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

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Outline

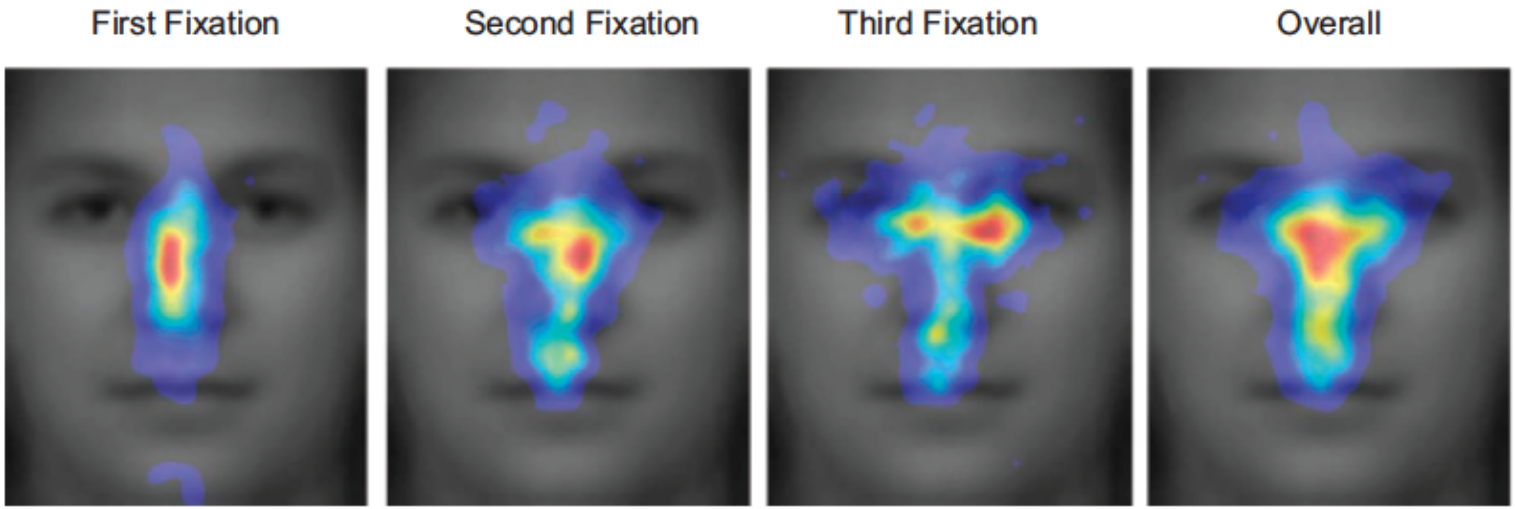
- **Introduction to EMHMM and Its Applications**
  - EMHMM: Face recognition + other examples
  - EMHMM with co-clustering: Scene perception
  - EMSHMM (Switching HMM): Preference decision making

- **Demo + Break:**
  - Face recognition task + personalized report

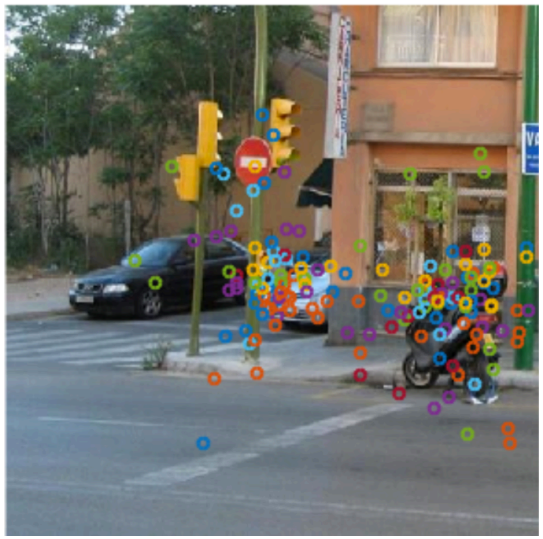
- **Tutorial and Hands-on Experience**
  - Simulation study
  - EMHMM toolbox tutorial
  - Hands-on experience/demo

Background

- Eye movement reflects underlying cognitive processes.



(Hsiao & Cottrell, 2008)

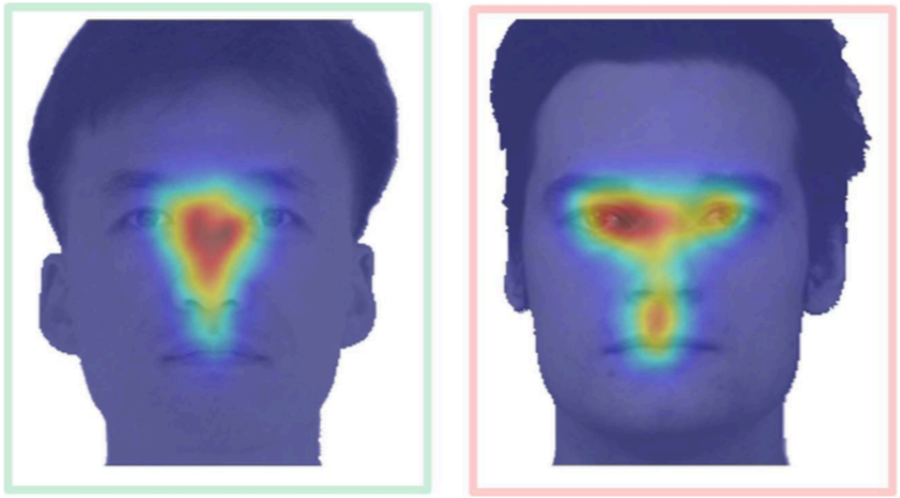


(Coutrot, Hsiao, & Chan, 2018)

Background

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

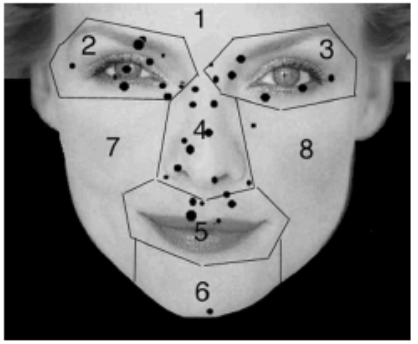
Website viewing (Eckhardt et al., 2013)

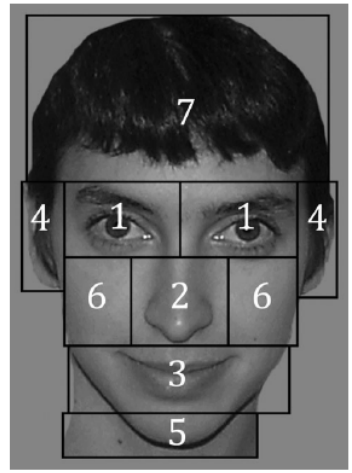


Face recognition (Kelly et al., 2011)

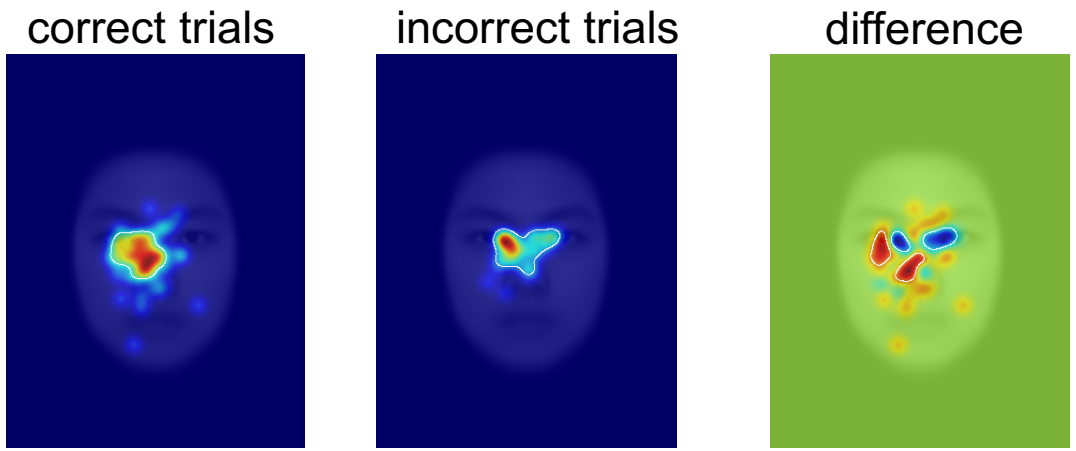
Eye Movement Analysis

- **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



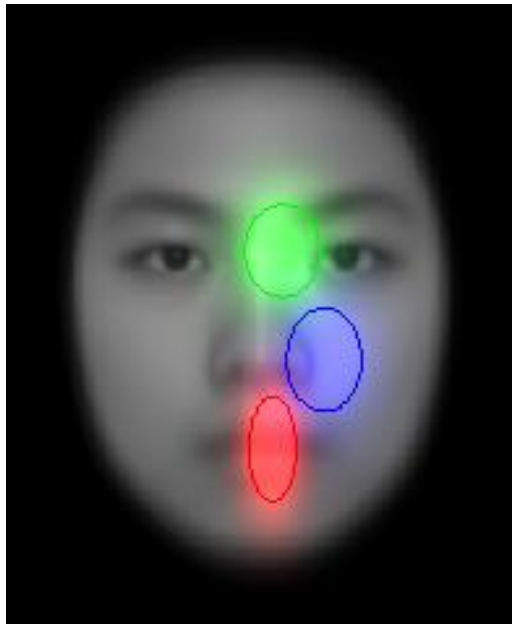


  - Heat map approach (iMap, Caldara & Miellet, 2011)
    Problems: Difference maps can be hard to interpret; it does not handle transition information between ROIs



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**

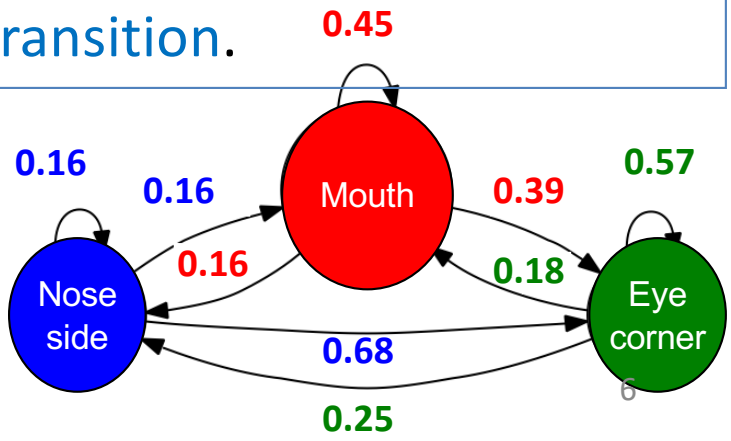


The ellipses show the ROIs as 2-D Gaussian emissions; number of ROIs is automatically determined using Bayesian methods.

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

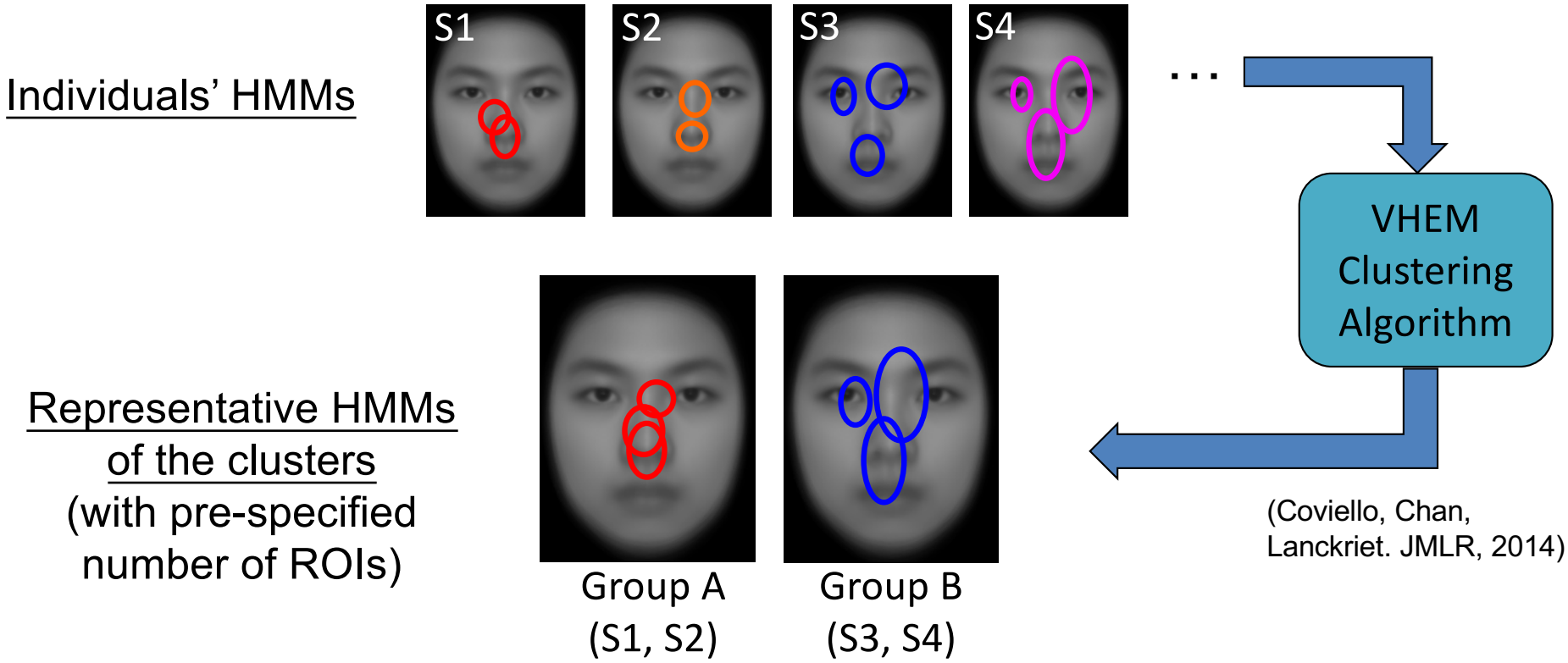
The transition probabilities indicate the probabilities of observing a particular transition.

	to red	to green	to blue
prior	.23	.58	.19
from red	.45	.39	.16
from green	.18	.57	.25
from blue	.16	.68	.16



EMHMM: Clustering

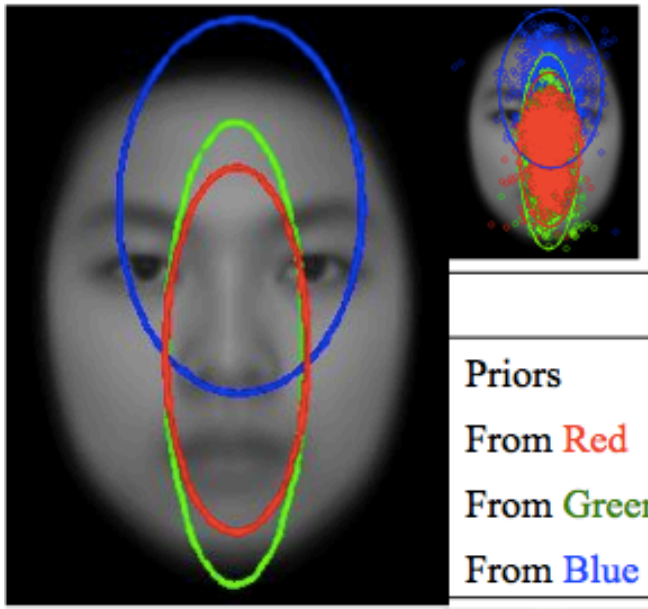
- **A data-driven approach to discover common strategies:**
  - Representative HMMs of common strategies
  - Log likelihood measures to quantify eye movement pattern similarities

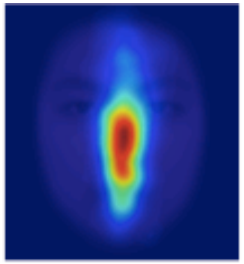


Chuk, T., Chan, A. B., & Hsiao, J. H. (2014). Understanding eye movements in face recognition using hidden Markov models. *Journal of Vision*, *14*(11):8, 1-14.

Example of EMHMM Clustering

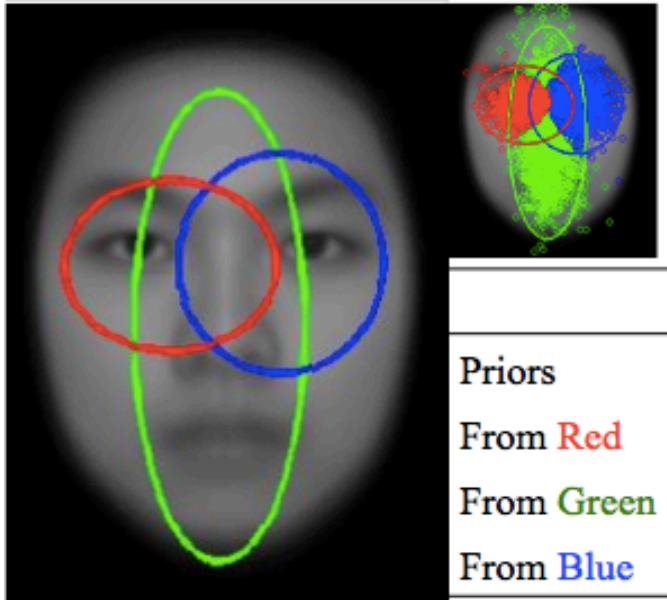
- 34 young and 34 older adults performed a face recognition task.
- We clustered individual HMMs into 2 groups.

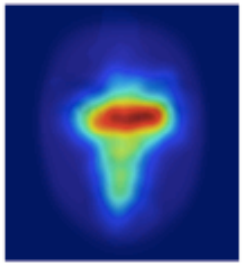




Holistic

	To Red	To Green	To Blue
Priors	.16	.80	.04
From Red	.82	.12	.06
From Green	.93	.02	.05
From Blue	.07	.00	.93





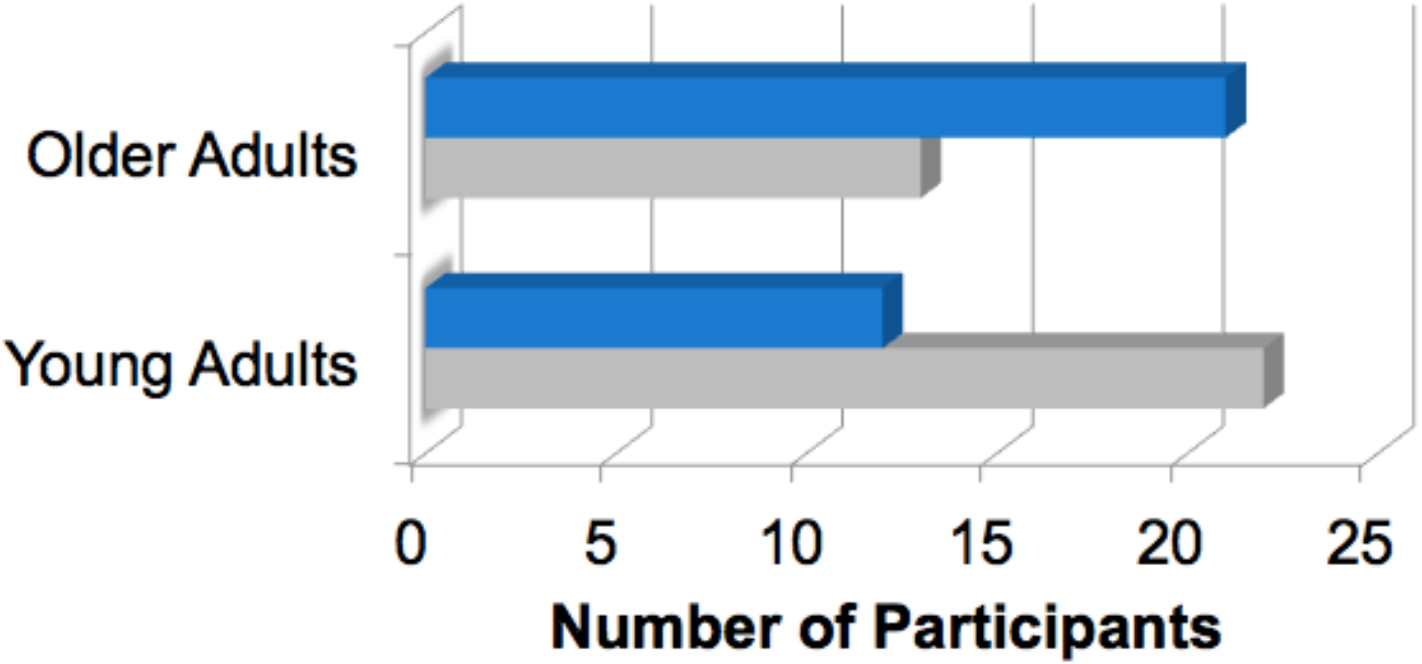
Analytic

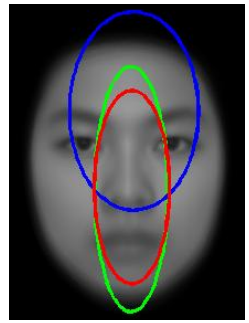
	To Red	To Green	To Blue
Priors	.03	.82	.15
From Red	.21	.34	.45
From Green	.25	.36	.39
From Blue	.27	.26	.47

Chan, C. Y. H., Chan, A. B., Lee, T. M. C., & Hsiao, J. H. (2018). Eye movement patterns in face recognition are associated with cognitive decline in older adults. *Psychonomic Bulletin & Review, 25*(6), 2200-2207.

Example of EMHMM Clustering : age difference

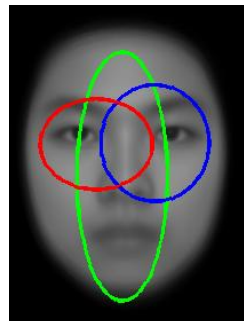
- **More older adults adopted holistic patterns while more young adults adopted analytic patterns**, X(2) = 4.77, p = .03 (Chi-square test)





Holistic

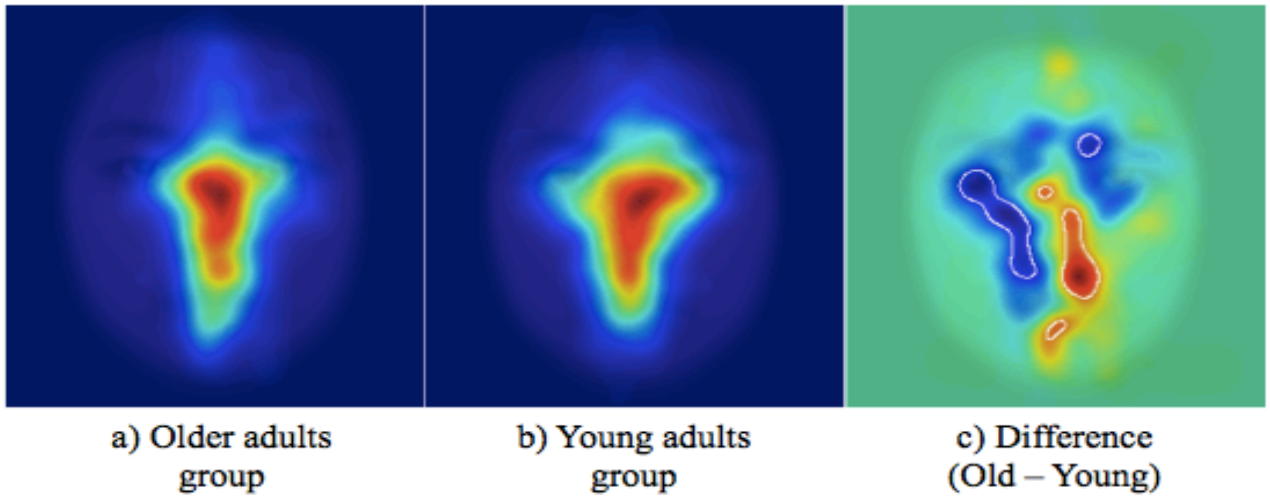
Analytic



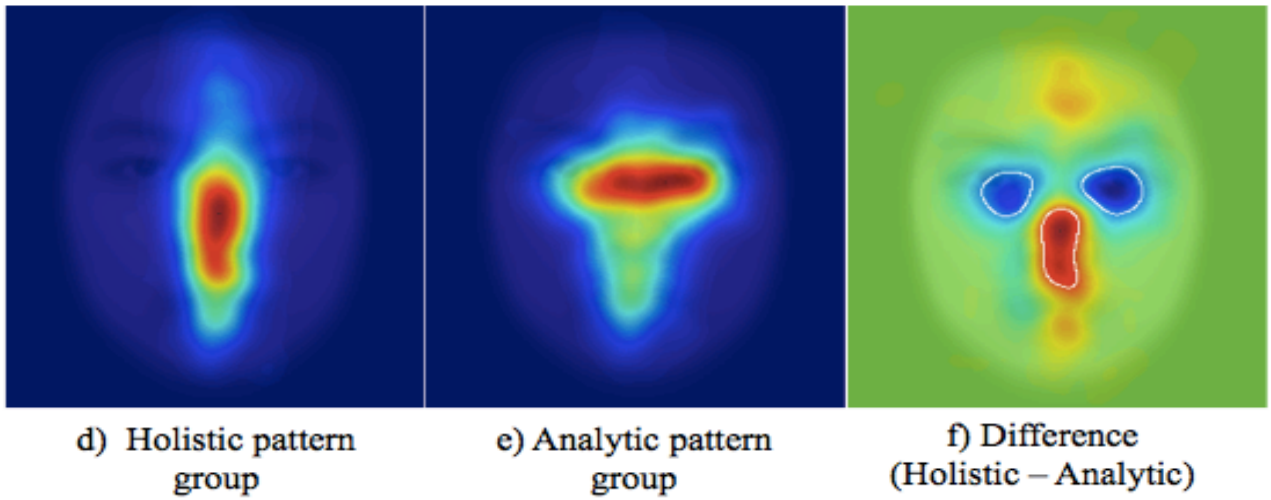
Example of EMHMM Clustering : Traditional group comparison vs. EMHMM

- **Individual differences are obscured in direct group comparisons**

Traditional Age group comparison



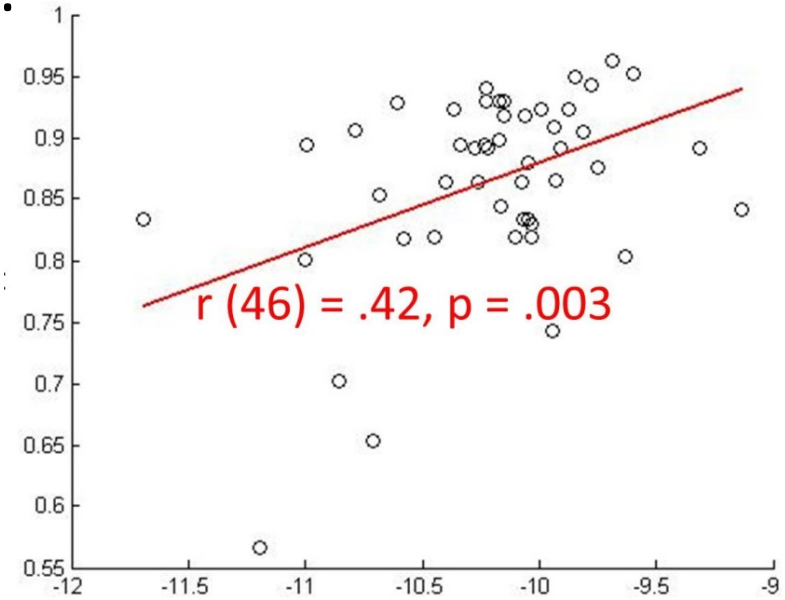
HMM subgroup comparison



Example of Similarity Measures

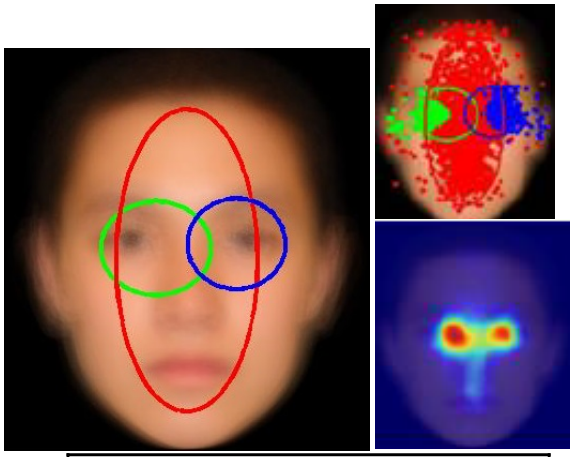
- We can quantify the *similarity* of a participant's eye movement pattern to a common strategy using log-likelihood measures.
- E.g., Examine the correlation between the similarity and performance .

Recognition performance (A')



Log-likelihood of being analytic

less analytic ⟷ *more analytic*



	to red	to green	to blue
prior	.79	.14	.07
from red	.39	.38	.23
from green	.25	.09	.66
from blue	.29	.62	.09

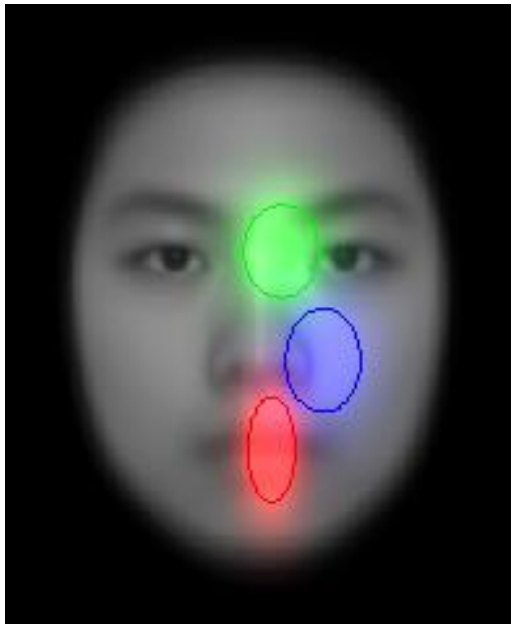
- **EMHMM is particularly suitable for examining the link between eye movement patterns and other measures.**

Chuk, T., Crookes, K., Hayward, W. G., Chan, A. B., & Hsiao, J. H. (2017). Hidden Markov model analysis reveals the advantage of analytic eye movement patterns in face recognition across cultures. *Cognition*, *169*, 102-117.

EMHMM Summary

Feature 1: Generate Individual HMMs

- Personalized regions of interest (ROIs)
- Transition probabilities among the ROIs



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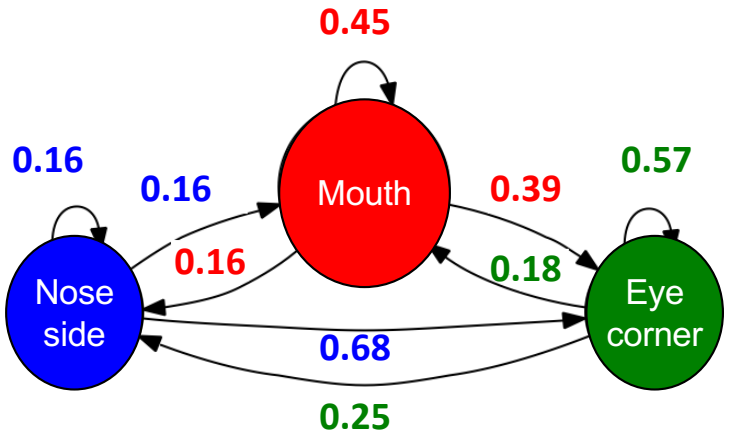
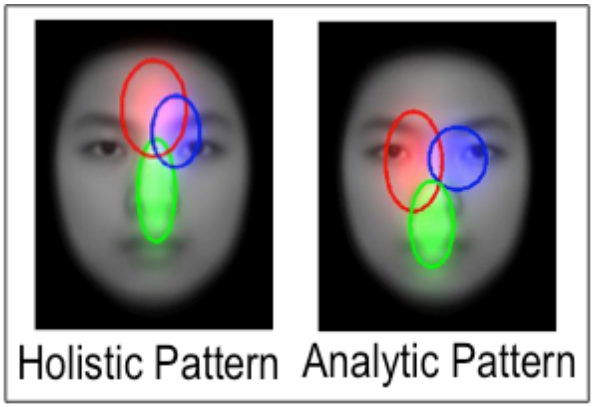


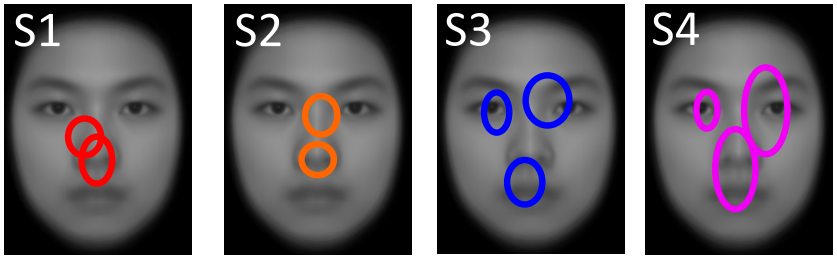
EMHMM Summary

Feature 2:
Discover Common Patterns through Clustering



(Chuk, Chan, & Hsiao, 2014)

Individuals' HMMs



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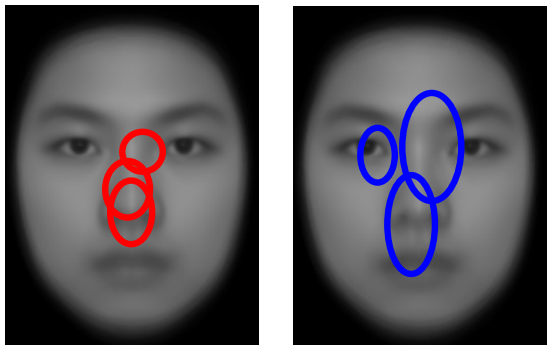
VHEM Clustering Algorithm

Representative HMMs of the clusters



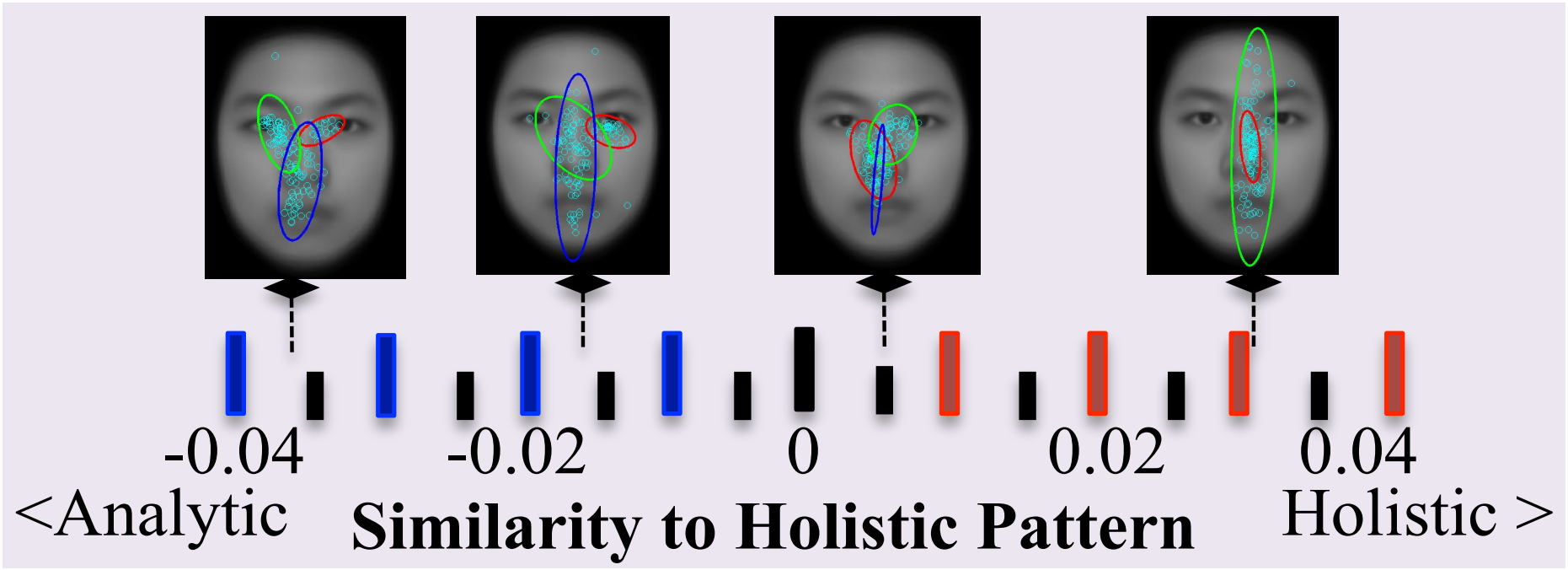
Group A (S1, S2)

Group B (S3, S4)

(Coviello, Chan, Lanckriet. JMLR, 2014)

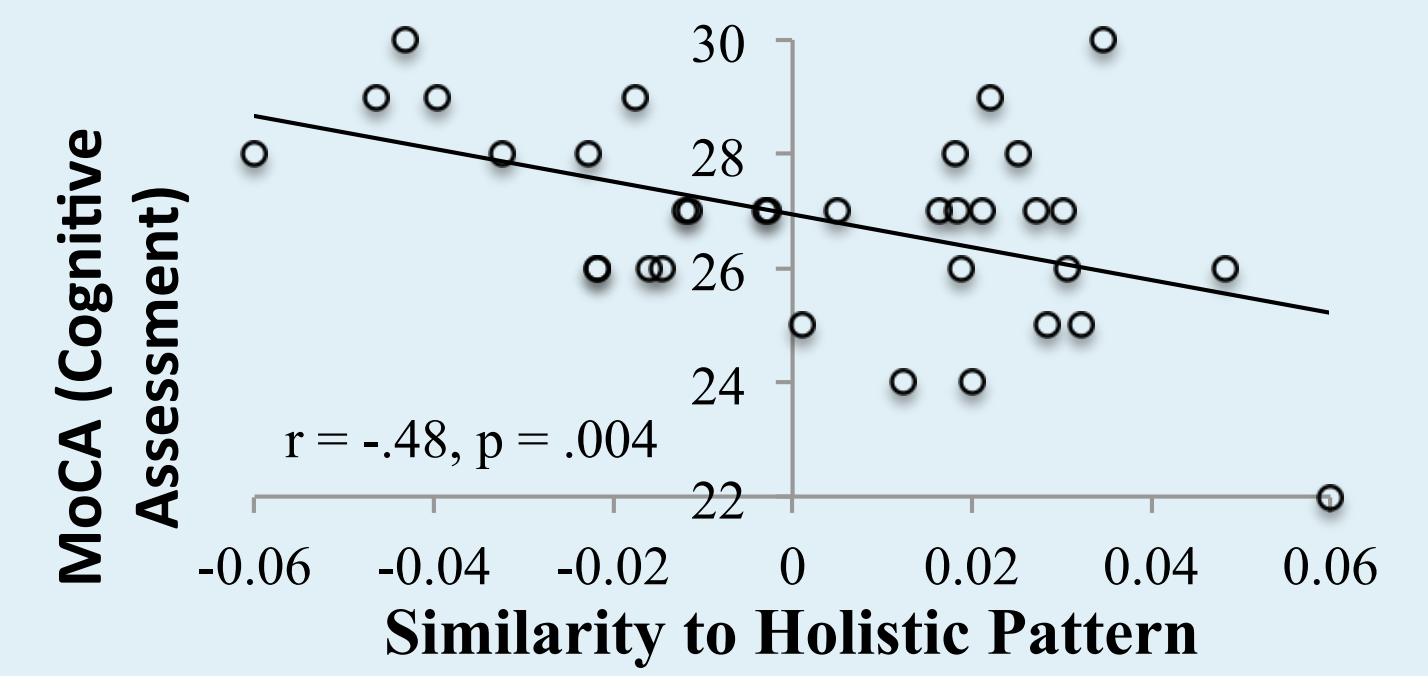
EMHMM Summary

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



EMHMM Summary

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



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.

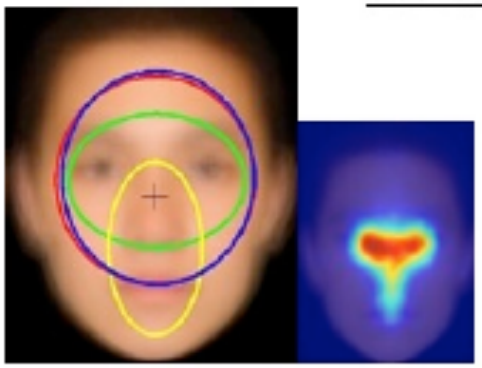
- **Is the similarity between eye movement patterns in face learning and recognition related to recognition performance?**

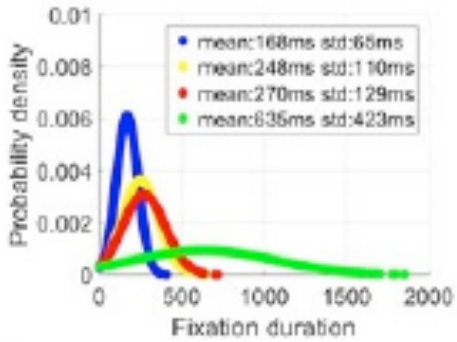
Chuk, T., Chan, A. B., & Hsiao, J. H. (2017). Is having similar eye movement patterns during face learning and recognition beneficial for recognition performance? Evidence from hidden Markov modeling. *Vision Research*, *141*, 204-216.

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.

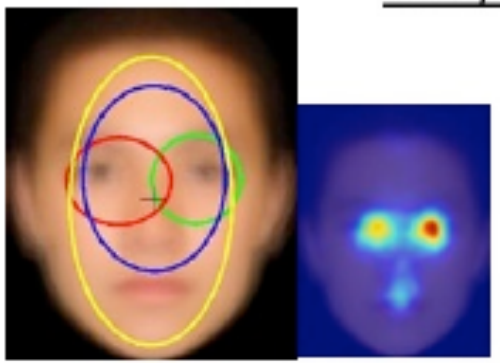
Holistic Pattern

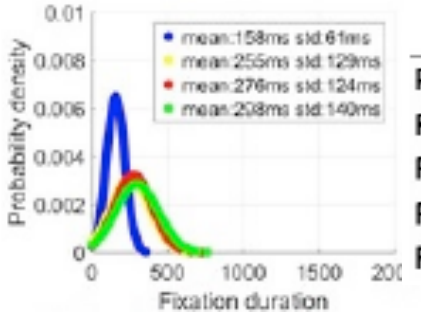




	To Blue	To Yellow	To Red	To Green
Priors	.47	.08	.43	.02
From Blue	.30	.11	.56	.03
From Yellow	.11	.34	.52	.03
From Red	.03	.09	.79	.09
From Green	.02	.06	.58	.34

Analytic Pattern





	To Blue	To Yellow	To Red	To Green
Priors	.66	.23	.05	.06
From Blue	.22	.15	.27	.36
From Yellow	.11	.55	.14	.20
From Red	.05	.29	.12	.54
From Green	.10	.41	.37	.12

Face learning vs. face recognition Results

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

Pattern switch		*recognition phase*		
		same	different	**Total**
learning	holistic	18	17	**35**
phase	analytic	11	2	**13**
Total		**29**	**19**	**48**

- 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)

Chuk, T., Chan, A. B., & Hsiao, J. H. (2017). Is having similar eye movement patterns during face learning and recognition beneficial for recognition performance? Evidence from hidden Markov modeling. *Vision Research*, *141*, 204-216.

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.**

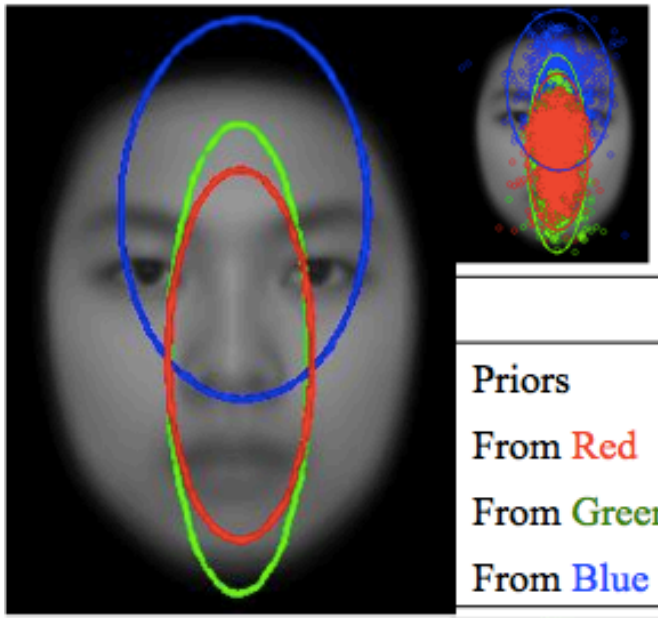
- 34 young and 34 older adults recognized 20 learned faces among 20 new faces.

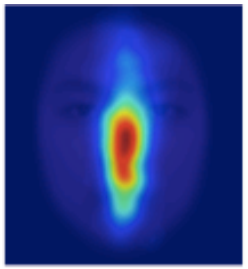
- Older adults' cognitive ability was assessed by the Montreal Cognitive Assessment (MoCA) Hong Kong version (Wong et al., 2009)

Chan, C. Y. H., Chan, A. B., Lee, T. M. C., & Hsiao, J. H. (2018). Eye movement patterns in face recognition are associated with cognitive decline in older adults. *Psychonomic Bulletin & Review, 25(6), 2200-2207.*

Eye movement & cognitive ability: EMHMM Clustering

- Cluster all individual HMMs into 2 clusters





Holistic

	To Red	To Green	To Blue
Priors	.16	.80	.04
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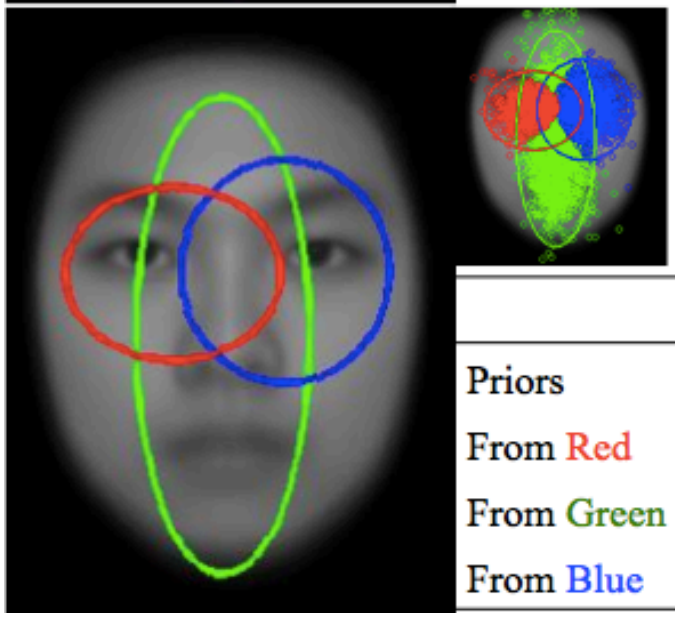
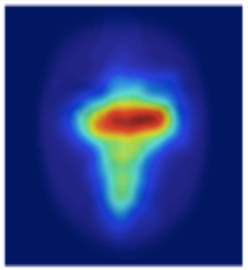


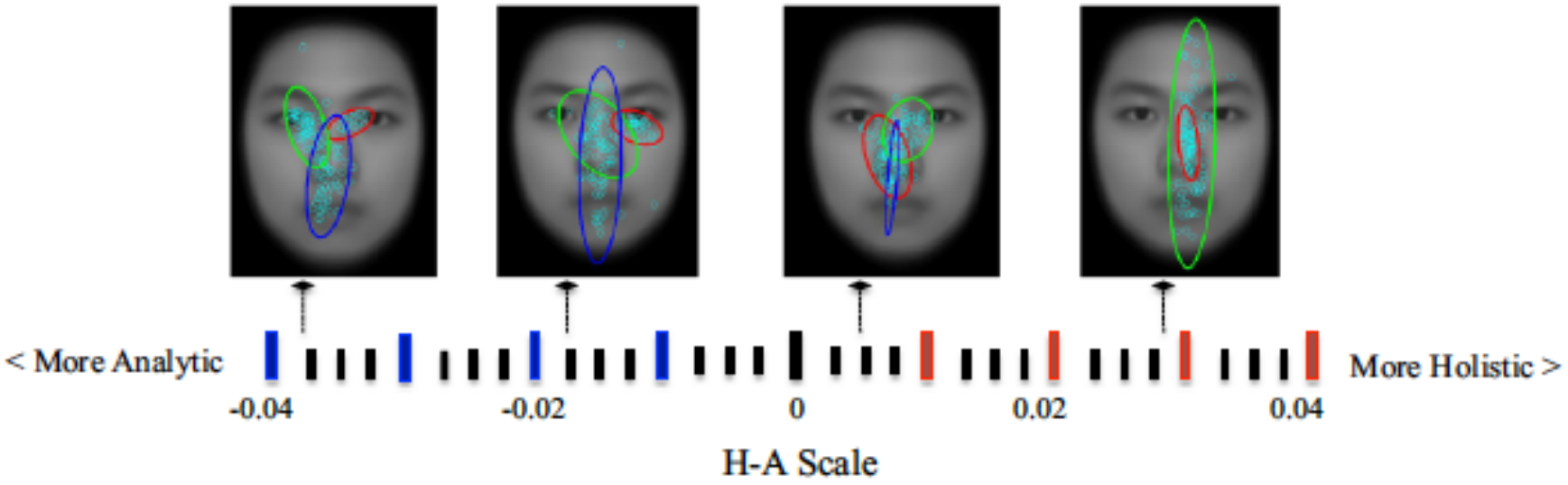


Analytic

	To Red	To Green	To Blue
Priors	.03	.82	.15
From Red	.21	.34	.45
From Green	.25	.36	.39
From Blue	.27	.26	.47

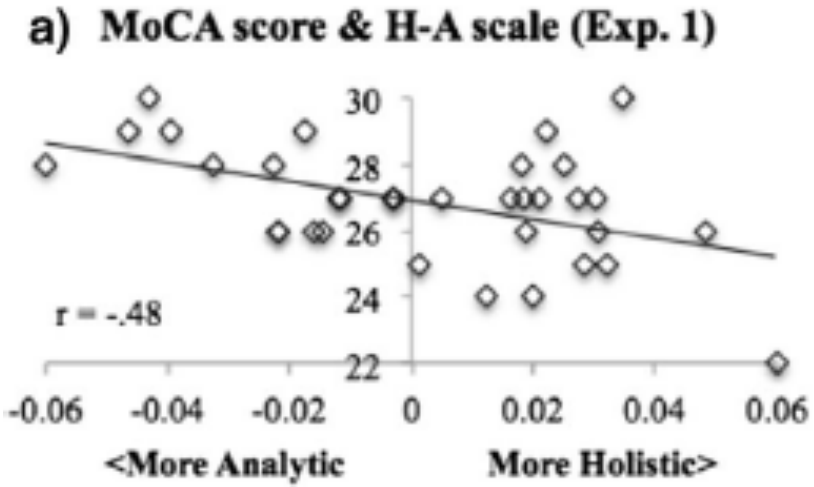
Eye movement & cognitive ability: Correlations

$$\text{H-A } Scale = \frac{Holistic\ \log\text{-}likelihood - Analytic\ \log\text{-}likelihood}{|Holistic\ \log\text{-}likelihood| + |Analytic\ \log\text{-}likelihood|}$$



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

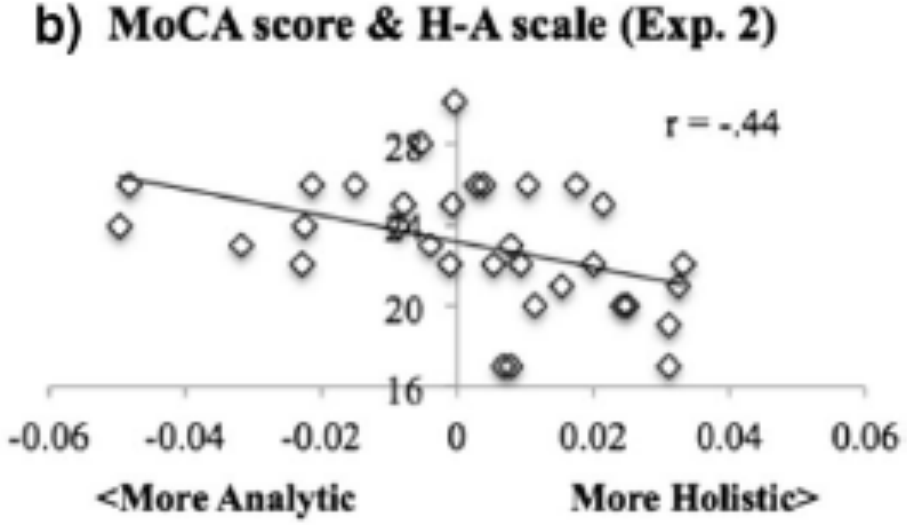
R = -.48, P = 0.004



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

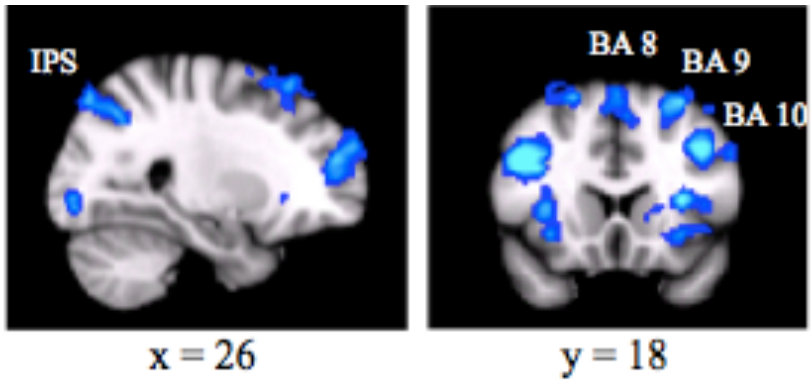
- **H-A scale was particularly correlated with executive and visual attention functions**.

	Correlation with H-A Scale	
	r	p
1. General Cognitive assessment (MoCA)	-.44	.010*
2. Executive Planning (TOL; Total moves)	.36	.043*
3. Visual Attention (TMT)	.37	.034*
4. Working Memory - Verbal 2-back	-.35	.062
- Spatial 2-back	-.35	.066
5. Verbal Memory (CAVLT)	-.17	.337
6. Verbal Fluency (CVFT)	-.15	.394

Chan, C. Y. H., Chan, A. B., Lee, T. M. C., & Hsiao, J. H. (2018). Eye movement patterns in face recognition are associated with cognitive decline in older adults. *Psychonomic Bulletin & Review, 25(6), 2200-2207.*

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.



Chan, C. Y. H., Wong, J. J., Chan, A. B., Lee, T. M. C., & Hsiao, J. H. (2016). Analytic eye movement patterns in face recognition are associated with better performance and more top-down control of visual attention: an fMRI study. In Papafragou, A., Grodner, D., Mirman, D., & Trueswell, J.C. (Eds.), *Proceeding of the 38th Annual Con-ference of the Cognitive Science Society* (pp. 854-859). Austin, TX: Cognitive Science Society.

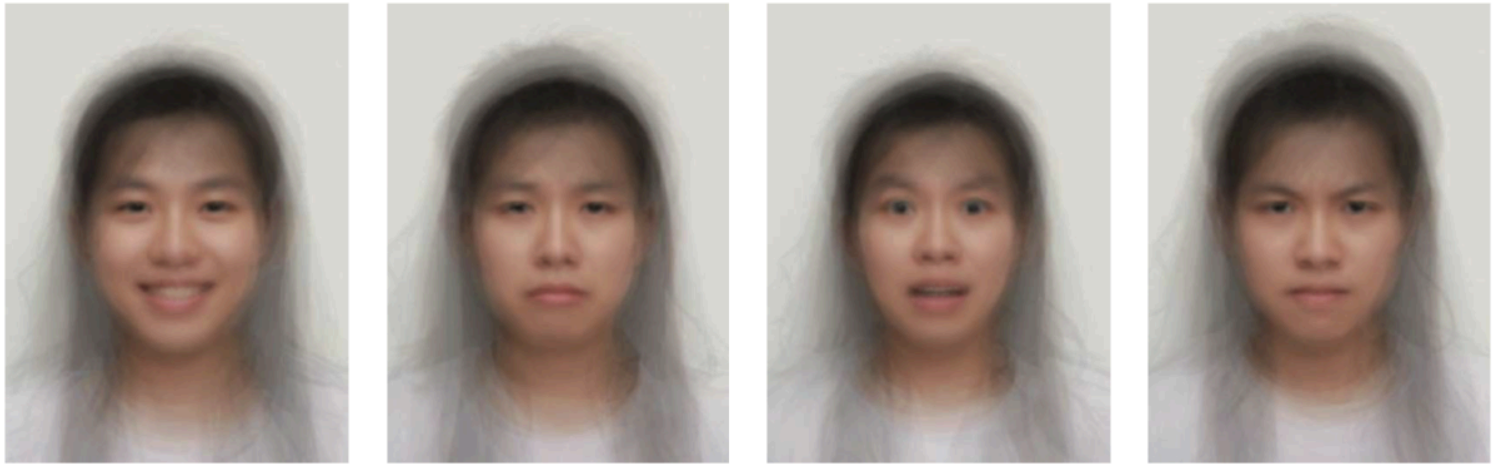
EMHMM: Face Recognition

- 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?**

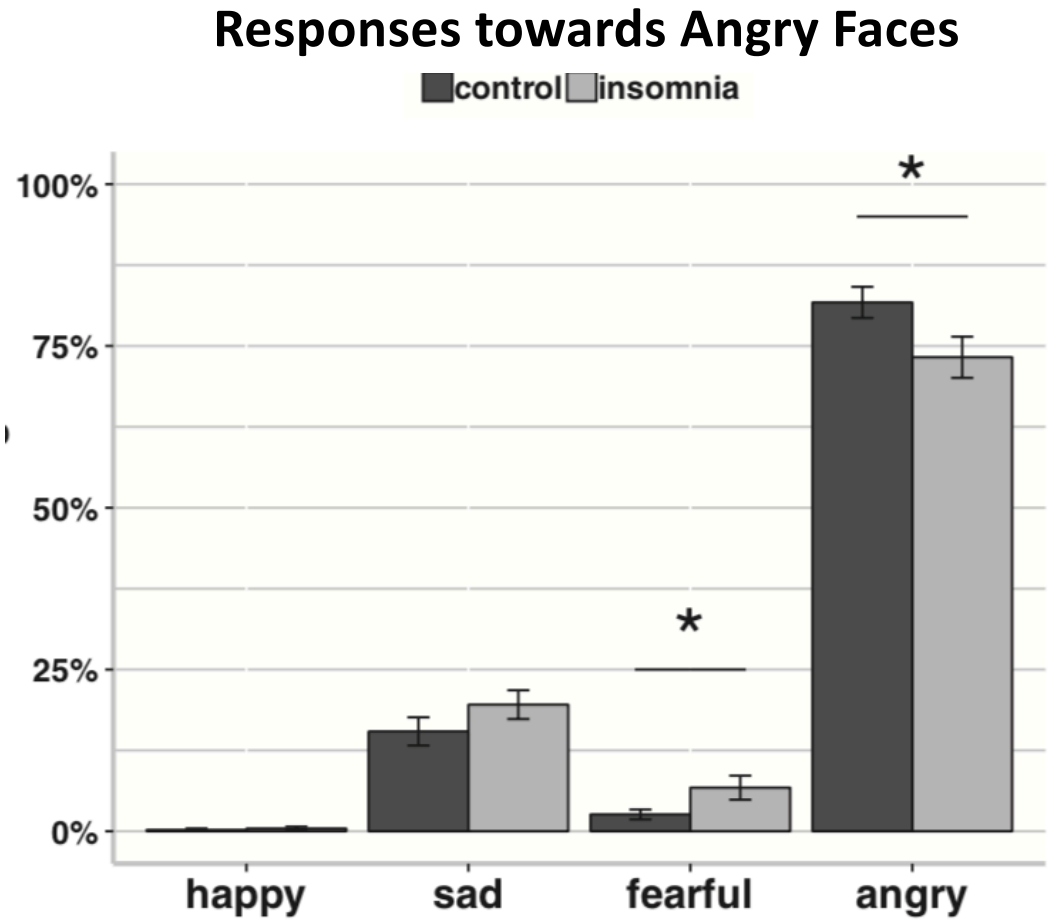
- 23 individuals with insomnia and 23 controls, performed a facial expression recognition task with happy, sad, fearful, and angry faces.



Zhang, J., Chan, A. B., Lau, E. Y. Y., & Hsiao, J. H. (2019). Individuals with insomnia misrecognize angry faces as fearful faces while missing the eyes: An eye-tracking study. *Sleep*, *42*(2), zsy220

Insomnia and facial expression recognition: Insomnia vs. control

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



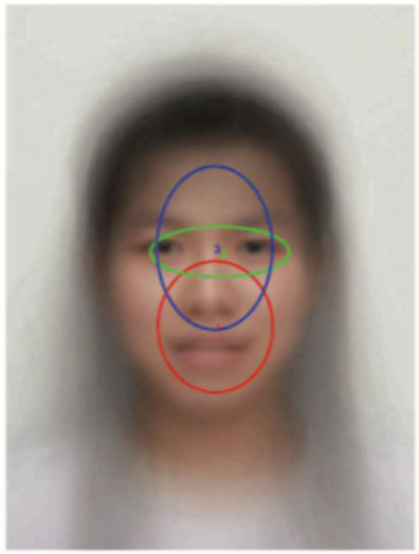
Insomnia and facial expression recognition: EMHMM Clustering

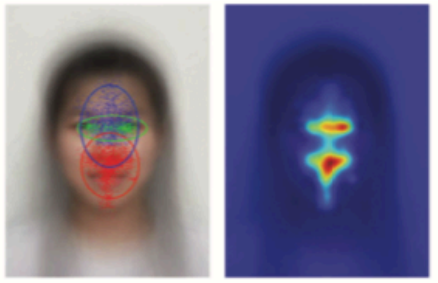
- Cluster individual HMMs into 2 groups:

Eyes-mouth patterns

A1

Overall

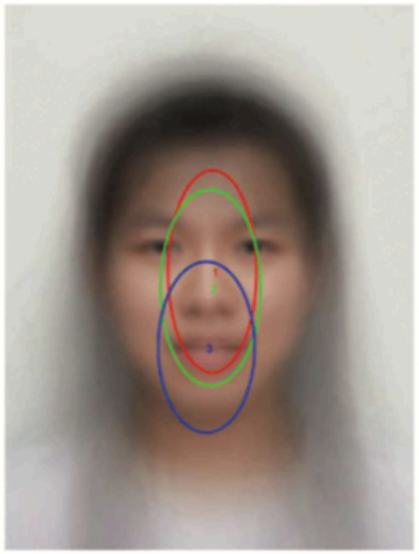


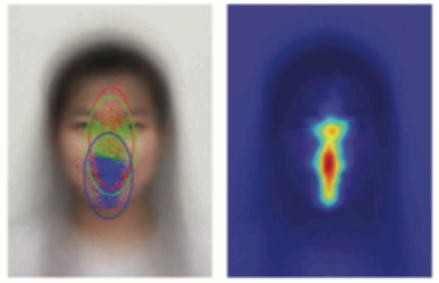


	To Red	To Green	To Blue
Priors	.54	.00	.46
From Red	.96	.04	.00
From Green	.11	.85	.04
From Blue	.01	.10	.89

Nose-mouth patterns

A2





	To Red	To Green	To Blue
Priors	.43	.15	.42
From Red	.75	.24	.01
From Green	.02	.97	.01
From Blue	.00	.01	.99

- Individuals adopting eyes–mouth patterns (accuracy: 84.5% ± .091) were more accurate to recognize angry faces than those adopting nose–mouth patterns (accuracy: 72.6% ± .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

	Control (n = 23)	Insomnia (n = 23)	Total
Eyes–mouth patterns	13 (56.5% control)	6 (26.1% insomnia)	19
Nose–mouth patterns	10 (43.5% control)	17 (73.9% insomnia)	27

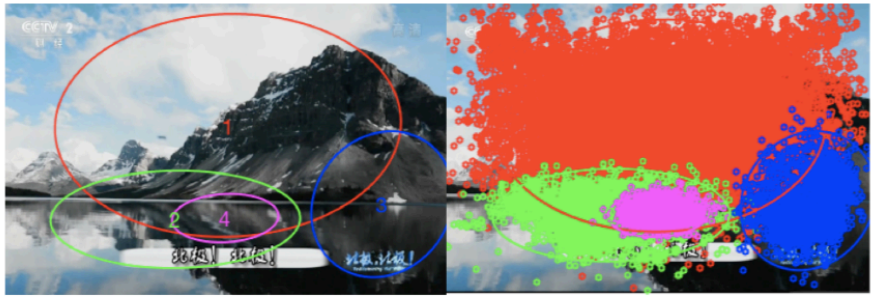
- The compromised emotion perception in individuals with insomnia may be related to impaired visual attention control as reflected in eye movement pattern.

Zhang, J., Chan, A. B., Lau, E. Y. Y., & Hsiao, J. H. (2019). Individuals with insomnia misrecognize angry faces as fearful faces while missing the eyes: An eye-tracking study. *Sleep*, *42*(2), zsy220

EMHMM: Other examples

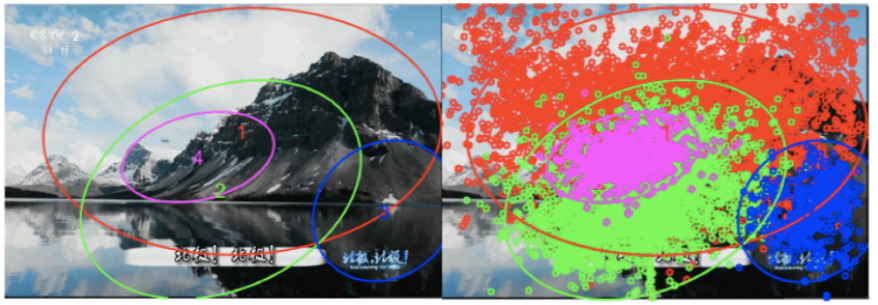
- Eye movements when watching documentary videos (Zheng, Ye, & Hsiao, Cog Sci 2019):

Distributed Strategy



Distributed	To Red	To Green	To Blue	To Pink
Priors	1.0	.00	.00	.00
From Red	.92	.05	.02	.01
From Green	.37	.56	.07	.00
From Blue	.38	.12	.47	.04
From Pink	.27	.00	.08	.64

Centralized Strategy



Centralized	To Red	To Green	To Blue	To Pink
Priors	.46	.44	.01	.00
From Red	.91	.08	.01	.00
From Green	.18	.78	.04	.01
From Blue	.17	.39	.44	.00
From Pink	.03	.04	.00	.93

Friday July 26th, 10:20 am-12:00 pm, Paper Session 23 Thinking

[Student Travel Grant Award]

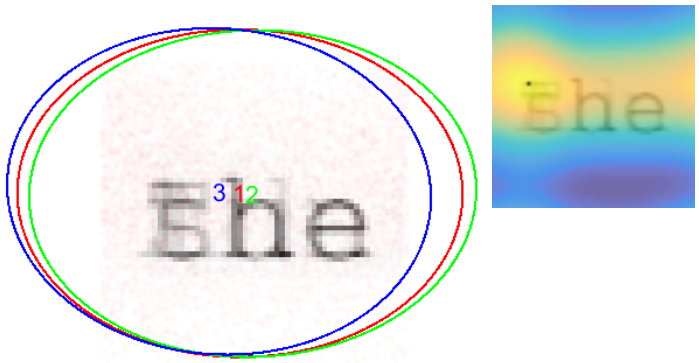
Zheng, Y., Ye, X., & Hsiao, J. H. (2019). Does Video Content Facilitate or Impair Comprehension of Documentaries? The Effect of Cognitive Abilities and Eye Movement Strategy. *Proceeding of the 41th Annual Conference of the Cognitive Science Society.*

EMHMM: Other examples

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

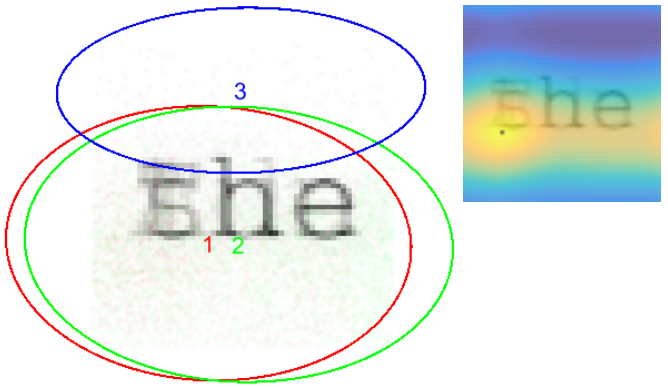
English short words
(2 – 3 letters)

Top-focus pattern



	To Red	To Green	To Blue
Priors	.70	.08	.22

Bottom-focus pattern



	To Red	To Green	To Blue
Priors	.65	.34	.01

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

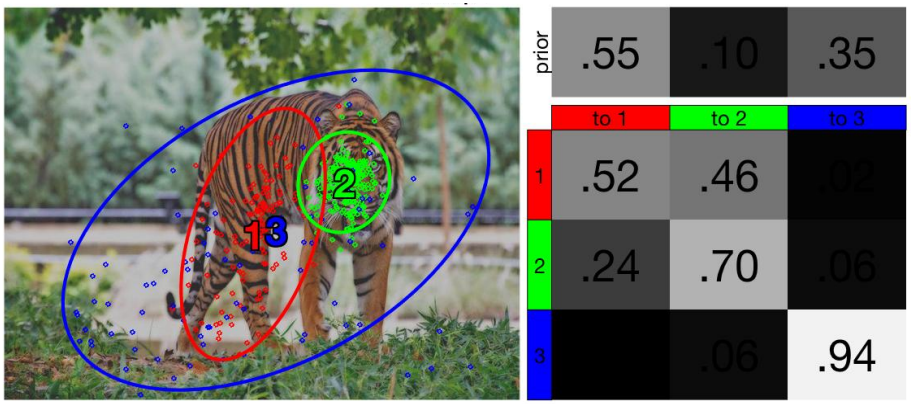
EMHMM with co-clustering

- **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.

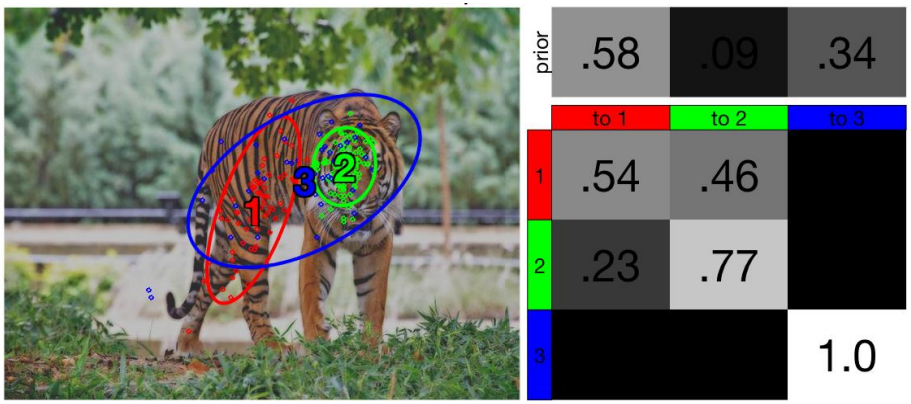
EMHMM with co-clustering: Scene perception clustering

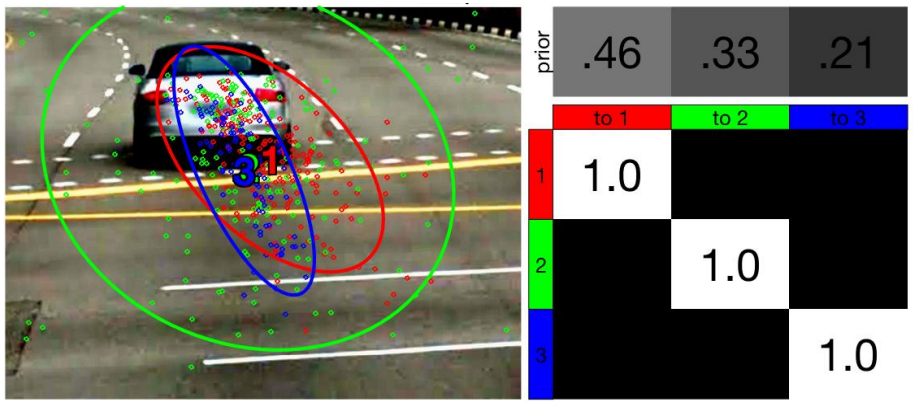
- 61 Asian participants viewed 150 natural and 150 urban scene images and rated their preference (1 to 5), followed by a surprise foreground object recognition task.

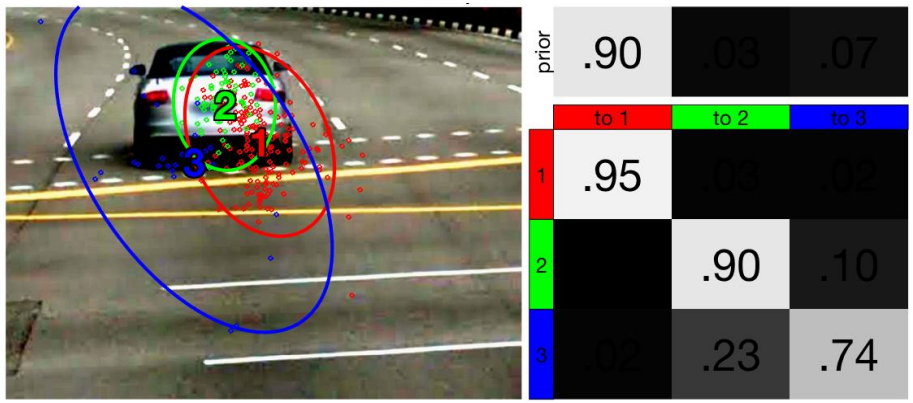
Explorative pattern (37 participants)



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.

- Explorative 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

Hsiao, J. H., Chan, K. Y., Du, Y. & Chan, A. B. (2019). Understanding individual differences in eye movement pattern during scene perception through hidden Markov modeling. *Proceeding of the 41th Annual Conference of the Cognitive Science Society*

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:**
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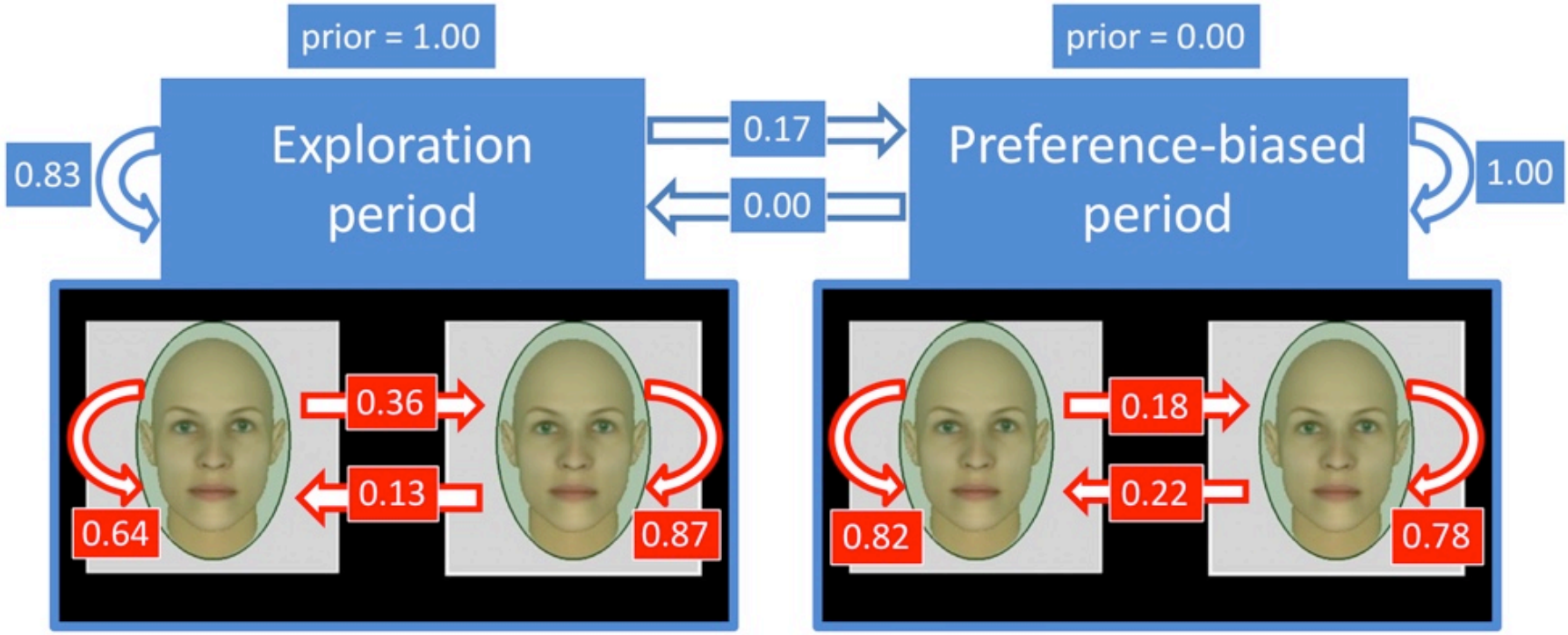
  - Hands-on experience/demo

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

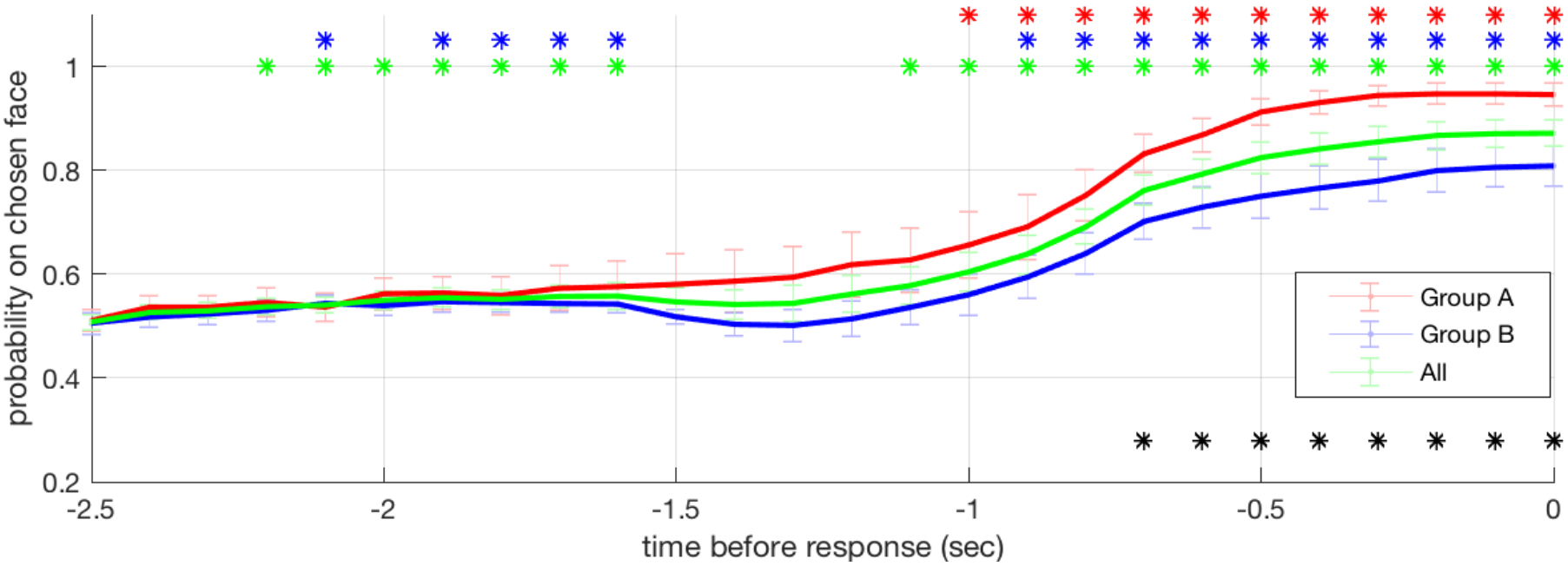
Group A	Chosen	Not-chosen
Prior	0.50	0.50
Chosen	0.83	0.17
Not-chosen	0.25	0.75

Group B

Group B	Chosen	Not-chosen
Prior	0.54	0.46
Chosen	0.71	0.29
Not-chosen	0.39	0.61

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.



Chuk, T., Chan, A. B., Shimojo, S., & Hsiao, J. H. (in press). Eye movement analysis with switching hidden Markov models. *Behavior Research Methods*.

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/**

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