Joint analysis of eye movements and EEGs using coupled hidden semi-Markov models to identify and characterize reading strategies

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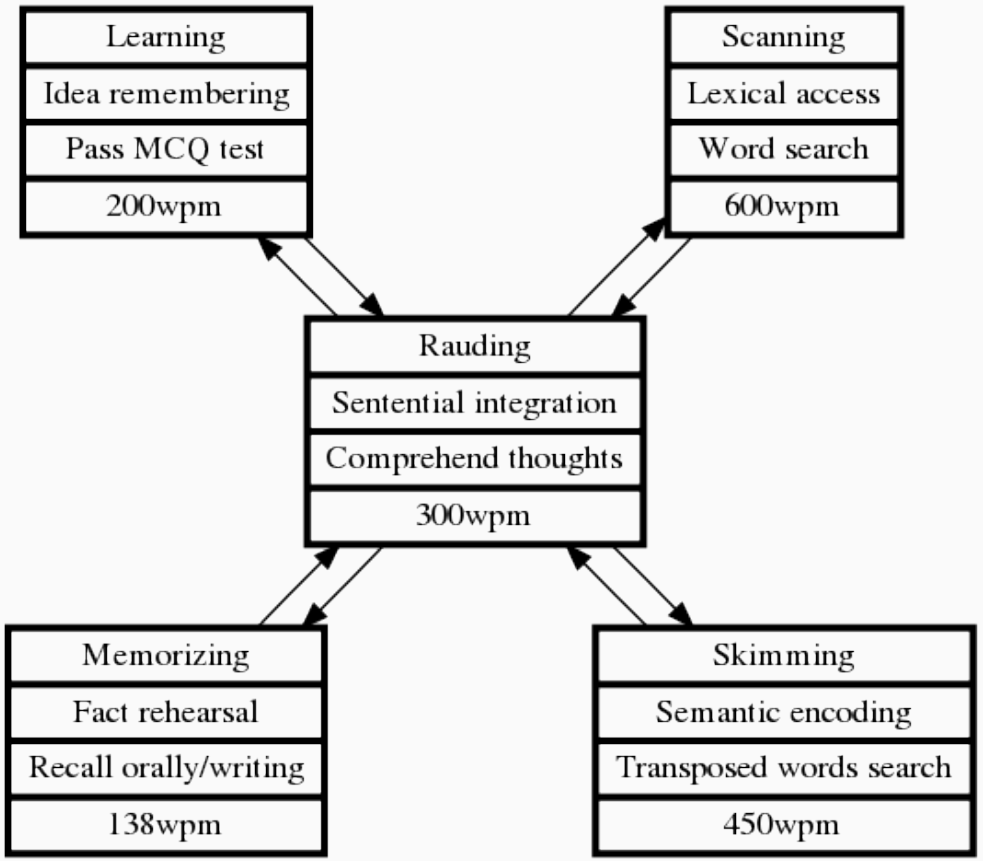
Reading strategies & segmentation

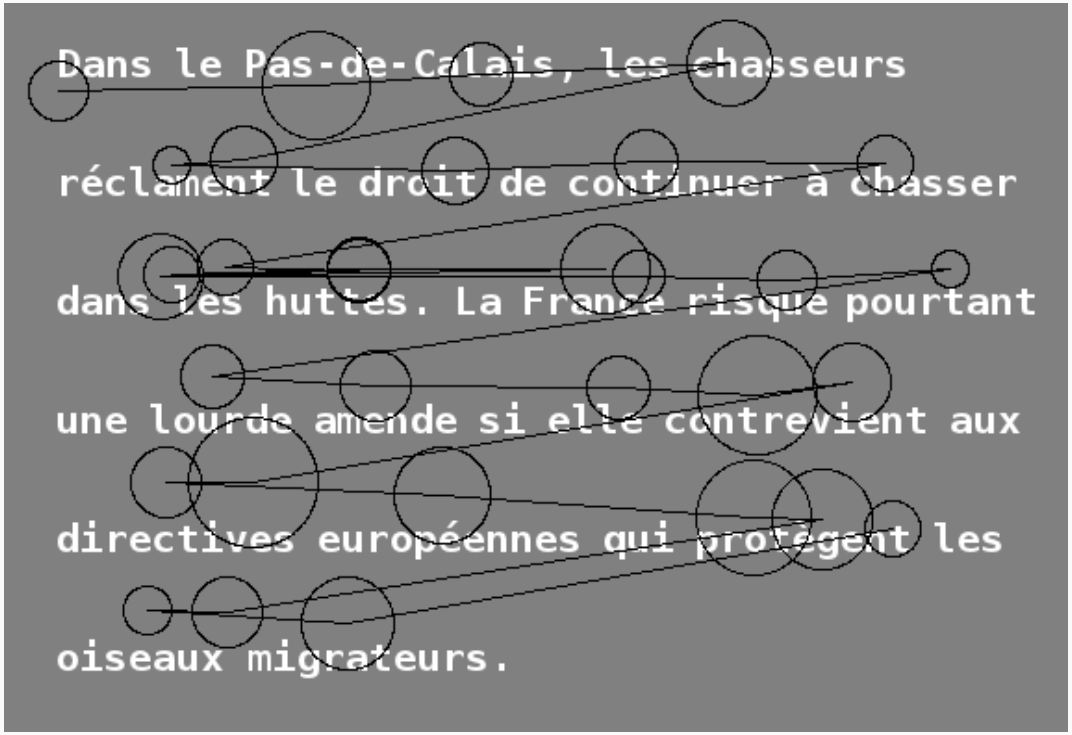
- Aim: identifying strategies within text reading trials and characterizing these with EEG patterns.
- Carver (1990) identified **5 reading strategies**
- Reading strategies were defined in controlled settings using **reading rates**
- **Issue**: how to identify strategies in free reading trials from eye-tracker and EEG data?
- Proficient readers are not faster but switch more efficiently between strategies (can we check this?)



5 reading strategies by Carver (1990)

Eye movements & eye-tracking

- During reading, eyes move across words and can be tracked with an **eye-tracker**



- **Fixation** (circles): immobilization of visual gaze during few ms.
- **Saccade** (lines): brief movement of the eye between two fixations.
- **Scanpath**: series of fixations and saccades recorded during a given task.

Material and method - Ecological settings

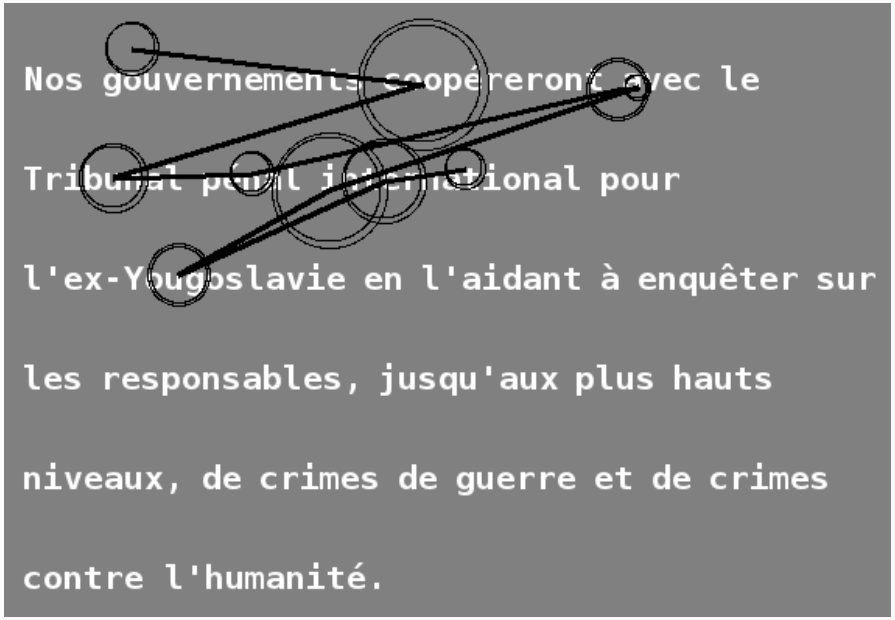
- Ecological context: **information search** tasks involving both **semantic information gathering** and **decision making processes** (Frey *et al.*, 2013)
- Simulate press review task through binary decision:

  Is the text related to the topic or not ?

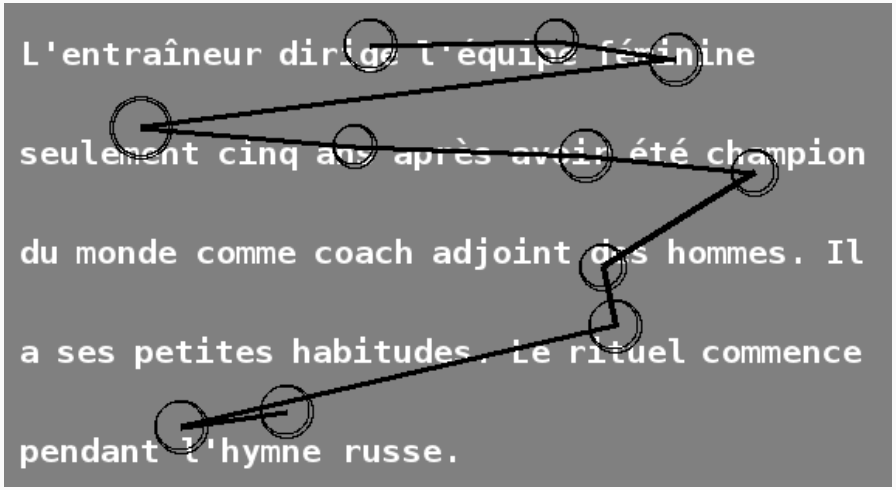
  - positive decision: target words
  - negative decision: incongruent words
- Experimental settings:
  - 15 participants
  - 180 texts per participant
  - Target topics are nominal phrases. e.g. “modern art”
  - 60 Highly- / 60 Moderately- / 60 Un-related texts to the topic
- Data sets: eye movements, electroencephalograms (EEGs)

Scanpath examples - HR / UR texts

"International tribunal"
(Highly related)



"Iraq conflict"
(Unrelated)



Data-driven scanpath segmentation

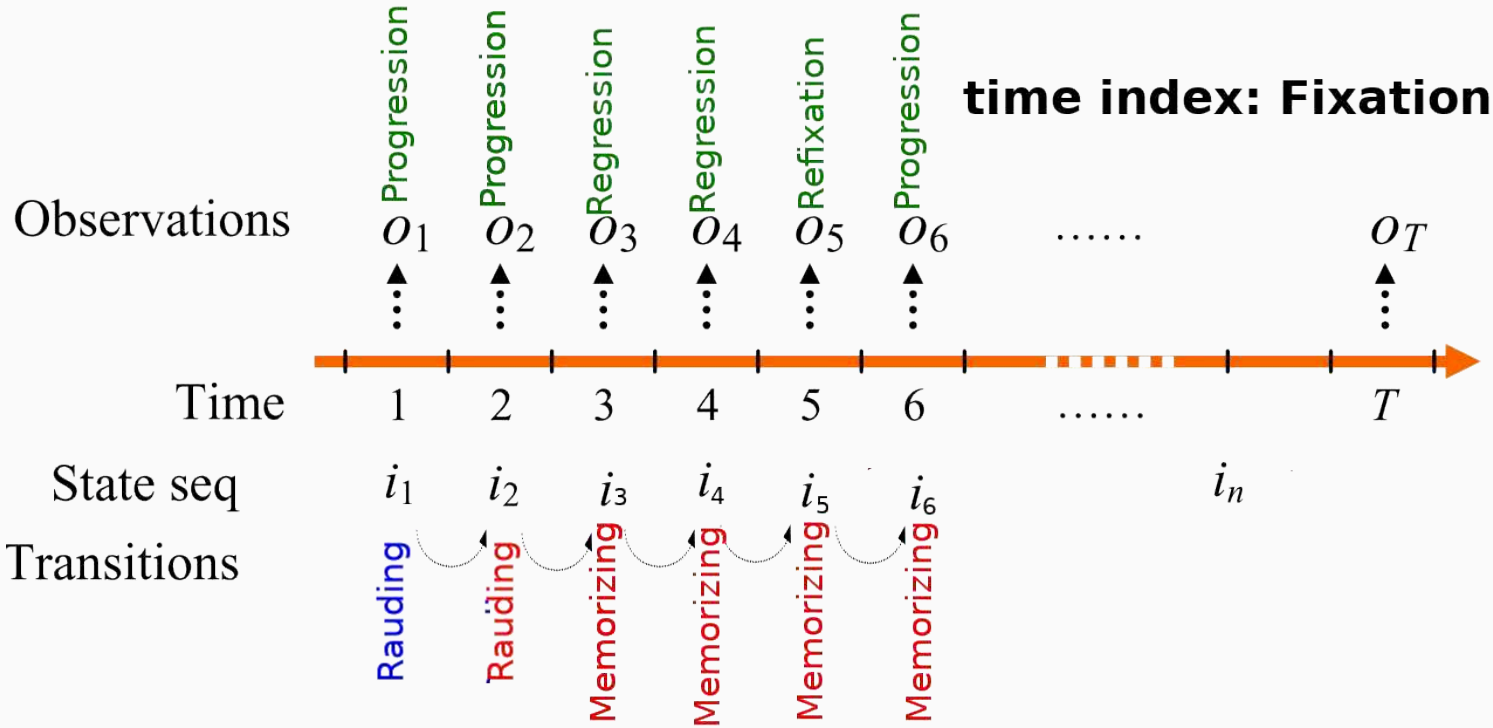
- Based on eye-movement features, **how to segment scanpaths** into interpretable segments (reading strategies) that reflect changes in cognitive processes in information acquisition and processing?
- How can we use **covariates** (text types, EEGs) to interpret and validate segmentations based on eye movements?
- How can we **model both eye movements and EEGs** into a coherent framework to enhance segmentation?
- Segmentation of temporal data based on **statistical tools** (Simola *et al.*, 2008)

Outline

1. Hidden (semi-)Markov Models
2. HSMM estimation on scanpaths
3. A posteriori analysis of restored states from covariates (text, EEGs)
4. Joint modeling of eye movements and EEGs
5. Contributions & Perspectives

Hidden (semi-)Markov Models

Hidden Markov Model (HMM)



$\mathcal{S} = \{Rauding, Skimming, Memorizing\}$ $\mathcal{V} = \{Regression, Refixation, Progression\}$

State sequence $\mathbf{S} = \{S_1, ..., S_T\}$

Observation sequence $\mathbf{O} = \{O_1, ..., O_T\}$

Model parameters:

Initial probabilities

$\forall j \in \mathcal{S}, \quad \pi_j = P(S_1 = j)$

Transition probabilities

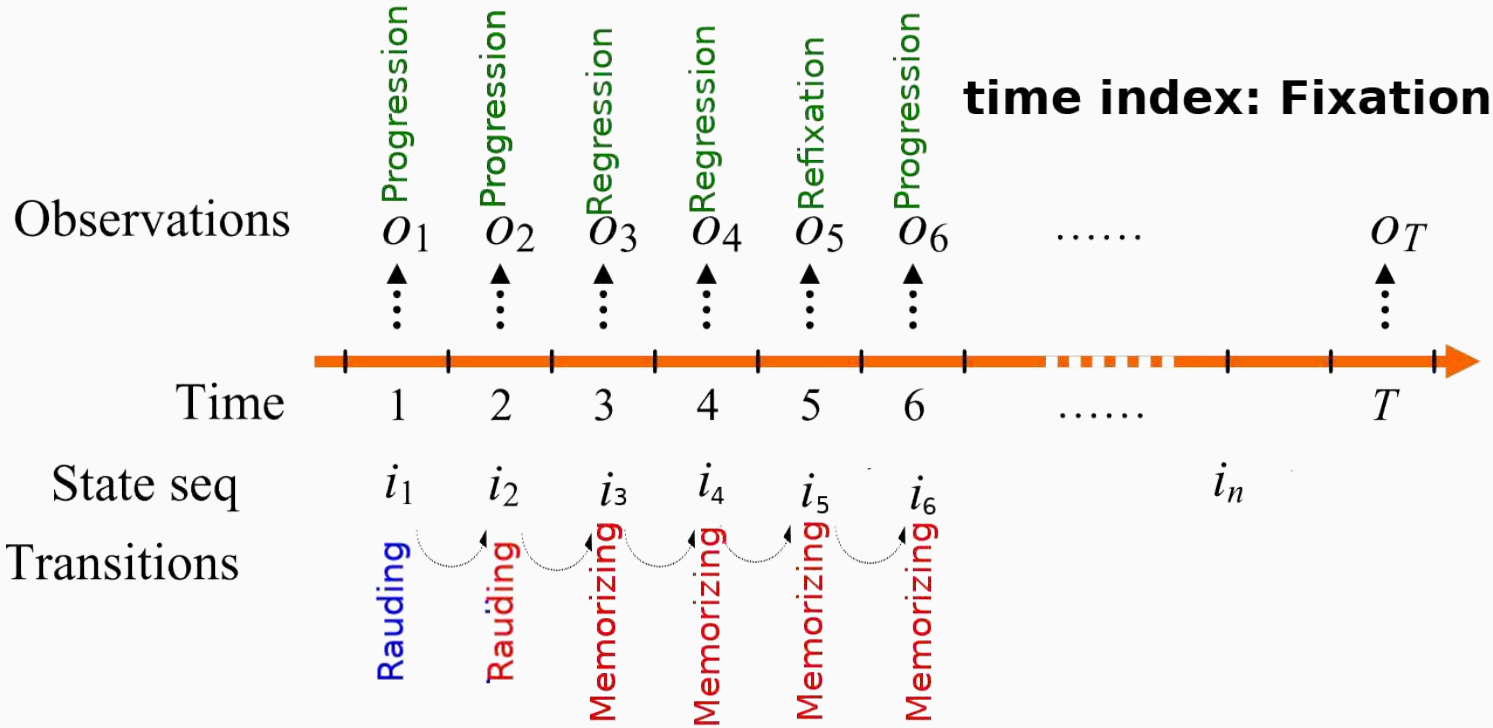
$\forall i, j \in \mathcal{S}, \quad A_{ij} = P(S_t = j | S_{t-1} = i)$

emission distributions

$\forall j \in \mathcal{S}, v_g \in \mathcal{V}$

$b_j(v_g) = P(O_t = v_g | S_t = j)$

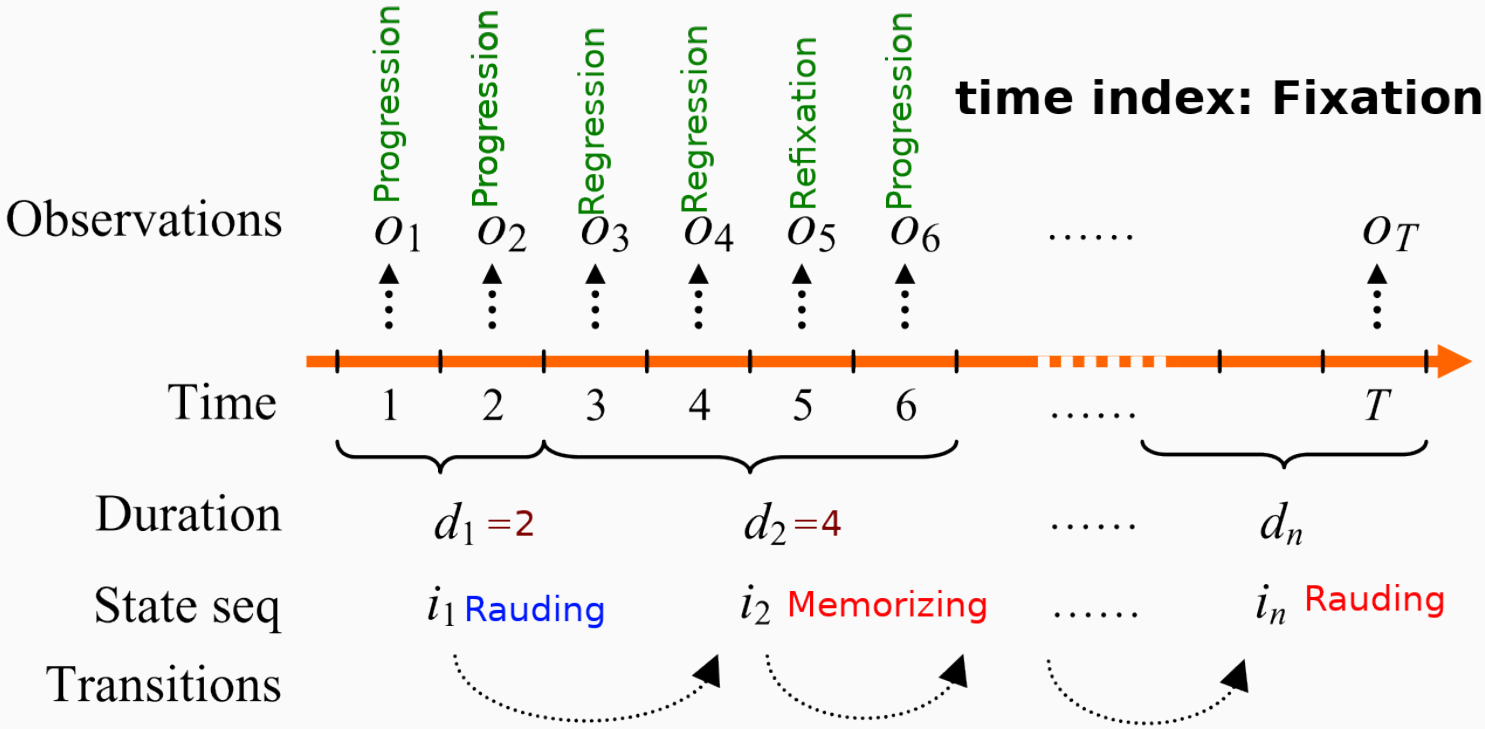
Hidden Markov Model (HMM)



Say $\theta = \{\pi_j, A_{ij}, b_j(v_g)\}$ are unknown, **S** hidden, and I just observed **O**:

- How do I estimate the model parameters $\hat{\theta}$? (MLE)
- How do I compute the most likely state sequence $\arg\max_{S_{1:T}} P(S_{1:T}|O_{1:T}, \hat{\theta})$? (Viterbi)
- How do I find $Card(\mathcal{S})$? (BIC)
- How do I identify $\mathcal{S}$? (interpretation)

Hidden semi-Markov Model (HSMM – Yu, 2010)



$\mathcal{S} = \{Rauding, Skimming, Memorizing\}$

$\mathcal{V} = \{Regression, Refixation, Progression\}$

Duration sequence $\mathbf{D} = \{D_1, ..., D_T\}$

Sojourn distributions

$\forall d \in [\![1, \infty]\!]$

$p_j(d) =$

$P(D_t = d, S_{t+1:t+d} = j, S_{t+d+1} \neq j | S_t = j)$,

Transition probabilities

$\forall i \neq j \in \mathcal{S}$

$P(S_t = j | S_{t-1} = i, D_{t-1} = d) =$

$$\begin{cases} A_{ij}, & \text{if } d = 1 \\ 0, & \text{if } d > 1 \end{cases}$$

HSMM estimation on scanpaths

Output process construction

Observed Process: "Readmode"

- Categorical variable with 5 levels from long regression to long progression, i.e. **bounded number of words crossed in one saccade** $\in \mathcal{V} = \{< -1, -1, 0, 1, > 1\}$
- Invariant by changes of screen layout.
- **Time index: fixations**

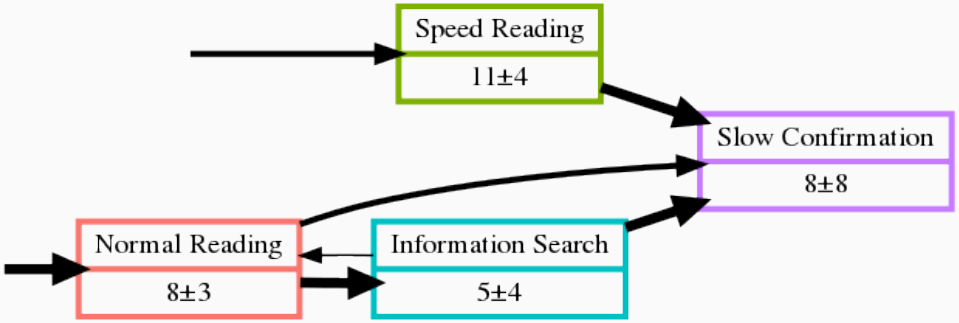
Latent Process

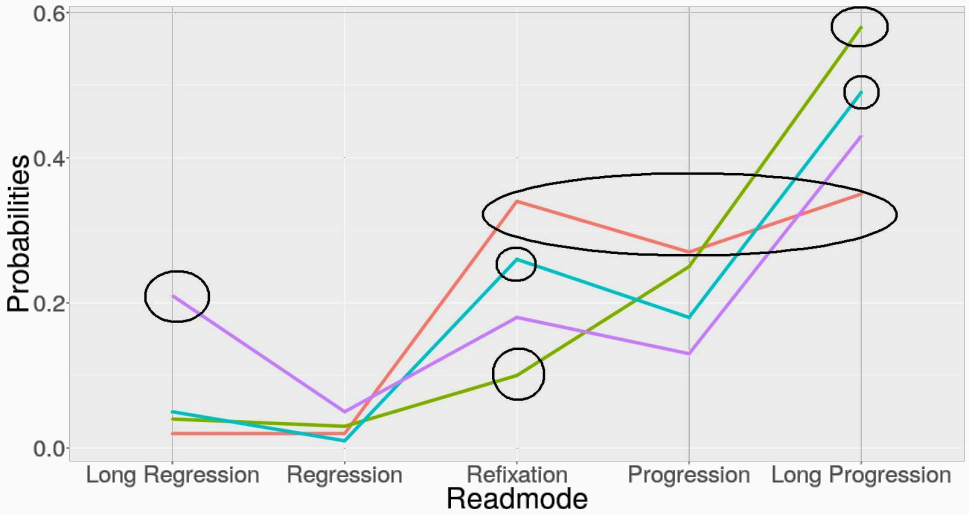
- **Reading strategies:** "hidden", to be recovered through different patterns of Readmode frequencies.
- **Number of reading strategies:** unknown, to be determined by information criteria.

Model covariates

- Fixation duration, Saccade amplitude, **Text properties, EEGs**

Estimated model parameters

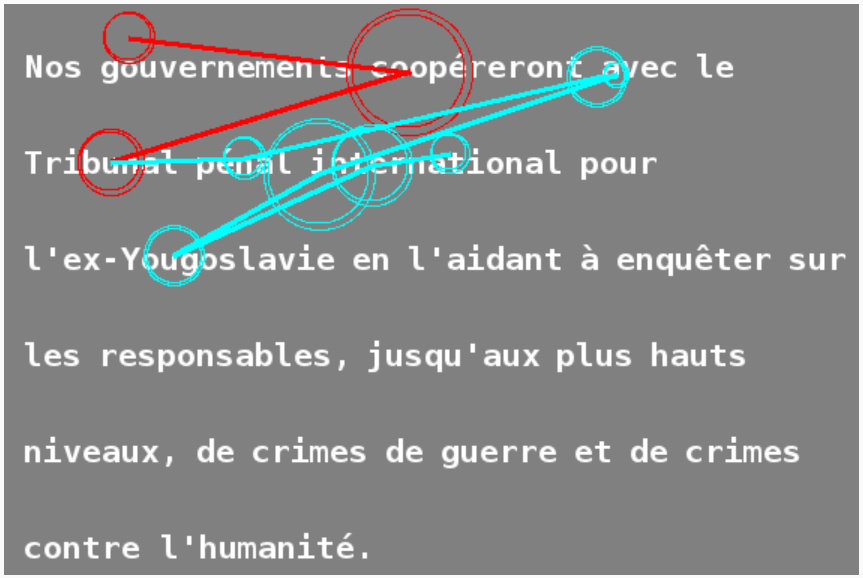




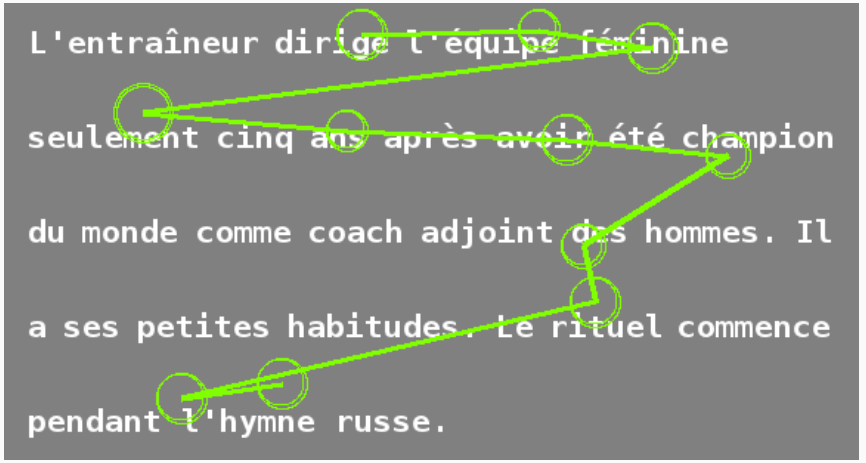
Each reading strategy is characterized by: a **readmode pattern**, a **sojourn distribution**, **probabilities to switch** to other reading strategies and an **initial probability.**

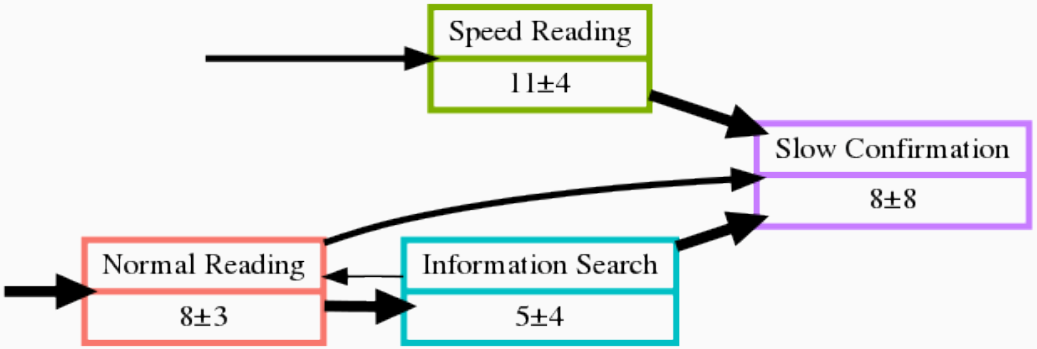
Scanpath restoration - HR / UR texts

"International tribunal" (Highly related)



"Iraq conflict" (Unrelated)

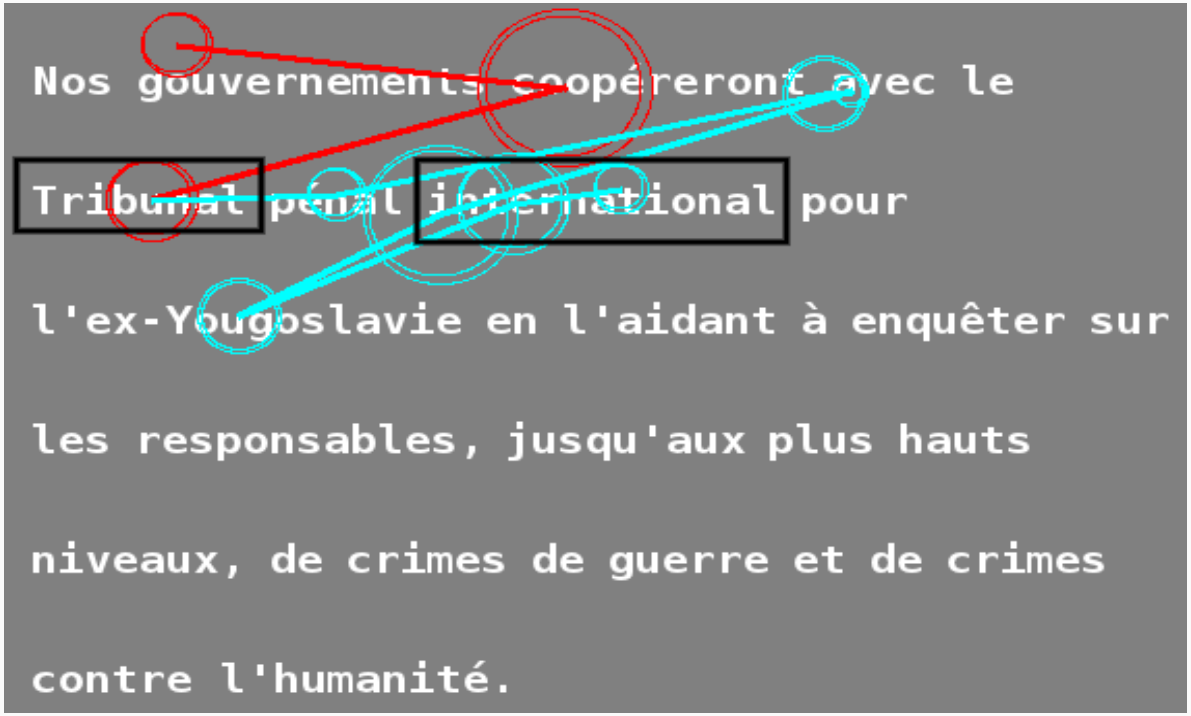




A posteriori analysis of restored states from covariates (text, EEGs)

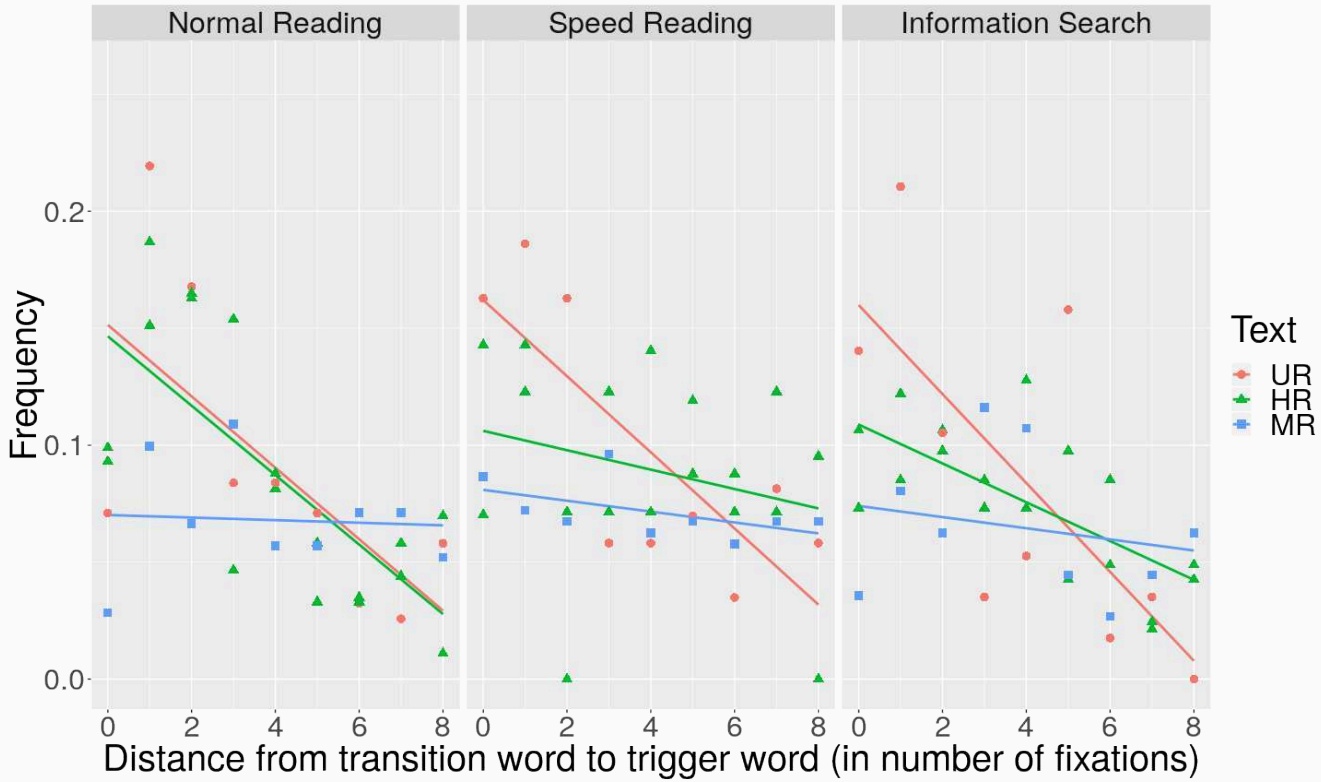
Text covariate – Trigger word detection

"International tribunal" (Highly related +)



- **Do transitions occur around keywords more often?**
- **Automatic detection of trigger words** w.r.t. topics
- Using vector-space word representations and distances
- In UR texts, inclusion of log frequency factors for **specificity**

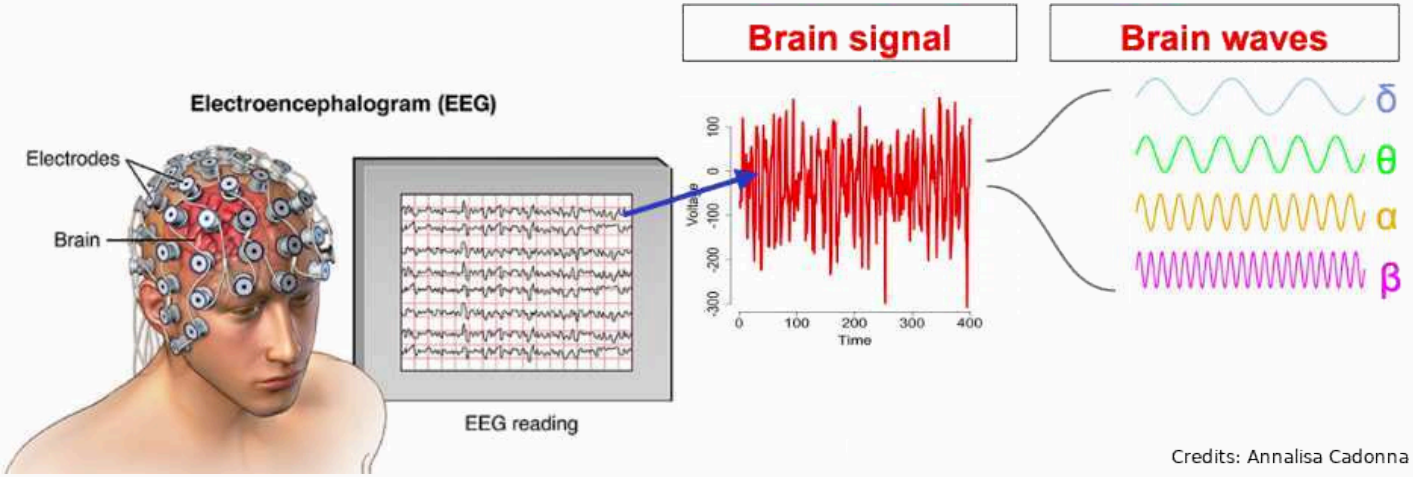
Text covariate – Distance between target words and times of transition



- Reading strategy **transitions occurs around keywords** when exiting states Normal Reading and Information search.
- The effect is less salient when exiting Speed Reading, except for UR texts.

EEG analysis - Bands, activities, tasks

- **Issue:** In free reading tasks, EEG patterns are not synchronized in trials. EEGs kind of resynchronized by strategy changes.



- **MODWT**: Highlights patterns that might not be visible on time domain.
- Scales of decomposition associated with characterized brain waves in the literature: β to δ (e.g., memory performance and encoding; Neuper and Klimesch, 2006).
- Same principle for locality (e.g., left hemispheric lateralization for **verbal working memory**, right hemisphere lateralization for spatial working memory; Nagel *et al.*, 2013).

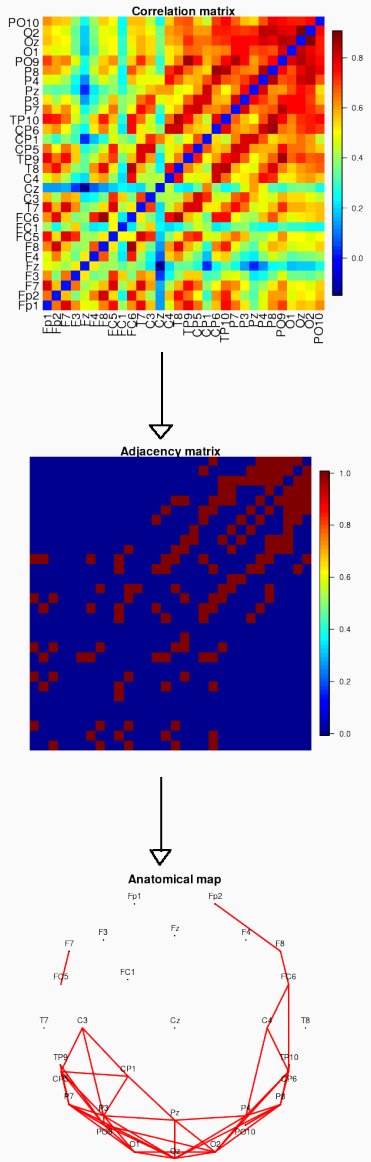
EEGs - Inference of functional connectivity graphs

Small-world network analysis (Achard *et al.*, 2006)

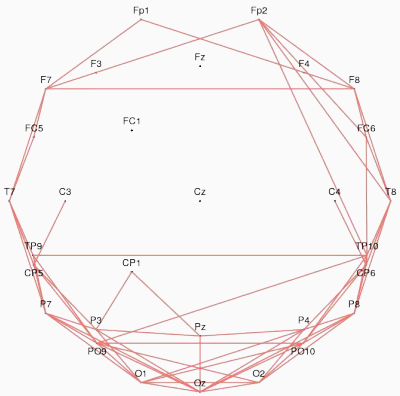
1. Confidence intervals on (MODWT) wavelet correlations and **hypothesis testing**
2. Global **thresholding** into adjacency matrix
3. Graph and associated metrics
   - mean degree
   - inverse mean shortest path distance = efficiency

Particular issue:

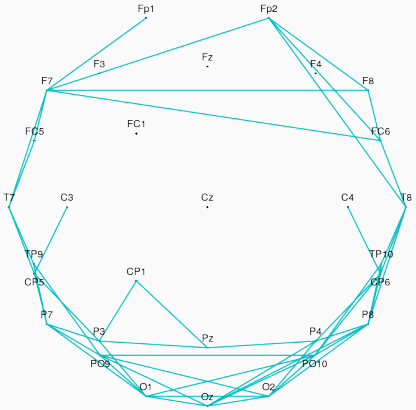
- **Individual variability** (requires further individual thresholding)



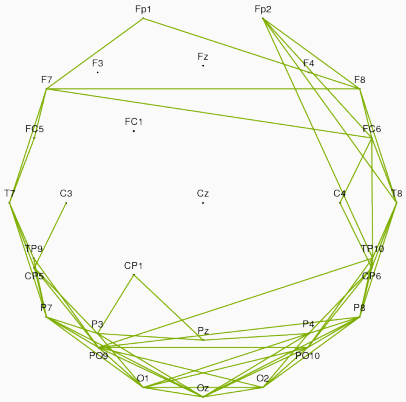
EEGs - Anatomical maps for scale θ



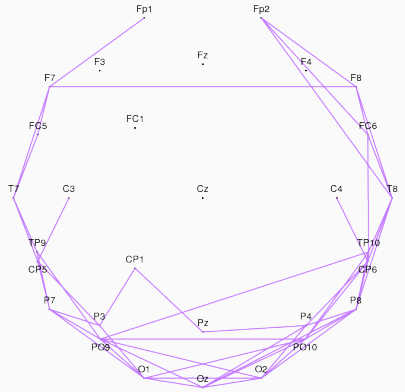
Normal reading - mean degree: 3.46, efficiency: 0.31



Information search - mean degree: 3.2, efficiency: 0.30



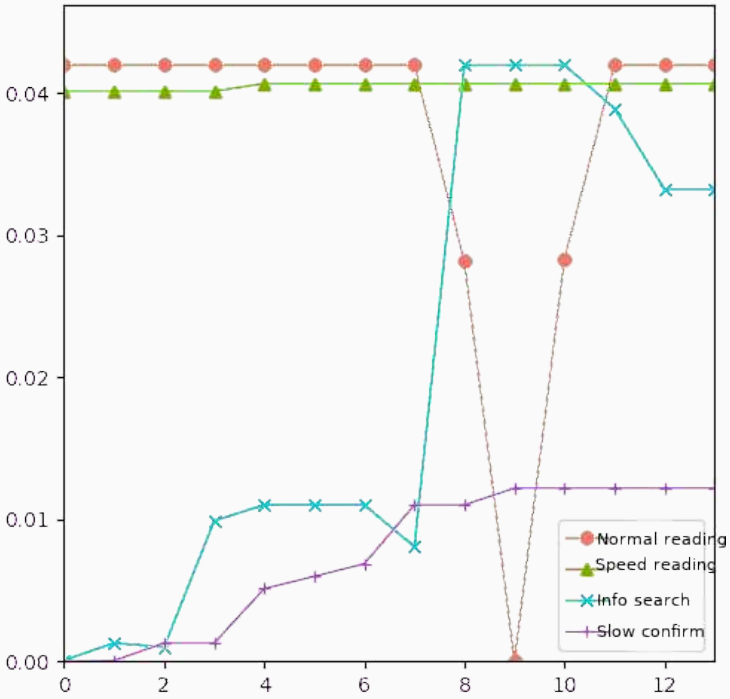
Speed reading - mean degree: 3.6, efficiency: 0.33



Slow confirmation - mean degree: 3, efficiency: 0.27

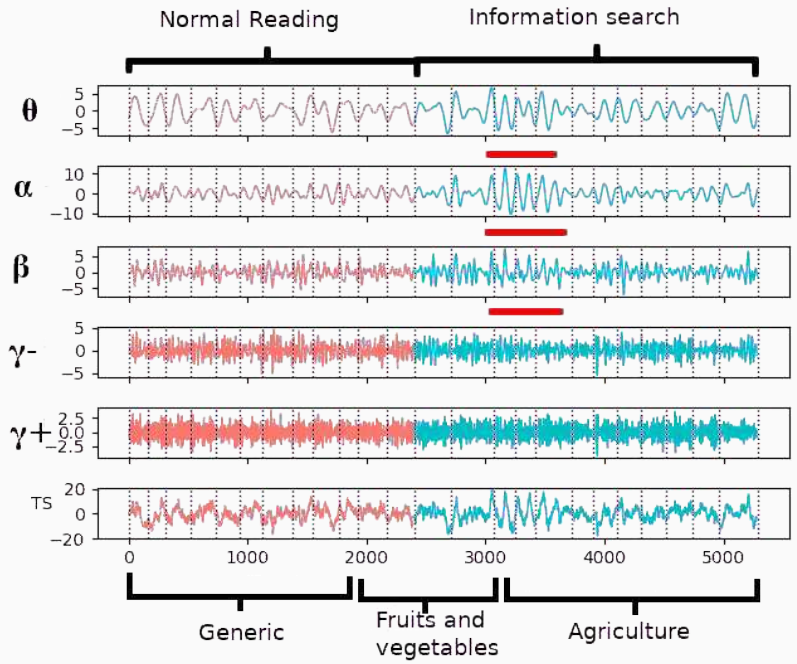
Shortcomings - Uncertainty of state sequence restoration

- Uncertainty in state restoration not accounted for (state entropy).
- Delays in switches wrt regimes in eye movements an EEGs.



Computation of Posterior probabilities of state sequence

$$s_t^{(k)} = \max_{s_{1:t-1}, s_{t+1:T}} P(S_{1:t-1} = s_{1:t-1}, S_t = k, S_{t+1:T} = s_{t+1:T} | O_{1:T})$$



"Economic growth" - Unrelated text

Modeling specifications

- **Asynchronous, heterogeneous** hidden semi-Markov model (AHHSMM)

Different sampling rates

- $t \in \{1, ..., T\}$ now denotes a temporal index in ms.
- Let N_t, the number of fixations from 1 to t

Delayed State

- Let $\{S_1^{(2)}, ..., S_T^{(2)}\}$ a discrete latent state taking values in $\mathcal{S}$ and encoding the first SMC $\{S_1, ..., S_{N_T}\}$ at a higher sampling rate, plus a lag.
- We denote the lag $\{\epsilon_{N_1}, ..., \epsilon_{N_T}\}$, with $\epsilon_{N_t} \in \{1, ..., \mathcal{L}\}$ in its most general form.
- Hence we have: $S_t^{(2)} = S_{N_t - \epsilon_{N_t}}, \forall t \in [\![\epsilon_1, \tau]\!]$.
- ϵ_{N_t} could be deterministic, random, autoregressive, dependent on channels and / or states (model selection)
- Estimation through adapted Expectation-Maximization algorithm (Dempster *et al.*, 1977)

Contributions & Perspectives

Contributions

- Towards a comprehensive model to analyse heterogeneous signals with desynchronized regime switches.
- Deeper understanding and statistical characterization of reading mechanisms in press review-like tasks.

Perspectives

- Individual variability: quantification and EEG correction with mixed models.
- EEGs: strengthen result interpretation on graphs based on literature.
- Model comparison and selection : different assumptions on delays; specific properties of channels and brain waves.
- Fine-grain hierarchical modelling of reading processes (word decoding, semantic integration, etc.)

Thank you

References

Achard, Sophie et al. (2006). "A resilient, low-frequency, small-world human brain functional network with highly connected association cortical hubs". In: *Journal of Neuroscience* 26.1, pp. 63–72.

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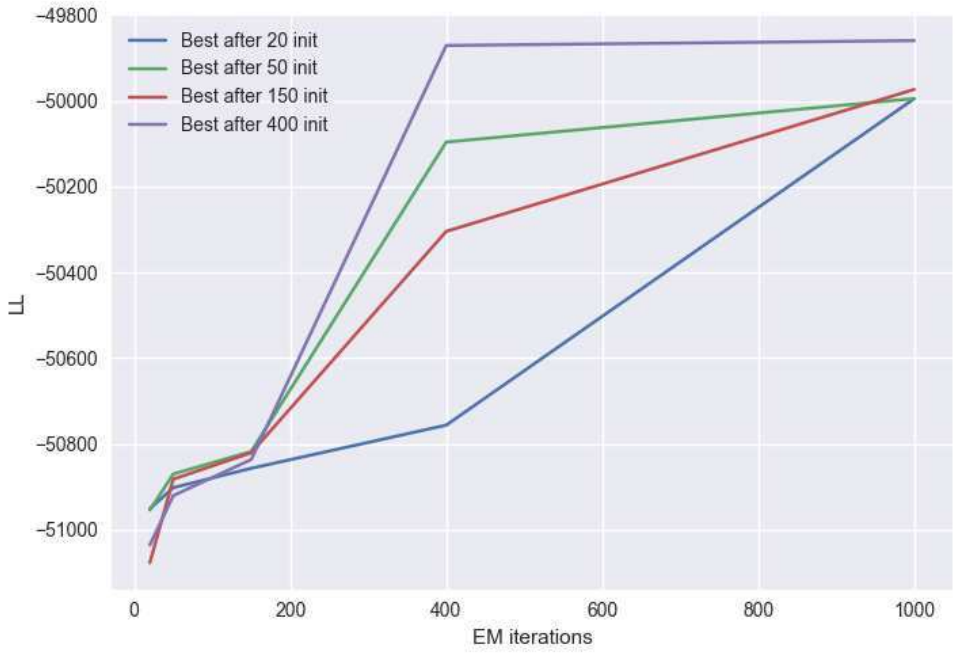
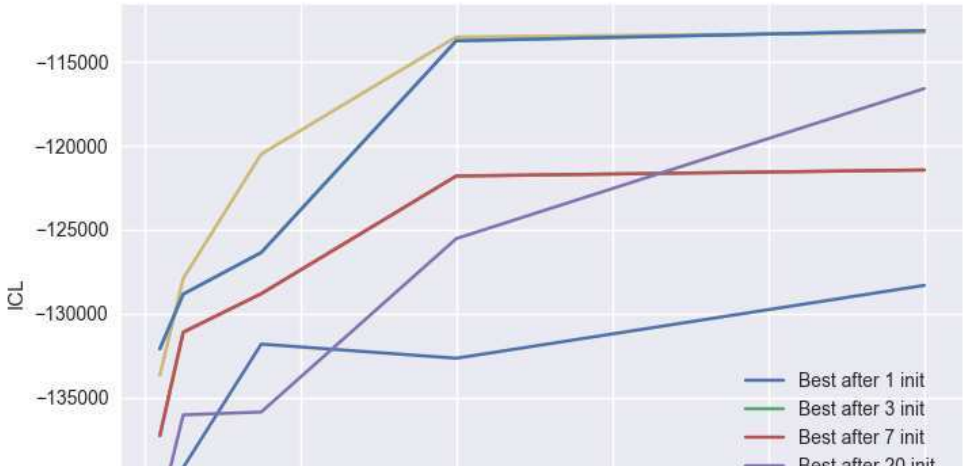
Supplementary material

Quick reminder of HMM - Limitations

- State sojourn time are by definition Geometric
- Let $X \sim G(p), \mathbb{E}[X] = 1/p, \mathbb{V}[X] = \frac{1-p}{p^2}$. Expectation and Variance linked by one single parameter p.

Model selection - RandomInit - choosing of K, L





Model validation - Several indicators

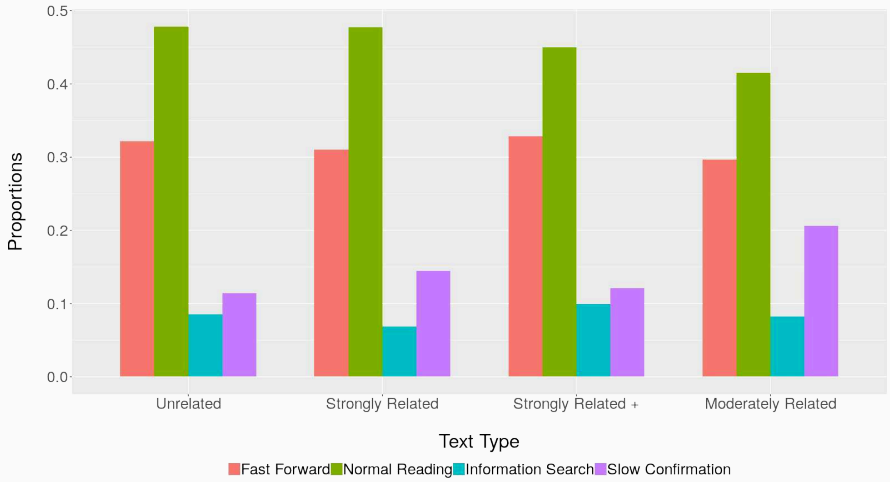
		Normal reading	Fast Forward	Information Search	Slow Confirmation
Fixation duration (ms)		183 ± 68	170 ± 60	190 ± 70	188 ± 68
Saccade amplitude (px)		121 ± 103	150 ± 94	136 ± 103	144 ± 98
Reading speed (wpm)		382	600	436	227
Cumulated cosine*		$.33 \pm .28$	$.33 \pm .30$	$.51 \pm .23$	$.47 \pm .26$
Saccade direction	Backward	.09	.09	.18	.19
	Upward	.01	.02	.04	.10
	Downward	.14	.22	.19	.19
	Forward	.71	.61	.51	.44
	Last	.05	.05	.07	.08

* Measure of cumulated gathered semantic information

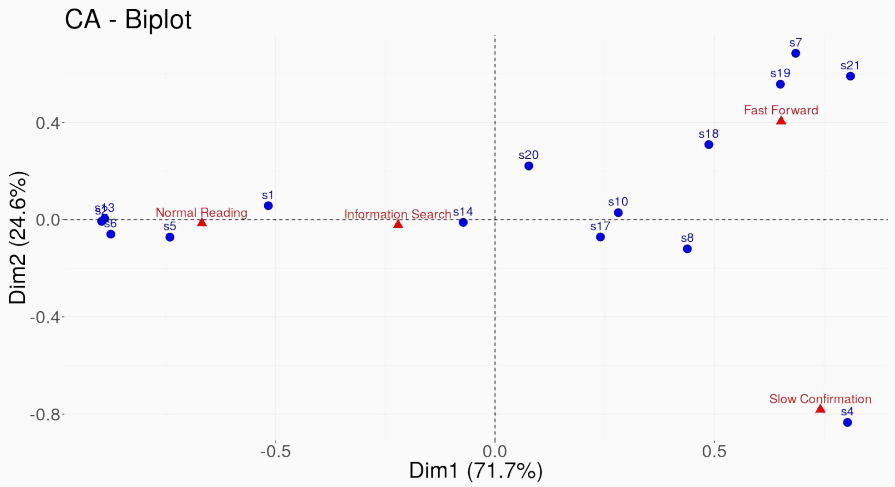
Speed reading suggests to be an easy task and therefore shorter fixations - *Rayner (1998), Simola et al. (2008)*

Model validation - Understanding the usage

Strategies usage wrt text types



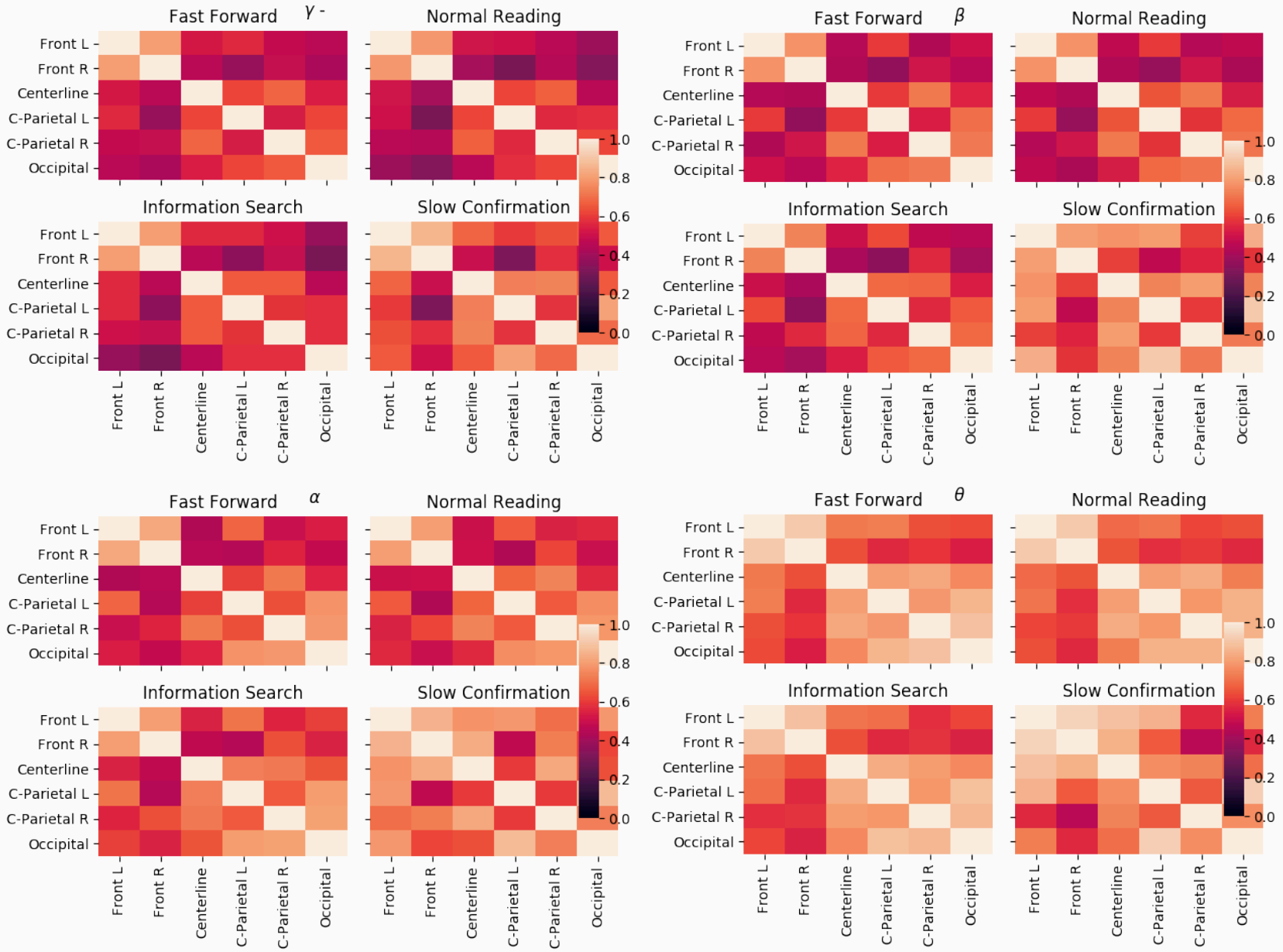
Factorial Correspondence Analysis: Strategies and Subjects



In practise:

- strategies are used differently according to the text type,
- not all strategies are used for every trial or by every subject.

Model validation - EEGs - Information Diffusion



EEGs - Choosing the correlation threshold