Complementary benefits of hierarchical modeling and MVPA for identifying individual differences in cognitive control

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INTRODUCTION

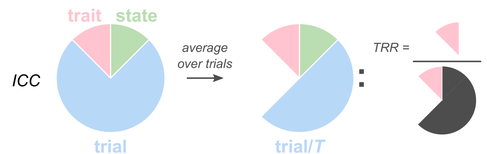
Are neuroimaging data too unreliable for individual differences analyses?

- Trait-like individual differences depend on measures with high Test-Retest Reliability (TRR)
- Standard TRR measure is Intra-class correlation (ICC): univariate summary statistics
- **PROBLEM #1**: fMRI measures show poor ICC reliability (< 0.4), particularly for cognitive control brain regions and tasks (~0.05 for DLPFC in HCP tasks; Elliott et al., 2020)
- **PROBLEM #2:** ICC systematically underestimates true reliability when there is high trial-to-trial variation
- **PROBLEM #3:** Trial-to-trial variation also increases the uncertainty of TRR estimates.

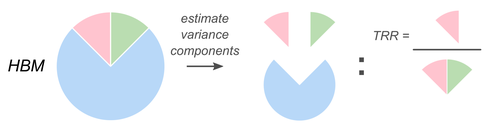
STUDY GOALS

A possible solution?
Use alternative approaches to improve reliability estimation

- **Hierarchical Bayesian Modeling (HBM)** estimates trial-to-trial variation and renders unbiased TRR.



- **Multivariate Pattern Analysis (MVPA)** reduces trial-to-trial variation and TRR uncertainty.



Questions:

1) ***Does HBM improve TRR relative to standard ICC approach?***
2) ***Does MVPA reduce TRR uncertainty relative to univariate (UV)?***
3) ***What about the combination of HBM + MVPA?***

METHOD

Stroop task and fMRI preprocessing

- Stroop task: color naming ("Incongruent": e.g., White vs. "Congruent": e.g., Blue)
- 28 subjects; 25 to 852 (median: 105) days between test and retest; 216 trials per test
- fMRI data were detrended; then averaged across TRs-of-interest (2.4s-4.8s post stimulus onset) within each trial; then centered within each run.

Parcel-level activation – univariate mean and MVPA

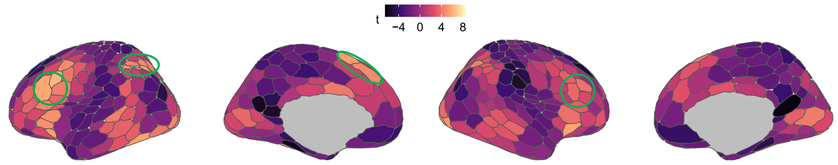
- "Univariate mean" (UV): averaging across vertices within each parcel for each trial
- MVPA: weighted sum of vertices within each parcel, where the weight w maximizes the between class variance (Stroop effect) relative to within class variance (trial-level noise)

Reliability estimation: ICC and Hierarchical Bayesian Model

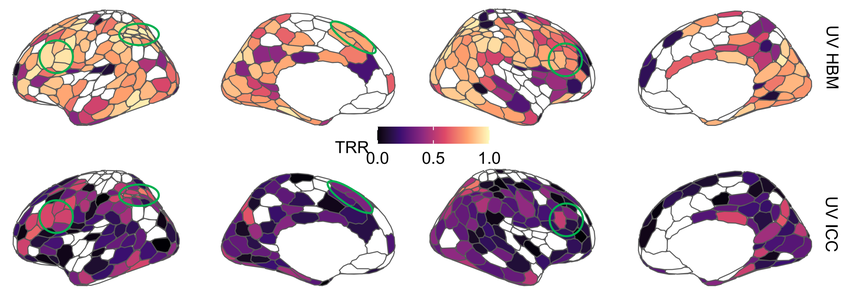
- ICC: $\text{Stroop}_{r,p} = \bar{y}_{(\text{Incon},r,p)} - \bar{y}_{(\text{Con},r,p)}$, $\text{ICC} = (\text{Stroop}_{\text{test},\cdot}, \text{Stroop}_{\text{retest},\cdot})$
- HBM: modeling trial-level activation by a t-distribution; modeling Stroop effect as a two-dimensional (test/retest) normal distribution; TRR is extracted from the covariance matrix

RESULTS

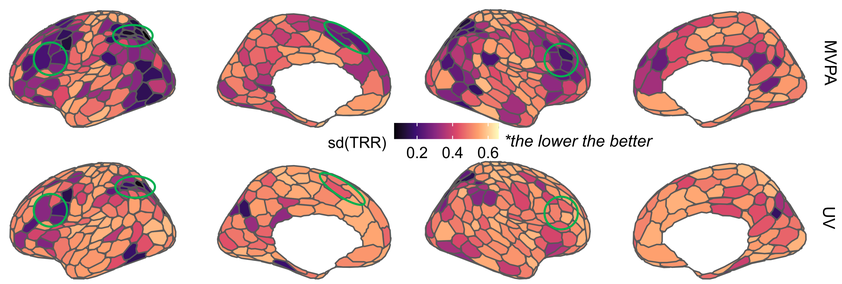
Group average Stroop effect (Schaefer et. al., 2018 atlas)



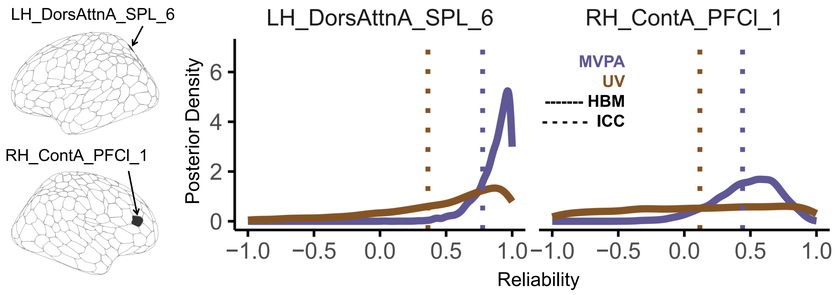
Question #1: HBM did improve TRR relative to standard ICC; TRR was high in frontoparietal regions



Question #2: MVPA did reduce uncertainty in TRR estimates; TRR estimate was quite precise in frontoparietal regions

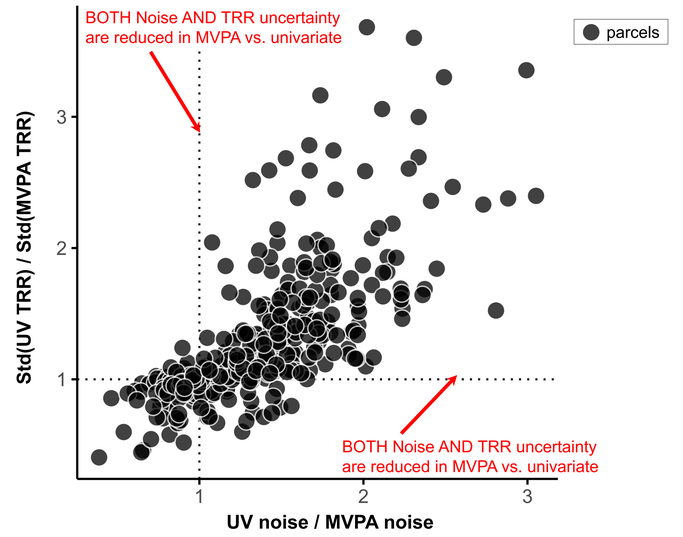


Question #3: MVPA made estimated TRR distribution narrower, improving its interpretability



RESULTS

Reduction of TRR uncertainty correlated with reduction of trial-level noise in MVPA vs. UV



TAKE-AWAYS

Both HBM and MVPA improved estimation of test-retest reliability, but in different ways

- Compared to standard ICC, HBM methods revealed much higher TRR, particularly in task-related and cognitive control regions, such as frontoparietal cortex (FPN).
- Compared to traditional univariate activation indices, MVPA reduced relative trial-level noise, making more precise TRR estimates, again particularly in FPN.

Combination of HBM + MVPA might be best for estimating and interpreting trait-like individual differences

- HBM alone can improve TRR, but in some cases revealed high uncertainty in estimates.
- HBM + MVPA reduced the dispersion of the posterior distribution, making TRR estimates more interpretable.

Conclusion:

- ***Neuroimaging data may not actually be unreliable. Traditional psychometric approaches could be the problem.***
- ***The solution may be to use methods (HBM, MVPA) that more effectively estimate reliability in task fMRI data.***

Elliott, M. L., Knodt, A. R., Ireland, D., Morris, M. L., Poulton, R., Ramrakha, S., Sison, M. L., Moffitt, T. E., Caspi, A., & Hariri, A. R. (2020). What Is the Test-Retest Reliability of Common Task-Functional MRI Measures? New Empirical Evidence and a Meta-Analysis. *Psychological Science*, *31*(7), 792–806.
Schaefer, A., Kong, R., Gordon, E. M., Laumann, T. O., Zuo, X.-N., Holmes, A. J., Eickhoff, S. B., & Yeo, B. T. T. (2018). Local-Global Parcellation of the Human Cerebral Cortex from Intrinsic Functional Connectivity MRI. *Cerebral Cortex*, *28*(9), 3095–3114.