Compositional representation of tasks in human multiple-demand cortex

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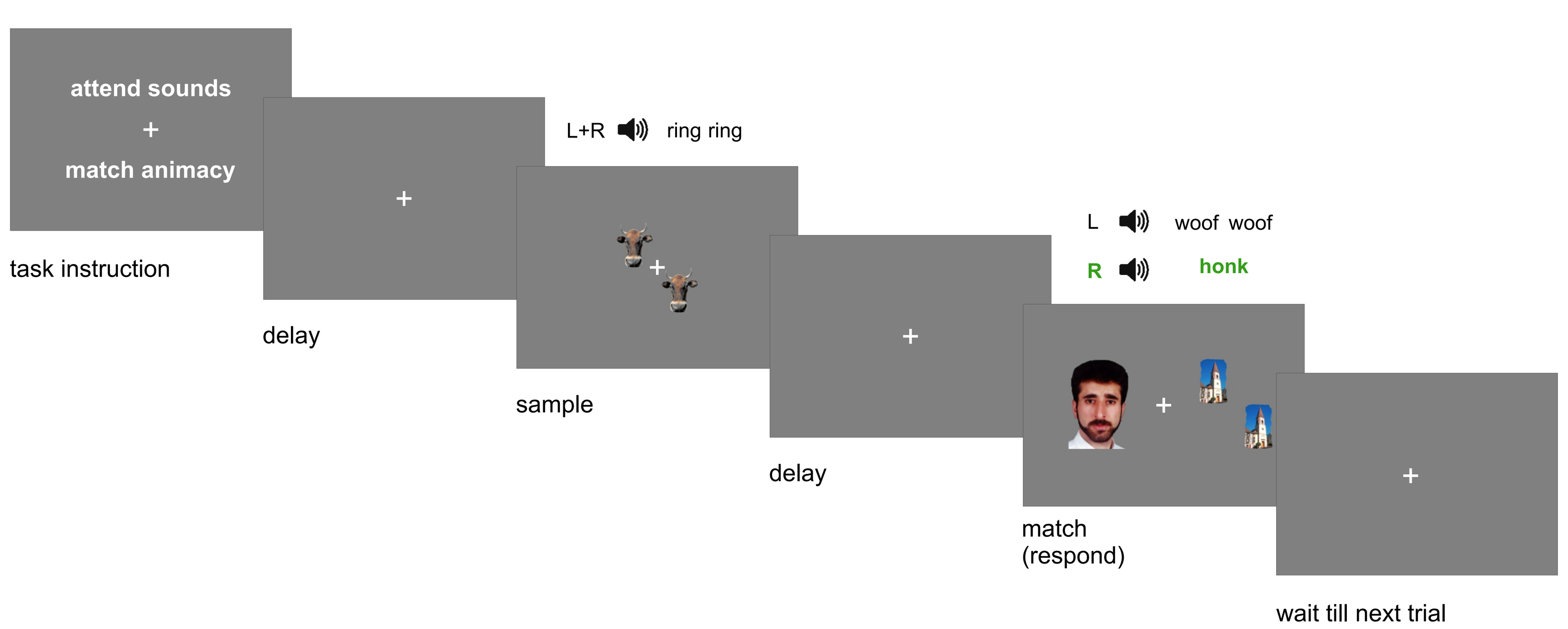
Introduction

The execution of complex cognitive tasks activates an extensive network of frontal and parietal regions, known as the multiple-demand (MD) system, whose distributed activity patterns carry information about the task[1,2,5].
However, the functional organization of task representation remains unclear. Do certain tasks elicit more similar activity patterns than others? If so, what drives the functional organization?
Computational work suggests that tasks may be represented in a compositional fashion in prefrontal cortex, where the representation of a task can be expressed as the algebraic sum of vectors representing the underlying sensory, cognitive and motor processes[3].
Empirical evidence for compositional coding is limited[2,7]. It remains to be tested if this principle generalizes to tasks that require context-dependent decisions[4].

Methods

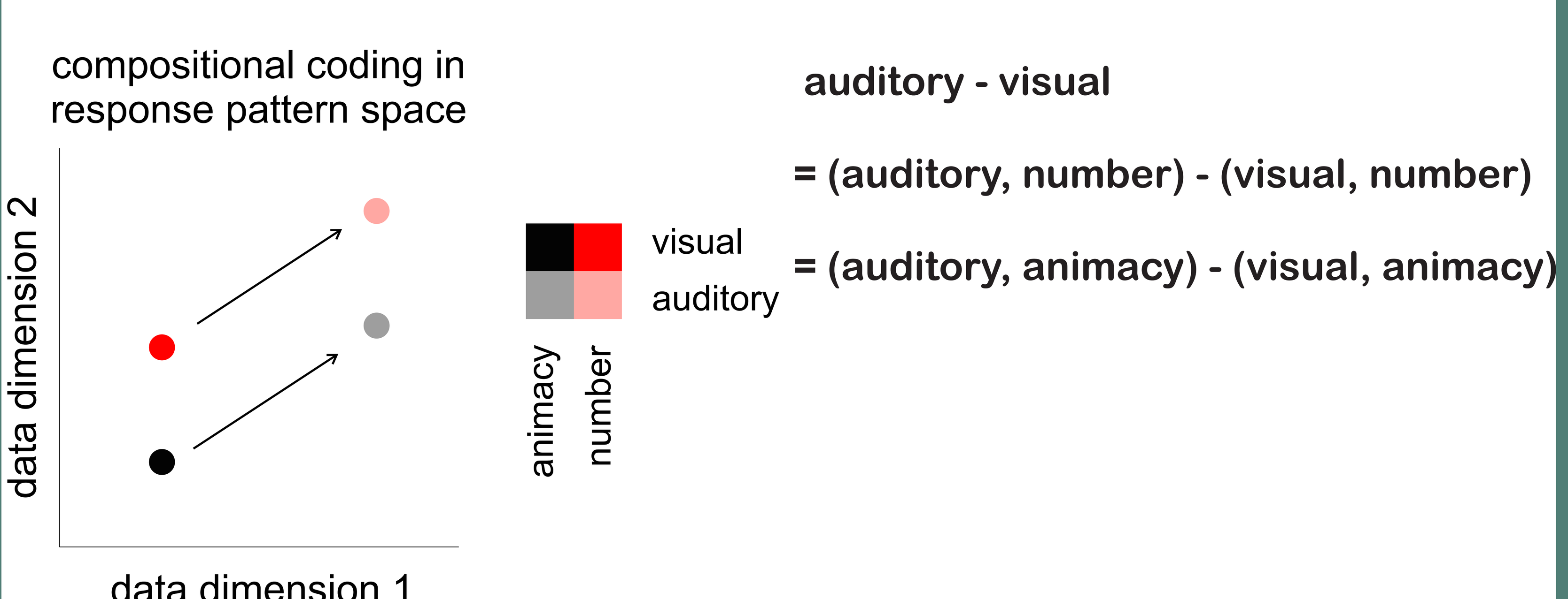
(1) Experimental design



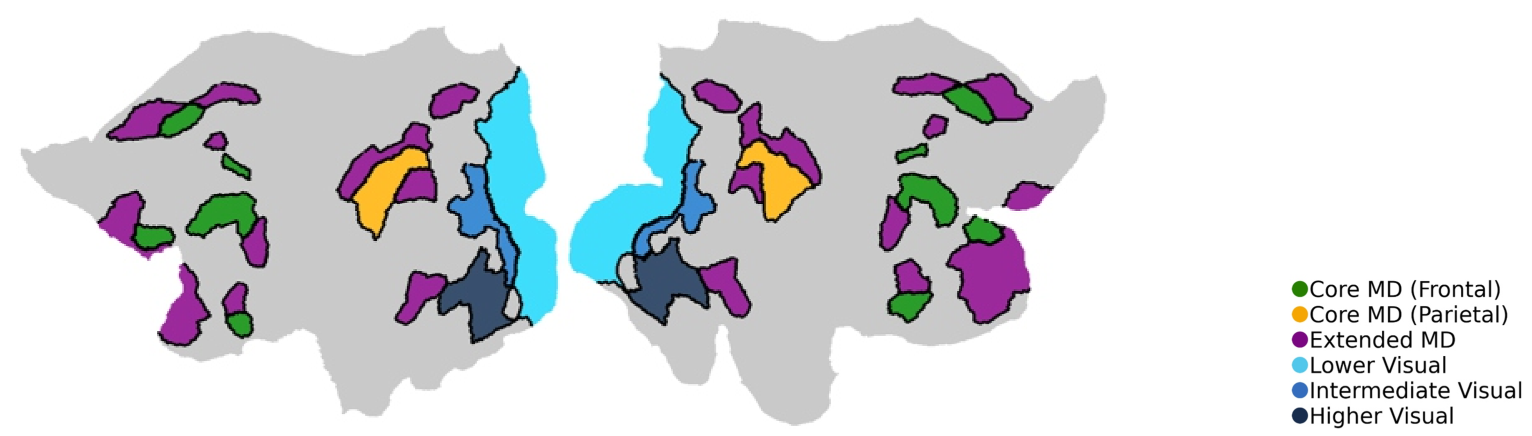
task dimensions:
1. attended sensory modality
2. match rule

- 32 subjects
- 3T fMRI
- 2.5 x 2.5 x 2.5 mm^3 voxels
- TR = 1.53 s

(2) Schematics for compositional coding

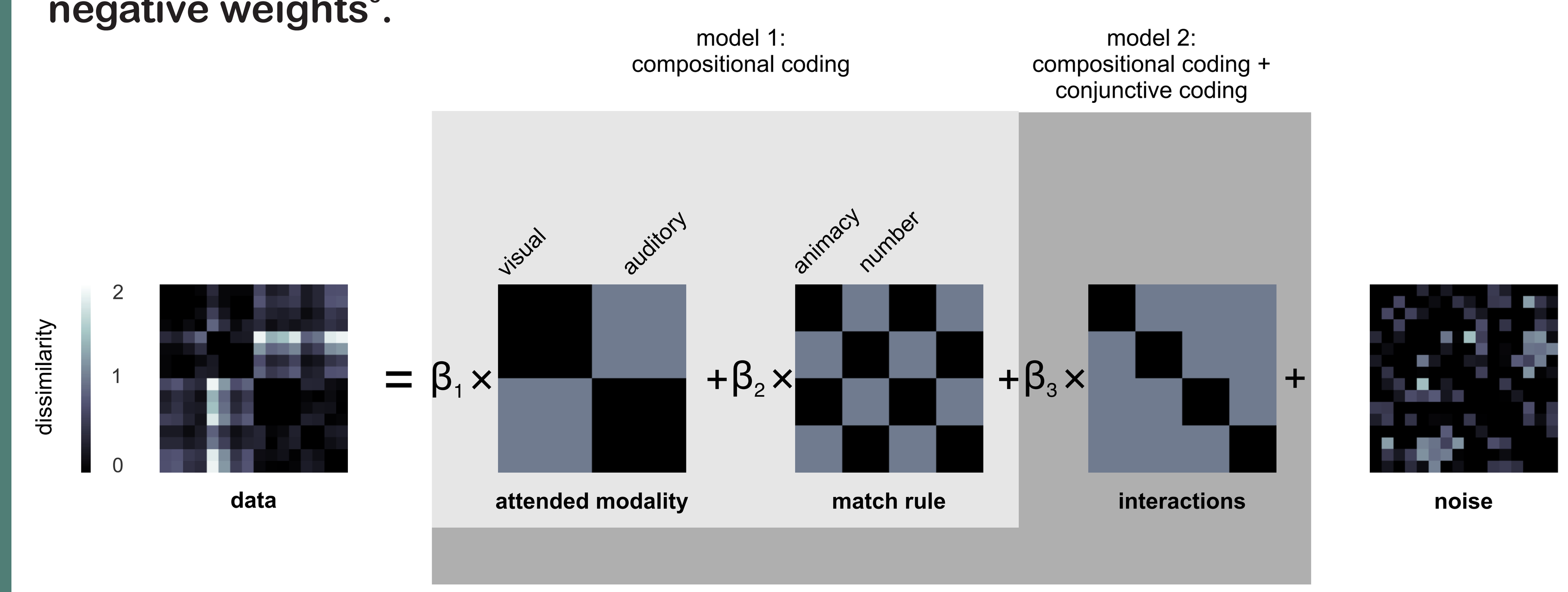


(3) Regions of interest (ROIs)[6]



(4) Representational similarity analysis

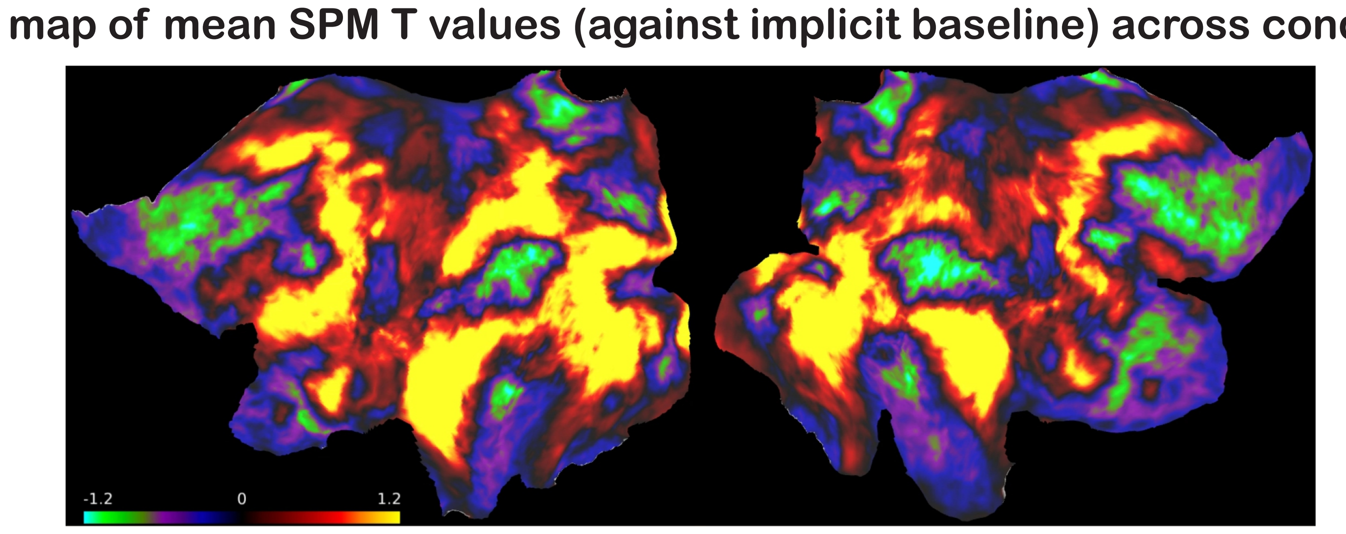
- Representational dissimilarity matrices (RDMs) for each ROI are estimated using cross-validated Mahalanobis distance.
- Data RDMs are modeled as a linear combination of model RDMs using non-negative weights[8].



Results

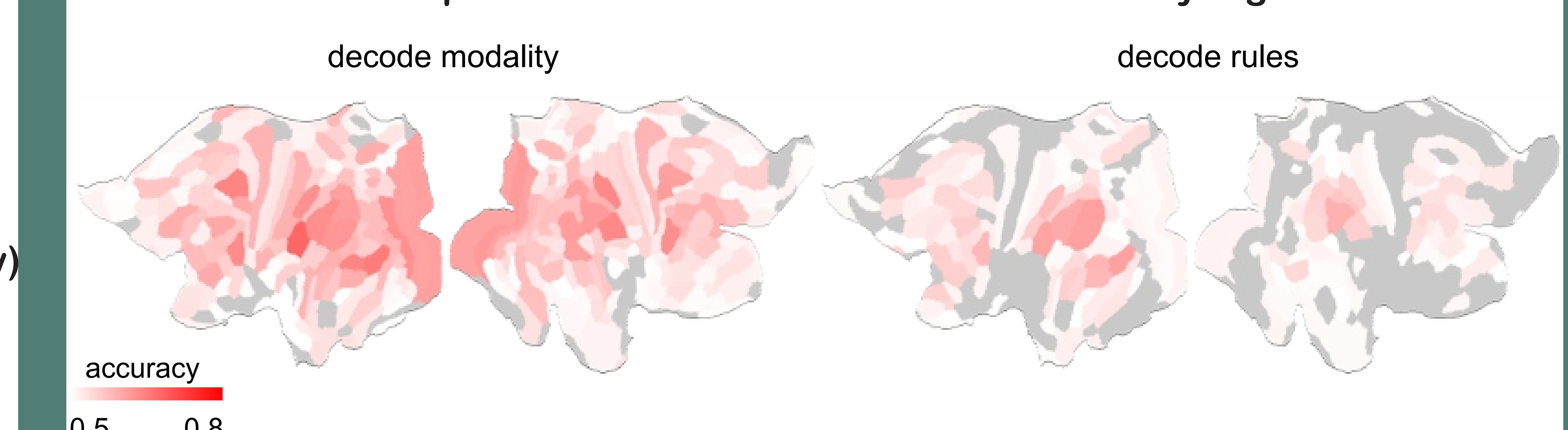
(1) The task engages the MD cortex

Group map of mean SPM T values (against implicit baseline) across conditions



(2) Task-relevant information can be decoded from neural activity

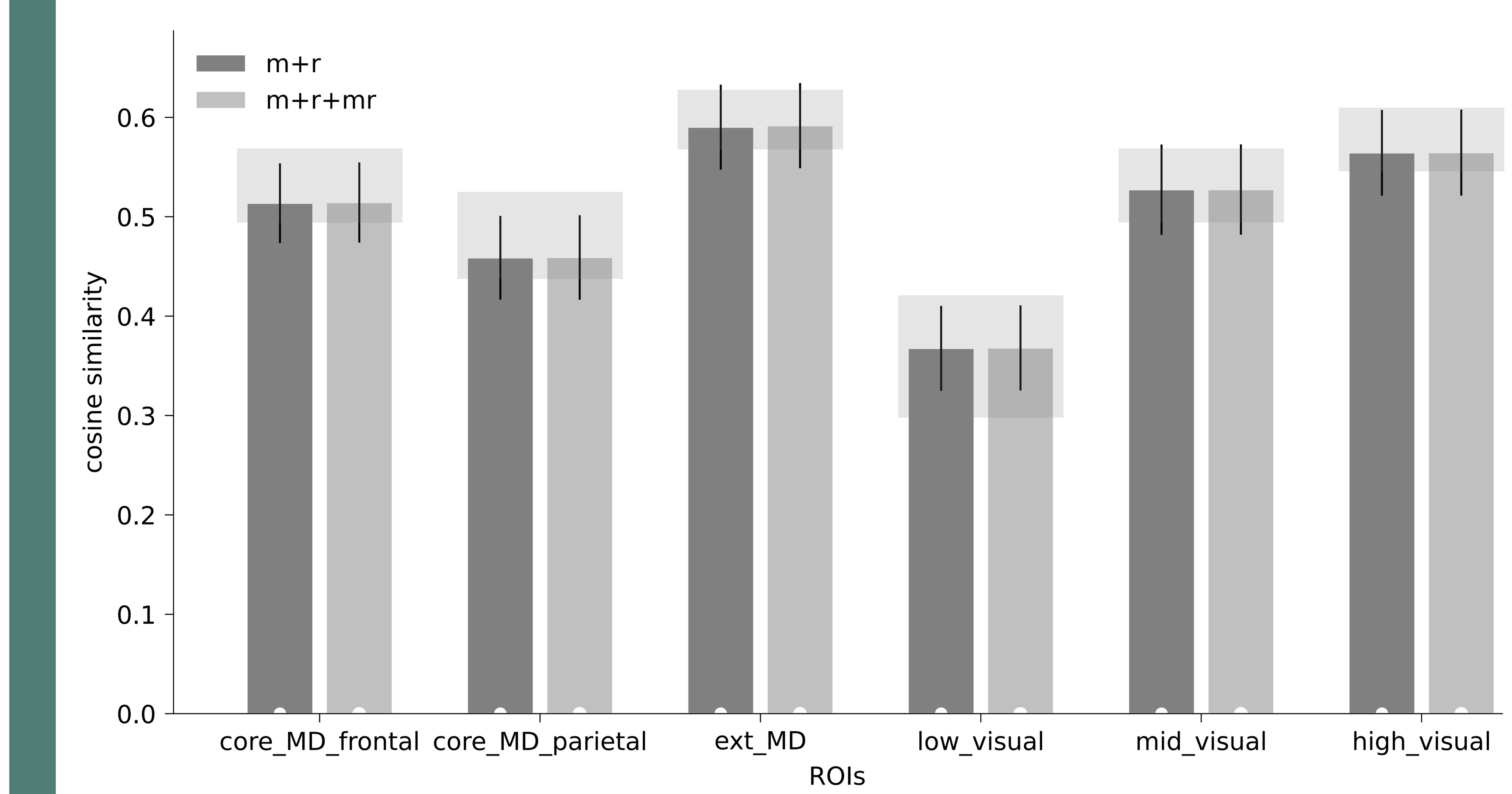
(a) Both the attended sensory modality and the match rule are decodable from cortical regions comprising the MD system.
(b) Attended sensory modality is more widely decodable than match rule, consistent with the presence of attentional effects in sensory regions.



- Linear Discriminant Analysis classifier with leave-one-run-out cross-validation for each subject.
- Decoding results were averaged across participants and thresholded using a one-sided t-test (against chance level, 0.5), corrected for multiple comparisons across all HCP parcels.

(3) Cross-validated RDM model performance across ROIs

- Representations in the MD system and higher visual regions are better modeled by task dimensions than those in lower visual regions.
- Across regions of interest, the interaction between task dimensions does not explain the task representation over and above their linear combination.
- These results suggest that tasks are represented in the MD system in a compositional fashion.



- Dark gray: model including RDMs for modality and rule only.
- Light grey: model including RDMs for modality, rule, and their interaction.
- Error bars show standard error of the mean across bootstrap resampled participants.
- White half circles at the bottom indicate above-zero model performance (bootstrap test, $p < 0.05$, uncorrected).
- Horizontal gray shaded areas show the noise ceiling.
- Neither model performed significantly worse than the lower bound of the noise ceiling across ROIs (bootstrap test, uncorrected).
- Model performance did not significantly differ in any ROI (bootstrap test, uncorrected).

Summary and conclusion

- The representation of tasks differs across the cortical hierarchy.
- Early processing regions show a representation that is more strongly dominated by attended sensory information and less by abstract task rules.
- Later processing regions such as the MD system show a representation that carries a broad array of task information.
- In addition, task representations can be modeled as a linear combination of the representations of task features, while their interactions do not contribute significantly, supporting the compositional coding strategy.
- Future work should test for compositional coding in a broader range of tasks and across spatial scales.

References

1 Duncan (2010) TiCS. 2 Cole et al (2011) Frontiers in Human Neuroscience. 3 Yang et al (2019) Nature Neuroscience. 4 Mante et al (2013) Nature. 5 Woolgar et al (2011) NeuroImage. 6 Assem et al (2020) Cerebral Cortex. 7 Reverberi et al (2012) Cerebral Cortex. 8 Jozwik et al (2016) Neuropsychologia.