Eye-tracking data analysis using hidden semi-Markovian models to identify and characterize reading strategies

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Introduction

Introduction I

"We remember the famous dollar symbol revised by Andy Warhol. With a simple sign, the american pop-artist amalgamated art and money, for the greatest please of his collectors."

- Newspapper information search
- Intertwined cognitive processes:
* Semantic information gathering
* Decision-making processes

Introduction II

- Time-heterogeneous processes: cognitive and eye movements

- Reading strategies for different purposes - *Carver (1990)*
- Reading strategies uncovery in information search task using Hidden Markov Models - *Simola et al. (2008)*

- How to segment scanpaths into interpretable zones, in terms of cognitive phases in information acquisition and processing ?

- Hypothesis: reading strategies changes reflect cognitive steps, influencing indirectly through eye movements regime changes (and Markovian regime changes)

Material and Method - Frey et al. (2013)

Material and Method I - Goal

Simulate press review task through binary decision:

Is the text related to the topic or not ?

- positive decision: target words
- negative decision: incongruent words

Material and Method II - Experimental Settings

Participants

15 participants

Textual material

180 texts per participants

Extracted from the french newspaper LeMonde

Goal is a nominal phrase. e.g. "modern art"

60 Highly / 60 Moderately / 60 Un - related texts to the topic (Latent Semantic Analysis control)

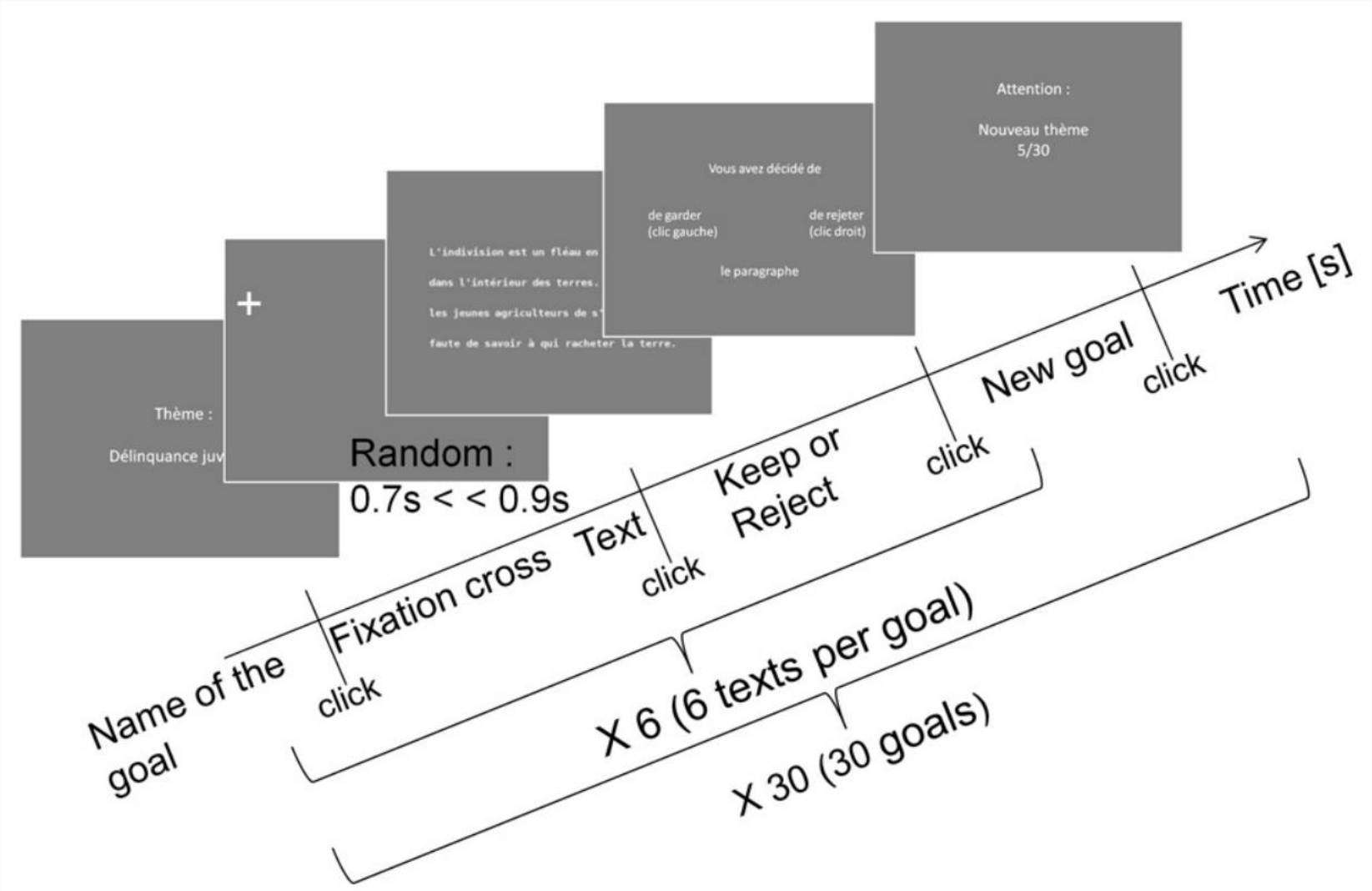
Focus on highly related texts

Data acquisition

SR Research - Eyelink 1000, sampling rate 1000 Hz

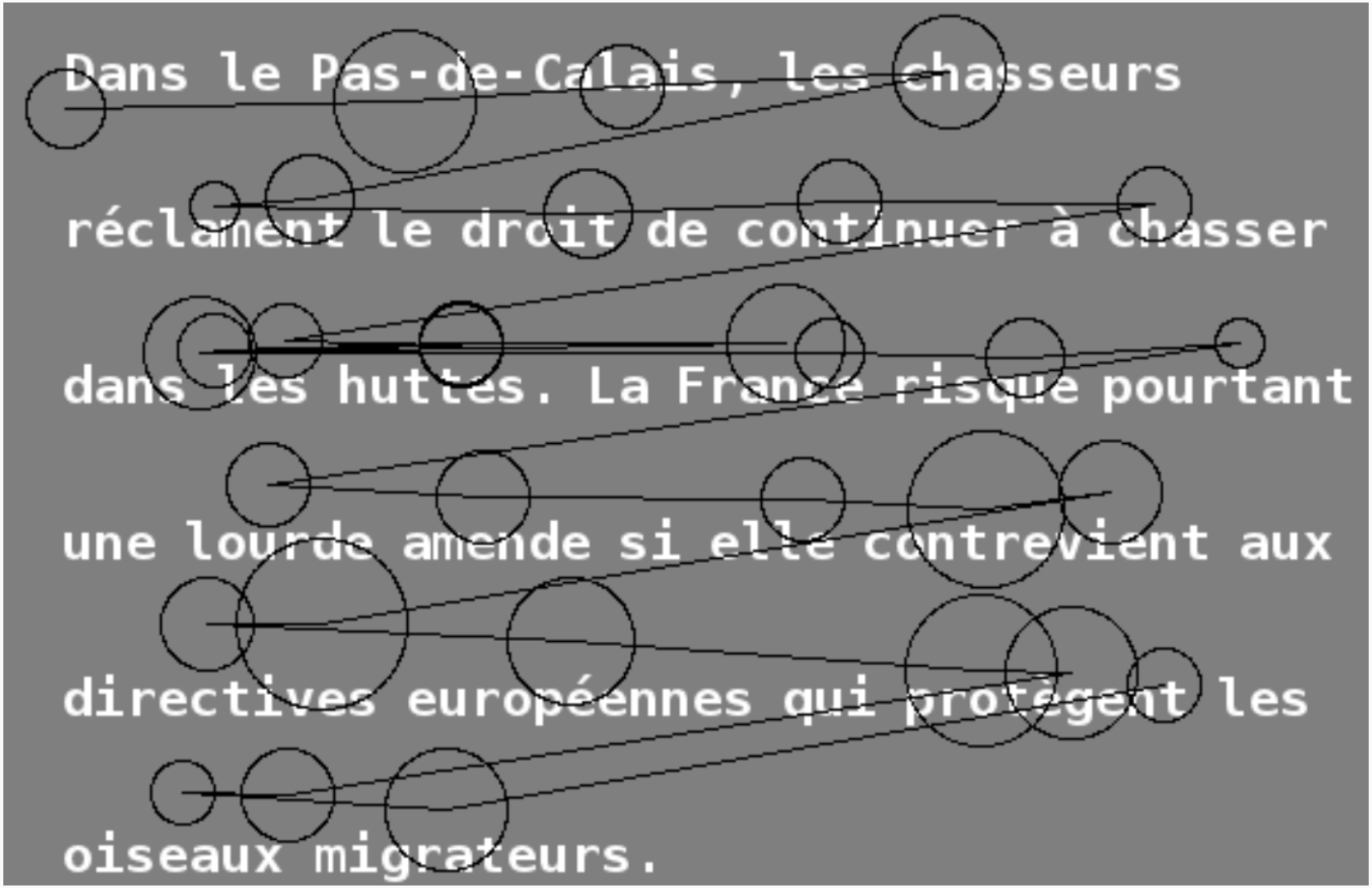
Text layout: 40 chars per line (avg), 3.8 chars in fovea area

Material and Method III - Experimental Procedure



Frey et al. 2013

Material and Method IV - Example of an acquisition



Material and Method V - data preprocessing

Fixation filtering

First fixation possesses an incoming saccade

Last fixation removed: usually longer

Threshold acceptance: min 80ms - max 600ms

From fixations to words

Word processing issue: predictability, distinguishibility, frequency

Word identification span - *Rayner et al. (1982)*

Word processing: 1/3 of the begining or 2/3 of the end - *Farid et al. (1996)*

Statistical modeling

Statistical modeling I - Statistical hypothesis

Observed Process: "Readmode"

Categorial variable with 5 levels from long progression to long regression, i.e. number of skipped words in one saccade $\in \{> 1, 1, 0, -1, < 1\}$

Time index: fixation onset

Latent Process

Reading strategies "hidden", observed through observed process

Number of reading strategies unknown and to be determined

Strong hypothesis

Scanpaths are independant and identically distributed

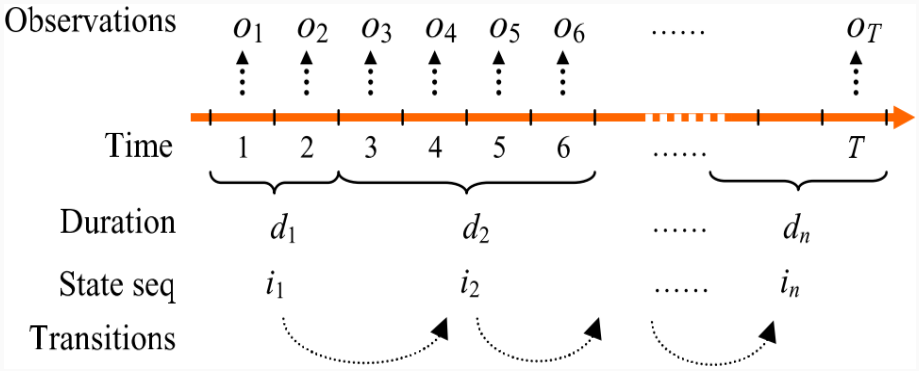
Model covariates

Fixation duration

Saccade amplitude

Textual properties

Statistical modeling II - HSMM - Yu (2010)



Notations

Set of observable values $\mathcal{V} = \{v_1, ..., v_K\}$. R.V. $O_t \in \mathcal{V}$, the observed state at time t

Set of hidden values $\mathcal{S} = \{1, ..., M\}$. R.V. $S_t \in \mathcal{S}$, the hidden state at time t

State duration $D \in \mathcal{D} = \{1, ..., \infty\}$

Probability distributions

Initial distribution: $\pi_j \equiv P(S_1 = j)$

Sojourn distribution: $p_{\theta_j}(d) \equiv P(D = d, S_{t+1:t+d} = j, S_{t+d+1} \neq j | S_t = j)$

Transition distribution: $a_{ij} \equiv P(S_{t+1} = j | S_t = i)$

Emission distribution: $b_j(v_k) \equiv P(O_t = v_k | S_t = j)$

Model parameters

$\lambda \equiv \{a_{ij}, b_j(v_k), \pi_j, \theta_j\}$

Statistical modeling III - Inference and Learning in HSMM

Inference

Forward-Backward algorithm to maintain tractability in inference problems. (e.g. probabilities such as $P(o_1, ..., o_T|\lambda)$)

Learning

MLE of $\hat{\lambda}$ via the iterative **Expectation-Maximization** algorithm:

E-step: decomposition of $E[\ln P(S_{1:T}, O_{1:T}|\lambda)|O_{1:T}, \lambda^{old}]$ and simplification

M-step: maximize with respect to λ

Restoration

Estimation of the most likely state sequence using the **Viterbi** algorithm:

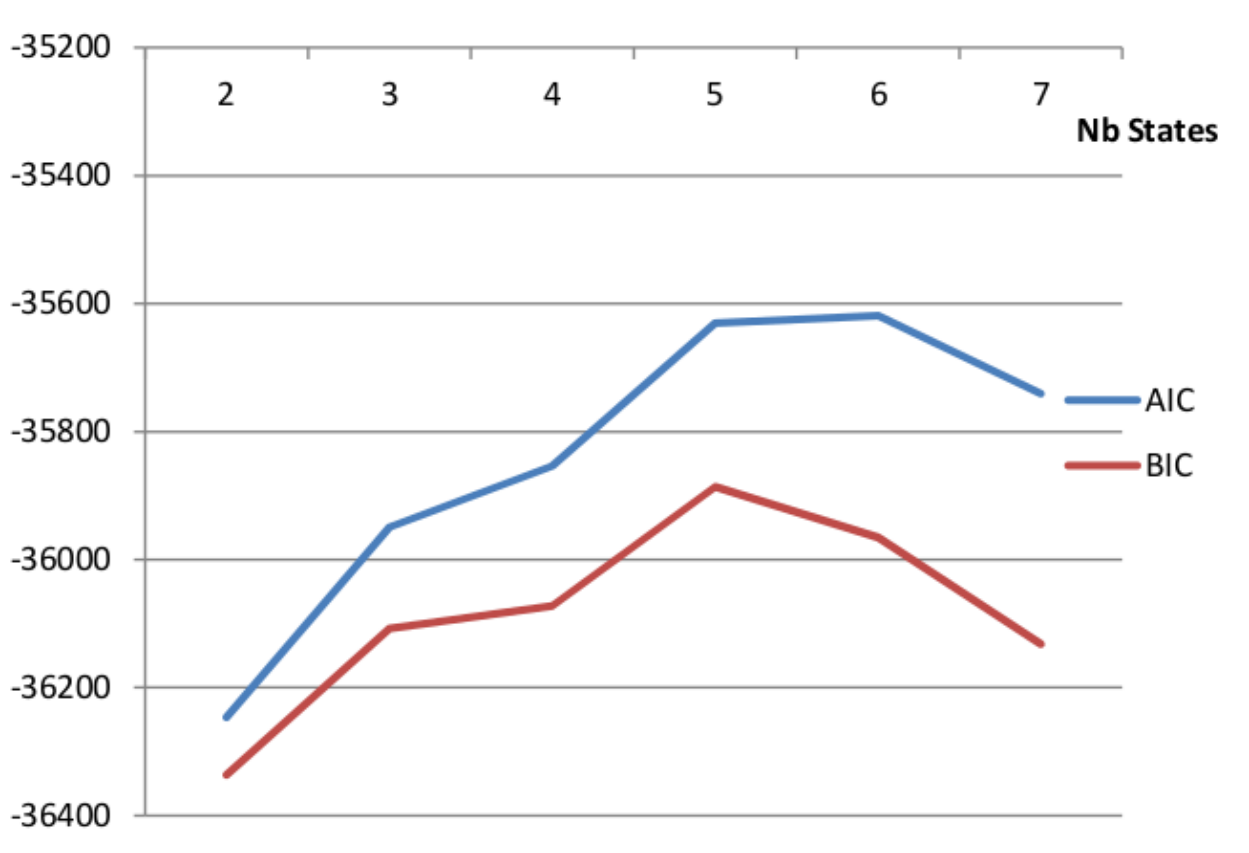
$$\hat{S}_{1:T} = \arg\max_{S_{1:T}} \; P(S_{1:T}|O_{1:T}, \hat{\lambda})$$

Results

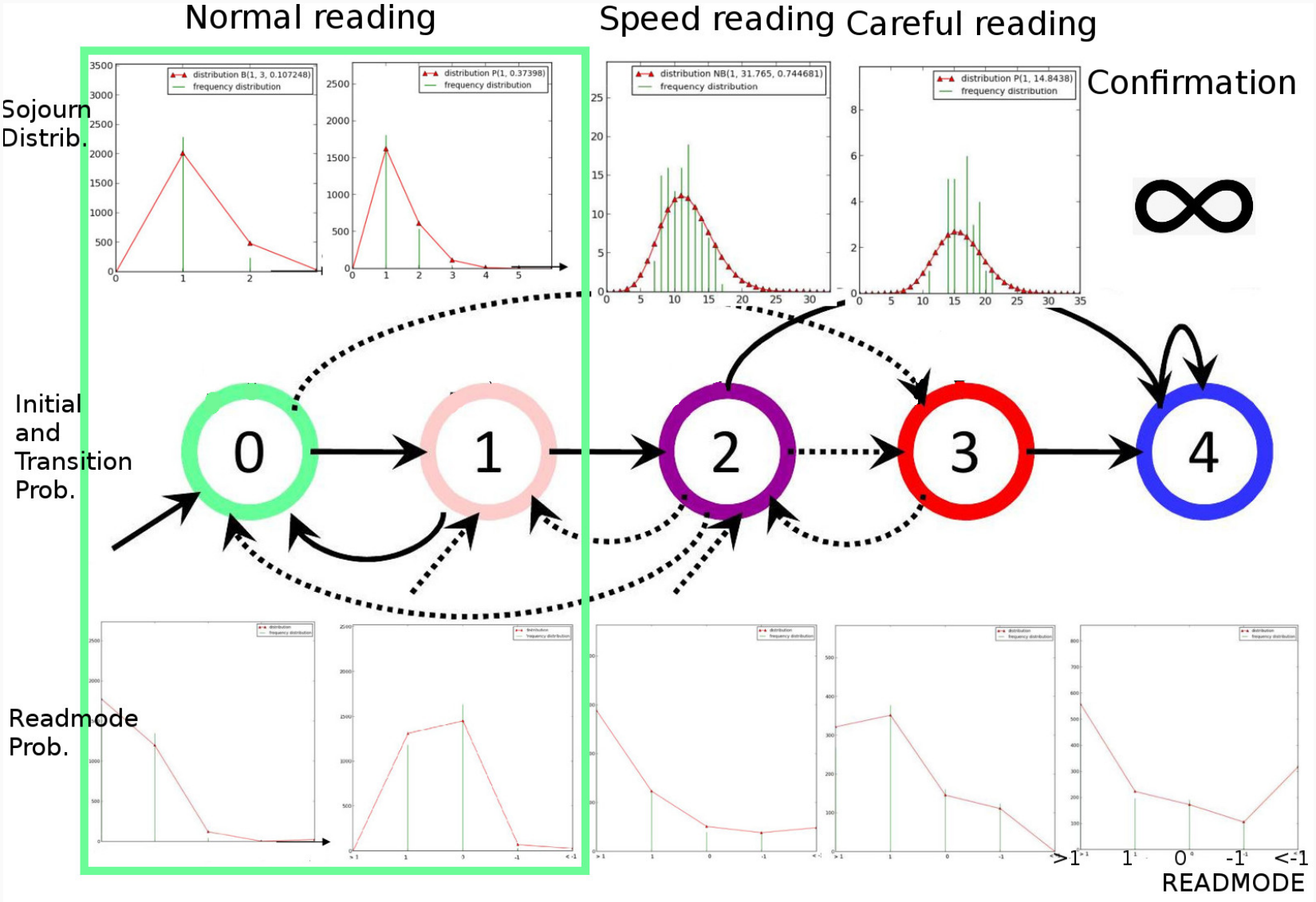
Results I - Model selection

Number of hidden states $card(\mathcal{S})$ unknown and to be determined

Information theory-based criterion suggest $card(\mathcal{S}) = 5$ reading strategies

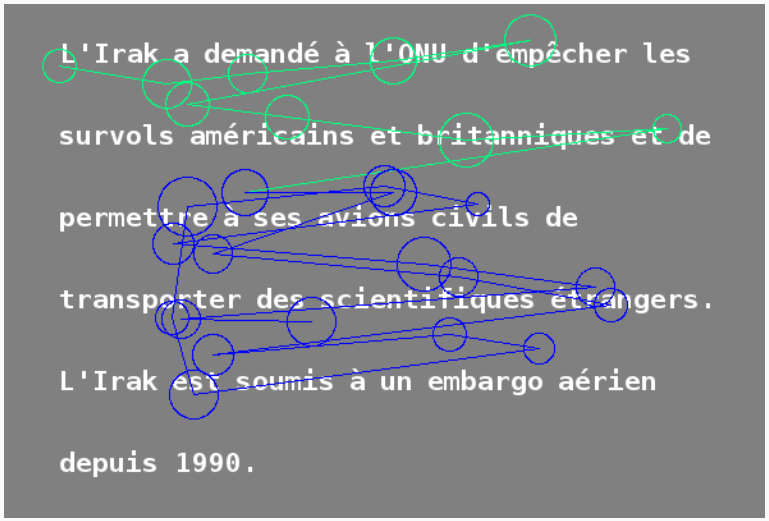


Results II - Parameter interpretation

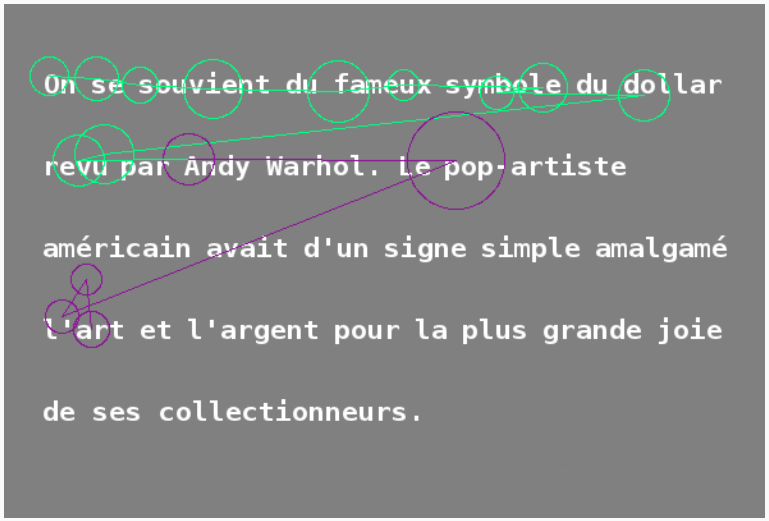


Each reading strategy is caracterized by: a **readmode pattern**, a **sojourn distribution**, **probabilities to transit** to other reading strategies and an **initial probability**

Results III - Scanpath restoration



"Irak asked ONU to stop american and britanic flights and to allow civil planes to transport foreign scientists. Irak flights are forbidden since 1990."



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Results IV: Model covariates

		Normal reading	Scanning	Careful reading	Confirmation
Fixation duration (ms)		**187** $\pm$ 64	**170** $\pm$ 68	**193** $\pm$ 66	195 $\pm$ 71
Saccade amplitude (px)		**95** $\pm$ 51	**126** $\pm$ 57	**100** $\pm$ 55	124 $\pm$ 79
Word increment		1.2 $\pm$ 1.12	1.7 $\pm$ 3.23	1.28 $\pm$ 1	0 $\pm$ 5.23
Cumulated cosine*		.33 $\pm$ .28	.41 $\pm$ .30	.47 $\pm$ .26	**.51** $\pm$ .23
Saccade direction	Backward	**.08**	**.14**	**.21**	.25
	Downward	**.12**	**.23**	**.15**	.15
	Forward	**.75**	**.50**	**.60**	.42
	Upward	0	**.04**	0	.10
	Last	.03	.08	.03	.08
Word previously fixated		.21	.28	.37	.45

* Measure of the evolution of the semantic relatedness of the text to the topic over the words

Scanning suggests an easier task and therefore shorter fixations - *Rayner (1998), Simola et al. (2008)*

Discussion

Discussion

Likelihood maximization

Stochastic versions of EM - *Celeux et al. (1995)*

↳ Maximize likelihood over interpretability ? - Biernacki et al. (2003)

Experiment variability

Text variability

Individual variability

↳ Propose a mixture of HSMM. Issue : Unsufficient data

State entropy

How legit is the state uncovery ? Durand et al. (2012)

↳ Couple EM and EEG data into a single model

References

- Aline Frey, Gelu Ionescu, Benoit Lemaire, Francisco López-Orozco, Thierry Baccino, and Anne Guérin-Dugué, *Decision-making in information seeking on texts: an eye-fixation-related potentials investigation.*, Frontiers in systems neuroscience **7** (2013), no. August, 1–22.
- Yann Guédon, *Estimating Hidden Semi-Markov Chains From Discrete Sequences*, Journal of Computational and Graphical Statistics **12** (2003), no. 3, 604–639.
- Jaana Simola, Jarkko Salojärvi, and Ilpo Kojo, *Using hidden Markov model to uncover processing states from eye movements in information search tasks*, Cognitive Systems Research **9** (2008), no. 4, 237–251.
- Shun Zheng Yu, *Hidden semi-Markov models*, 2010, pp. 215–243.