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COMBINING ACT-R MODELS WITH EEG DATA

MATHPSYCH/ICCM 2021

28TH ACT-R WORKSHOP

LINDA HEIMISCH

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Department of Psychology and Ergonomics

Chair of Cognitive Modeling in dynamic Human-Machine Systems /

Kognitive Modellierung in dynamischen Mensch-Maschine-Systemen (kModyS)

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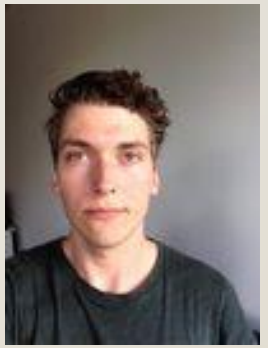

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OUTLINE

- Identifying cognitive processing stages from EEG data
- Using ACT-R models as guides for functional stage content
- Mental Rotation as exemplary task model
- Correlating processing stages and ACT-R module activity

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INSIGHTS FROM EEG DATA: PROCESSING STAGES

- Established EEG analysis methods:
  - Event-related potentials (ERPs)
  - Frequency / spectral analyses
- With advanced analysis methods, EEG data can give insight into stages of cognitive processing during task solving
- **Processing stages** = clearly and functionally separable sequences of mental problem solving during tasks

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THE HSMM-EEG METHOD

NeuroImage 108 (2015) 60–73

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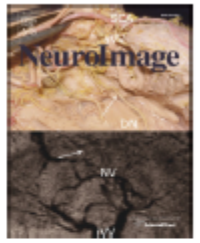

The discovery of processing stages: Analyzing EEG data with hidden semi-Markov models

Jelmer P. Borst [a,b,*], John R. Anderson [a]

[a] Carnegie Mellon University, Dept. of Psychology, Pittsburgh, USA
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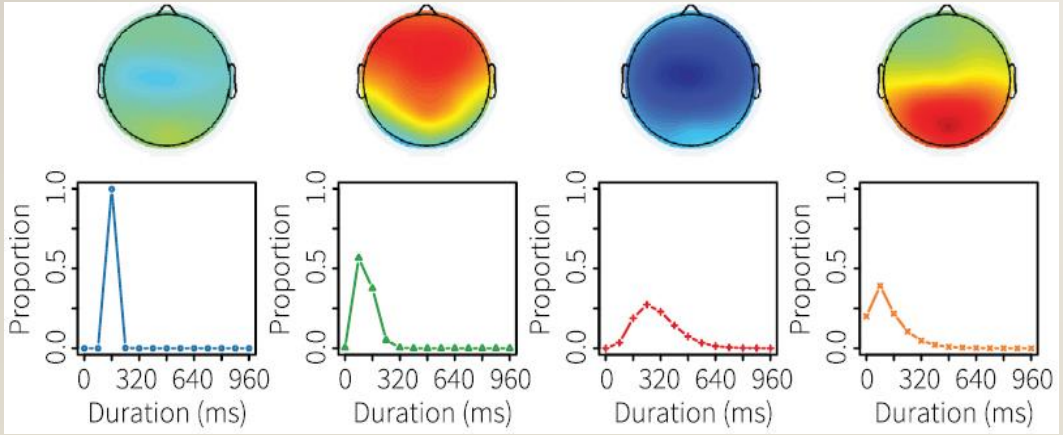
THE HSMM-EEG METHOD

- Hidden Semi-Markov Models (HsMMs) are used to analyse EEG data
- Identifies processing stages and how they vary with experimental condition
- Aim: Using trial-wise EEG data, find neural signatures that mark the existence of processing stages and their duration



Borst & Anderson (2015)

THE HSMM-EEG METHOD

- The method consists of four steps:

1. Fit HsMMs with different numbers of states to the trial-wise EEG data
2. Identify the number of states by comparing the likelihoods of the fitted HsMMs
3. Inspect the resulting HsMM: Number, order, durations, and neural signatures of the states
4. Using this information, deduce the functions of the identified processing stages

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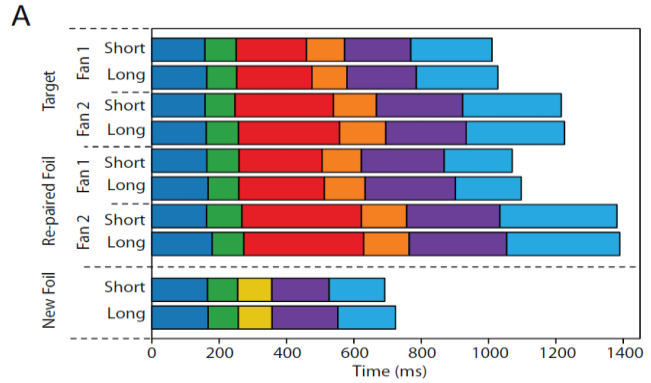
SHORTCOMING: FUNCTIONAL INTERPRETABILITY OF PROCESSING STAGES

- Functional content of processing stages can be deduced from
  - plausibility
  - Comparison of HsMM-EEG results for different experimental conditions

  → Is anything processed in a certain stage in relation to the information that differs between conditions?



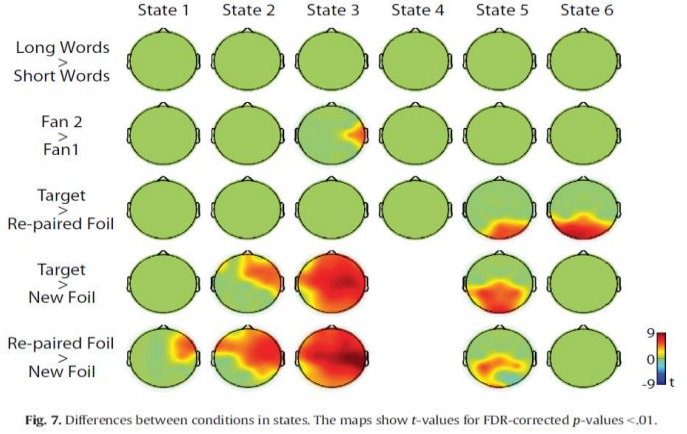


Fig. 7. Differences between conditions in states. The maps show *t*-values for FDR-corrected *p*-values <.01.

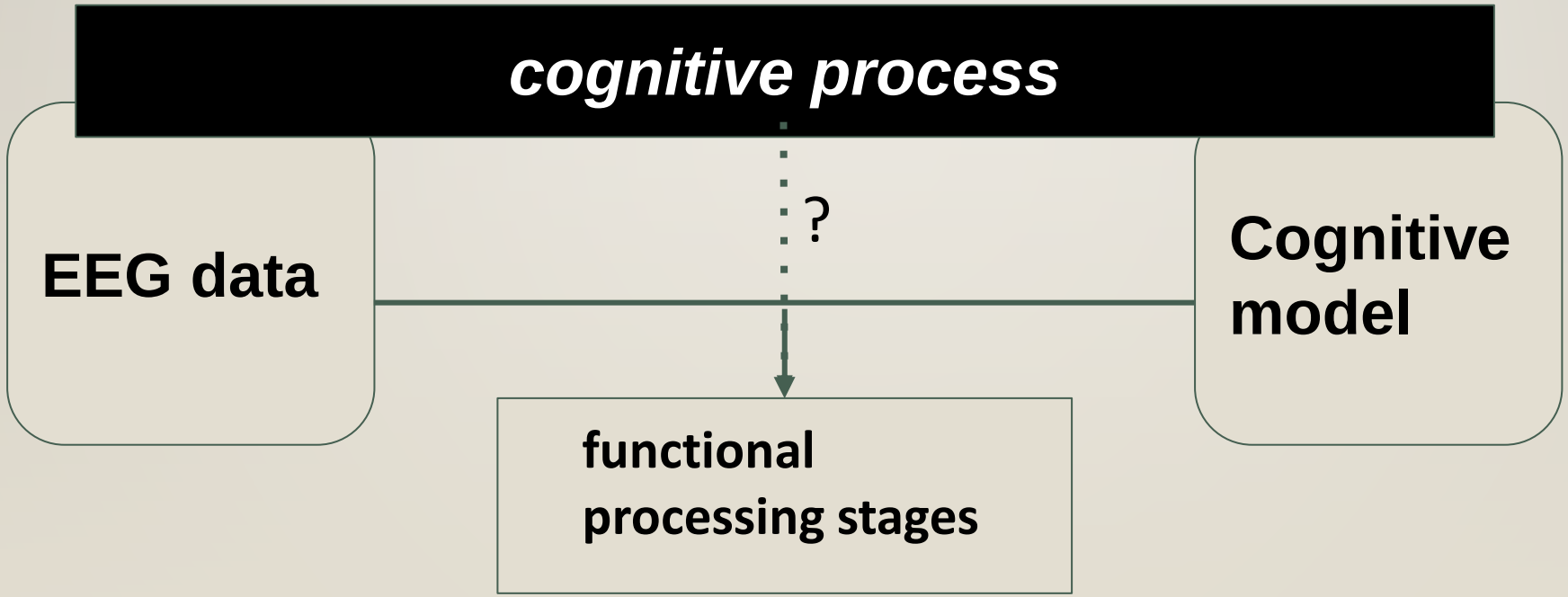
Borst & Anderson (2015)

→ Insufficient functional interpretability of processing stages limits the specificity and applicability of the HsMM-EEG method!

HOW ACT-R COMES TO HELP: USING ACT-R MODELS AS GUIDES FOR FUNCTIONAL STAGE CONTENT

Research aim: Enhance the functional interpretability of identified processing stages by combining ACT-R models with EEG data

Assumption: The ACT-R cognitive model provides us with information about the cognitive sub-processes underlying a task



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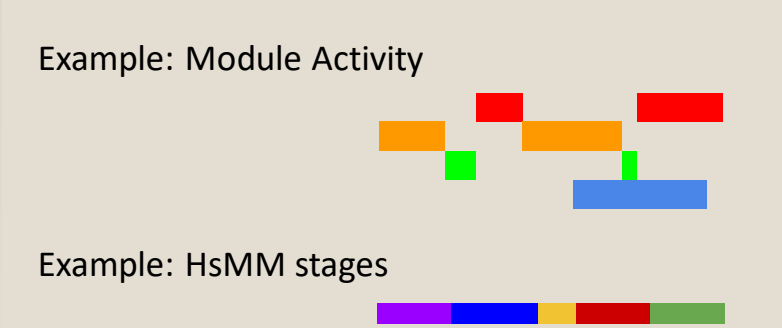
HOW ACT-R COMES TO HELP: USING ACT-R MODELS AS GUIDES FOR FUNCTIONAL STAGE CONTENT

- Proposed method:
  - cognitive model suggests certain cognitive process steps at specific times
  - aggregate these process steps functionally into rough general processes
  - generate HsMMs for existing or new EEG data
  - identify processing stages for specific conditions
  - compare modeled processes to HsMM processing stages

→ This allows us to interpret EEG processing stages functionally and contextually for specific tasks



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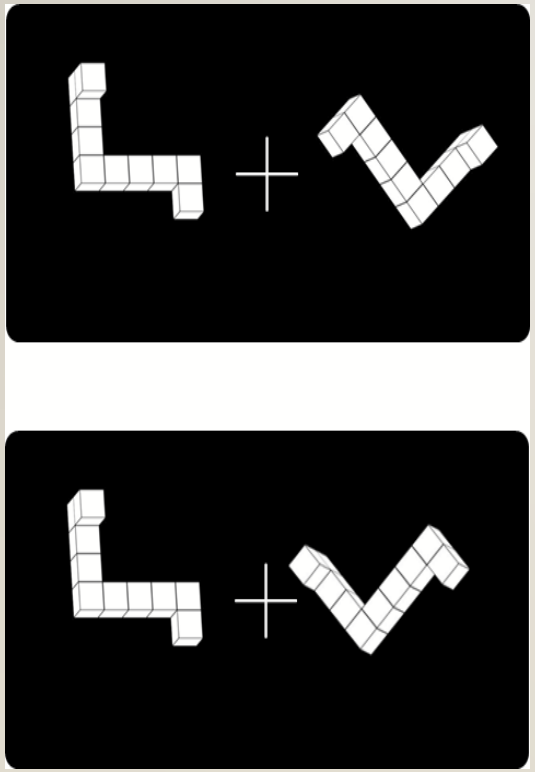
MENTAL ROTATION AS EXEMPLARY TASK

- We applied the method to a Mental Rotation Task
- Study by Raddatz (2014):



Two objects appear on the screen: first a **reference object**, then 1 second later a **target object,** either identical to or a mirrored reference object. Participants need to decide: is the new object the **same** or **mirrored**?

40 participants worked on 768 trials over 6 experiment blocks while behavioral and EEG data was collected

Typical result: the higher the rotational disparity is, the longer participants need to give their answer

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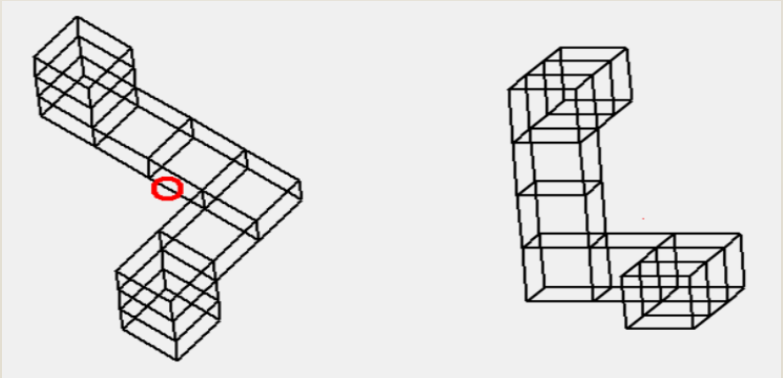
THE MENTAL ROTATION PROCESS MODEL

- Uses a custom additional module for ACT-R, the **spatial module,** designed for this and similar tasks
- Two strategies:
  - Holistic/"wholesale" comparison
  - „Piecemeal" comparison

  →Chosen by familiarity of the presented reference stimulus
- Model reacts to experiment with a cascade of processes, each of which activates certain modules depending on its function



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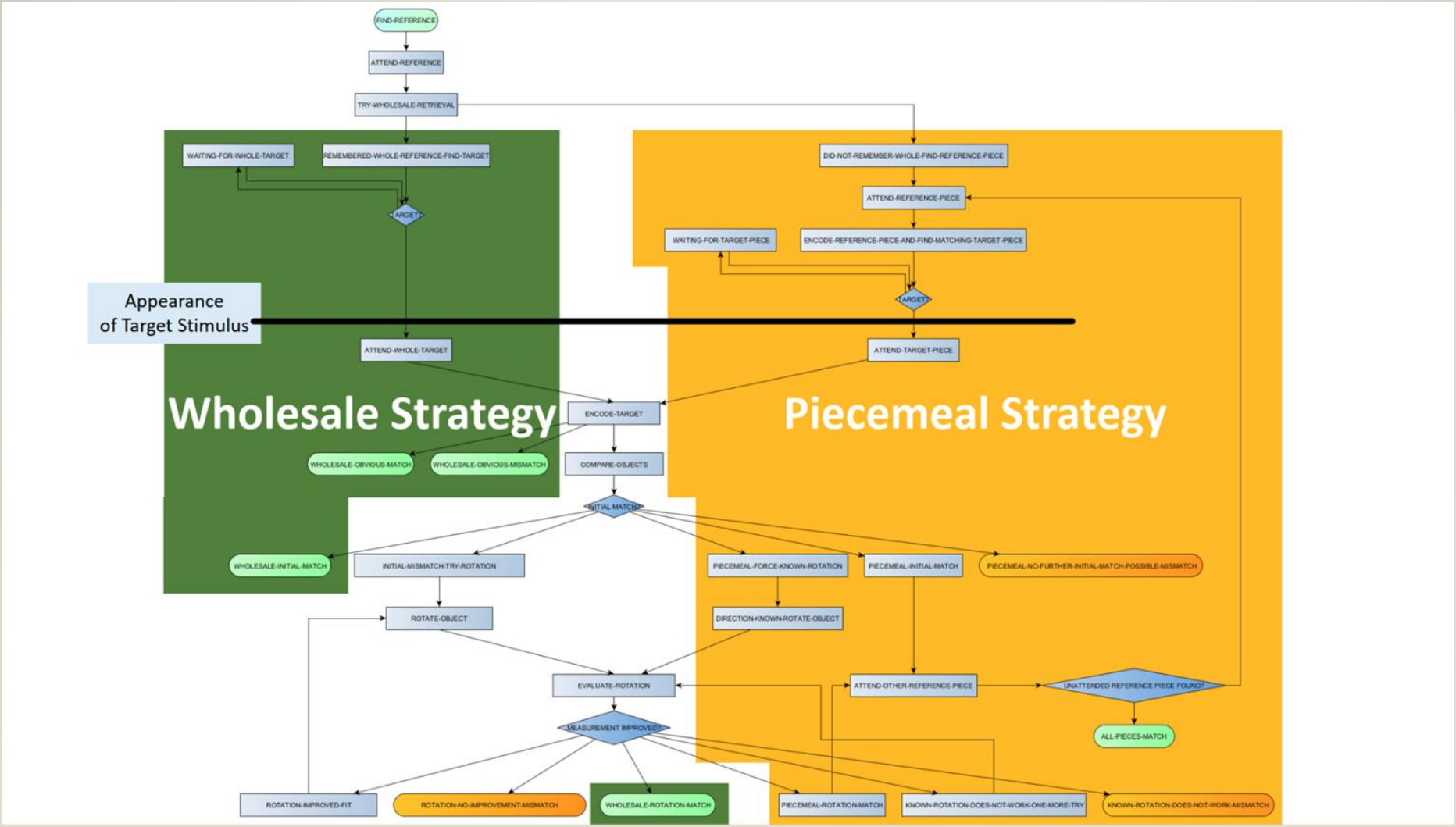
THE MENTAL ROTATION PROCESS MODEL



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CORRELATING PROCESSING STAGES AND ACT-R MODULE ACTIVITY

- General approach:
  - the model simulates activity for each participant and their specific order of trials, to accomodate for possible learning, order, or other effects
  - the resulting activity for every participant is then collected and combined into a single dataset, parsable by condition

- Great potential use in combination with EEG data: offers *functional, contextual* explanations for otherwise abstract results

- Caveats:
  - model needs to be a good fit
  - assumed processes must be *reasonable / cognitively plausible*

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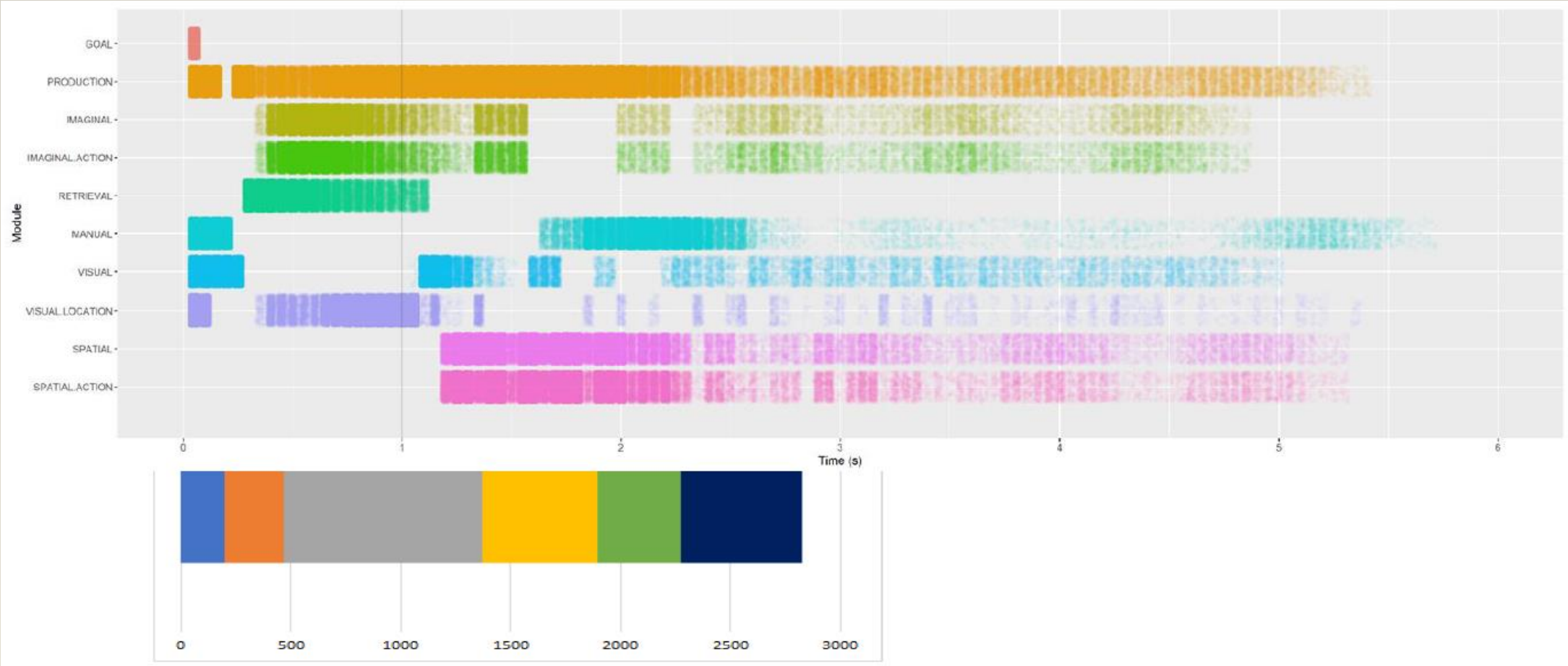
CORRELATING PROCESSING STAGES AND ACT-R MODULE ACTIVITY

50°, 100°, 150° rotational disparity (aggregated)



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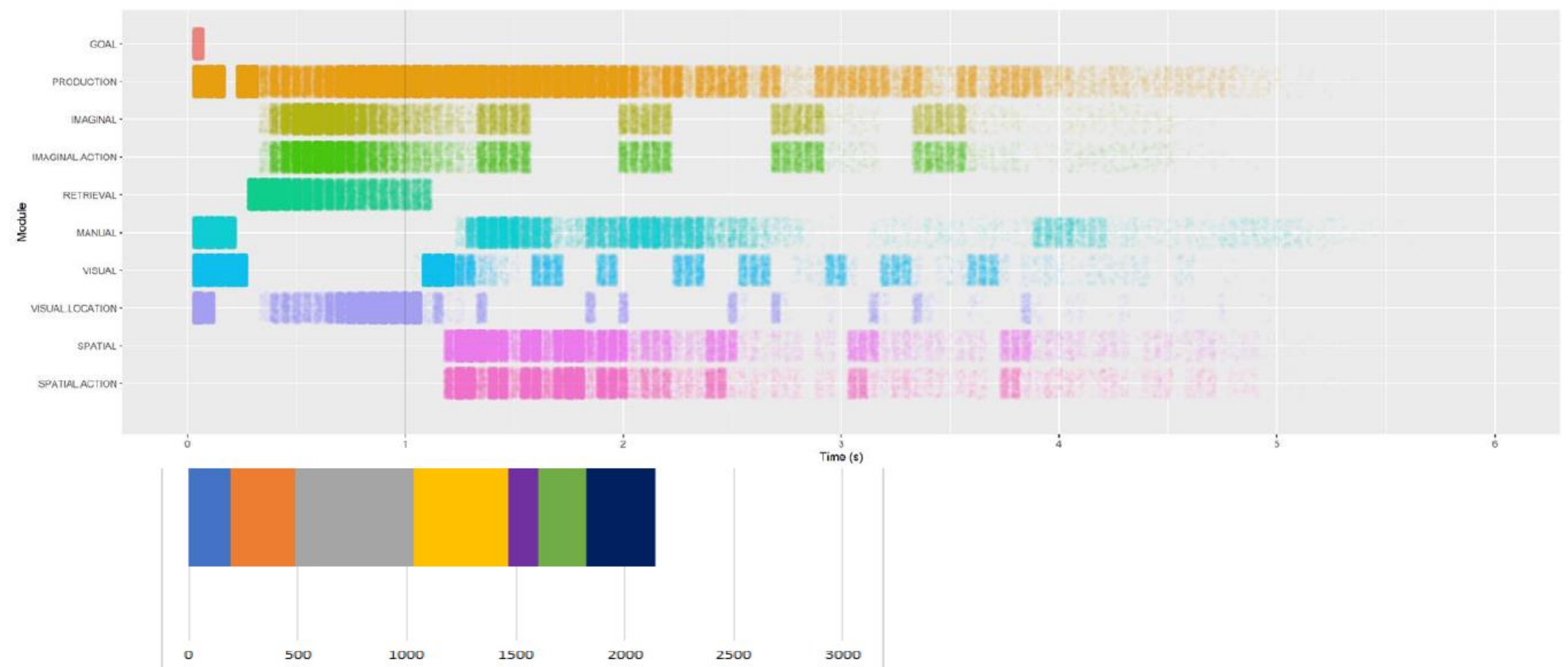
CORRELATING PROCESSING STAGES AND ACT-R MODULE ACTIVITY

0° rotational disparity



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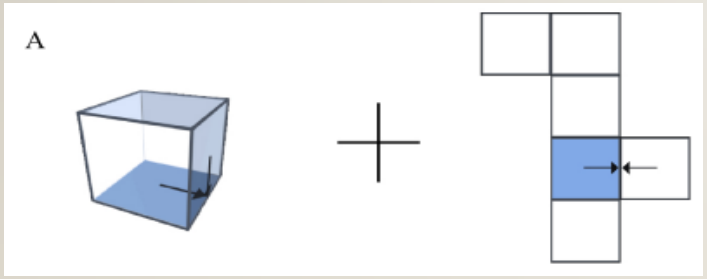
CORRELATING PROCESSING STAGES AND ACT-R MODULE ACTIVITY

- Interpretations:
  - Module activity and HsMM stages correspond at multiple points in time:
    - (early) visual encoding stages
    - retrieval/mental image building stage
    - visual-spatial transformation stage
    - motor stage (answer)
  - Module activity implies existence of differences not visible in HsMM
    - strategies & shortcuts
    - learning over experimental blocks

OUTLOOK: WHERE TO GO NEXT?

- Quantitative comparison of processing stages identified by HsMMs and module activity patterns
- Combining an ACT-R Model of Mental Folding with EEG data using the same approach (Student project Maximilian Plitt)



Preuss, Hilton, Gramann, & Russwinkel (2020)

TAKE-HOME MESSAGES

- The application of HsMM-EEG method gives unique insights into EEG data
- The combination with ACT-R models, especially their module activity predictions, allows for functional interpretations of the processing stages as identified by the HsMM-EEG method
- Caveat: No information about e.g. strategy use in EEG data

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THANK YOU FOR YOUR ATTENTION!

Borst, J.P. & Anderson, J.R. (2015). The Discovery of Processing Stages: Analyzing EEG data with Hidden Semi-Markov Models. *NeuroImage 108*, 60-73.

Preuss, K., Hilton, C., Gramann, K., & Russwinkel, N. (2020). Cognitive Processing Stages During Mental Folding Are Reflected in Eye Movements. In *Symposium on Eye Tracking Research and Applications (ETRA'20 Adjunct)*, June 2–5, 2020, Stuttgart, Germany. ACM, New York, NY, USA

Raddatz, L. (2014). EEG Correlates of Sex Differences during Mental Rotation (Unpublished bachelor's thesis). Leuphana Universität Lüneburg, Lüneburg, Germany

original EEG data acquisition by Leonie Raddatz, formerly Chair of Biological Psychology and Neuroergonomics, TU Berlin

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