>0.29</td>
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EMSHMM (Switching HMM): Preliminary findings

- As compared with Group B, Group A had a stronger tendency to look at the preferred stimulus at the end.
- As compared with EMHMM, EMSHMM better captured eye movement behavior in the task, resulting in higher decision inference accuracy.

Introduction to EMHMM and Its Applications : Summary

• EMHMM allows us to:
  – Summarize a person’s eye movements in terms of personalized ROIs and transition probabilities using an HMM.
  – Discover common eye movement patterns among participants.
  – Quantitatively assess eye movement pattern similarity.
  – Discover associations between eye movements and other measures (e.g., performance, brain imaging data, etc.).

• Eye Movement analysis with HMMs (EMHMM) Toolbox is available: [http://visal.cs.cityu.edu.hk/research/emhmm/](http://visal.cs.cityu.edu.hk/research/emhmm/)

• EMHMM with co-clustering & EMSHMM will be available on the same website soon.