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HIDDEN MULTIVARIATE PATTERNS TO LOCATE COGNITIVE EVENTS ON A TRIAL-BY-TRIAL BASIS

Gabriel Weindel, Leendert van Maanen, Jelmer Borst

October 30th 2025 @ PracticalMEEG

STARTS AT 14.30

Download the data at https://github.com/GWeindel/HMP_practicalMEEG

STATING THE PROBLEM
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HMP METHOD
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USE AND LIMITATIONS
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APPLICATIONS
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WRAPPING-UP
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5 WRAPPING-UP

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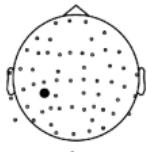
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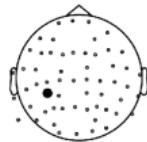
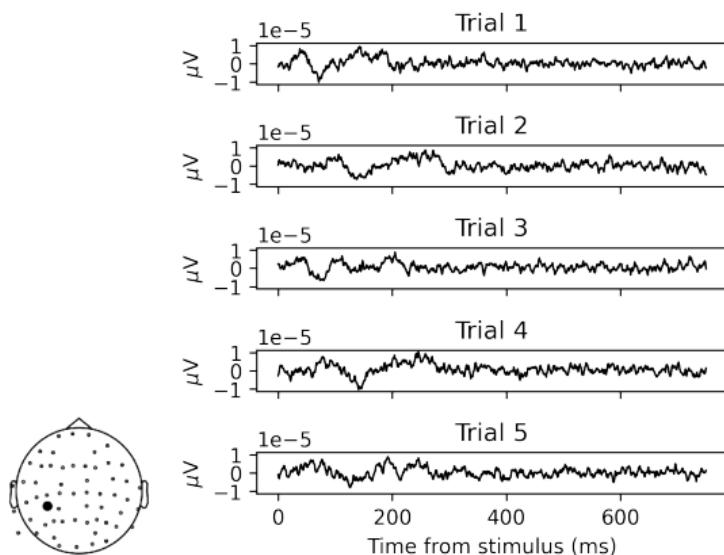
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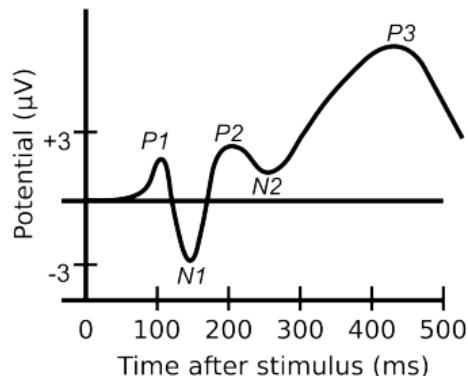
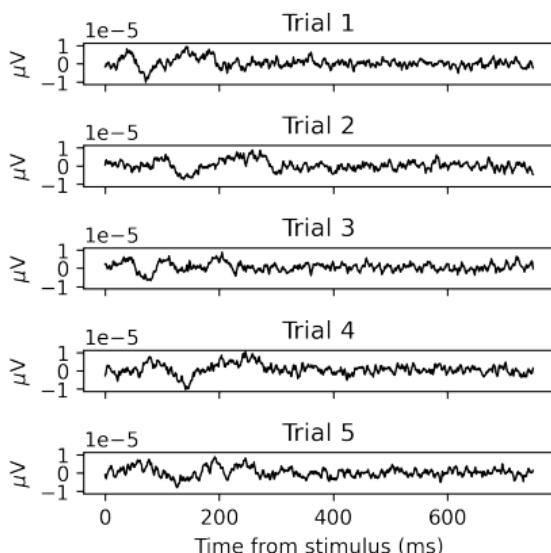
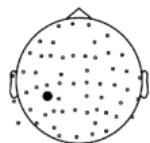


FIGURE: Wikimedia

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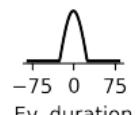
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Important facts:

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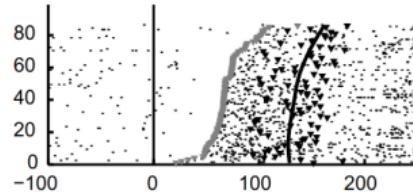
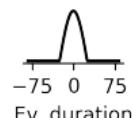


FIGURE: Lee et al., 2010

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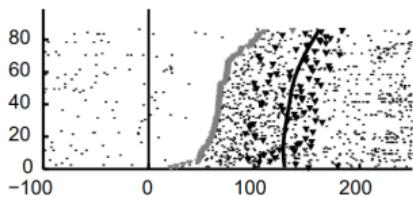
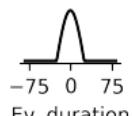
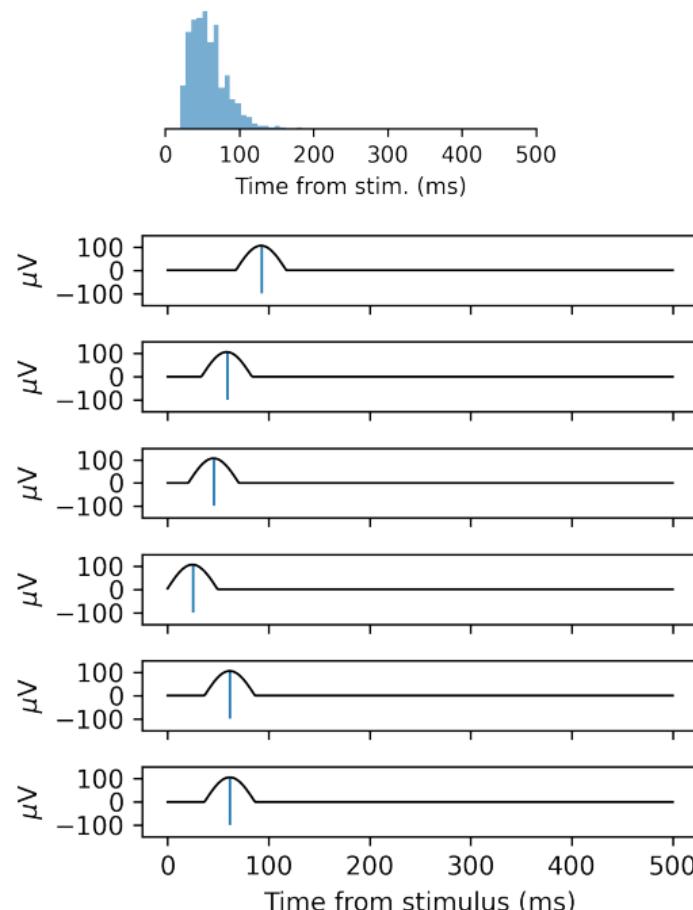


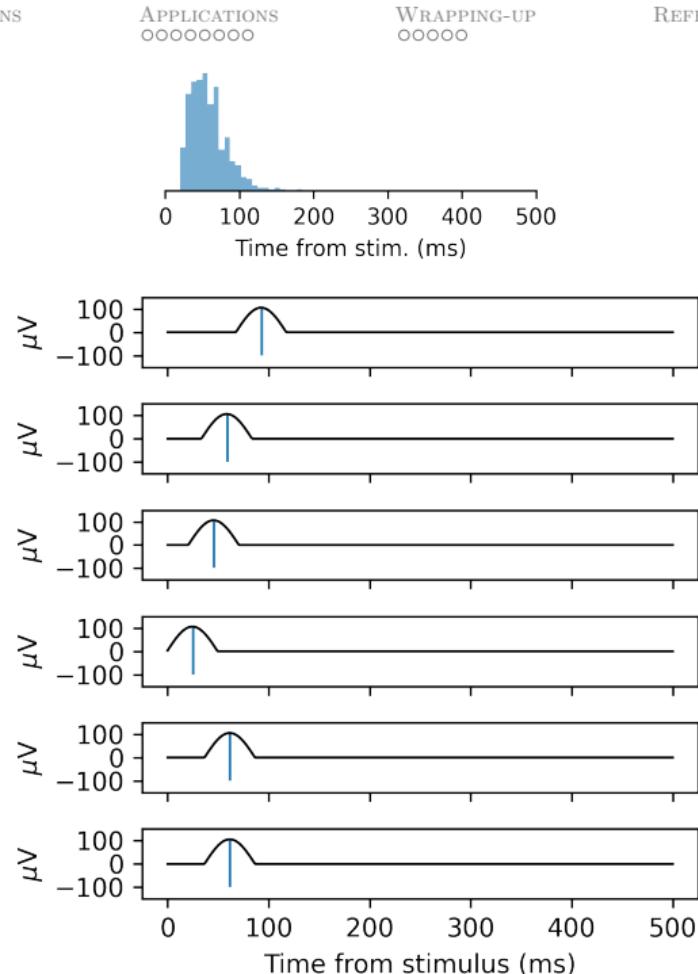
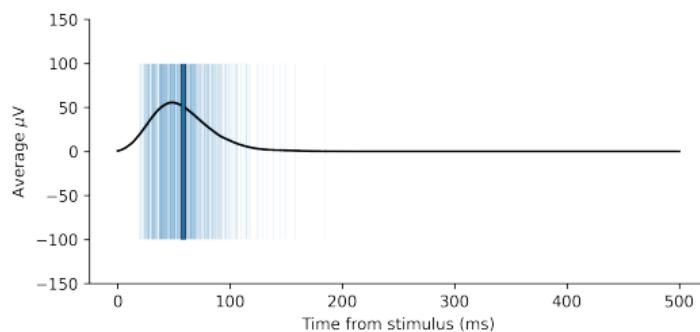
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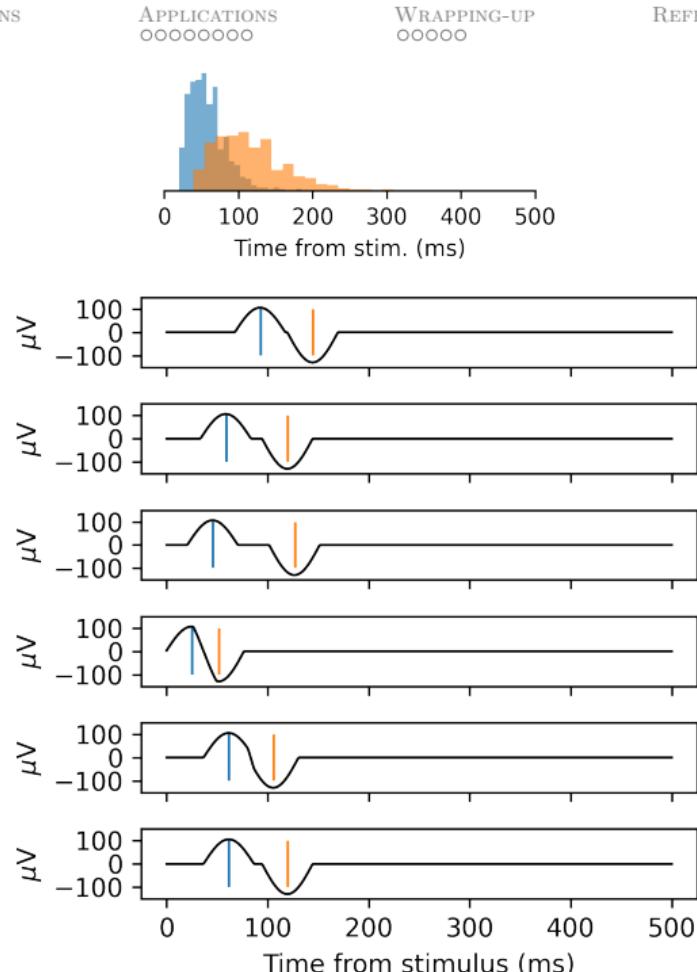
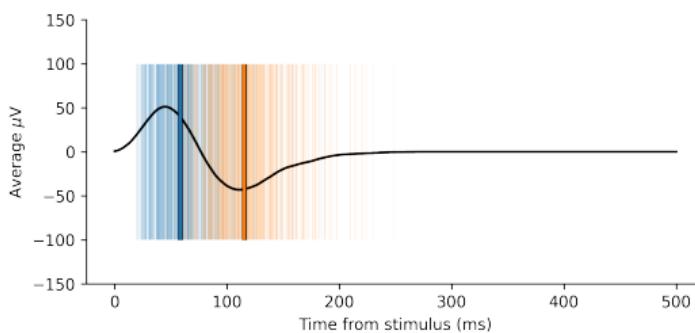
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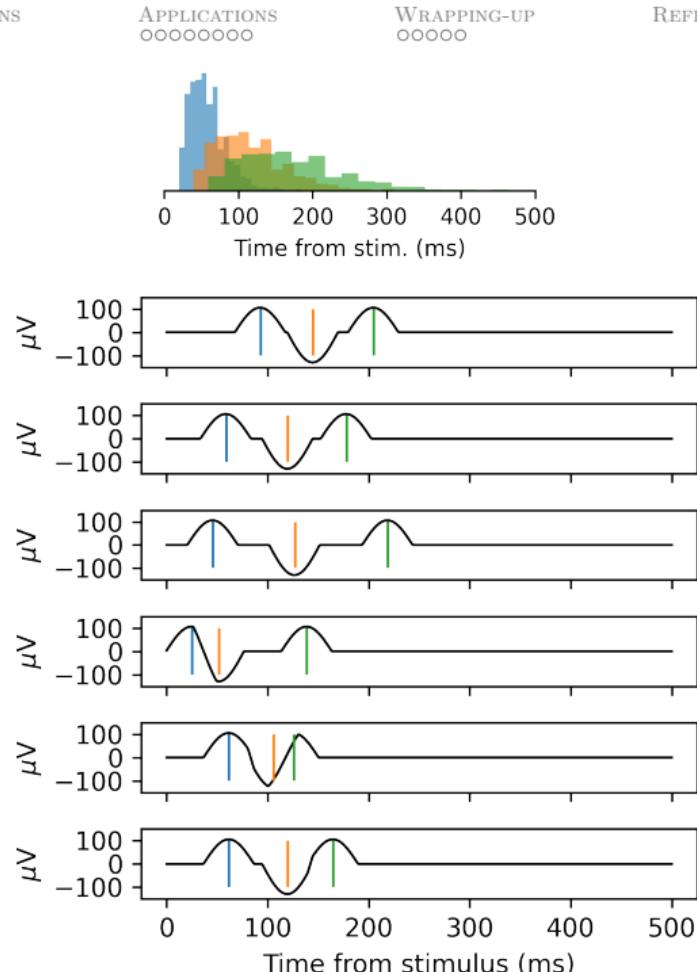
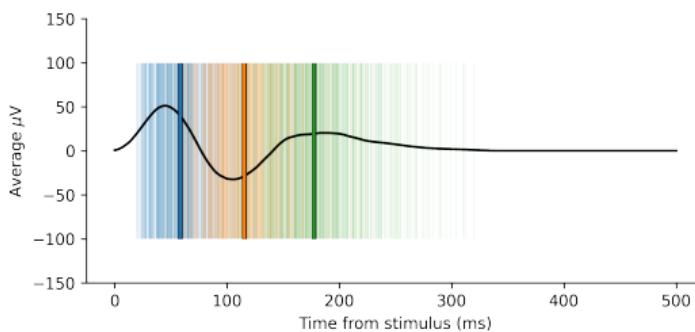
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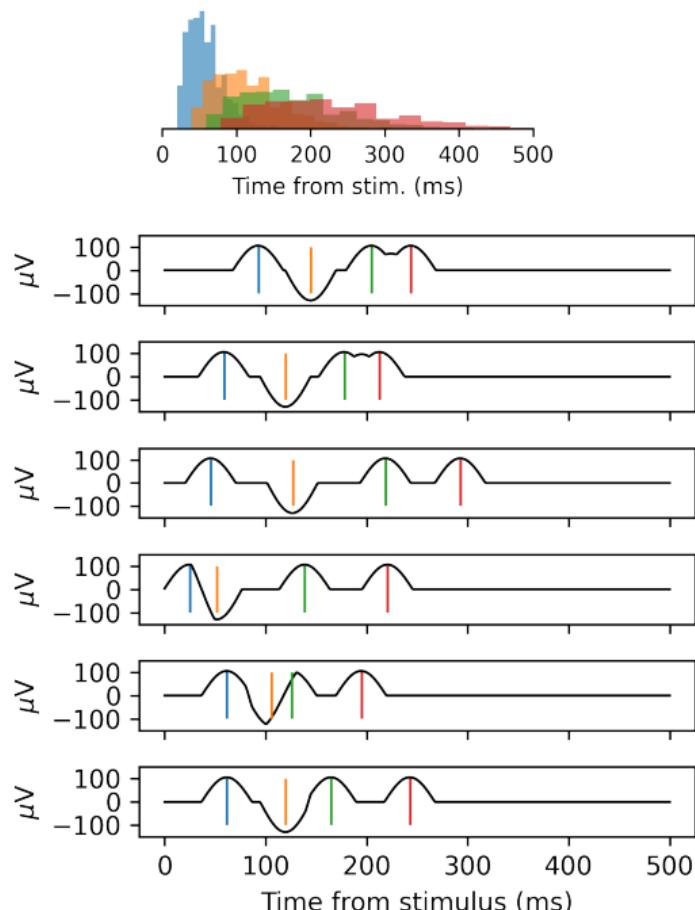
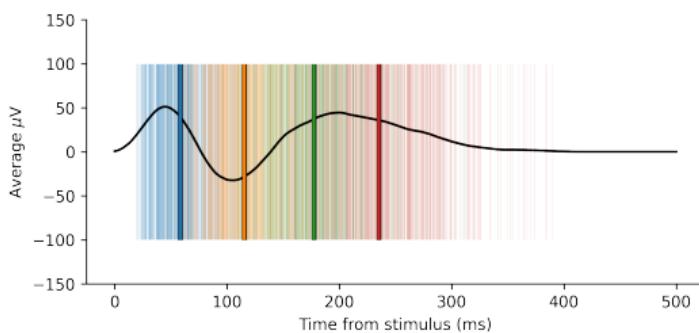
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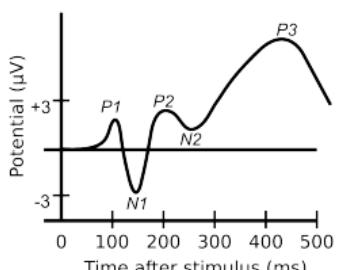
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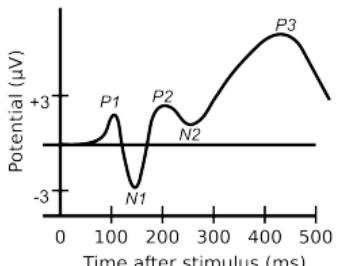
INFERRING FROM AVERAGE ERPs

Source: Wikimedia commons

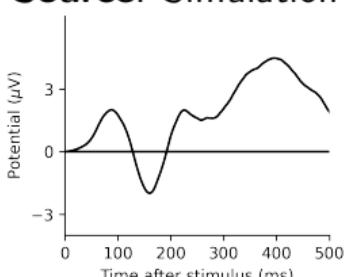


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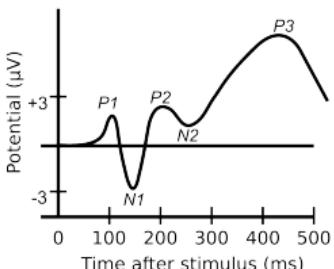


Source: Simulation

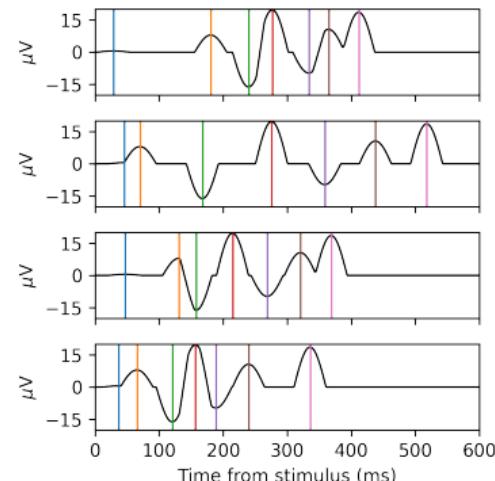
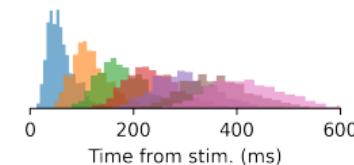
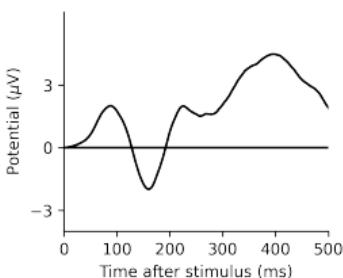


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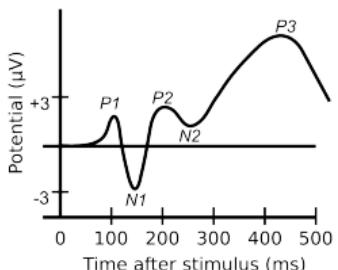


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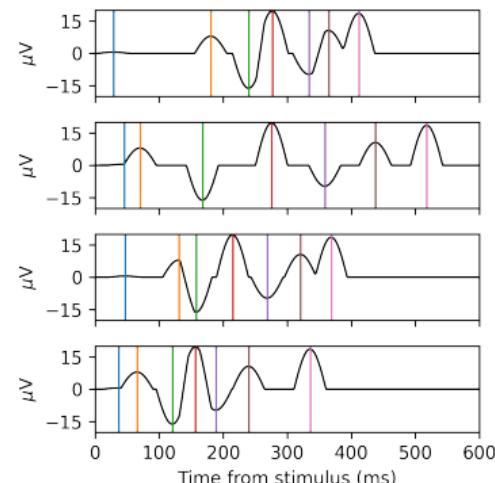
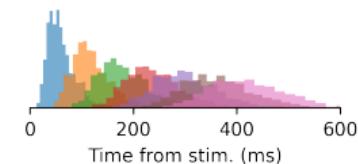
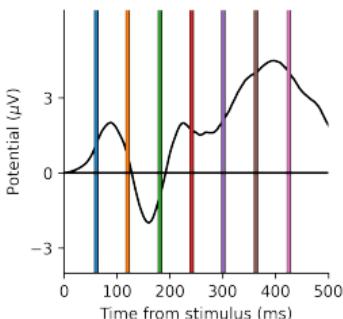


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HsMM-MVPA

Hidden semi-Markov Model Multivariate Pattern Analysis (Anderson et al., 2016)

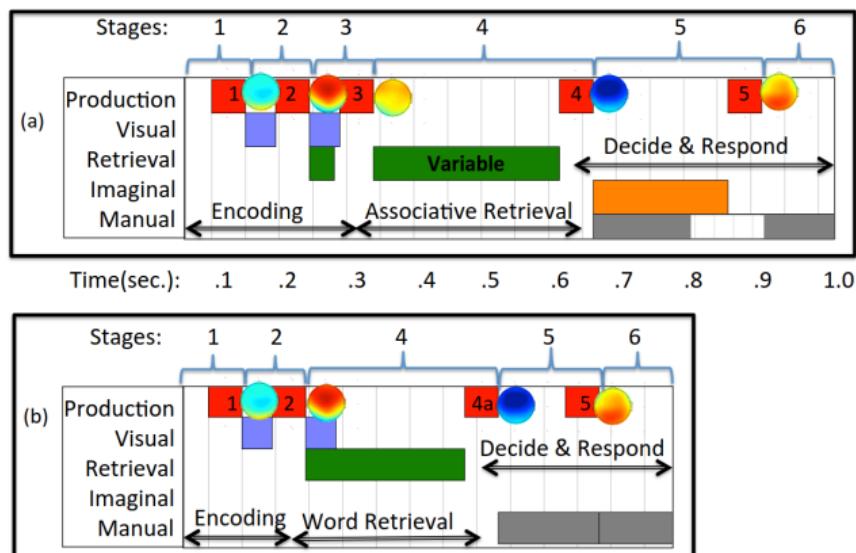
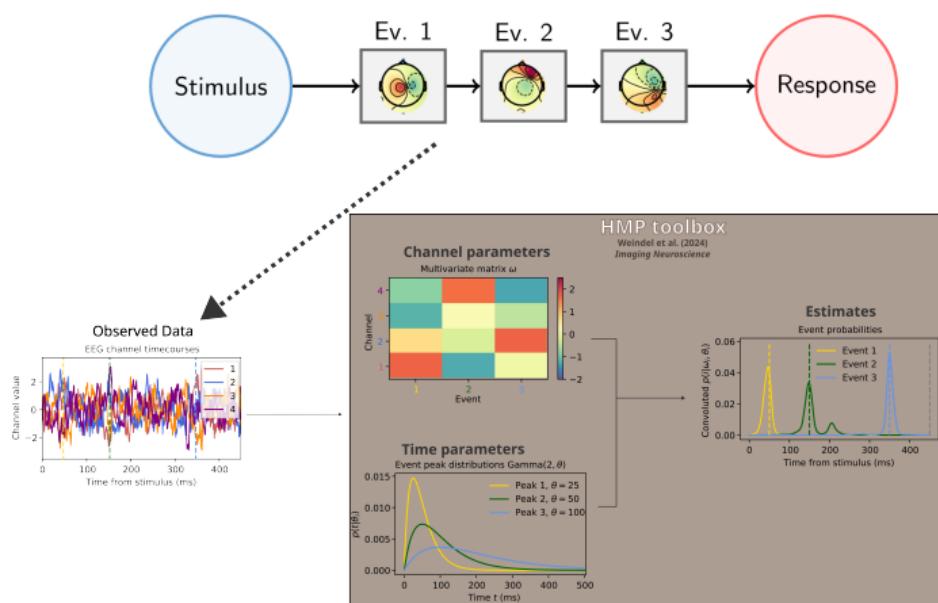


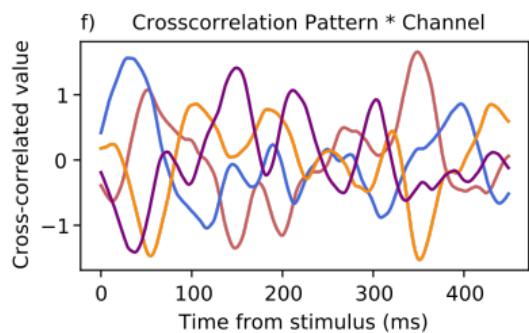
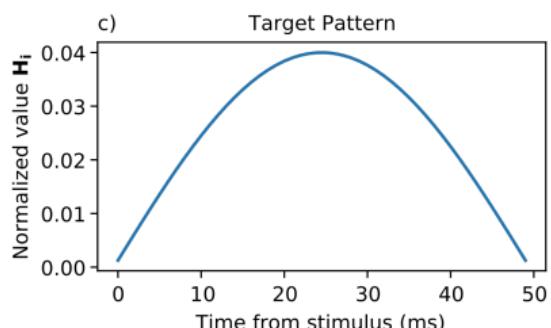
FIGURE: Anderson et al., 2016

HIDDEN MULTIVARIATE PATTERN MODEL

A generalization of HsMM-MVPA: **Hidden Multivariate Pattern model** (Weindel et al., 2024)



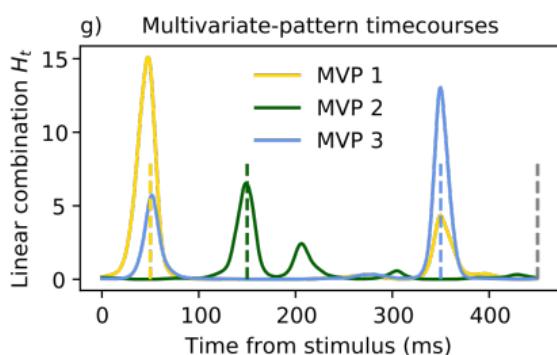
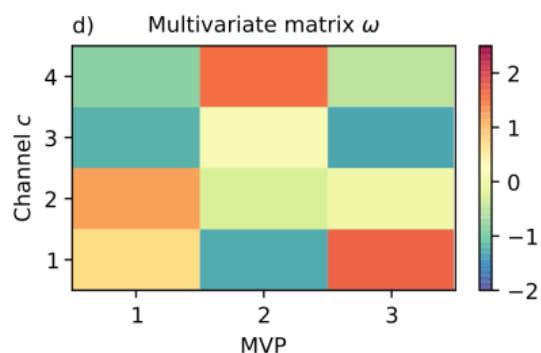
STEP-BY-STEP METHOD: CROSS-CORRELATION



Dot product of the value of the sample s at time t for channel c with the pattern of length L :

$$h_{tc} = \sum_{l=0}^{L-1} s_{t+l,c} H_l$$

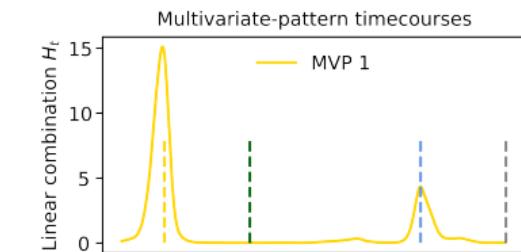
STEP-BY-STEP METHOD: MVPA



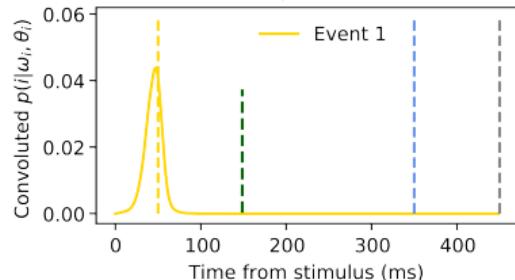
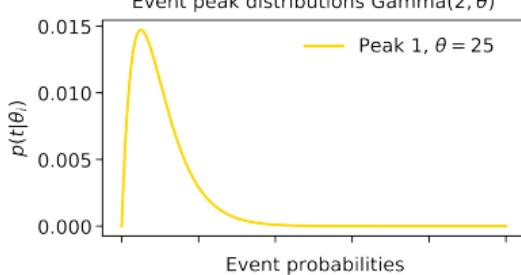
The match between the channels and the event i at time t :

$$H_{ti} = \exp \left(\sum_{c=1}^C h_{tc} \omega_{ci} - \frac{\omega_{ci}^2}{2} \right)$$

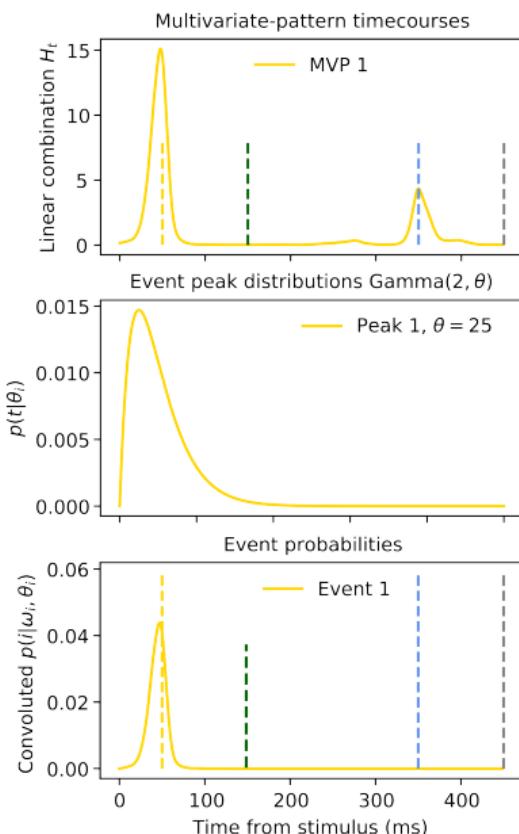
STEP-BY-STEP METHOD: CONVOLUTION (WITH ONE EVENT)



When N event = 1



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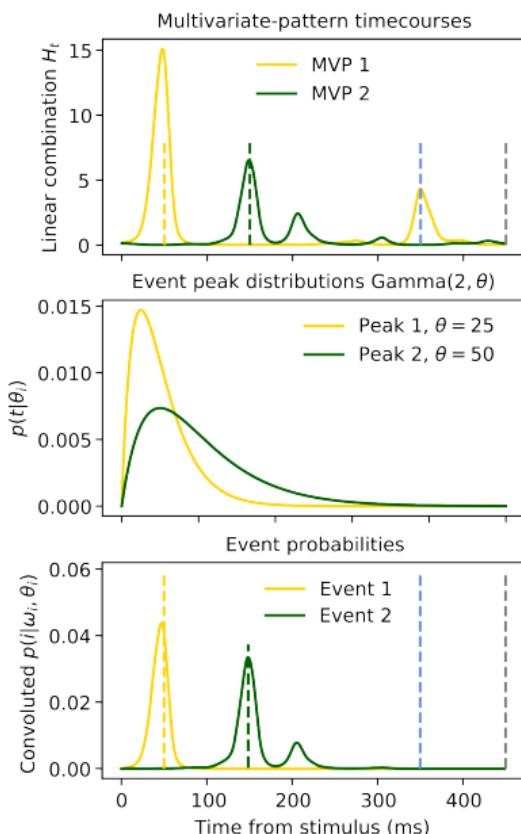
$$p(t|\theta) = \frac{g(t; \theta)}{\sum_{j=0}^T g(t_j; \theta)}$$

Where g is the PDF of a Gamma distribution with a shape of 2 and a scale of θ

$$p(i = t|\omega, \theta) = H_{ti} p(t - 1|\theta) p(T - t|T - \theta)$$

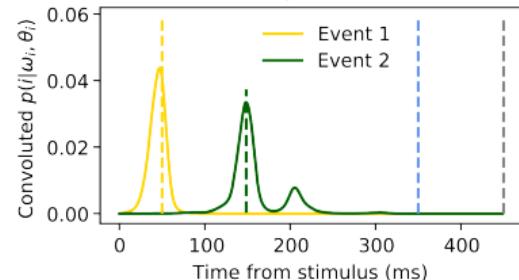
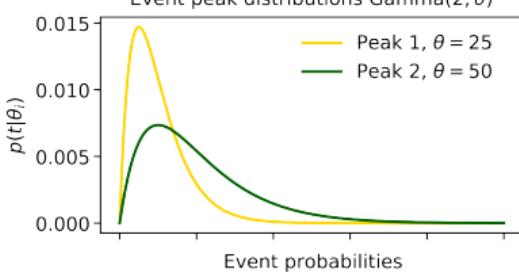
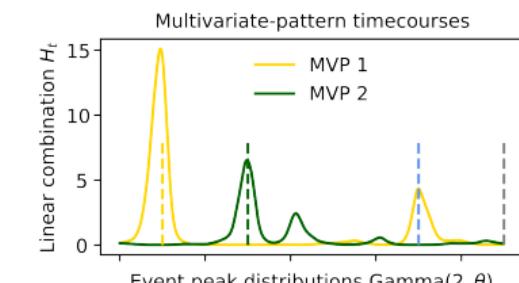
Thus the probability that the peak of Event i is at time sample t is given by the product of the **MVPA match** and the **time distribution of the event**.

STEP-BY-STEP METHOD: CONVOLUTION(S)



When N event is > 1, account for previous event

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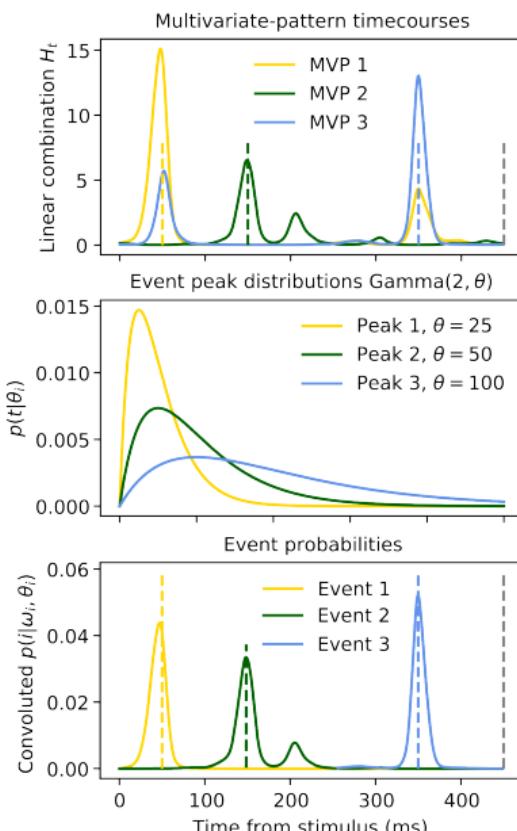
$$\alpha_t(i) = \begin{cases} p(t|\theta_i) H_{ti} & \text{for } i = 1 \\ (\alpha_{1:t}(i-1) * p(t|\theta_i)) H_{ti} & \text{for } 1 < i < I \end{cases}$$

$$\beta_t(i) = \begin{cases} p(t|\theta_i) & \text{for } i = I \\ (\beta_{T:t}(i+1) * p(t|\theta_i)) H_{ti} & \text{for } 0 < i < I \end{cases}$$

$$L[i = t | \theta_i, \omega_i] = \alpha_t(i) \beta_t(i)$$

$$p(i, t) = \frac{L[i = t | \theta_i, \omega_i]}{\sum_{t=1}^T L[i = t | \theta_i, \omega_i]}$$

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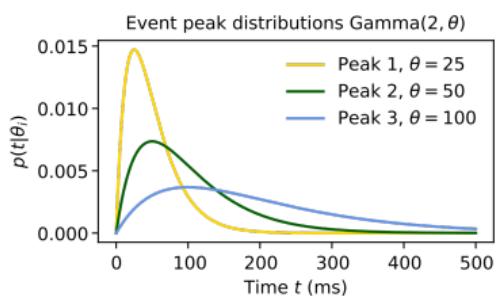
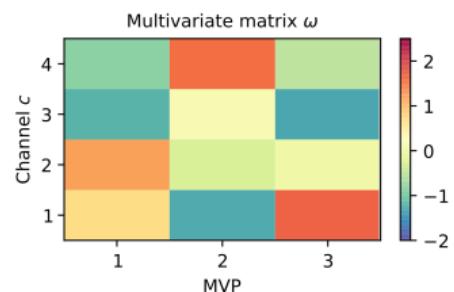
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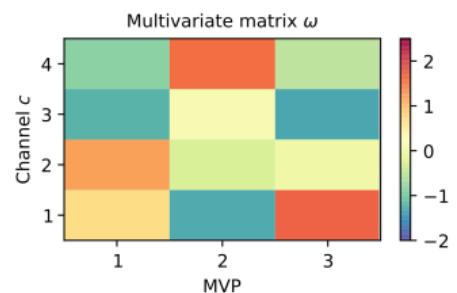
ESTIMATING PARAMETERS: EXPECTATION-MAXIMIZATION

Make a proposal for the set of parameters (λ_1):
 $I + 1$ peak times θ and $I \times C$ magnitudes ω

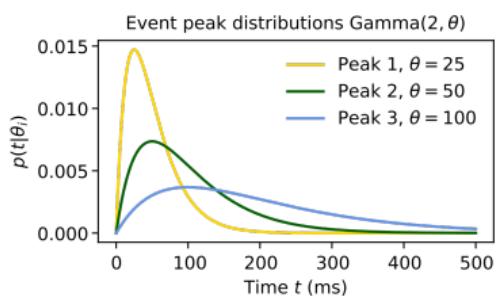


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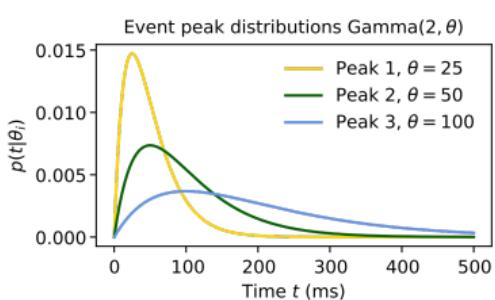
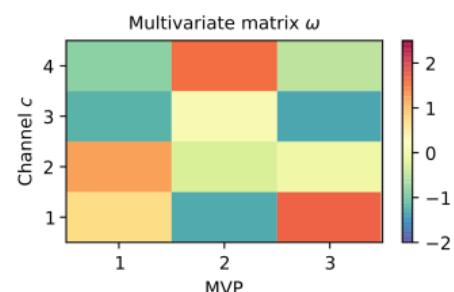
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$$LL = \log\left(\sum_t^T [L_t | \lambda_1]\right)$$



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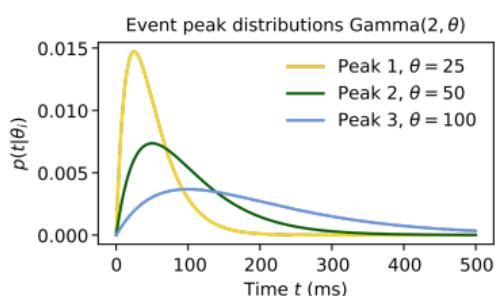
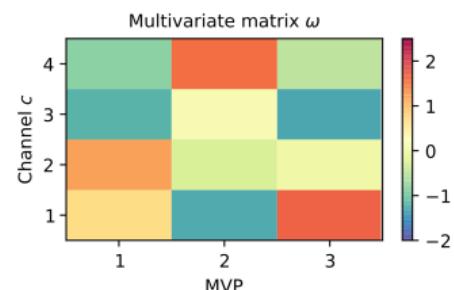
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Compute new λ^* on event probabilities:

$$\theta_i^* = \begin{cases} f\left(\frac{\sum_1^T p(i,t)t}{T}\right) & \text{for } i = 1 \\ f\left(\frac{\sum_1^T p(i,t)t}{T} - \frac{\sum_1^T p(i-1,t)t}{T}\right) & \text{for } 1 < i \leq I \end{cases}$$

$$\omega_{ci}^* = \sum_1^T h_{ct} p(i, t)$$

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End when $\epsilon > (LL_{n+1} - LL_n) / |LL_n|$

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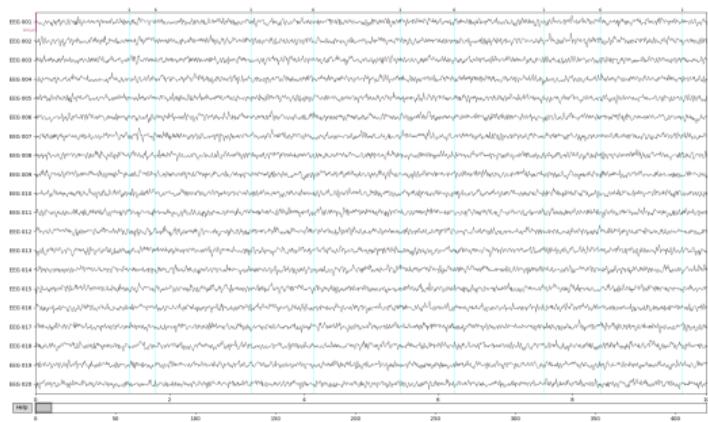
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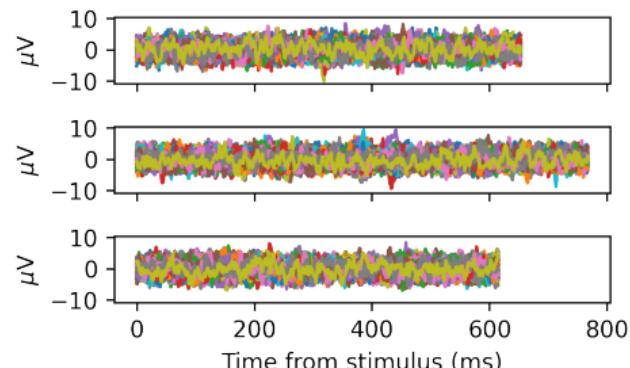
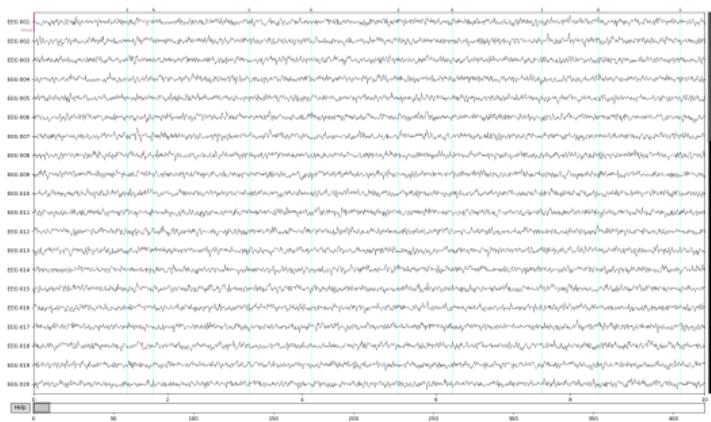
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- Physiological time-series (EEG, MEG, EcOG, iEEG?, ...)
- Parsing sequence start and end (e.g., stim to response)
- PCA + cross-correlation with expected pattern



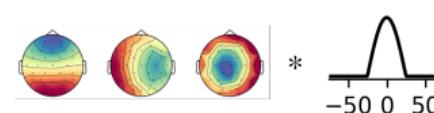
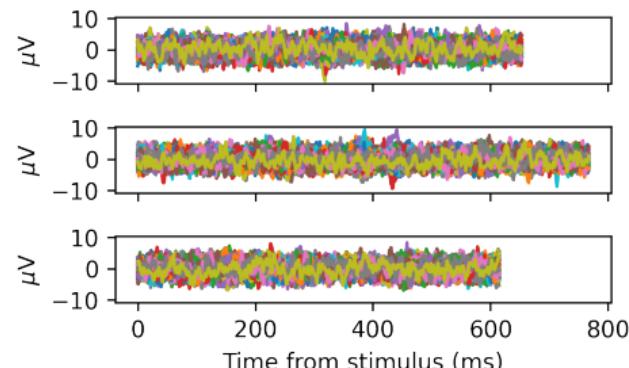
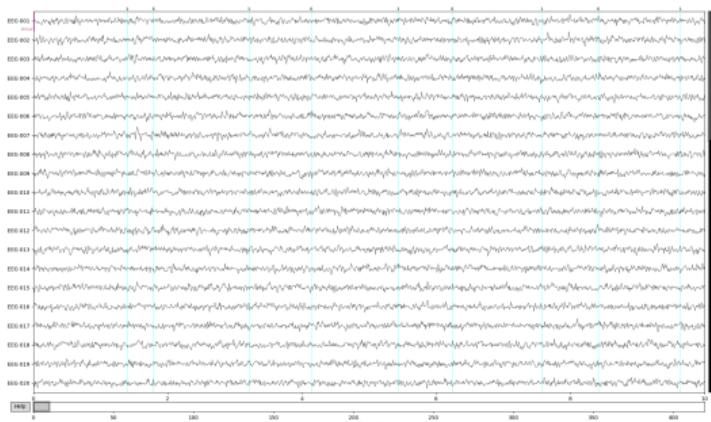
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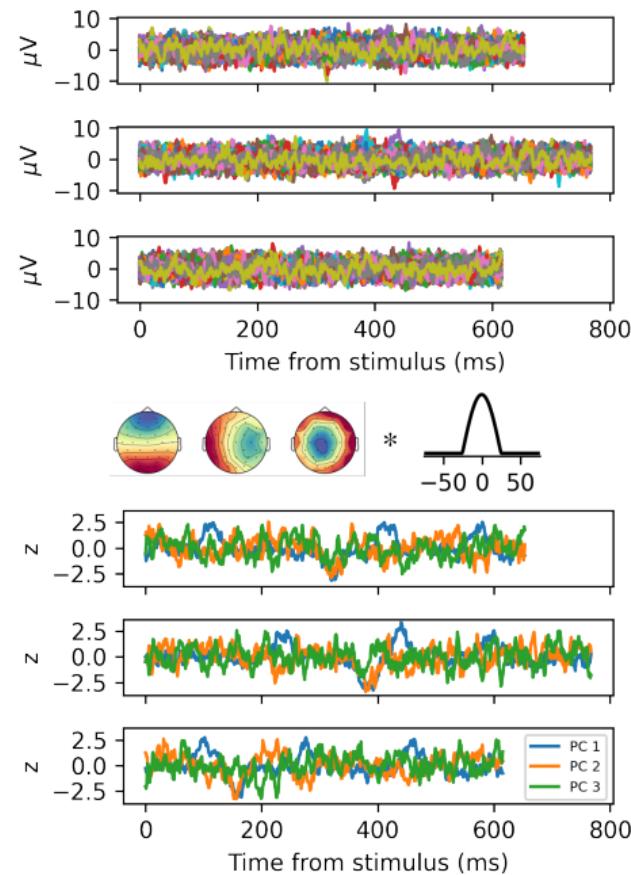
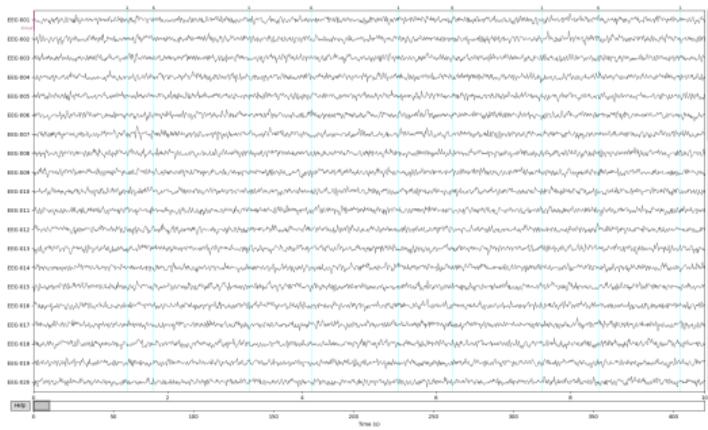
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- PCA + cross-correlation with expected pattern



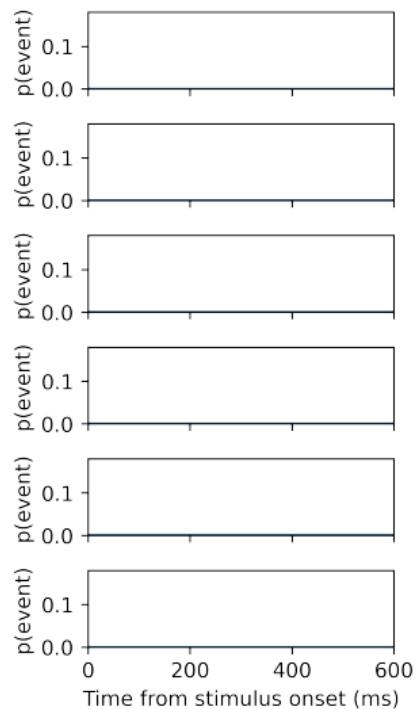
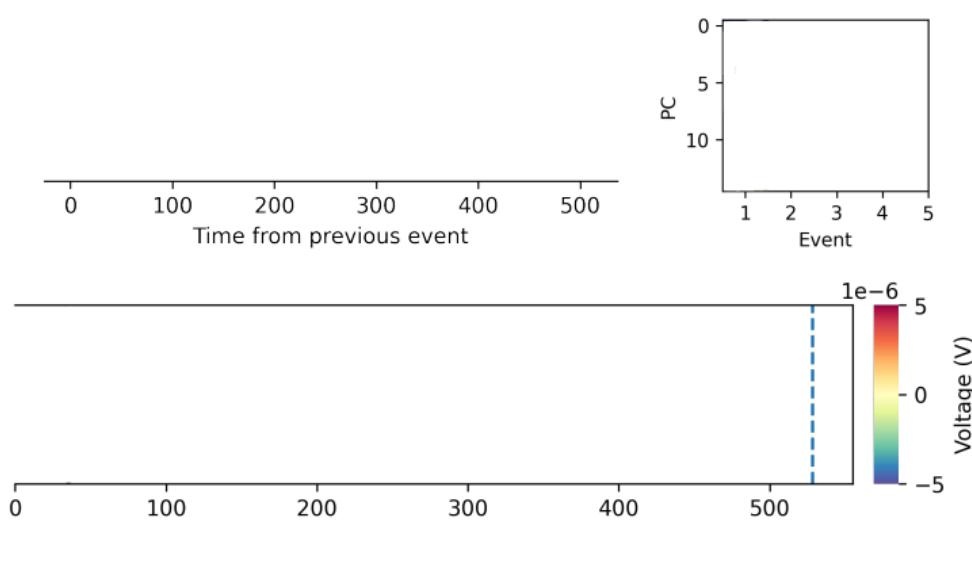
HOW TO USE HMP

- Physiological time-series (EEG, MEG, EcOG, iEEG?, ...)
- Parsing sequence start and end (e.g., stim to response)
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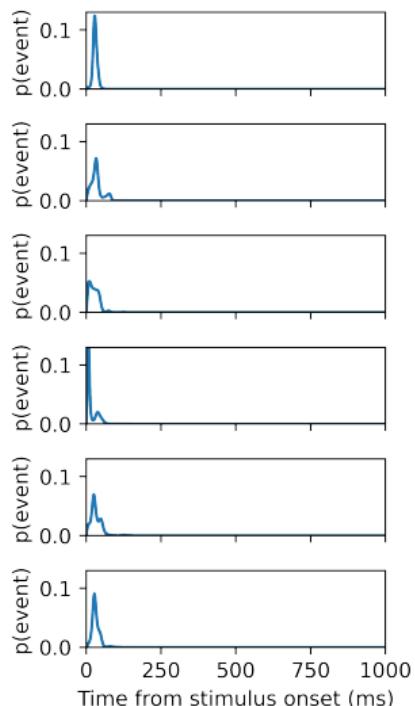
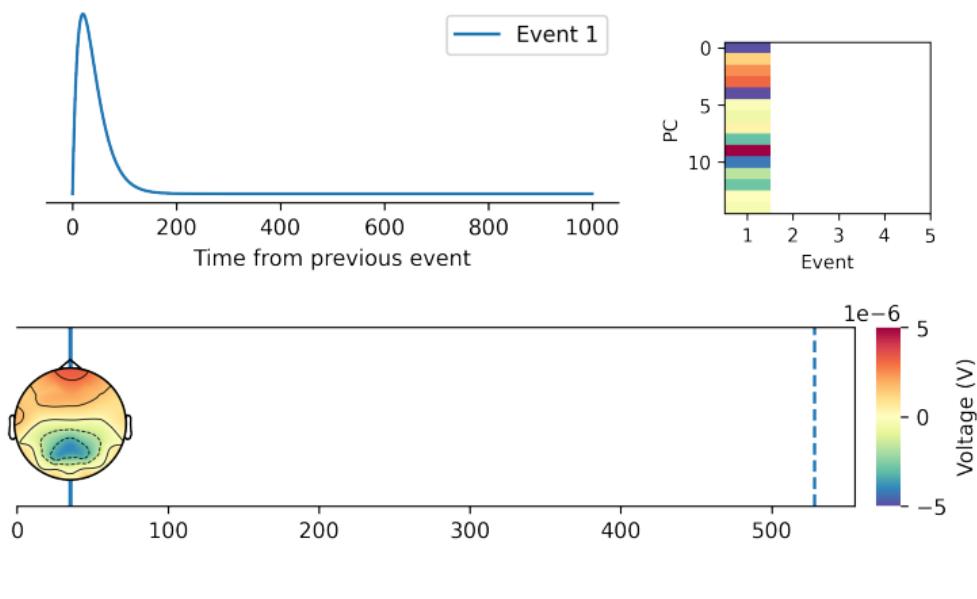
HOW MANY EVENTS?

Infer the number of events through a cumulative approach:



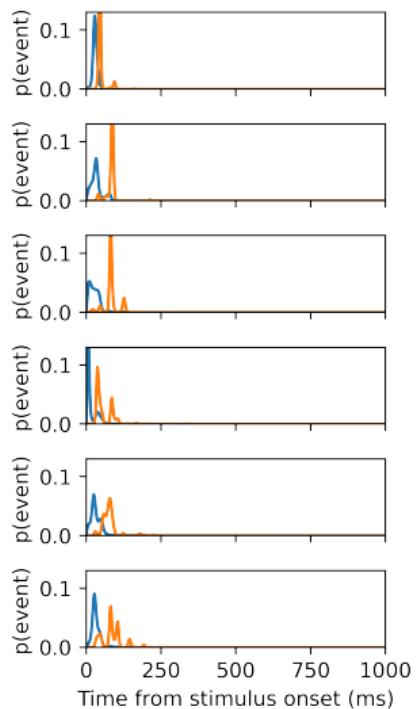
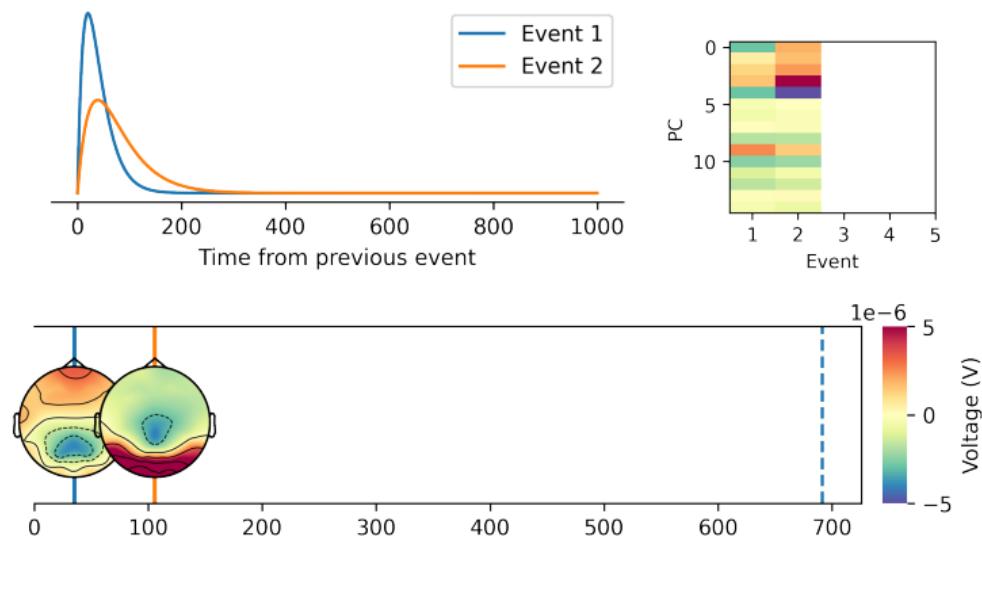
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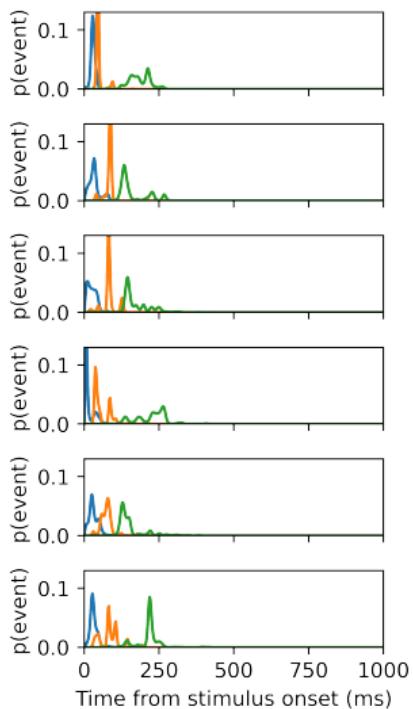
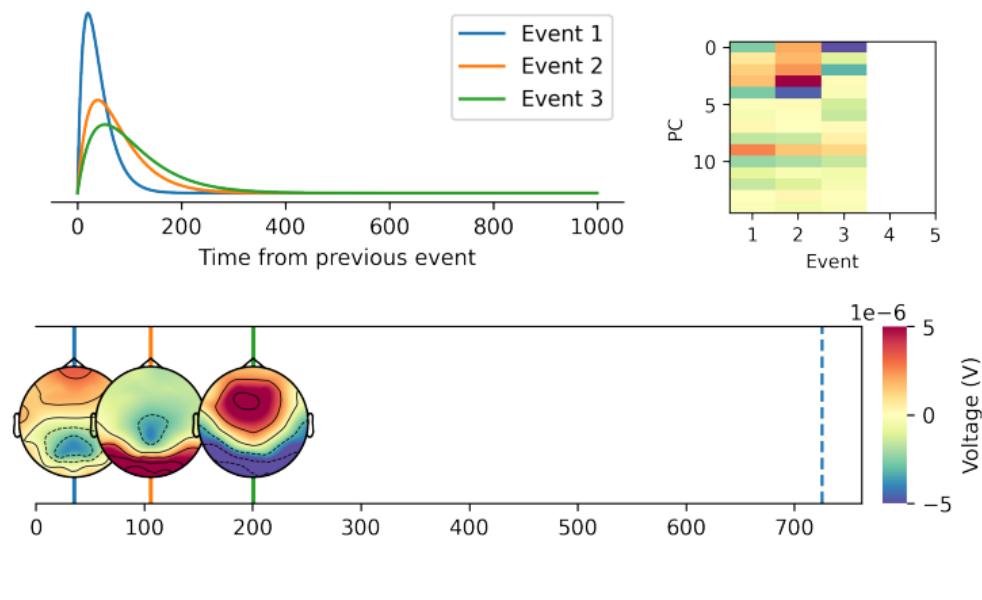
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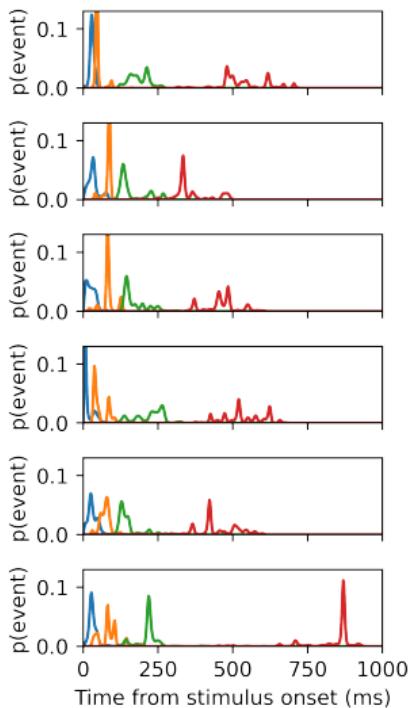
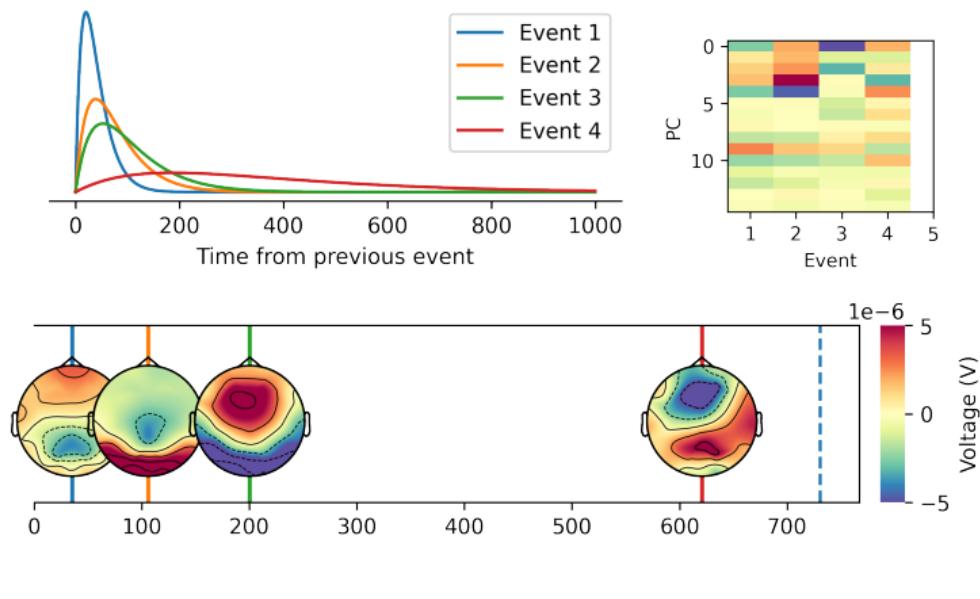
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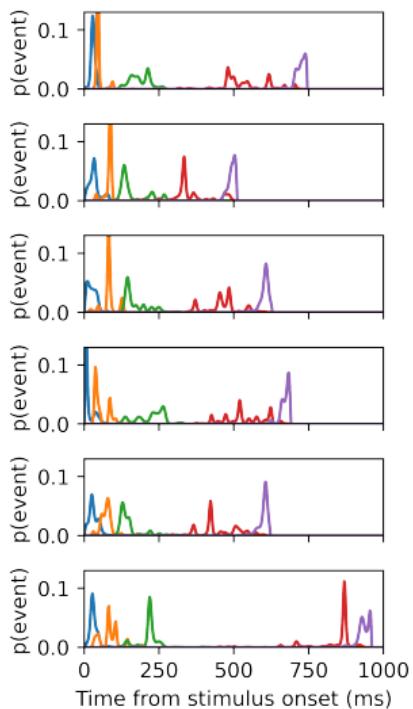
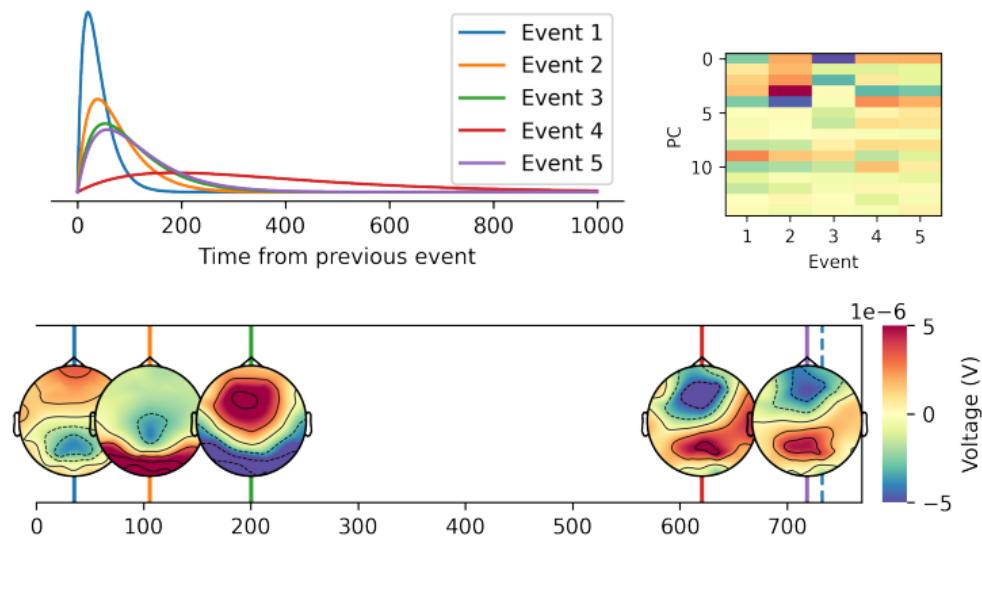
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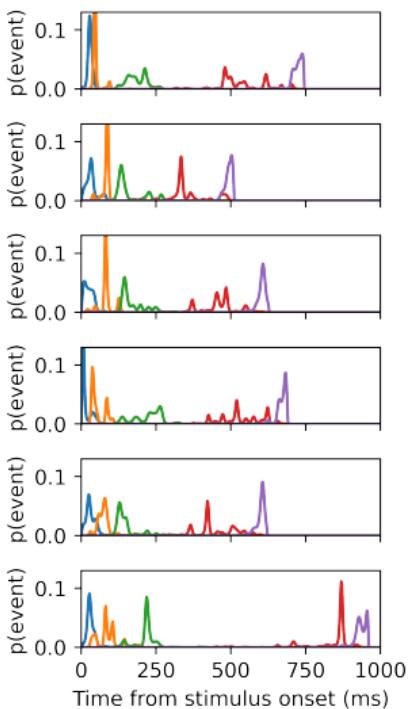
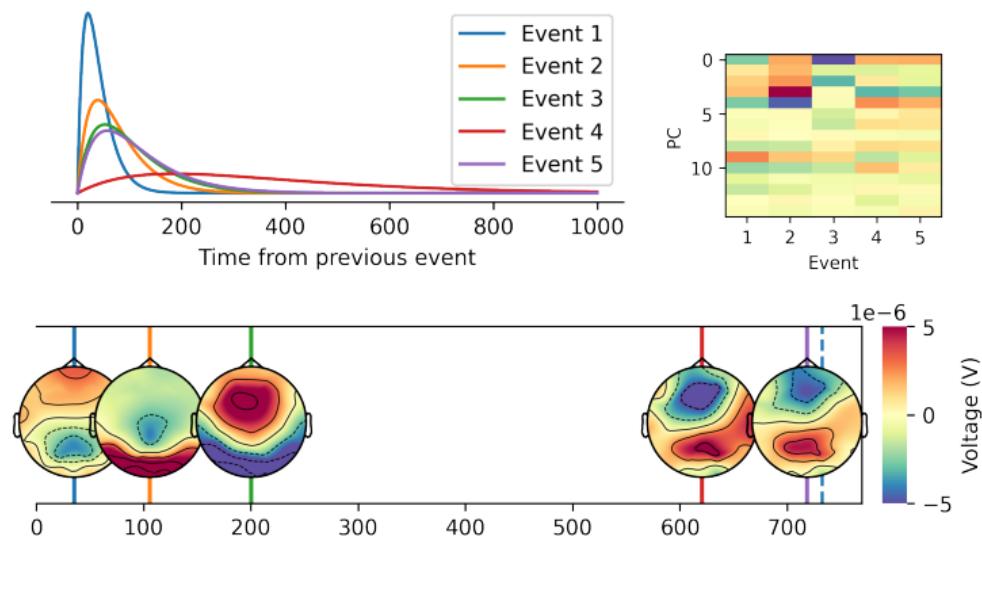
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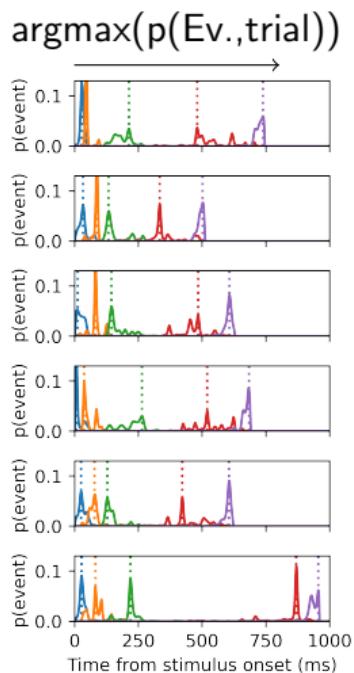
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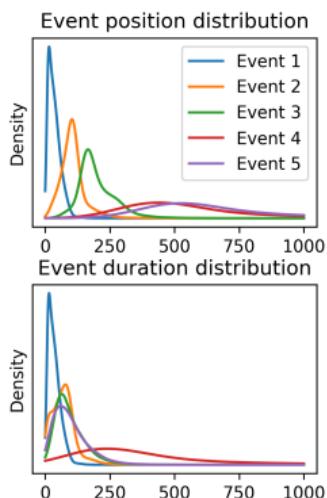
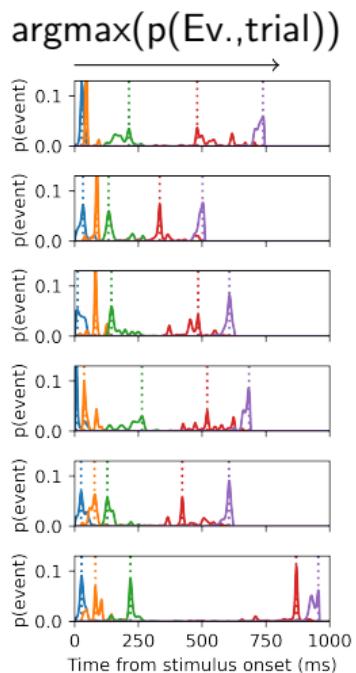


Alternatively: fit an I event model. With appropriate signal-to-noise ratio, the solution with I inferred events should be the same as directly estimating I events.

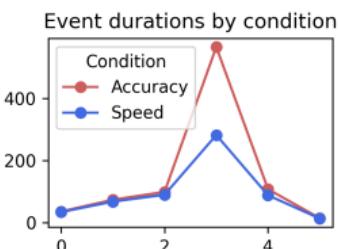
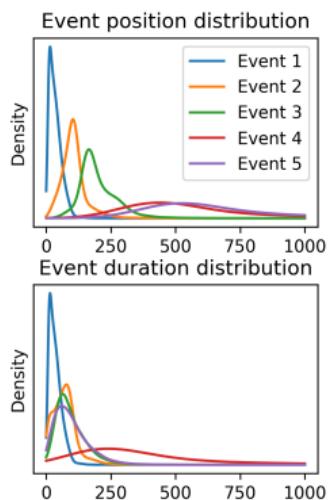
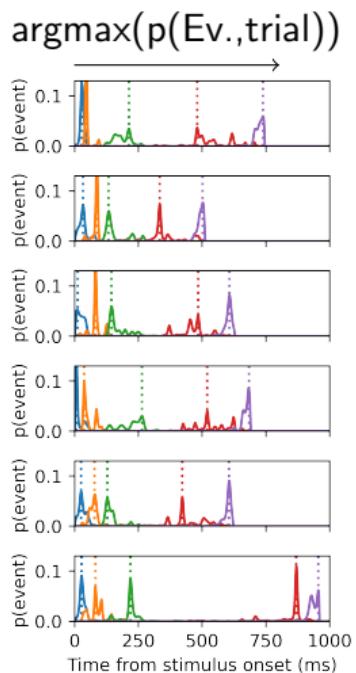
ESTIMATING SINGLE-TRIAL TIMES: INSPECTING TIME



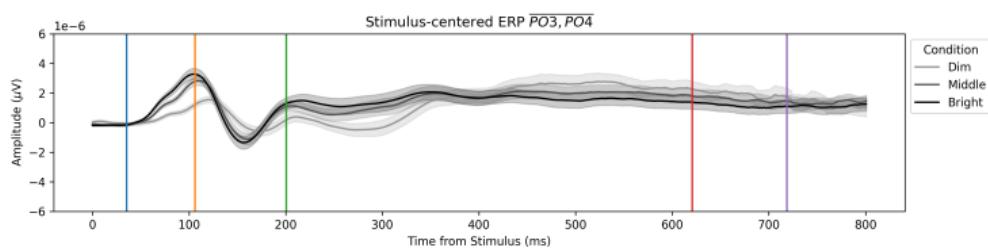
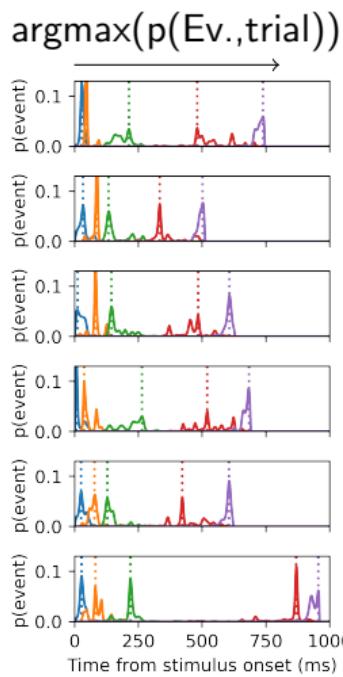
ESTIMATING SINGLE-TRIAL TIMES: INSPECTING TIME



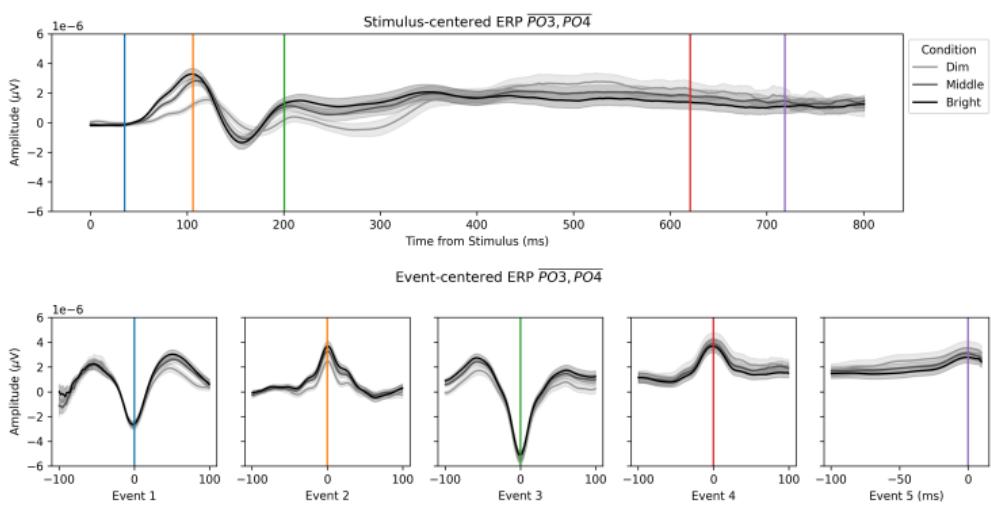
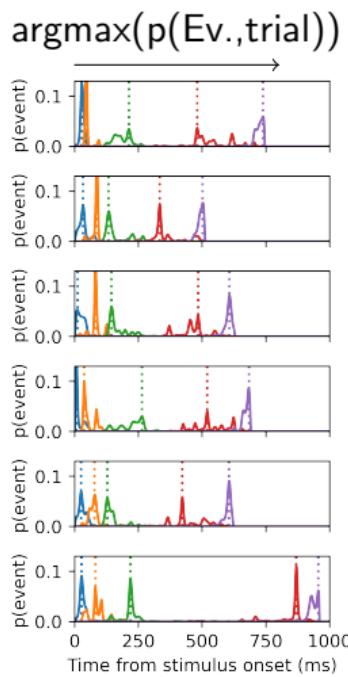
ESTIMATING SINGLE-TRIAL TIMES: INSPECTING TIME



ESTIMATING SINGLE-TRIAL TIMES: INSPECTING ELECTROPHYSIOLOGY

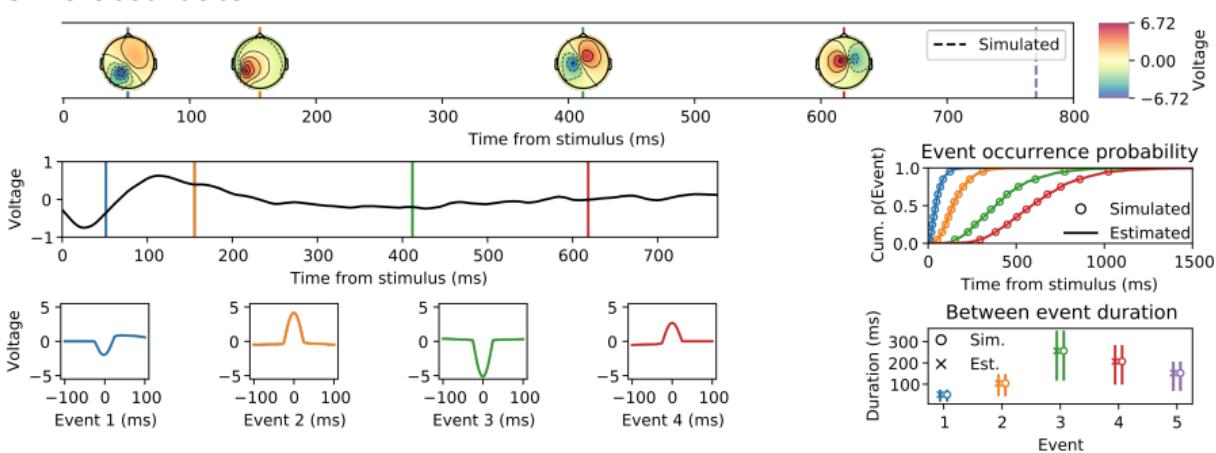
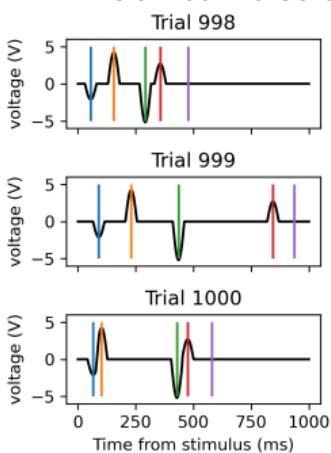


ESTIMATING SINGLE-TRIAL TIMES: INSPECTING ELECTROPHYSIOLOGY



EXAMPLE IN SIMULATED DATA

Back to noiseless simulated data:



CORE ASSUMPTIONS

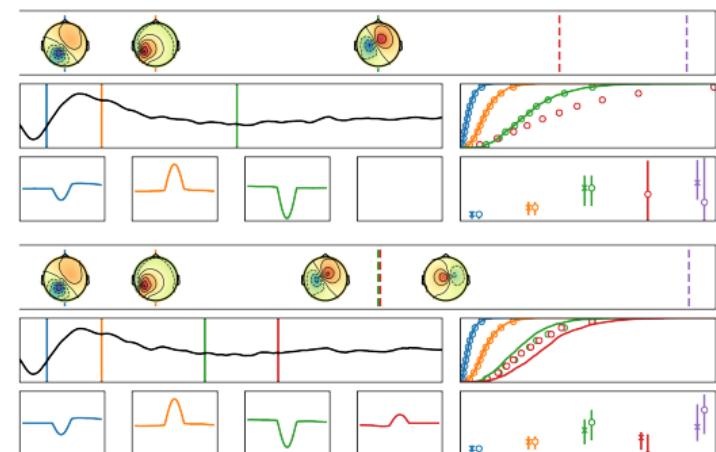
Three core assumptions

- Events in the interval are sequential

CORE ASSUMPTIONS

Three core assumptions

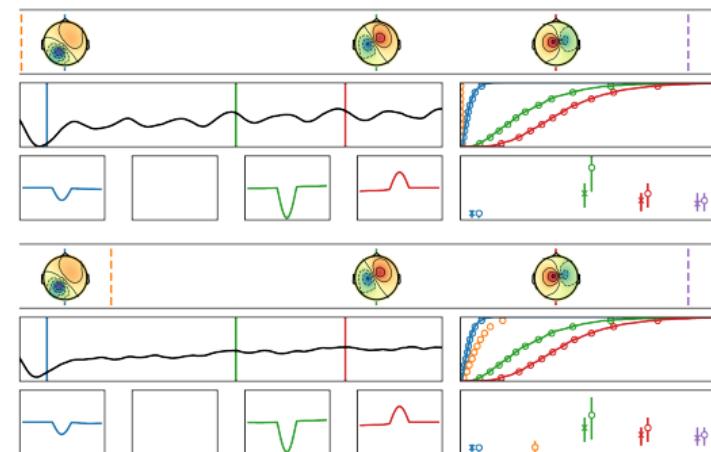
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CORE ASSUMPTIONS

Three core assumptions

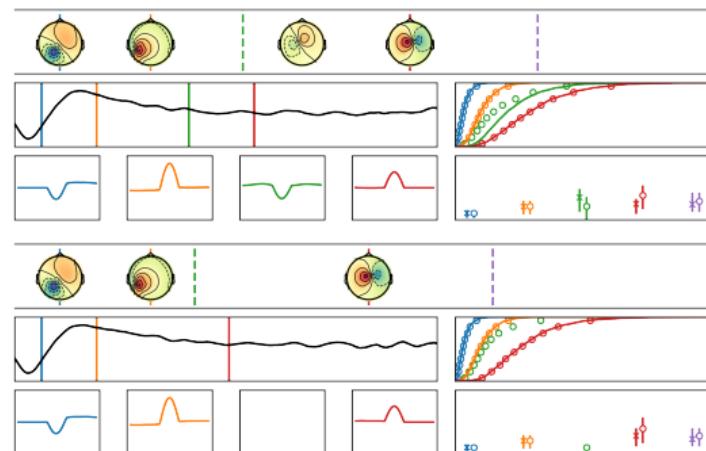
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- Events are transient



CORE ASSUMPTIONS

Three core assumptions

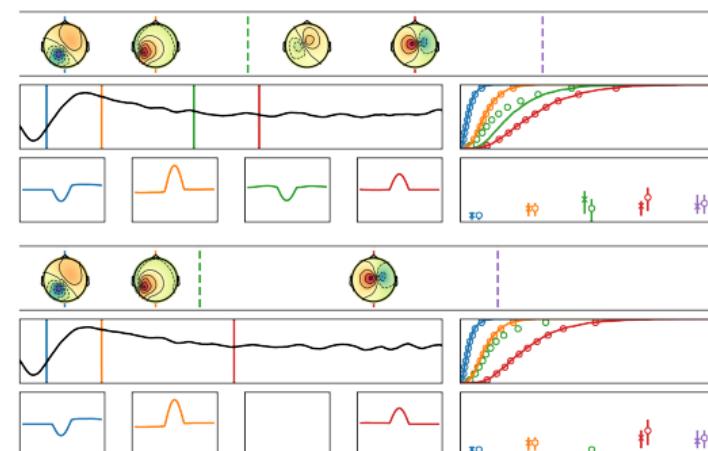
- Events in the interval are sequential
- Events are transient
- Events are repeated across trials



CORE ASSUMPTIONS

Three core assumptions

- Events in the interval are sequential
- Events are transient
- Events are repeated across trials
- (The modelled durations contain the sequence)



A NOTE ON ANCILLARY ASSUMPTIONS

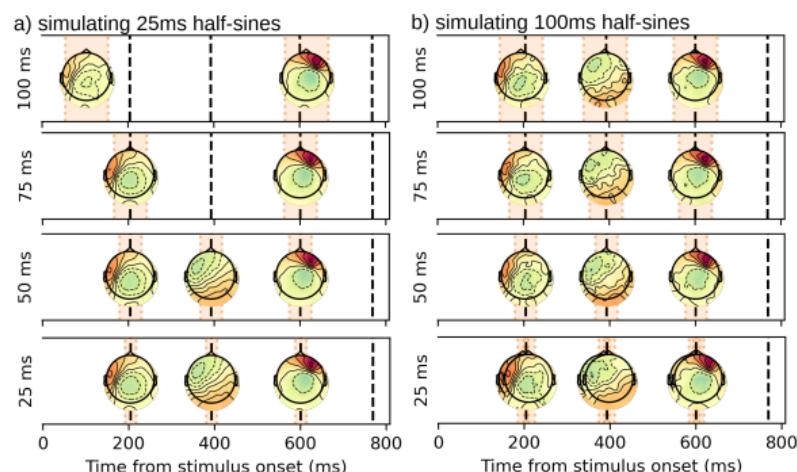
Ancillary assumptions:

- Events are equal or shorter than the expected duration

A NOTE ON ANCILLARY ASSUMPTIONS

Ancillary assumptions:

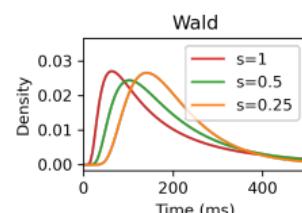
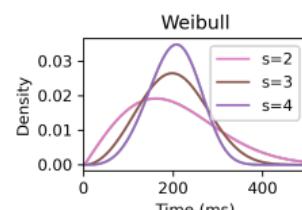
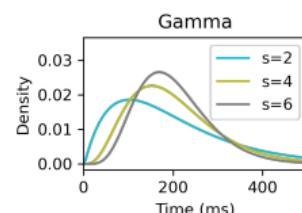
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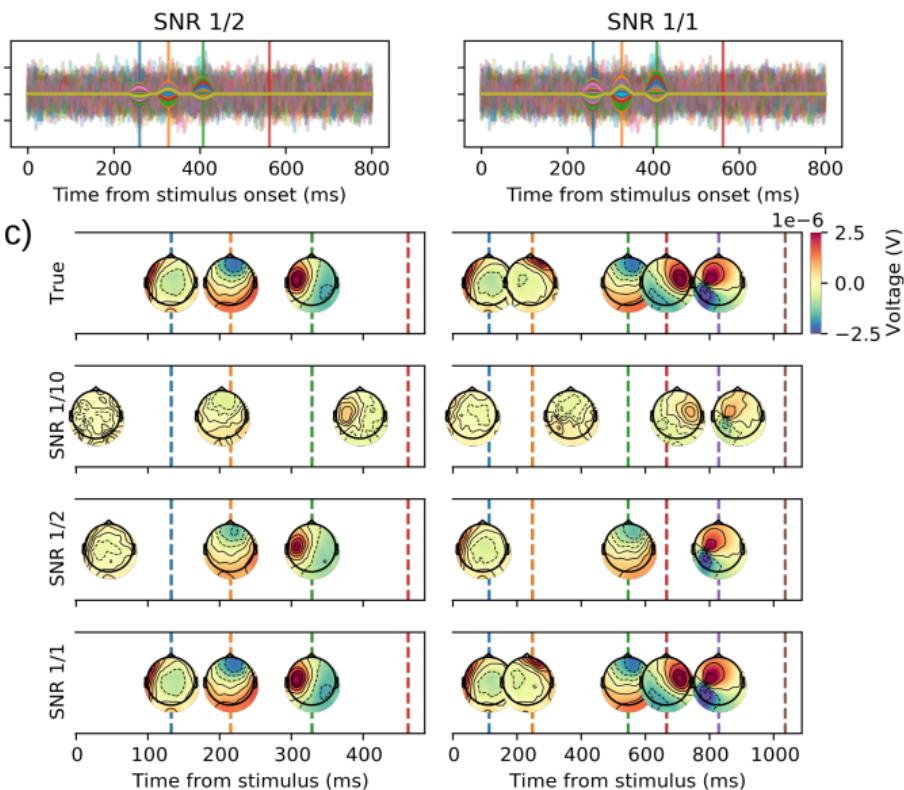
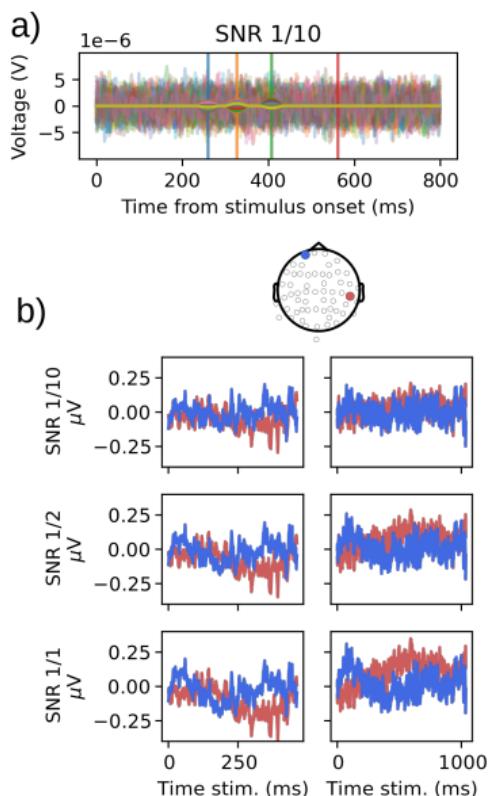
A NOTE ON ANCILLARY ASSUMPTIONS

Ancillary assumptions:

- Events are equal or shorter than the expected duration
- The time distribution family doesn't exclude likely values



A NOTE ON SIGNAL-TO-NOISE RATIO



STATING THE PROBLEM
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USE AND LIMITATIONS
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HMP AND THE P3

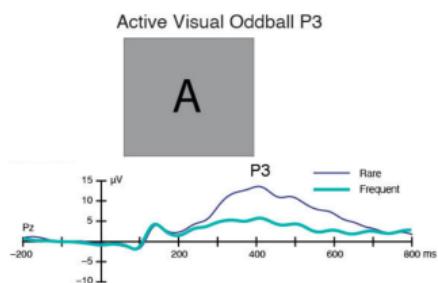


FIGURE: Adapted from
ERP Core (Kappenman
et al., 2021)

HMP AND THE P3

Active Visual Oddball P3

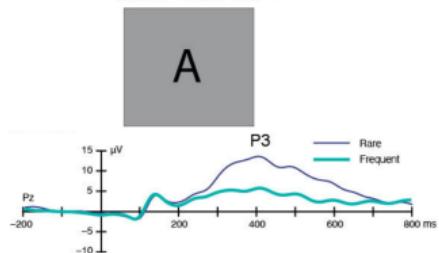
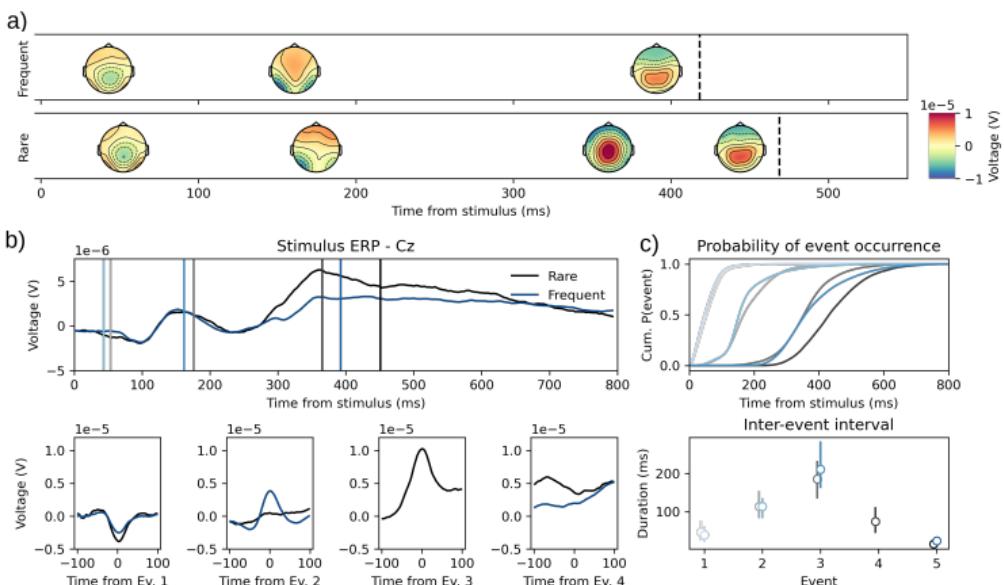
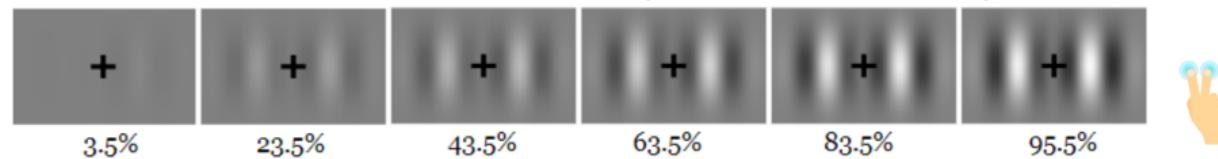


FIGURE: Adapted from
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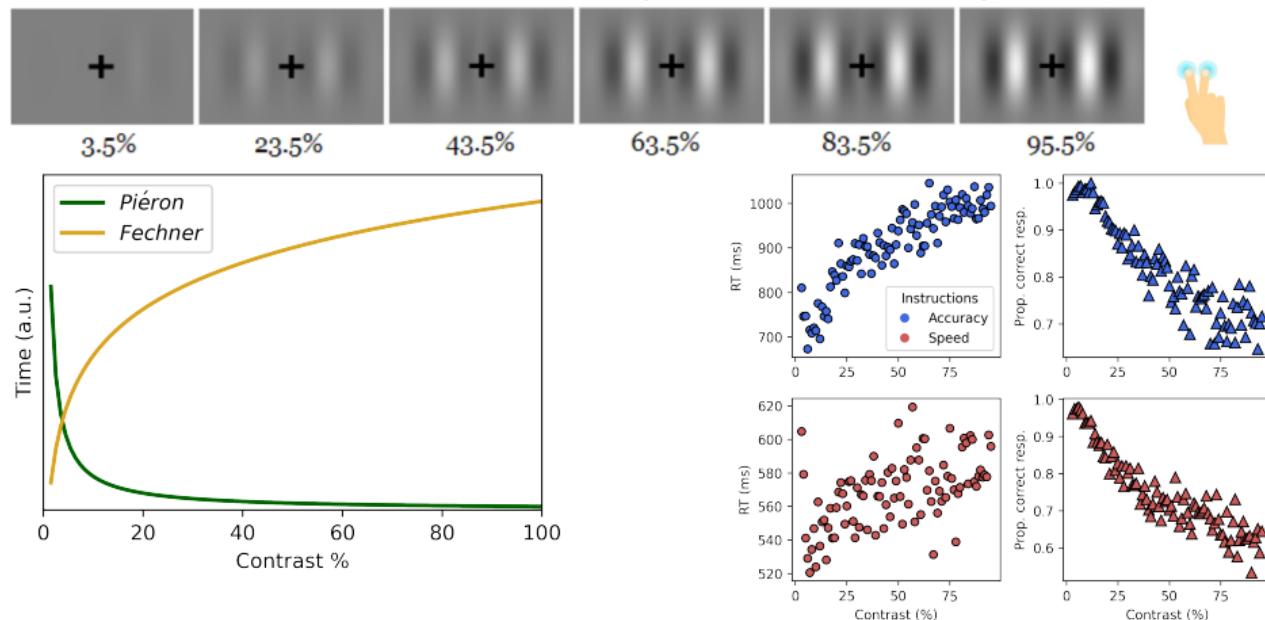
APPLICATION TO DECISION-MAKING: TIME-DOMAIN

Application to a decision making task (Weindel et al., 2025)



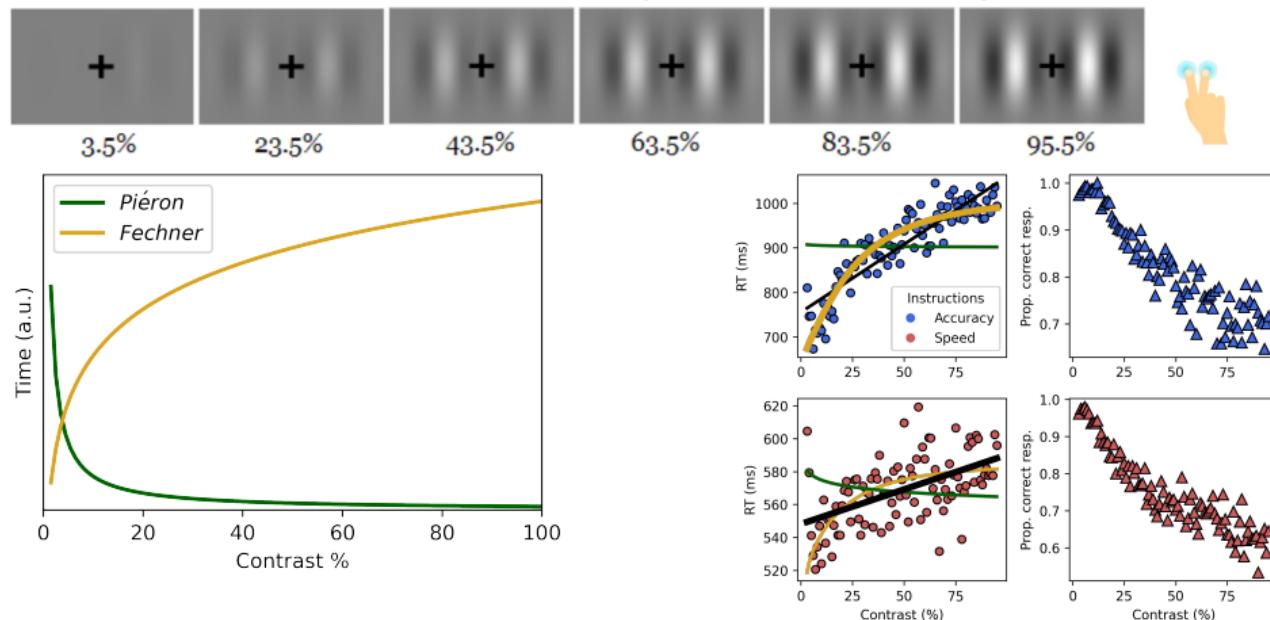
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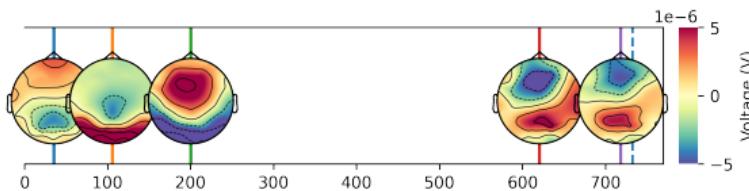


APPLICATION TO DECISION-MAKING: TIME-DOMAIN

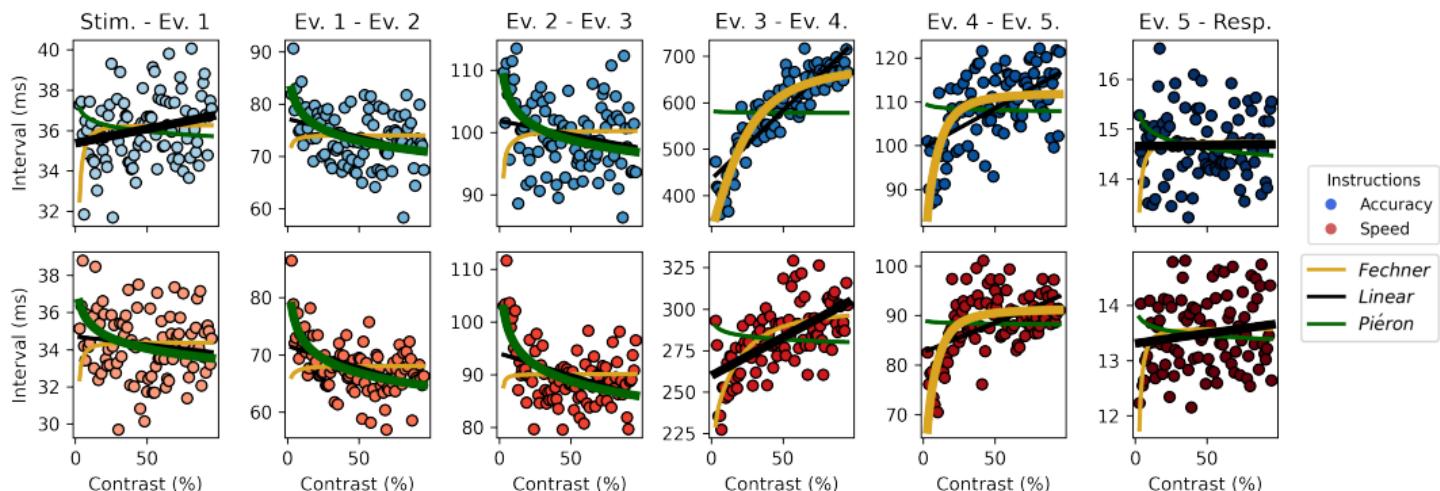
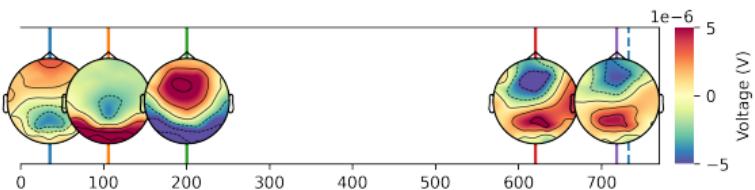
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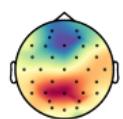
EEG RESULTS: INTER-EVENT TIMING



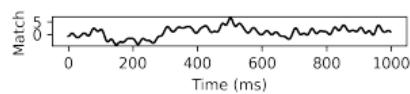
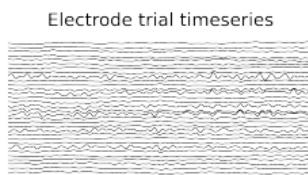
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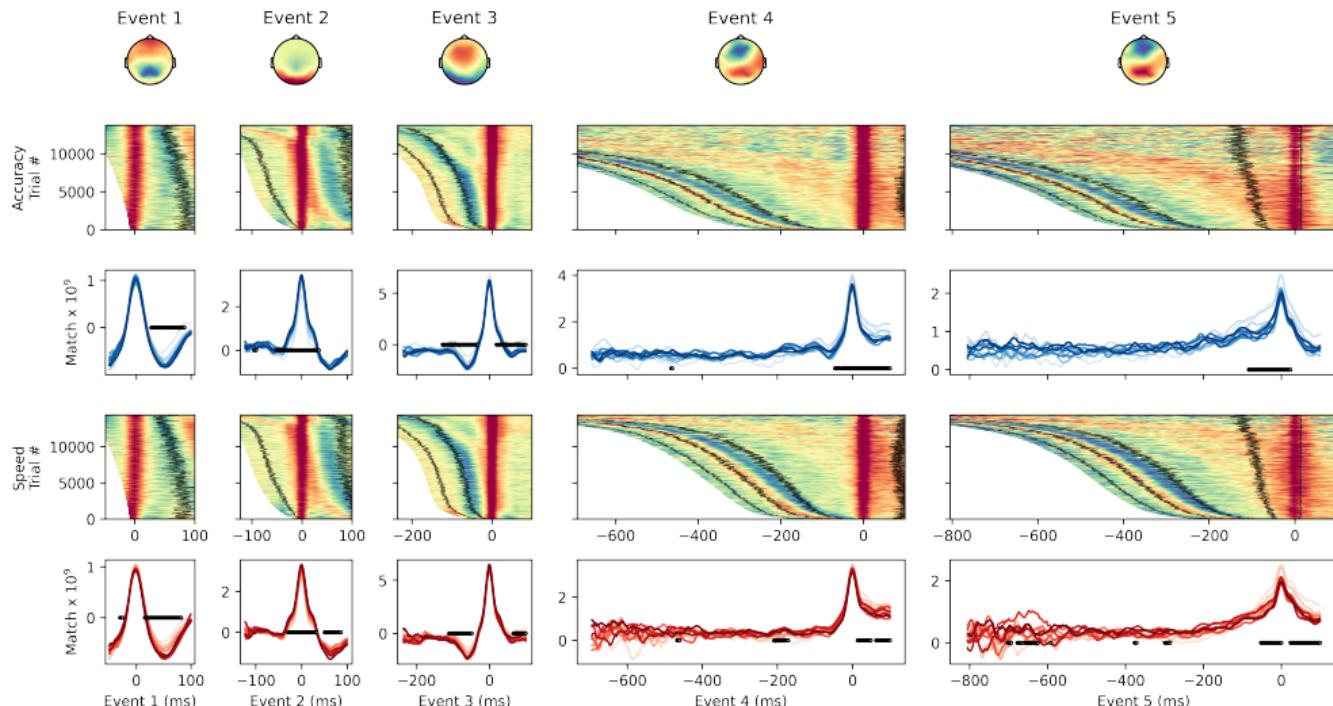
EEG RESULTS: ELECTROPHYSIOLOGICAL ACTIVITY I



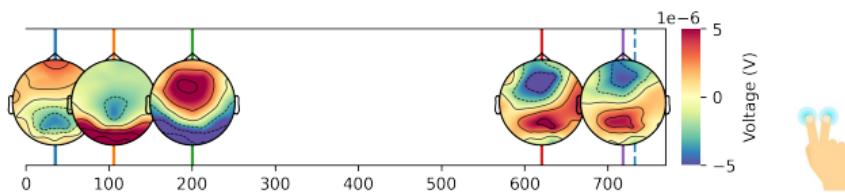
Weights



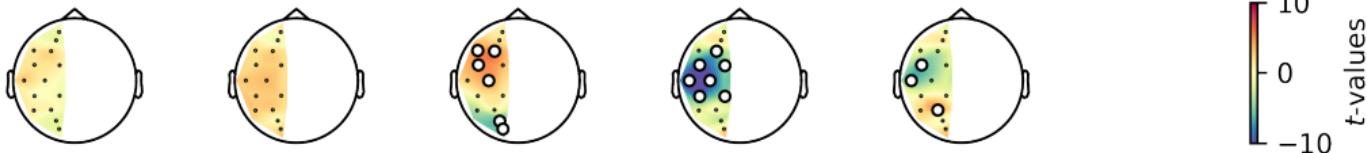
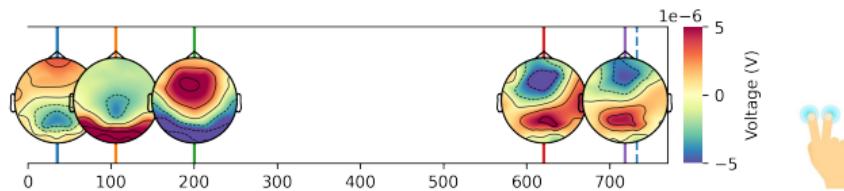
EEG RESULTS: ELECTROPHYSIOLOGICAL ACTIVITY II



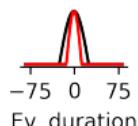
EEG RESULTS: ELECTROPHYSIOLOGICAL ACTIVITY III



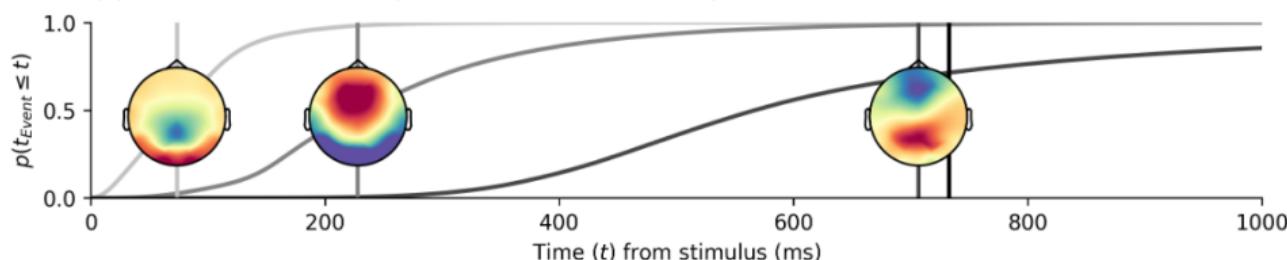
EEG RESULTS: ELECTROPHYSIOLOGICAL ACTIVITY III



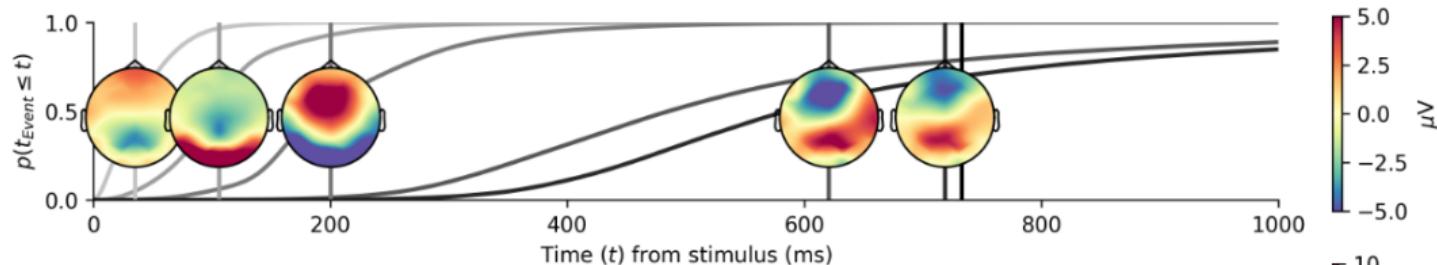
A NOTE ON PATTERN WIDTH



[https://elifesciences.org/reviewed-preprints/108049v1:](https://elifesciences.org/reviewed-preprints/108049v1)



[https://www.biorxiv.org/content/10.1101/2025.06.25.661505v2:](https://www.biorxiv.org/content/10.1101/2025.06.25.661505v2)



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PERKS

IFF all assumptions are correct, we access the single-trial time of information-processing related components in EEG and thus we can:

PERKS

IFF all assumptions are correct, we access the single-trial time of information-processing related components in EEG and thus we can:

- Decompose any duration (saccade, key strokes, movement time) into task-relevant sub-intervals
- Describe tasks and conditions based on an underlying sequence of components
- Describe components in time and space
- Time-lock follow-up analyses on specific events (source reconstruction, time-frequency,...)
- Use task-derived spatial filters

ADVICES (YET UNWRITTEN)

Note that the model and its implementation are work in progress. At this stage, here are a few recommendations based on user experiences:

ADVICES (YET UNWRITTEN)

Note that the model and its implementation are work in progress. At this stage, here are a few recommendations based on user experiences:

- Use design with strong hypotheses to constrain the interpretation (no HARKing).
- Start with relatively short intervals (e.g. avoid long 5 seconds durations)
- Start exploring with low precision on downsampled data (not less than 100Hz, 250Hz recommended)
- If inferring events from data, keep your amount of trials as high as possible (e.g. group model > participant model)
- Don't waste too much information at the preprocessing step (bad data rejection, ICA, PCA)

RESSOURCES

A list of resources:

- **Tutorials** <https://hmp.readthedocs.io/en/latest/notebooks/demo.html>
- **Codebook/API:** <https://hmp.readthedocs.io/en/latest/api/hmp.html>
- **Paper on HMP:**
https://direct.mit.edu/imag/article/doi/10.1162/imag_a_00400/125469
- **Repository of the decision-making study:**
<https://github.com/GWeindel/decision-times>
- **Upcoming mailing list** (send an email)

THANK YOU

Contributors 8



and you?

Thank you for being FOSS:



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-  Anderson, J. R., Zhang, Q., Borst, J. P., & Walsh, M. M. (2016). The discovery of processing stages: Extension of sternberg's method.. *Psychological review*, 123(5), 481.
-  Kappenman, E. S., Farrens, J. L., Zhang, W., Stewart, A. X., & Luck, S. J. (2021). Erp core: An open resource for human event-related potential research. *NeuroImage*, 225, 117465.
-  Lee, J., Kim, H. R., & Lee, C. (2010). Trial-to-trial variability of spike response of v1 and saccadic response time. *Journal of neurophysiology*, 104(5), 2556–2572.
-  Weindel, G., Borst, J. P., & van Maanen, L. (2025). Decision-making components and times revealed by the single-trial electro-encephalogram. *bioRxiv*. <https://doi.org/10.1101/2025.06.25.661505>
-  Weindel, G., van Maanen, L., & Borst, J. P. (2024). Trial-by-trial detection of cognitive events in neural time-series. *Imaging Neuroscience*, 2, 1–28.