UNCOVERING THE DECISIONAL DYNAMICS IN DIGIT COMPARISON TASK:

Insight from Electroencephalography Using Hidden semi-Markov Models with Multivariate Pattern Analysis (HsMM-MVPA)

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Digit comparison task is



- a commonly used paradigm to examine the underlying numerical representations
- used as index of semantic access to number
- linked to the development of more advanced mathematical abilities

Caviola et al. (2020). *Developmental Science*; Schneider et al. (2017). *Developmental Science*

The neurocognitive mechanisms* behind digit comparison performance remain unclear



- which number system is involved
- how task instructions, stimuli presentation and their relative frequency affect the distance effect

Numerical cognition currently lacks mechanistic* explanations to construct process models for interpreting diverse findings

seen from process-oriented perspective focusing on examining step-by-step the nature of specific cognitive processes responsible for forming specific associations (see Coolen. (2026). *Journal of Numerical Cognition

Example: inhibitory control processes underlying the inhibition and numerical judgement association are specific to the conflicting dimensions of magnitude (Viarouge et al., 2023)

Kojouharova & Krajcsi (2020); Krajcsi et al. (2018); Marinova et al. (2018), (2021); Wilkey & Ansari (2020); Starling-Alves & Wilkey. (2026). *Behavior Research Methods;* Ren et al*., 2022, 2025*

Signatures of number comparison

Behavioral

The ability to rapidly indentify visually presented digits and to determine a digit's ordinal position support successful digit comparison

(Sasanguie et al. (2017). *Cognition*)

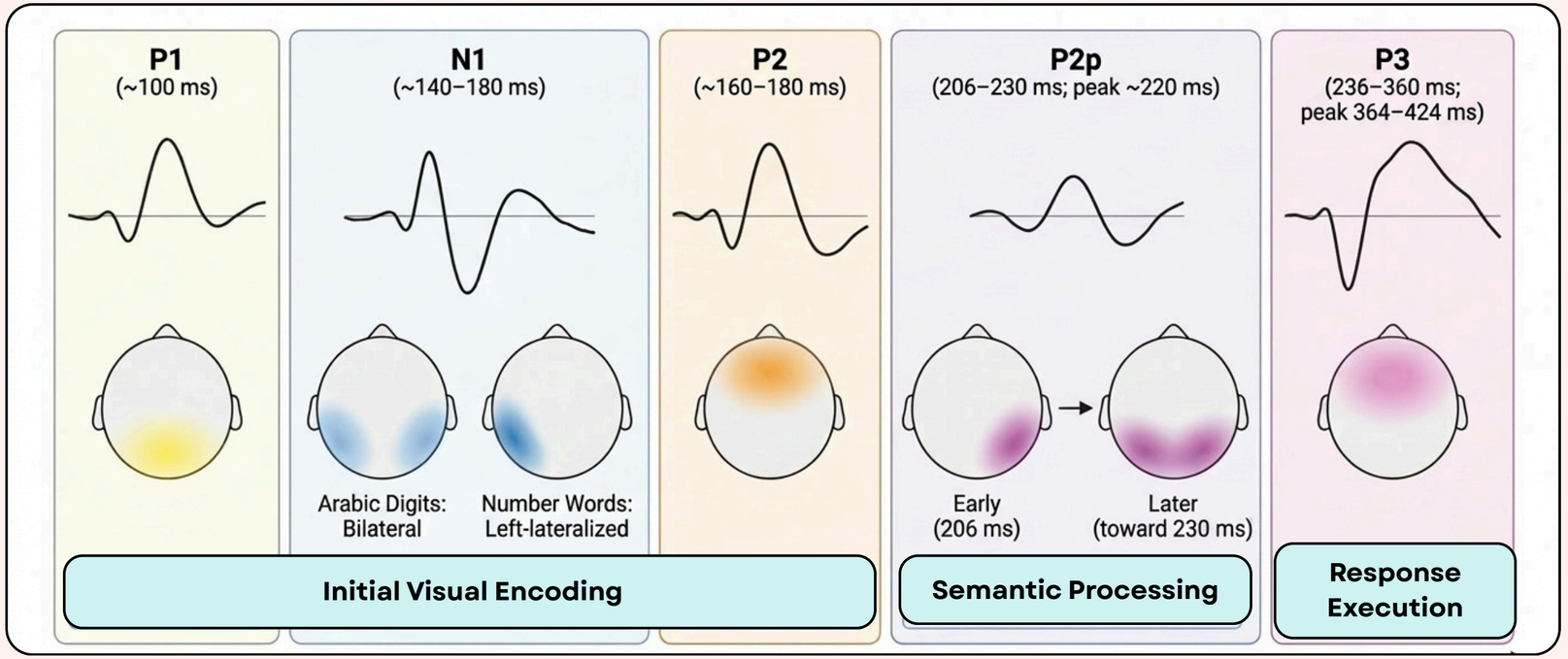
Table 3. Multiple regression analysis with the three digit tasks and letter comparison as predictors and digit comparison as dependent variable (Experiment 1).

Independent variables	Standardized β	t	p
Digit identification	0.291	2.487	0.016
Digit audiovisual matching	0.091	0.768	0.446
Digit order judgment	0.359	3.006	0.004
Letter comparison	0.163	1.407	0.165

Neurocognitive

Three Stage Model of Number Comparison

(Dehaene, 1996. *Journal of Cognitive Neuroscience*)

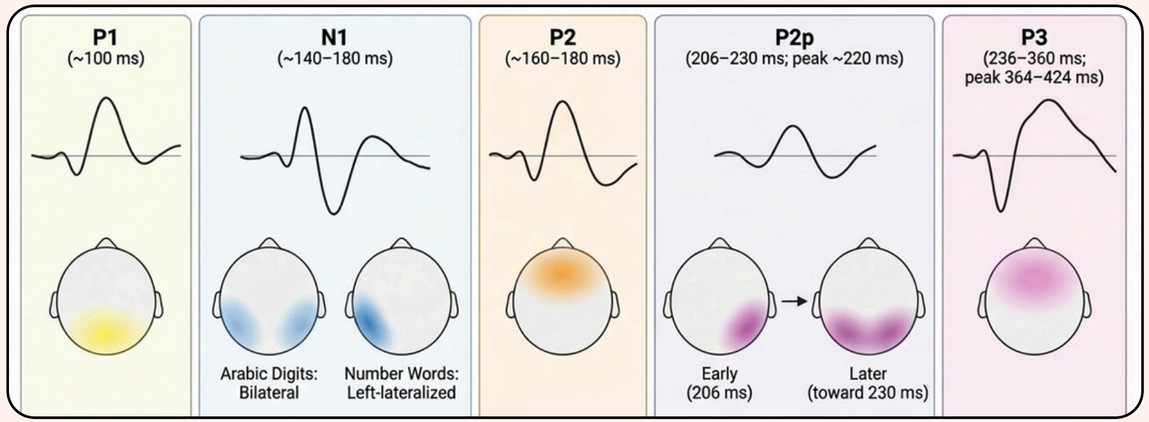


Schematic representation generated with FigureLabs

See also: Grasso et al., 2022; Libertus et al., 2007; Marlair et al., 2024; Temple & Posner, 1998; Van Hoogmoed & Kroesbergen, 2018.

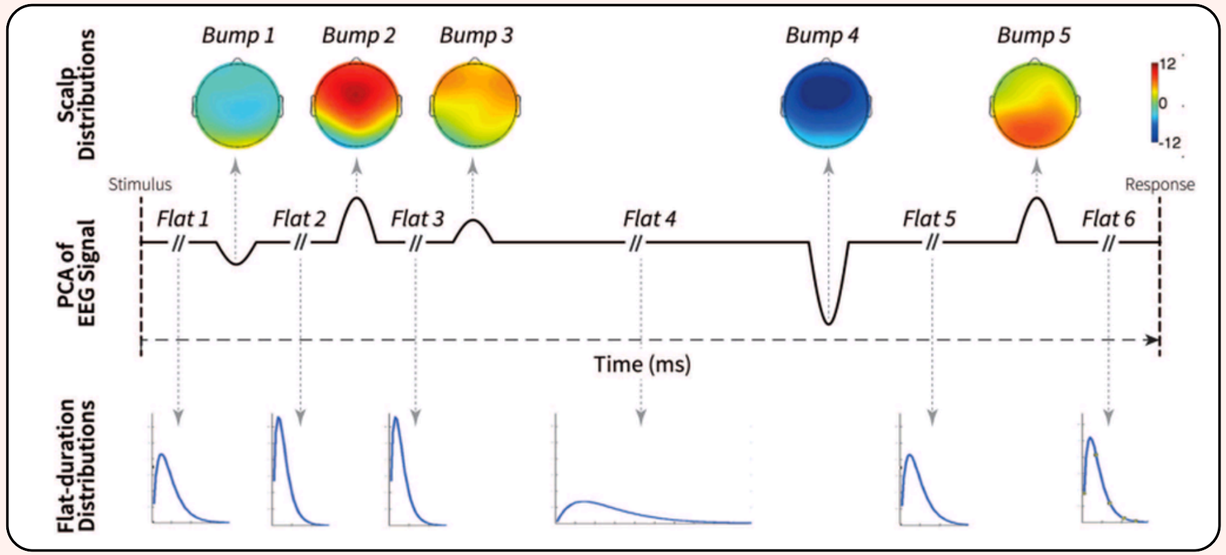
From Additive Factor Model to Data-driven Process Model

Classical ERP Approach



Most previous studies, typically relied on the additive factors method, where cognitive stages are inferred indirectly and in a top-down (i.e., theory-driven) manner.

Hidden semi-Markov Model Multivariate Pattern Analysis

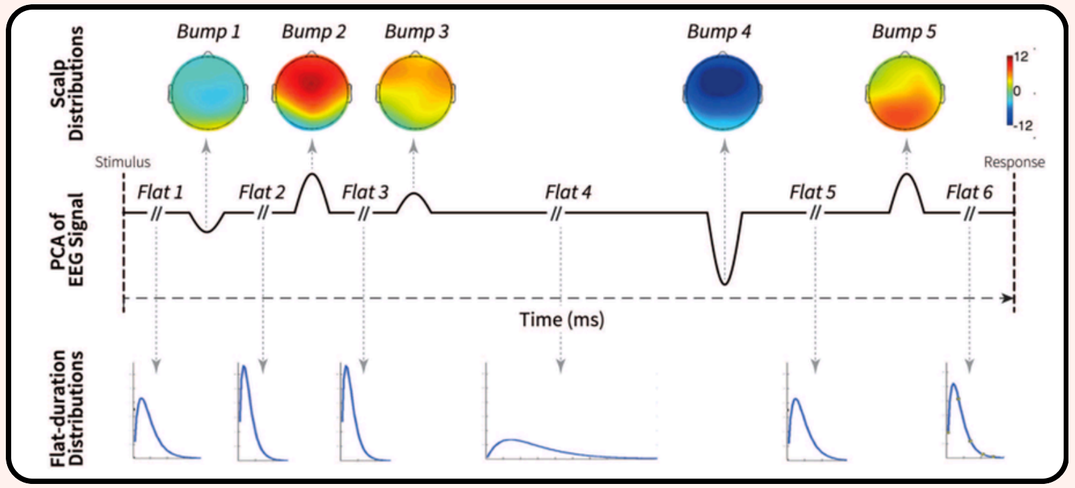


Anderson et al. (2016). *Psychological Review*

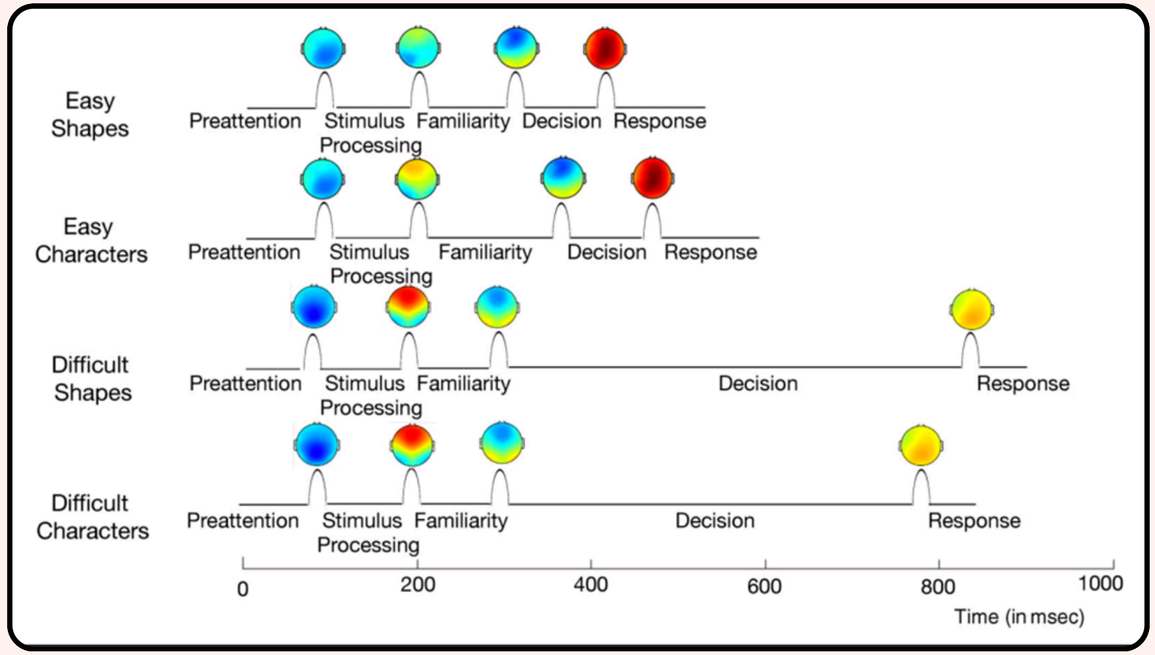
A data-driven method used to estimate the precise number and duration of (latent) cognitive processing stages in an EEG/MEG signal, potentially enabling the the formulation of a bottom-up process model.

HsMM-MVPA: Assumptions & Applications

Each stage is defined by a multivariate peak called bump, followed by oscillations centered around 0 (flats)



HsMM-MPVA is already validated in other decisional tasks: Shapes and Charaters Discrimination



Preprocessing
Standard & HsMM-specific

→

Fitting HsMM models
with 1 to n stages

→

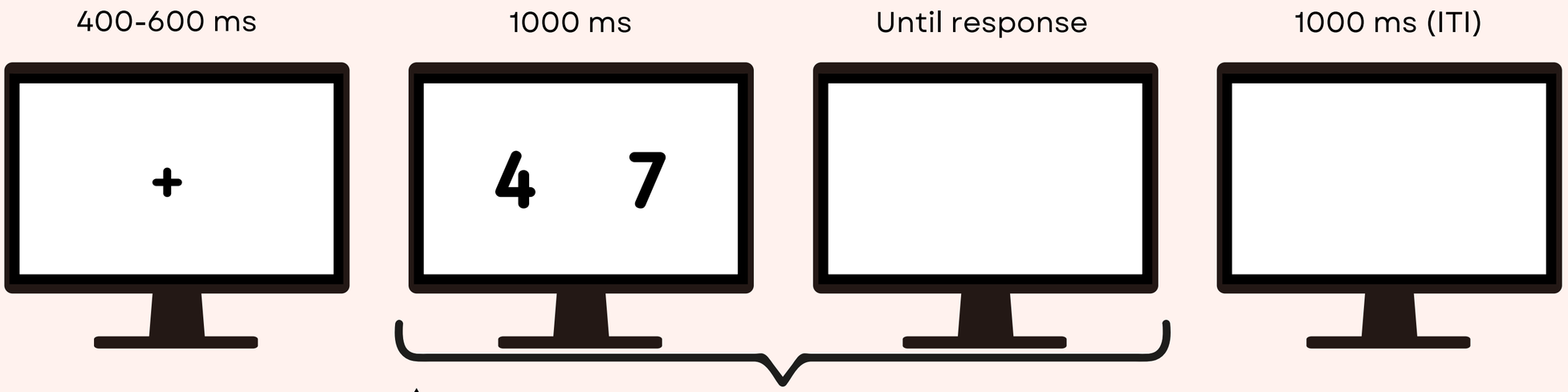
Identifying Optimal
Number of Stages

→

Final model selection

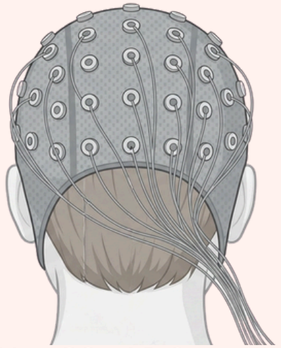
Berberyan et al., (2021). *Journal of Cognitive Neuroscience;* Berberyan et al., (2021). Brain and Cognition; Anderson et al., (2016). *Psychological Review.* Weindel et al., (2024). *Imaging Neuroscience*

Methods



384 trials per individual
192 trials of D1 (e.g., 4 vs 5)
192 trials of D3 (e.g., 4 vs 7)

60 cm



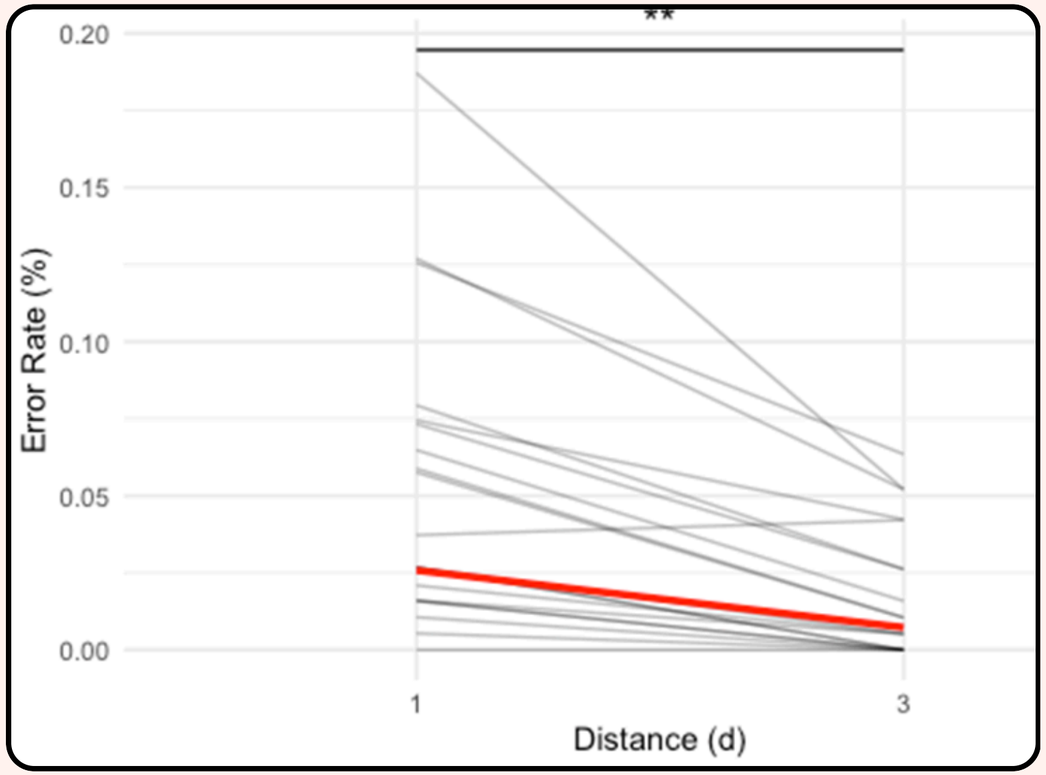
N = 20 (16 females; M age: 19.8 ; SD = 2.17)



Results (Behavioral)

Main effect of distance on accuracy

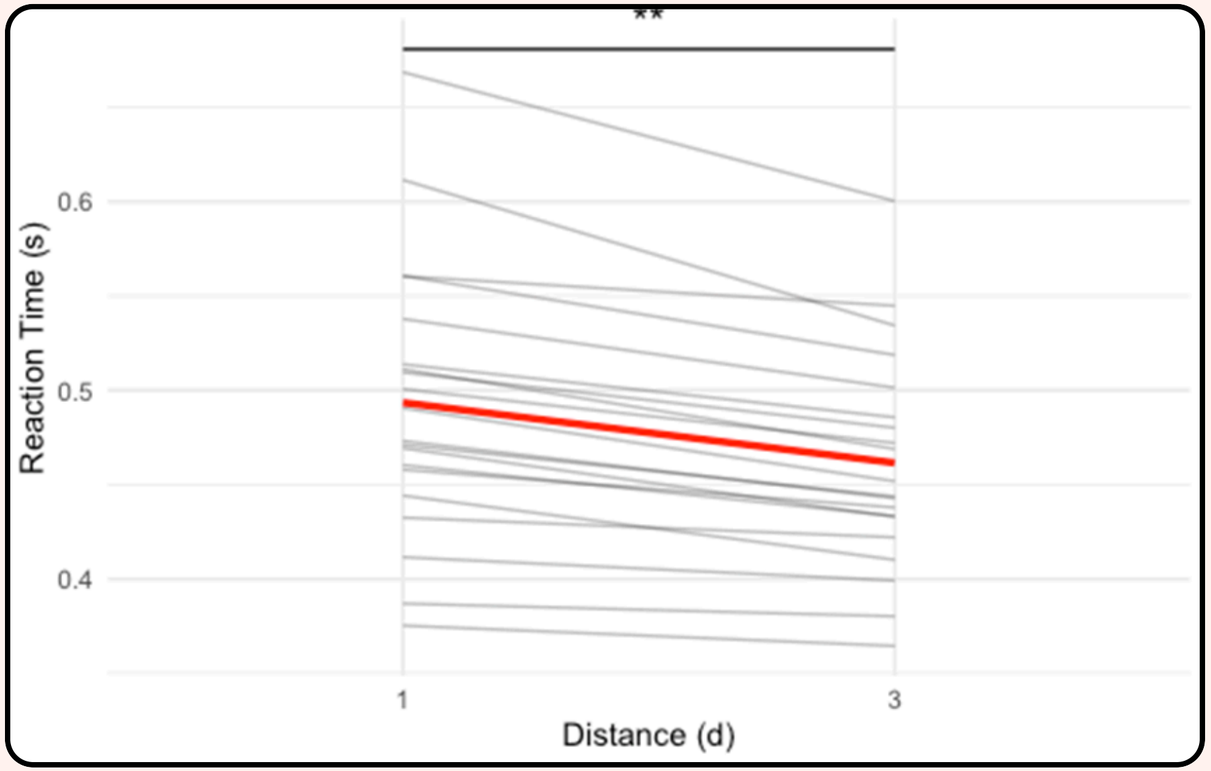
β = 1.29, z = 2.98, p = .003



glmer(Correct ~ Distance + (1 | Participant) + (1|Item))

Main effect of distance on reaction time

β = -0.03, t = -2.89, p = .008

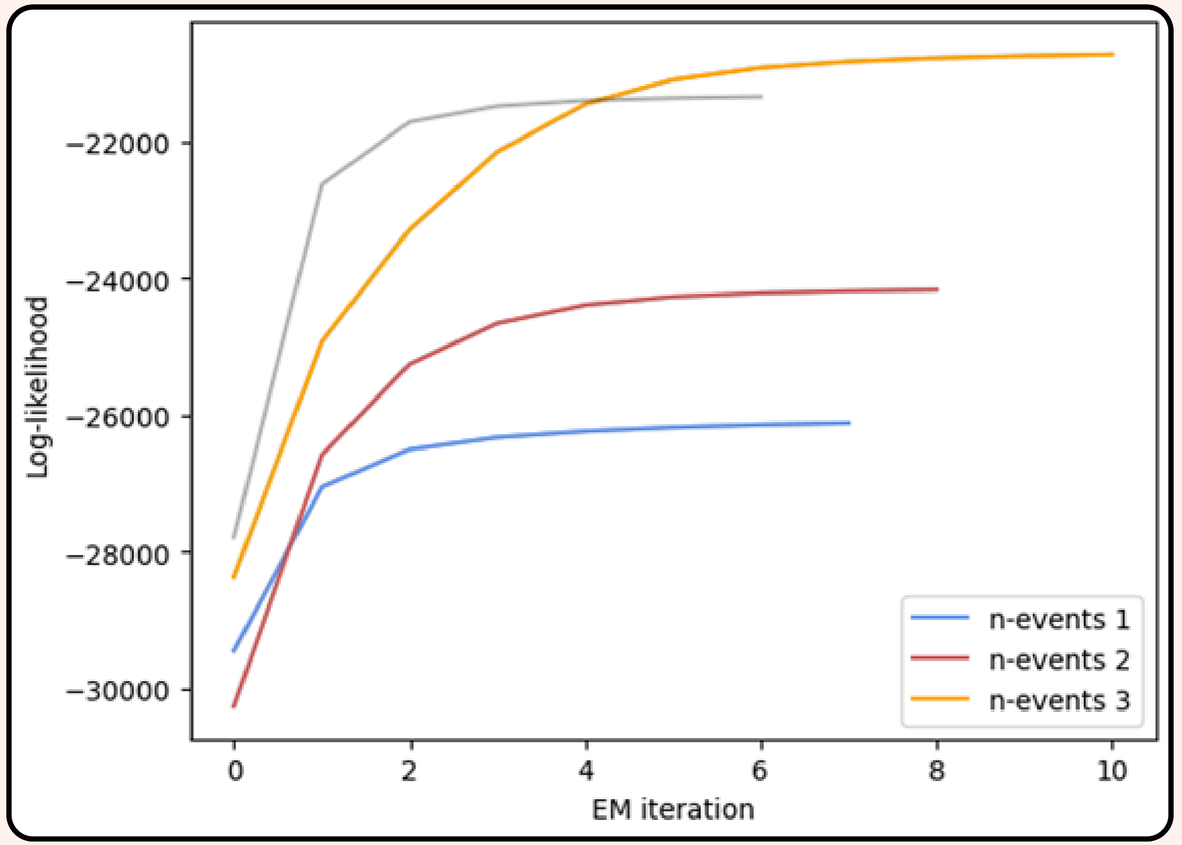


lmer(RT ~ Distance + (1 + Distance | Participant) + (1|Item))

Results (HsMM-MVPA 1/3)

Starting with a cumulative event fit to identify the number of cognitive stages in the EEG data (starting from 0 to the mean RT)

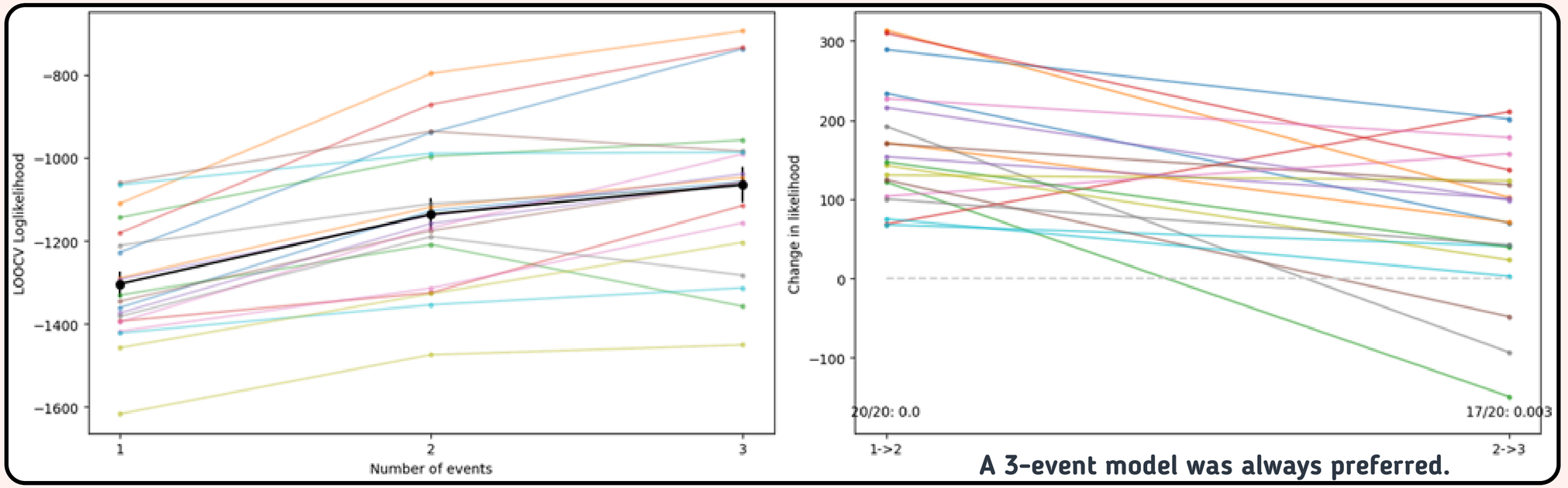
This method starts with a 1-event model and iteratively tests for convergence, adding events until the optimal number is found.



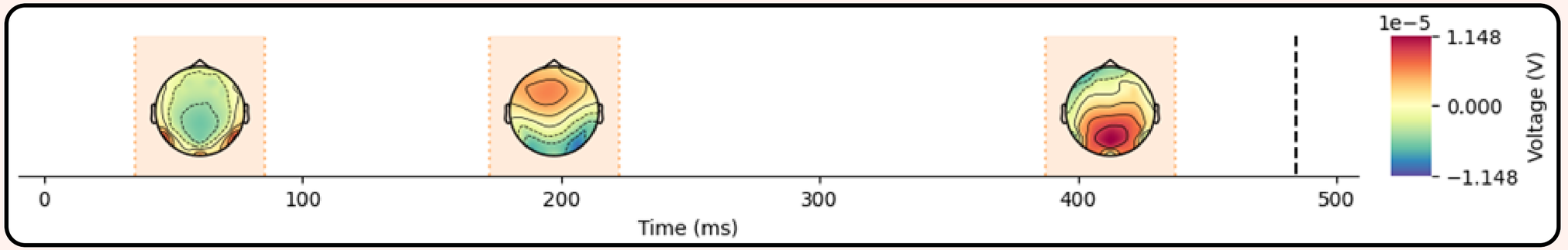
Results (HsMM-MVPA 2/3)

Compute the final model using LOOCV and backward estimation

Starting with the most complex model (3 events), we iteratively removed the least significant event (based on log-likelihood) and re-estimated the model with one fewer event. This process was repeated for each participant, leaving them out one at a time.



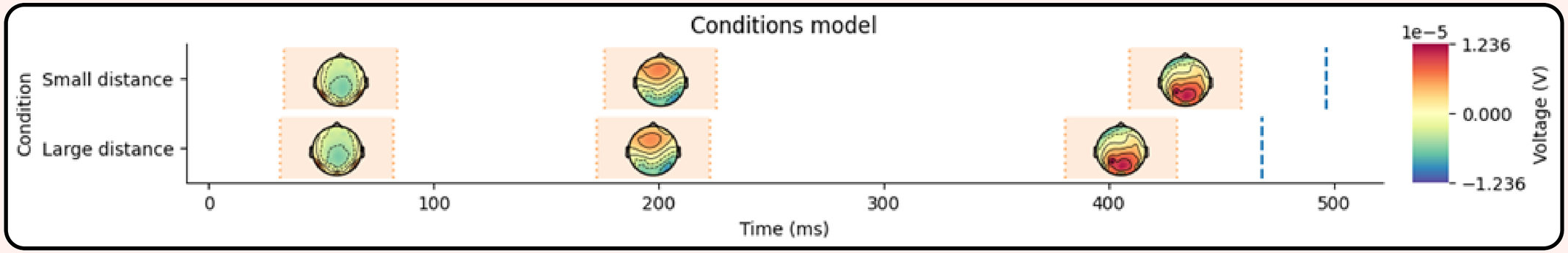
A 3-event model was always preferred.

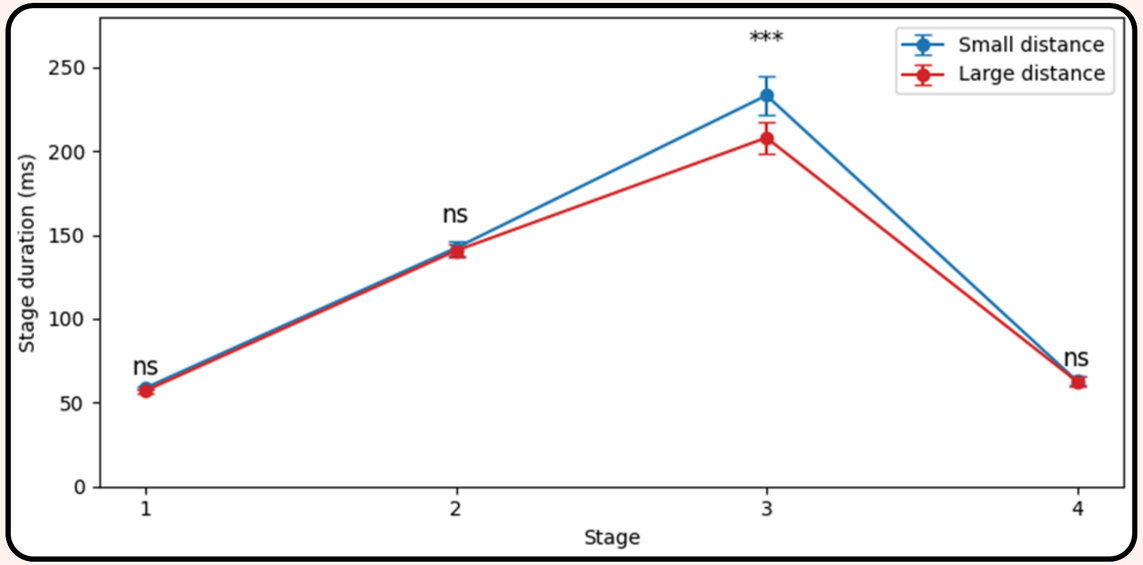


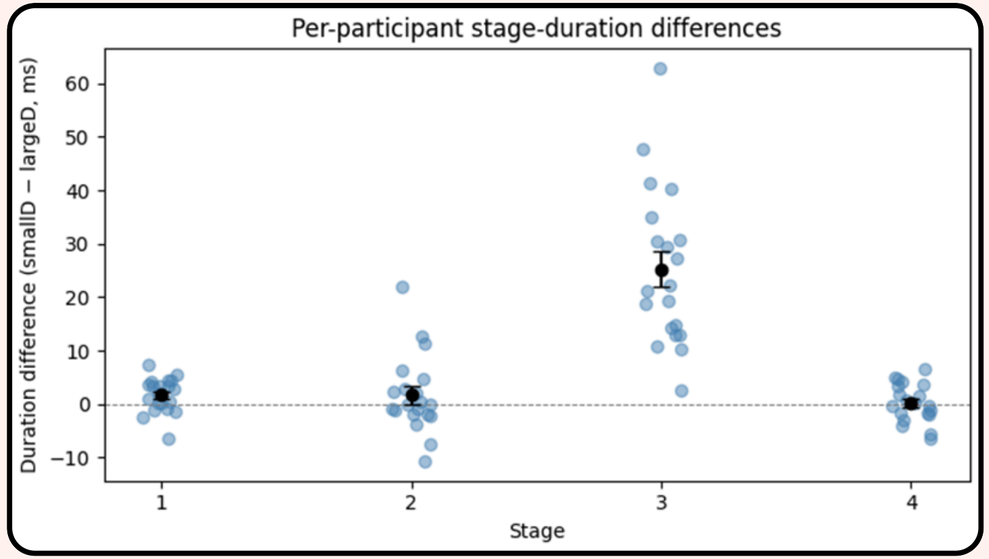
Results (HsMM-MVPA 3/3)

Fit the model by taking into account the Distance effect

Using the initial model parameters as a starting point and re-fitting based on the distance





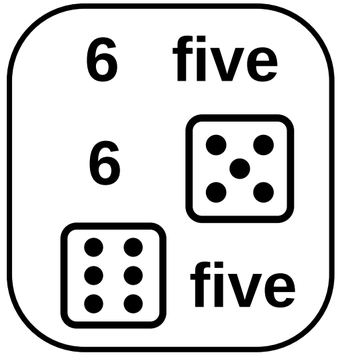


Evidence for a 3-event, 4-stage model. The RT distance effect is primarily accounted for by the third stage

Ongoing work using HsMM - Numerical Format Integration across Contexts and Ages

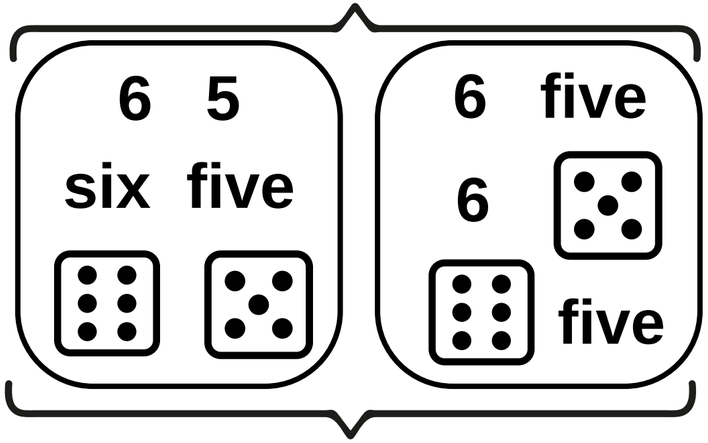
Map the Cognitive Stages





Contextual Dynamics

Explicit vs Implicit



Simultaneous vs Sequenntial



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Connecting the Numbers





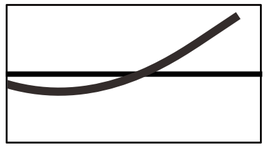
Ongoing work using HsMM - Numerical Format Integration

Drift Diffusion Model (DDM)/ Bayesian Decsion Models

Decisional

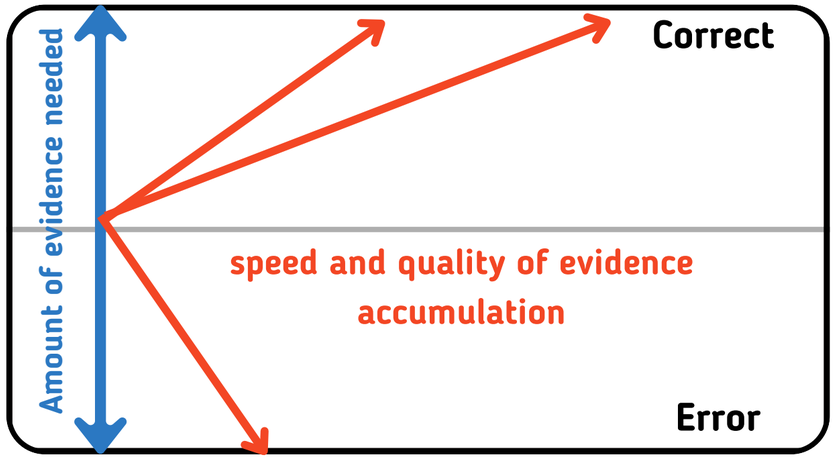
Non-decisional

- encoding
- transformation

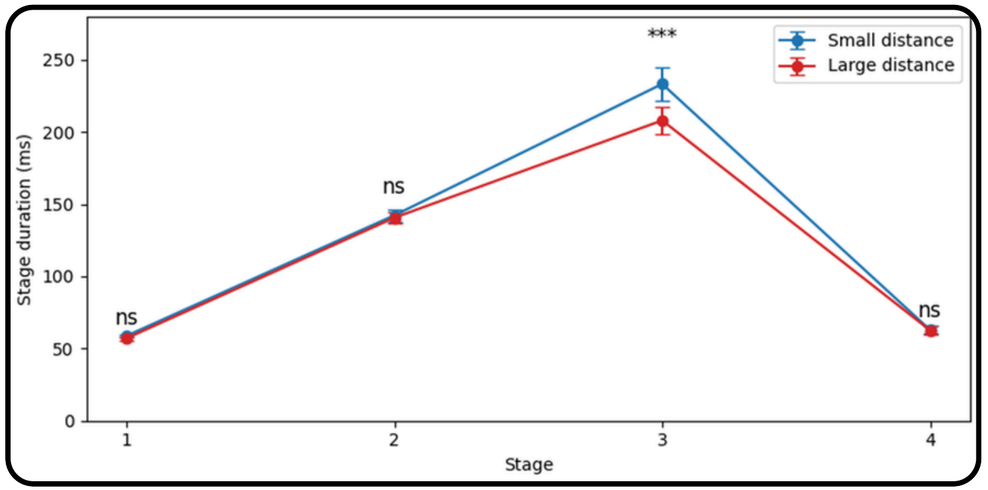


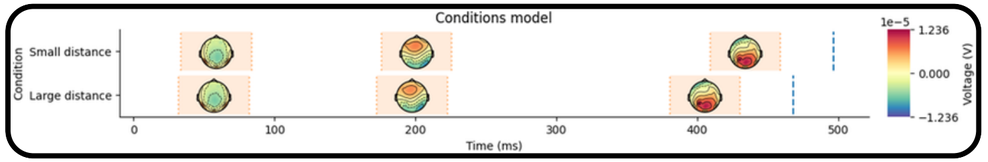
Non-decisional

- response execution



HsMM-MVPA

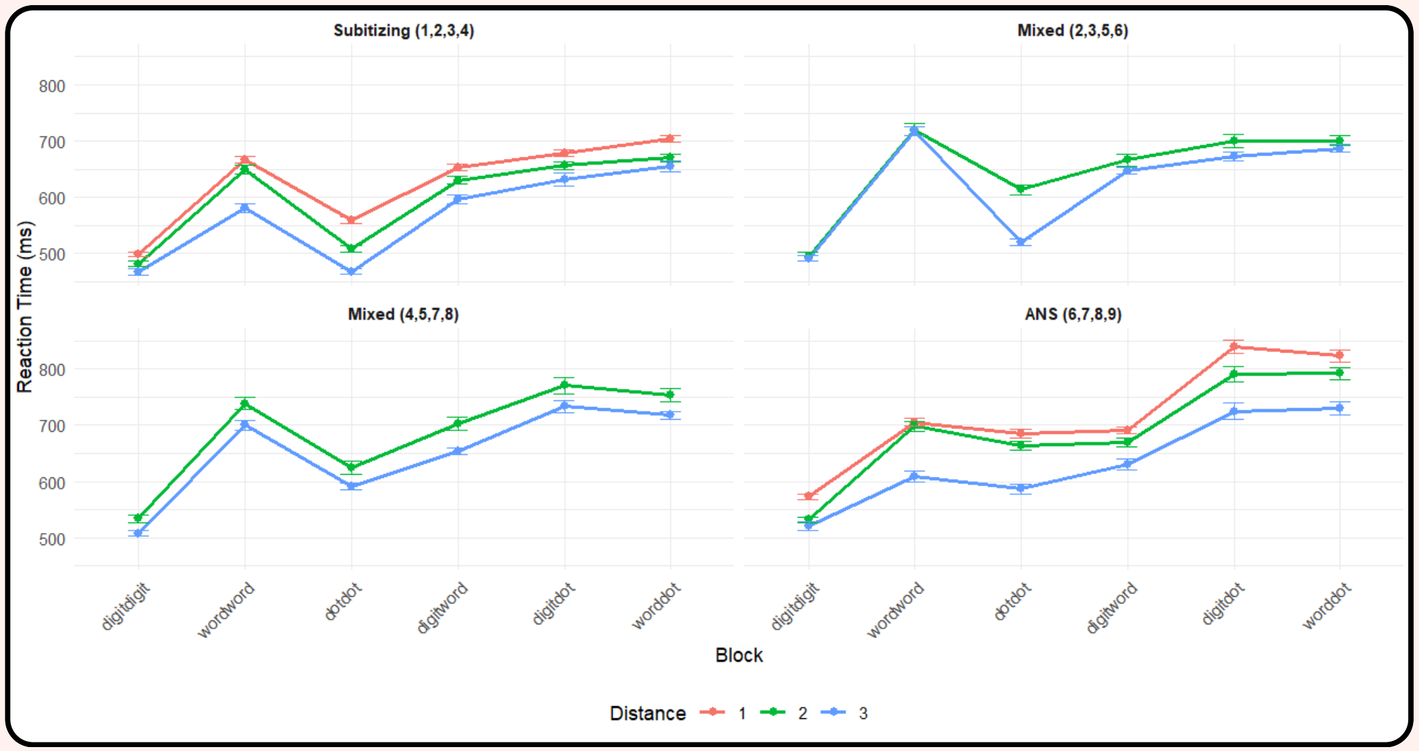


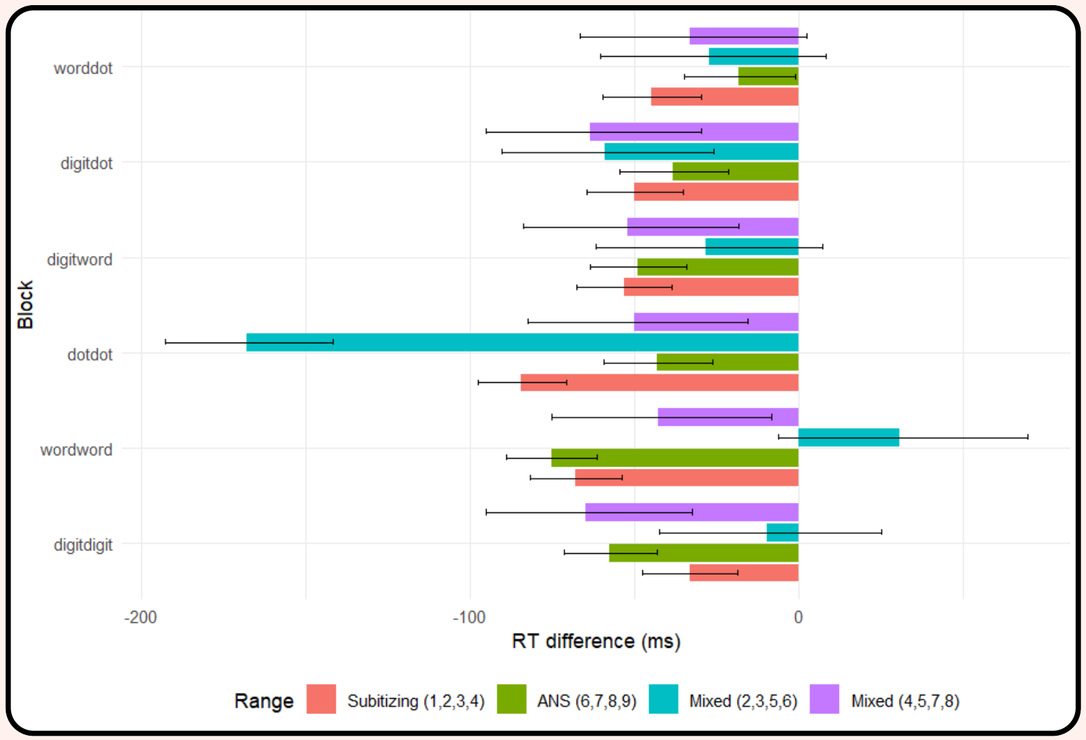


Rinaldini, Marinova, & Reynvoet (2026).In preparation

Preliminary Results: Connecting The Numbers - XP-01

Numerical Format Integration within OTS and ANS





Guyoncour et al., (2026).In preparation

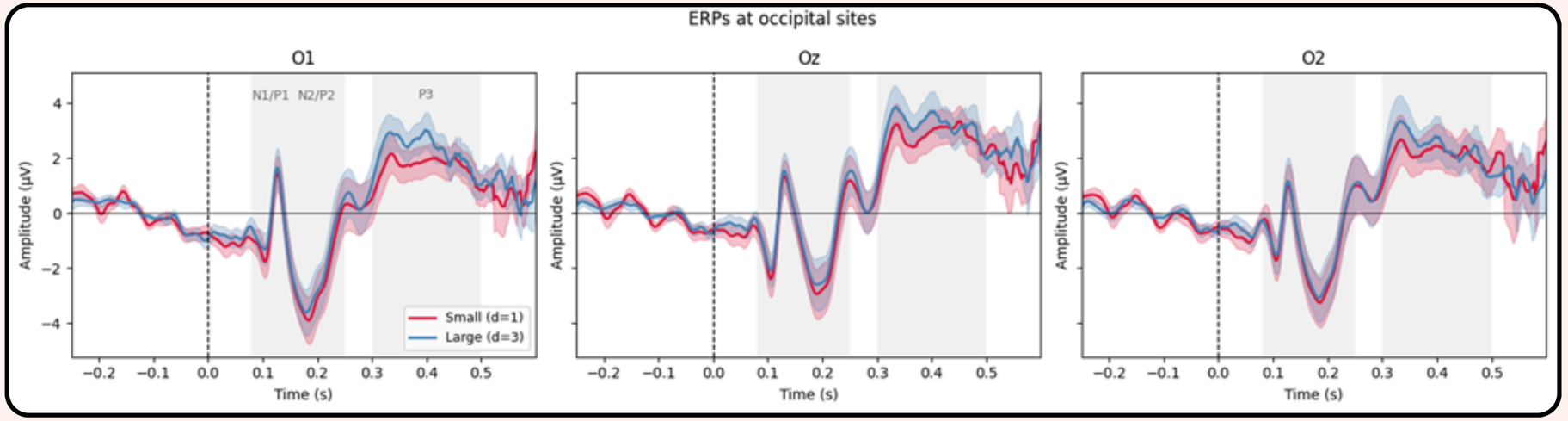
lmer(RT ~ Distance * Block * Range + (1 | Participant))

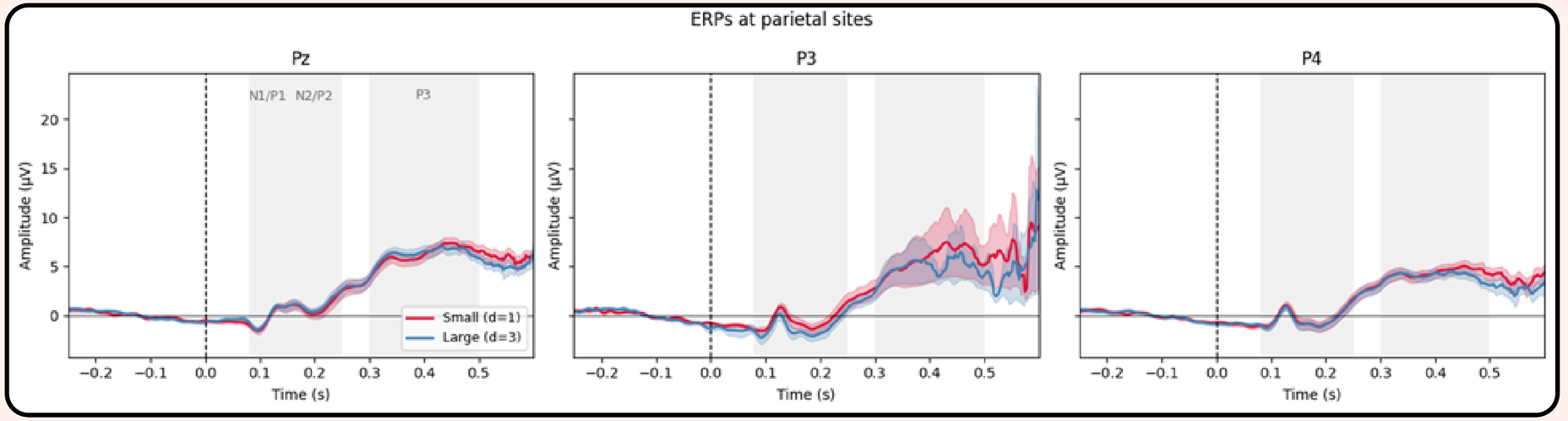
N = 35; app. 42 000 trials

See also: van den Berg, et al. (2020). *Journal of Cognitive* Neuroscience; Hutchison et al. (2019). *Developmental Science*

Rinaldini et al., 2026: ERP cross-reference

No significant distance effect at any of the ERP components



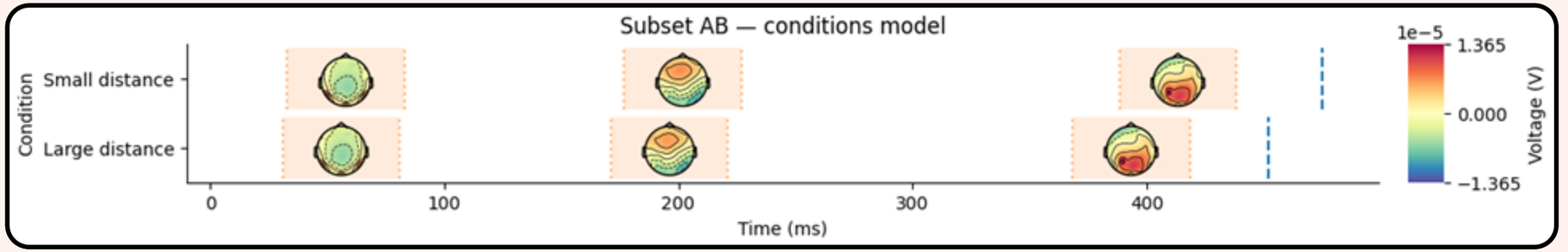


ERPs don't take into account within trial variance,

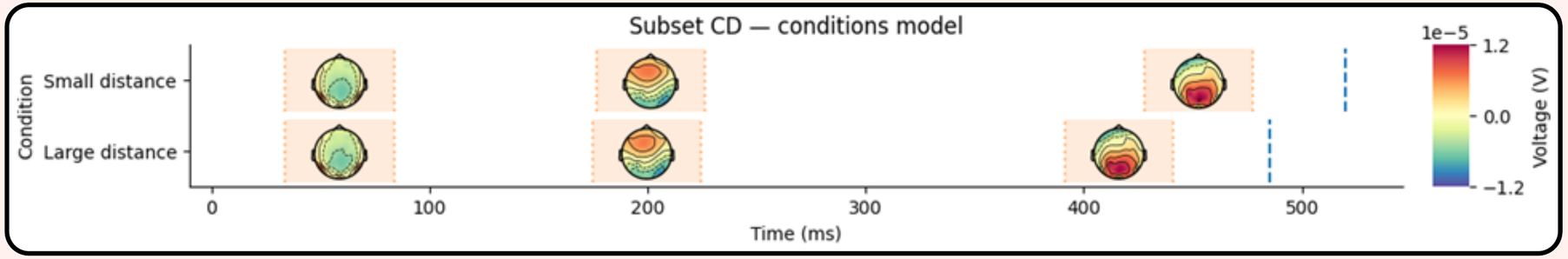
whereas HsMM estimates peaks per trial and gives a distribution over those estimated peaks

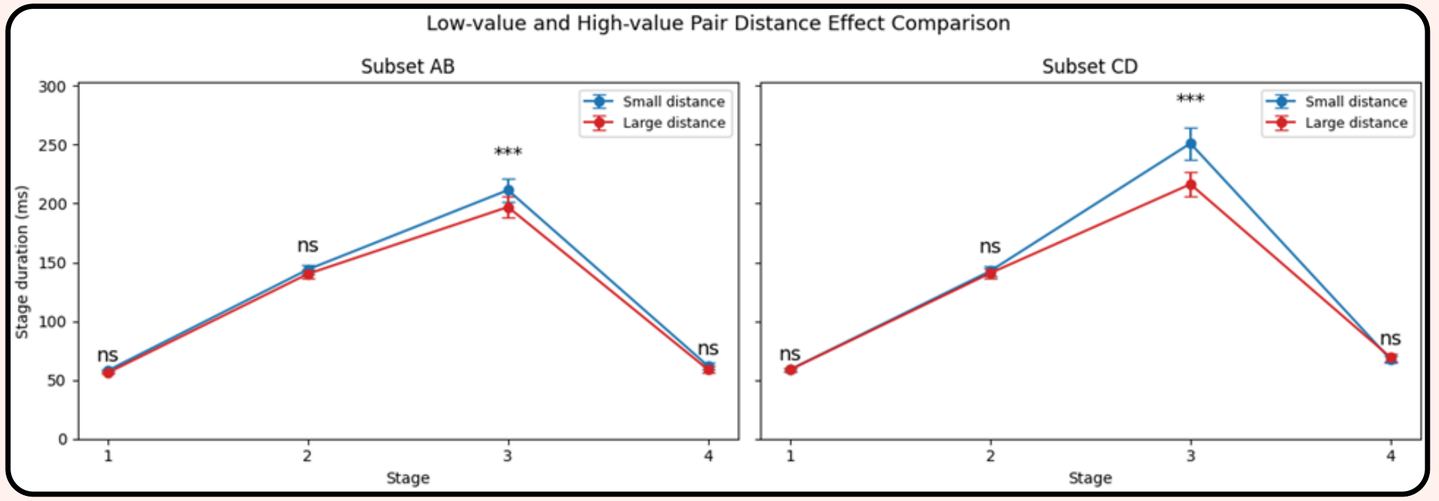
Finding the Distance Effect

Low Value Pairs:
D1: 1-2, 3-4, 4-5
D3: 1-4, 2-5, 3-6



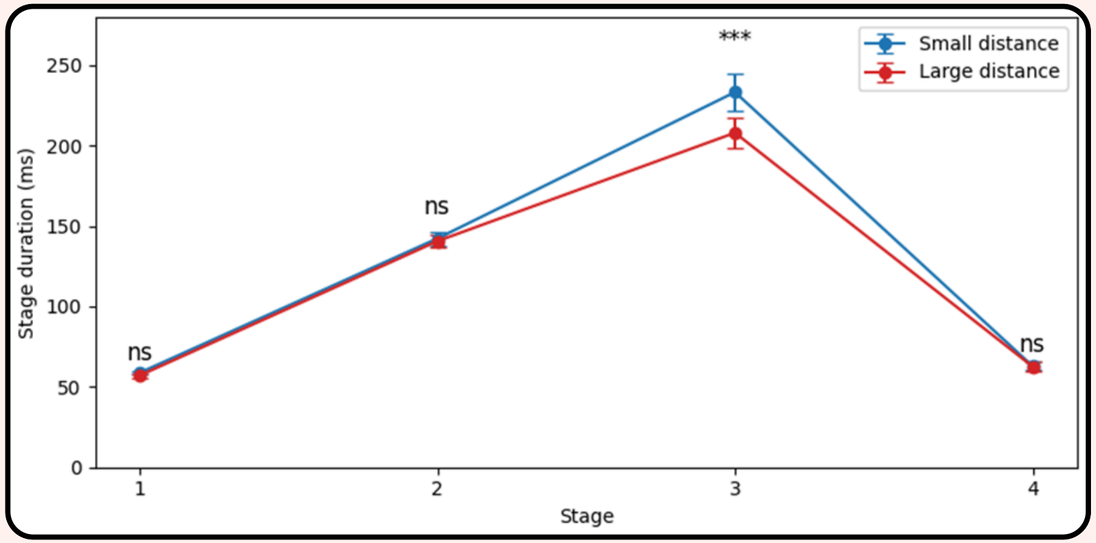
High Value Pairs:
D1: 5-6, 6-7, 8-9
D3: 4-7, 5-8, 6-9





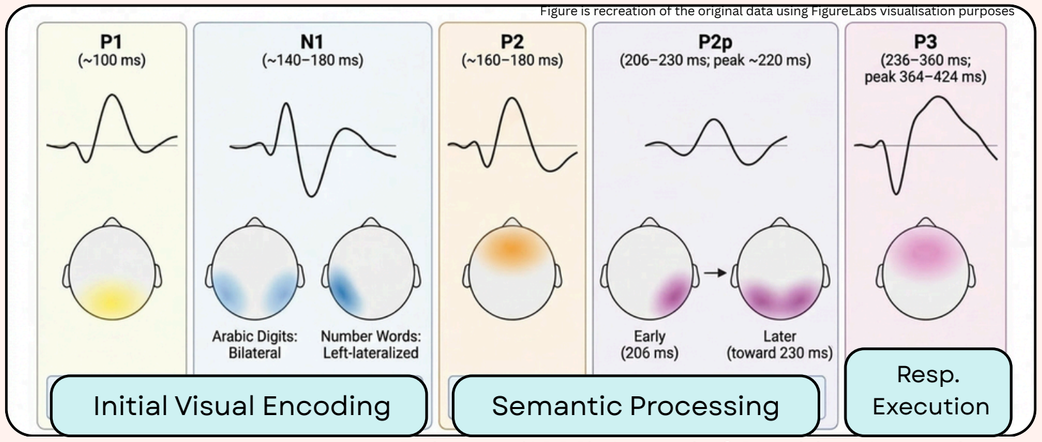
Distance effect within lower and higher ranges has variant stage duration

Conclusions



Rinaldini et al., (2026).In preparation

Using a data-driven machine learning approach (HsMM-MVPA), we successfully identified a bottom-up, four-stage, three-event model of the digit comparison task.



Dehaene. (1996).*Journal of Cognitive Neuroscience*

Extening previous top-down models of number comparison

Provided validation of HsMM/HMV approach in numerical cognition

Facilitate the creation of benchmark models and process-based cognitive model of various numnerical decision-making tasks

"It is the long history of humankind (and animal kind, too) that those who learned to collaborate and improvise most effectively have prevailed"

-Attributed to Charles Darwin



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Joann Guyoncour



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Let's connect here!