



# Reward motivation enhances decoding of task representations in frontoparietal cortex

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## a tale of two participants ...

During a break the experimenter asks, “What did you think of the task?”

**1** “Well, I tried my best, but I still missed 2 or 3, which makes me mad. Can I try it again? I’m pretty sure I could do better next time.”

**2** “Huh? Oh, I zoned out there. I’m only doing this experiment for the course requirement and it’s really boring.”

Obviously, **motivation** varies, and affects task performance.

But what is the mechanism? How does motivation affect brain functioning and change performance?

(these questions are **our** motivation for this study)

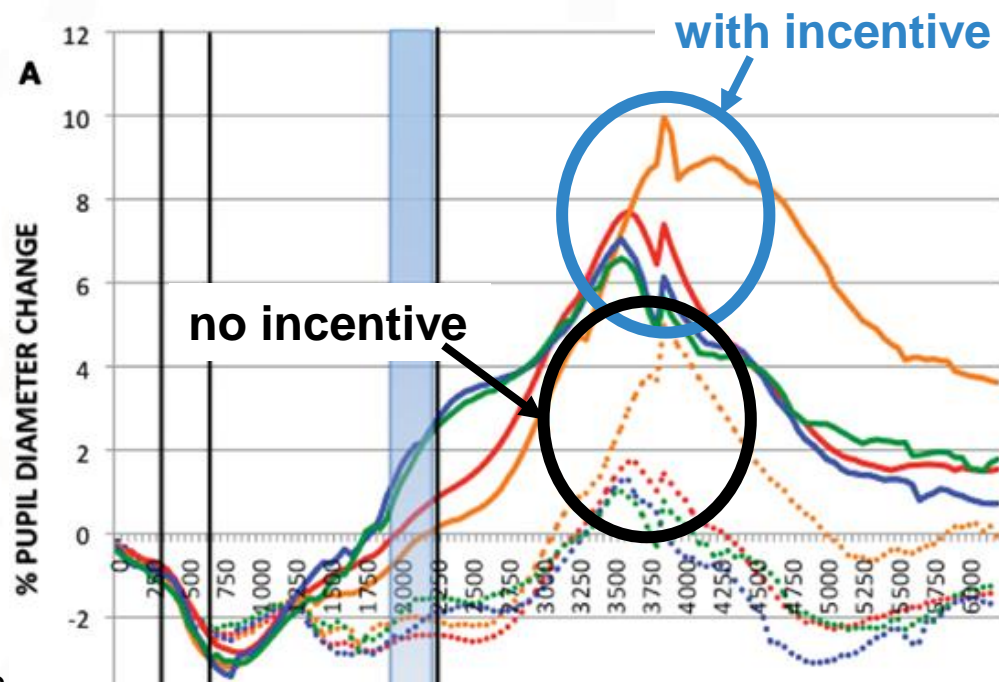


Experimentally, motivation is often manipulated by offering a **cash reward** for good performance or threatening punishment for poor performance.

Usually, incentives improve task performance, though not always; for example, performance could already be at ceiling or anxiety could interfere.

Besides motivation affecting **behavior** (accuracy, reaction time, etc.), there are **physical** changes (EEG, skin conductance, fMRI, etc.).

Rewarded trials in a cognitive control task (the AX-CPT) had **increased pupil dilation** (more arousal) during task preparation (and greater accuracy, faster reaction time).



Chiew & Braver. Temporal dynamics of motivation-cognitive control interactions revealed by high-resolution pupillometry. *Frontiers in Psychology*. 2013.

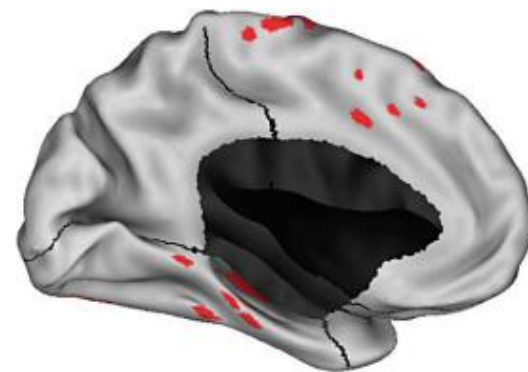
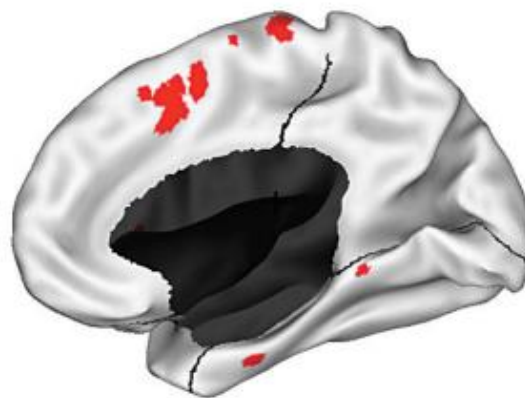
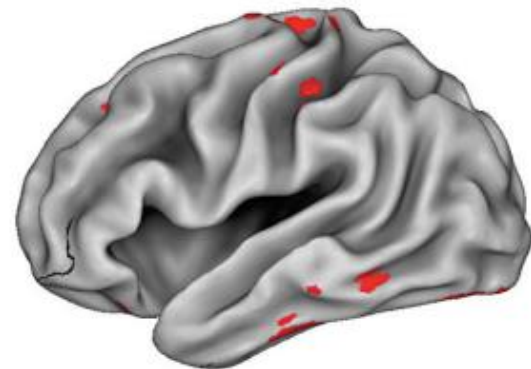
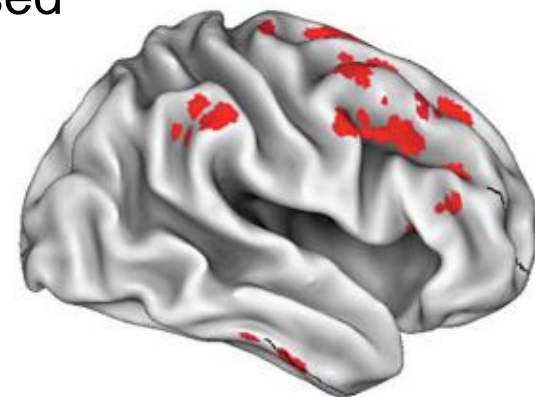




Locke & Braver 2008 also used the AX-CPT task, with **fMRI**.

They did a mass-univariate (GLM) analysis, looking for areas with greater cue-related activation in rewarded trials.

This mix of **frontal** and **parietal** areas is typical for fMRI studies with cognitive control tasks.



Locke & Braver. Motivational influences on cognitive control: Behavior, brain activation, and individual differences. Cognitive, Affective, & Behavioral Neuroscience. 2008.



## starting point:

- Changes in motivation affect behavioral performance of cognitive control tasks, and are accompanied by changes in the brain and nervous system.
- Many theories propose that motivation has a **primary influence** on cognitive control, by modulating activity in frontoparietal brain regions, which in turn improves the encoding, maintenance, and activation of task goals.

## this particular study:

**If** increasing participant **motivation** with reward incentives improves the encoding and maintenance of cognitive task goals,

**Then** we should find **better task-set decoding** (MVPA classification accuracy) of reward incentive trials,

**And** that reward-related improvement in classification accuracy should be **statistically related to** the improvement in behavioral performance,

**And** the voxel-level activation patterns should be more **distinct** and **less noisy** on reward incentive trials.

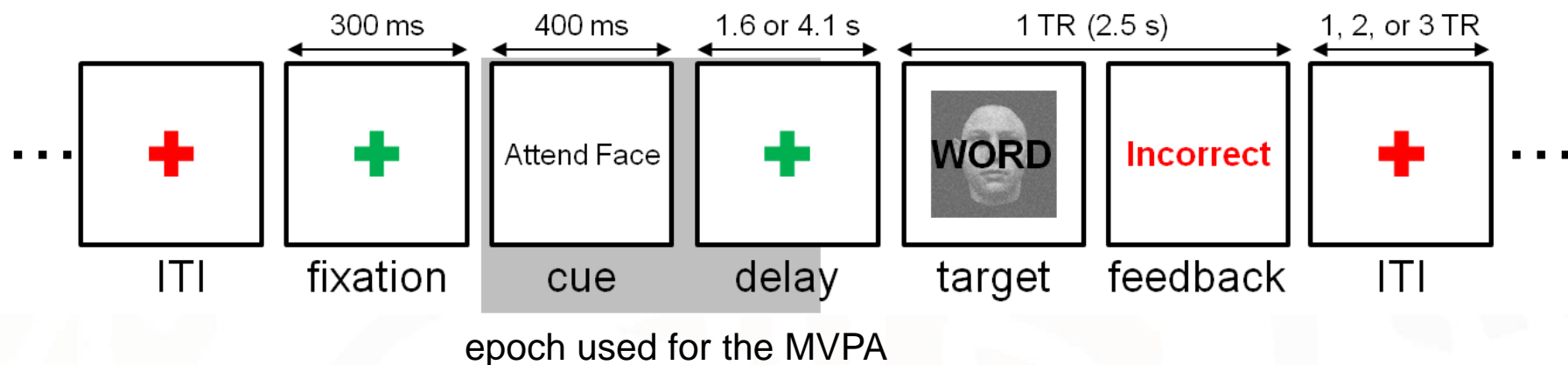
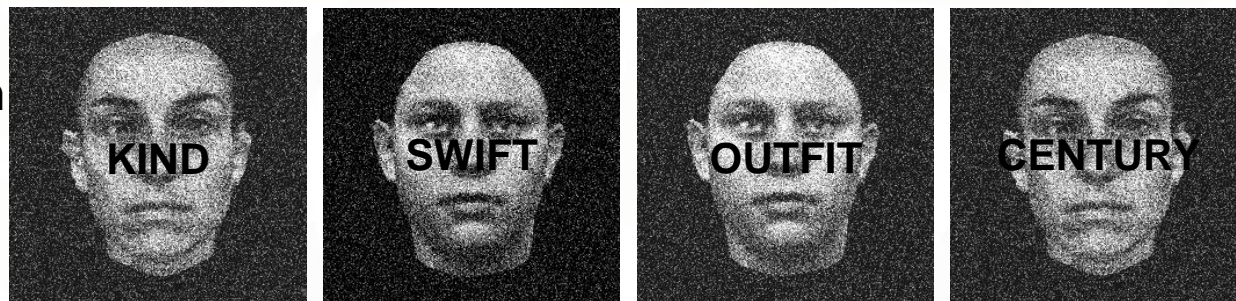


## First, the dataset.

Cued task-switching paradigm

**Word:** two syllables or not?

**Face:** female or male image?



- 20 participants: 14 female, 6 male; mean age 25, range 19 to 37 years
- 3T Allegra scanner, TR=2.5 sec, 4x4x4 mm voxels; whole-brain coverage
- preprocessing in SPM8: motion correction, voxels not resized; images not smoothed
- MVPA classification: within-subjects, linear SVM,  $c=1$ ; e1071 R interface to libsvm

Protocol carried out in two sessions on separate days: first **baseline** (naïve), second **incentive** (mixed Incentive and NoIncentive trials).





If increasing participant motivation with reward incentives improves the encoding and maintenance of cognitive task goals,

Then we should find **better task-set decoding** (MVPA classification accuracy) of reward incentive trials,

time during the experiment →



The voxels' BOLD activity patterns are consistent during Word and Face trials, so a classification algorithm can distinguish them (classify trials by task).

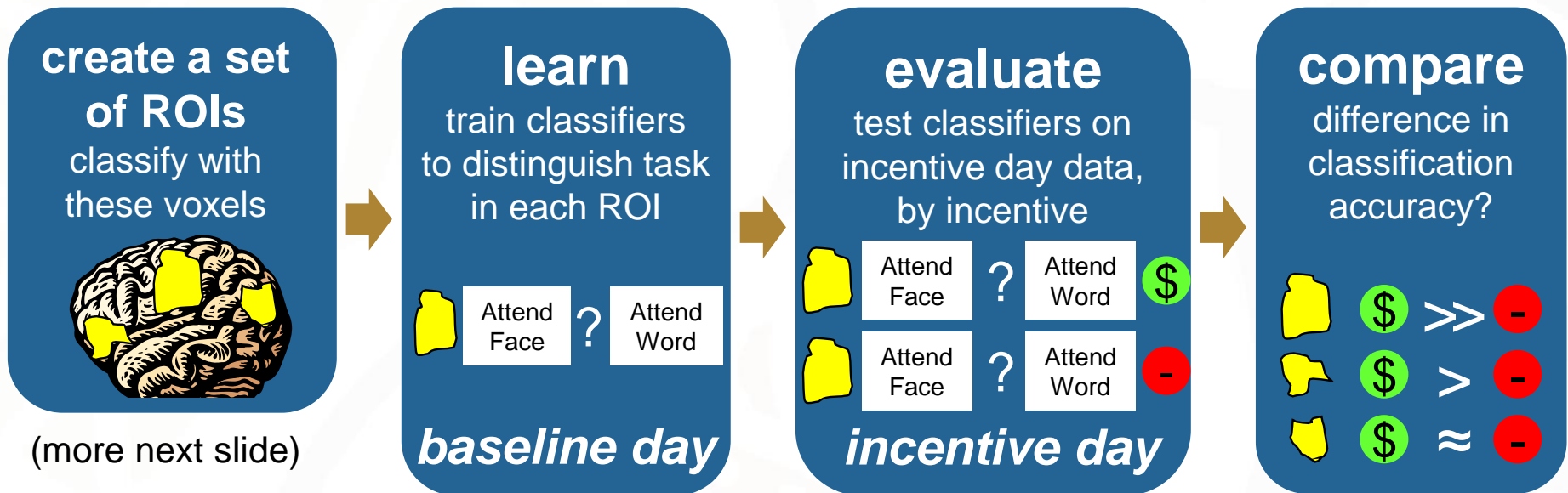
Concretely, the first prediction is that we will **more accurately distinguish** Word and Face task trials when a reward is possible than when it is not.





Directly comparing the accuracy from different classifiers can be tricky ...

... but we avoided those problems by classifying **across acquisition days**.

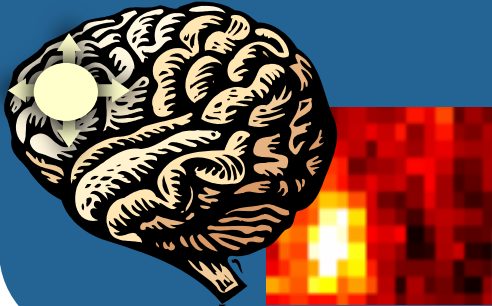




Since the areas relevant for cognitive control and reward are not established enough to use as anatomical ROIs, we used the **baseline session** data to create ROIs (not circular: test on incentive session images).

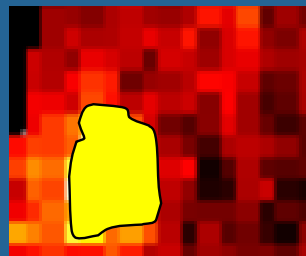
## localize

searchlight analysis:  
map local task  
information  
throughout brain



## generalize

cluster the info. map  
into ROIs (fewer  
spatial assumptions)



## validate

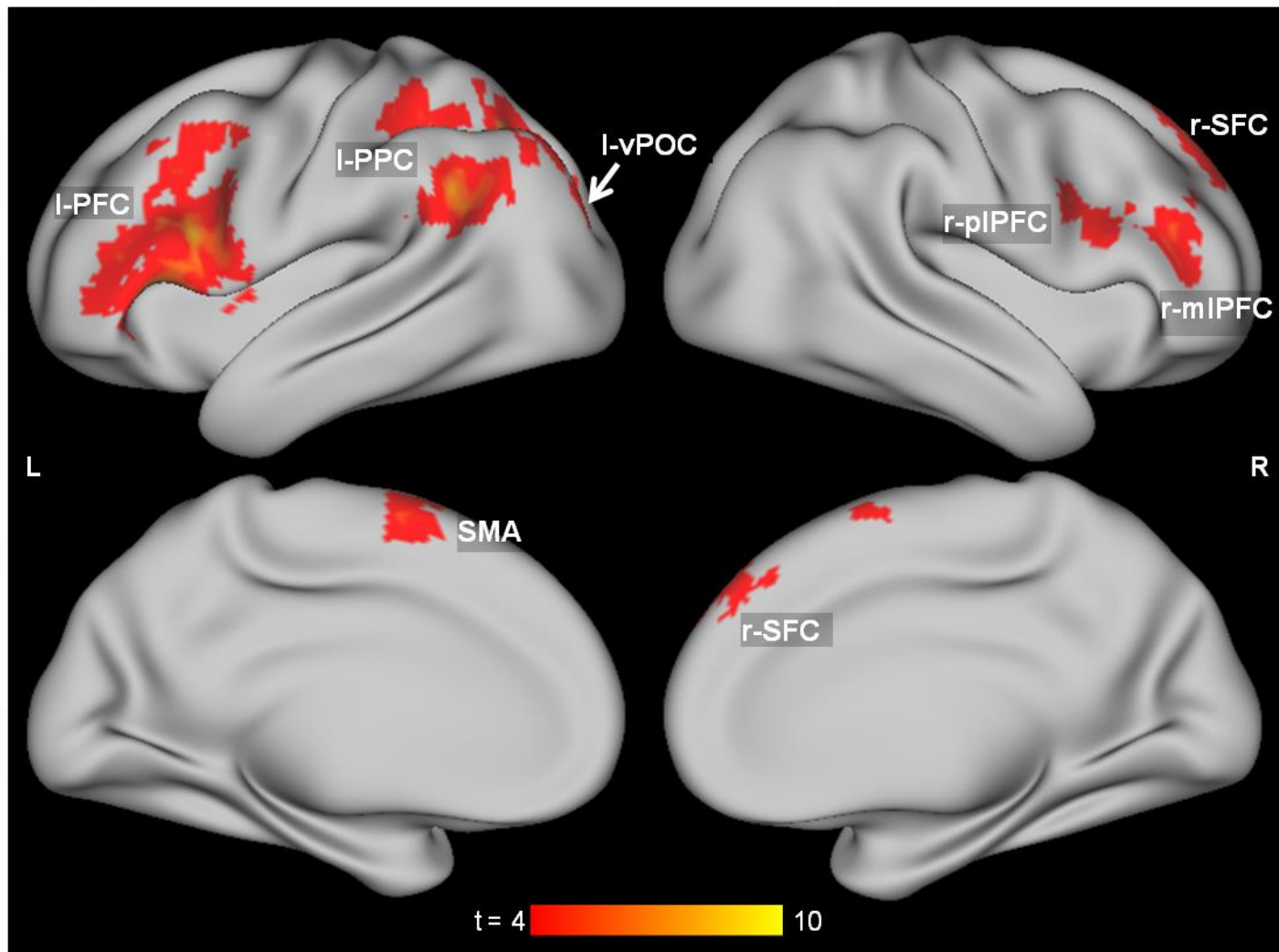
can each ROI  
classify task?

	Attend Face	?	Attend Word
	Attend Face	?	Attend Word
	Attend Face	?	Attend Word
	Attend Face	?	Attend Word



We identified seven **validated ROIs**

located in prefrontal and parietal areas typical for cognitive control experiments:

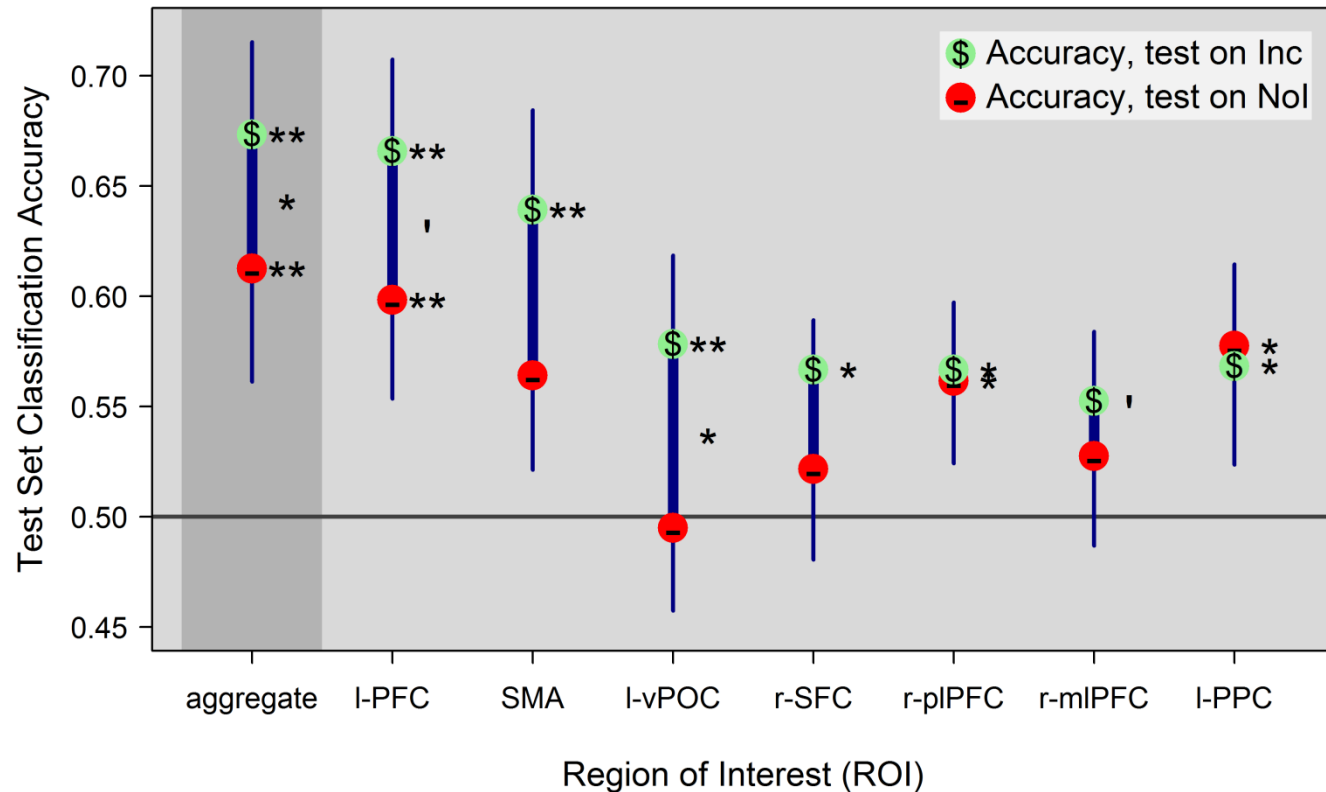


I-PFC	Left mid-lateral prefrontal cortex (BA 44/45/47)
SMA	Supplementary motor area (BA 6)
I-vPOC	Left ventral parieto-occipital cortex (BA 19)
r-SFC	Right superior frontal cortex (BA 9)
r-pIPFC	Right postero-lateral prefrontal cortex (BA 44)
r-mIPFC	Right mid-lateral prefrontal cortex (BA 45/46)
I-PPC	Left posterior parietal cortex (BA 7/40)

... but is classification accuracy better on Incentive trials?



Yes, classifier accuracy was higher on reward (Incentive) trials.



This is **cross-session accuracy**: classifiers trained on the baseline session and then tested on the incentive session, Incentive and NoIncentive trials separately.

Since the effects are consistent across ROIs, we created an **aggregate ROI** (all voxels from the validated ROIs), which was also significantly more accurate on Incentive trials.





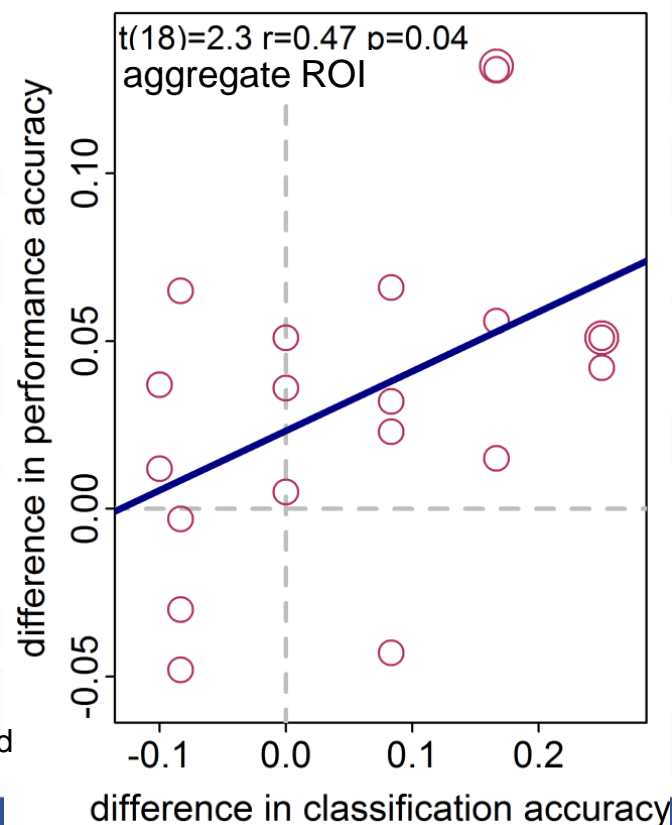
If increasing participant **motivation** with reward incentives improves the encoding and maintenance of cognitive task goals,  
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**And** that reward-related improvement in classification accuracy should be **statistically related to** the improvement in behavioral performance,



Behavioral performance was improved on reward (Incentive) trials.

Participants were both **faster** ( $t(19)=4.2$ ,  $p<.001$ ) and **more accurate** ( $t(19)=3.2$ ,  $p=.002$ ) on Incentive than NoIncentive trials.

The incentive-related difference in classification accuracy predicts the incentive-related difference in behavior: **classification accuracy is a mediator of behavioral performance.**



Judd, C.M., Kenny, D.A., McClelland, G.H., 2001. Estimating and testing mediation and moderation in within-subject designs. *Psychological Methods* 6, 115-134.



**If** increasing participant **motivation** with reward incentives improves the encoding and maintenance of cognitive task goals,

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**And** that reward-related improvement in classification accuracy should be **statistically related to** the improvement in behavioral performance,

**And** the voxel-level activation patterns should be more **distinct** and **less noisy** on reward incentive trials.



More distinct, less noisy task set representations could lead to more effective biasing of on-going behavior, and so better behavioral performance.

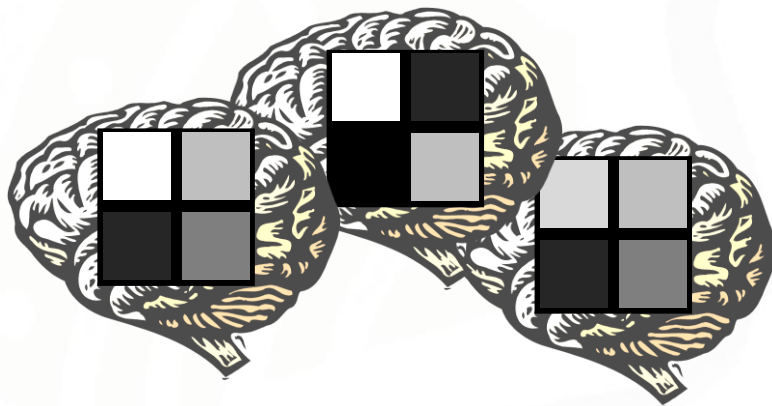
... what do I mean by “more distinct?”



— no incentive

\$ with incentive

Face  
task



Word  
task

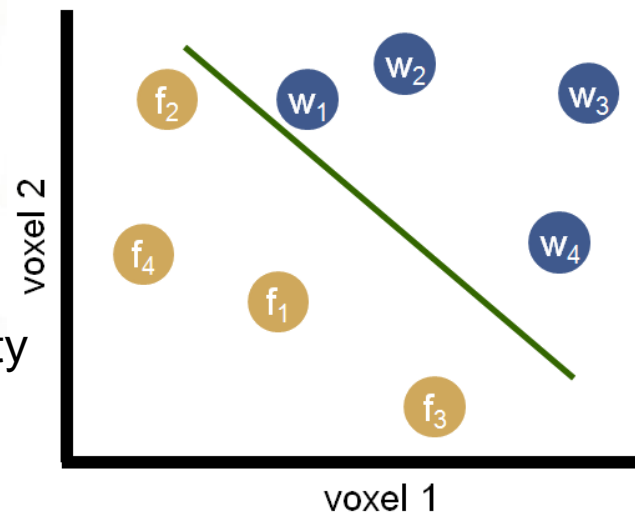


We quantified activity pattern distinctiveness and clarity in the aggregate ROI with two statistics: the **distance to the SVM hyperplane** and the **likelihood of distance concentration**.



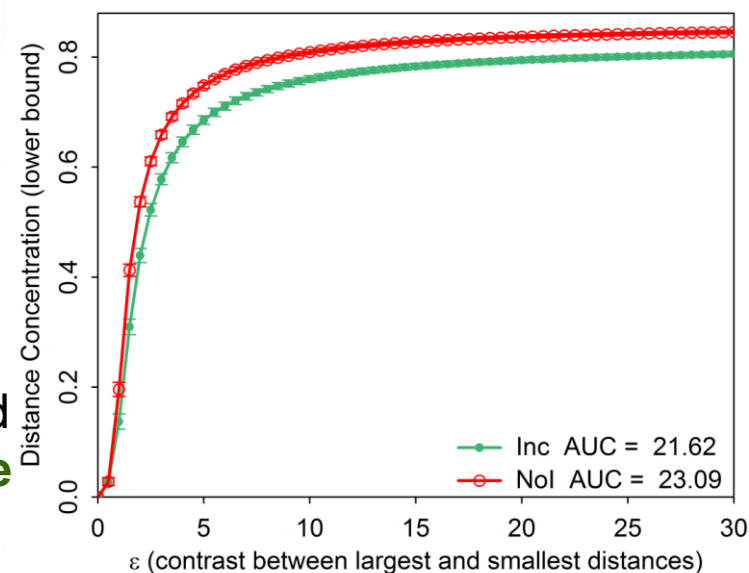
**SVM hyperplane distance** can be interpreted as classifier **confidence**: examples with greater distances are “more clearly” Word or Face.

- Distributions were further apart on Incentive (Cohen's  $d=.51$ ) than NoIncentive (Cohen's  $d=.3$ ).
- Difference is significant ( $p=.032$ ): Word and Face activity patterns **more distinct with reward incentive**.



The **likelihood of distance concentration** describes the amount of structure (noise) in high-dimensional datasets.

- Distances are more likely to be concentrated in NoIncentive (AUC=23.09) than Incentive (AUC=21.62) in the aggregate ROI voxels.
- This difference is significant ( $p=.007$ ): the Word and Face activity patterns had **more intrinsic structure (were less noisy) with reward incentive**.



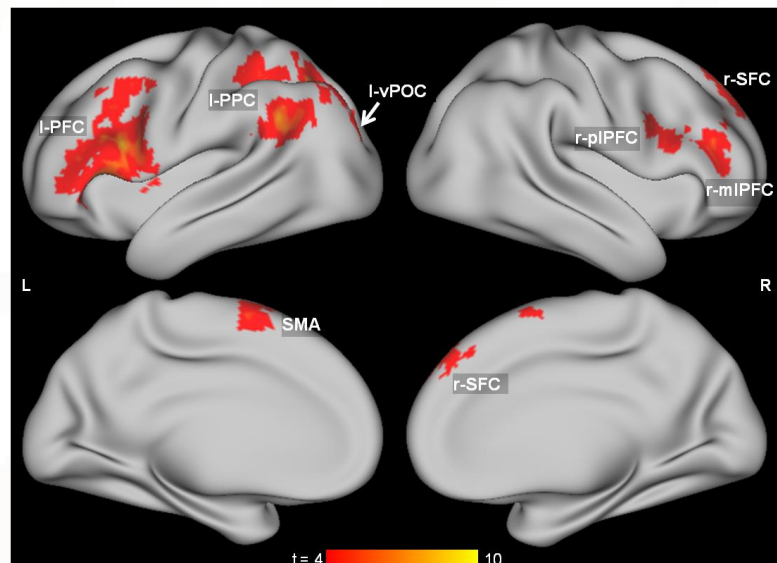
Kabán. Non-parametric detection of meaningless distances in high dimensional data. Statistics and Computing. 2012.





## Summary

- Replicating prior results, we decoded the upcoming task from fMRI activity patterns in frontoparietal brain regions.
- Cross-session task decoding accuracy was higher on reward incentive trials.
- Larger increases in task decoding accuracy on Incentive trials predicted larger increases in behavioral task performance.
- Frontoparietal activity patterns more clearly specified the upcoming task on Incentive trials (Incentive trial patterns were more distinct, less noisy).
- Suggests that reward motivation enhances cognitive control by improving the discriminability of task-relevant information coded and maintained in frontoparietal brain regions.

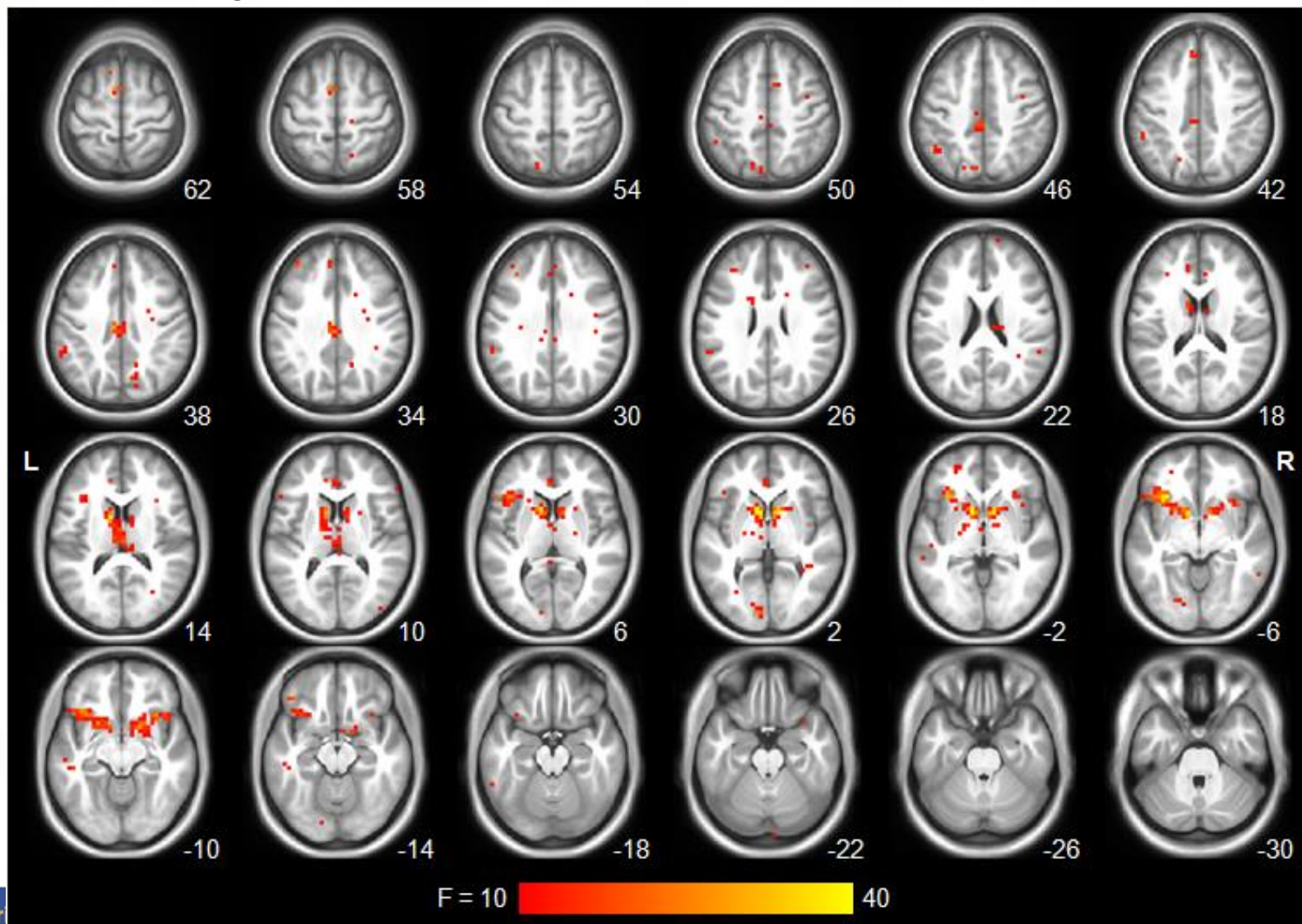


thank you





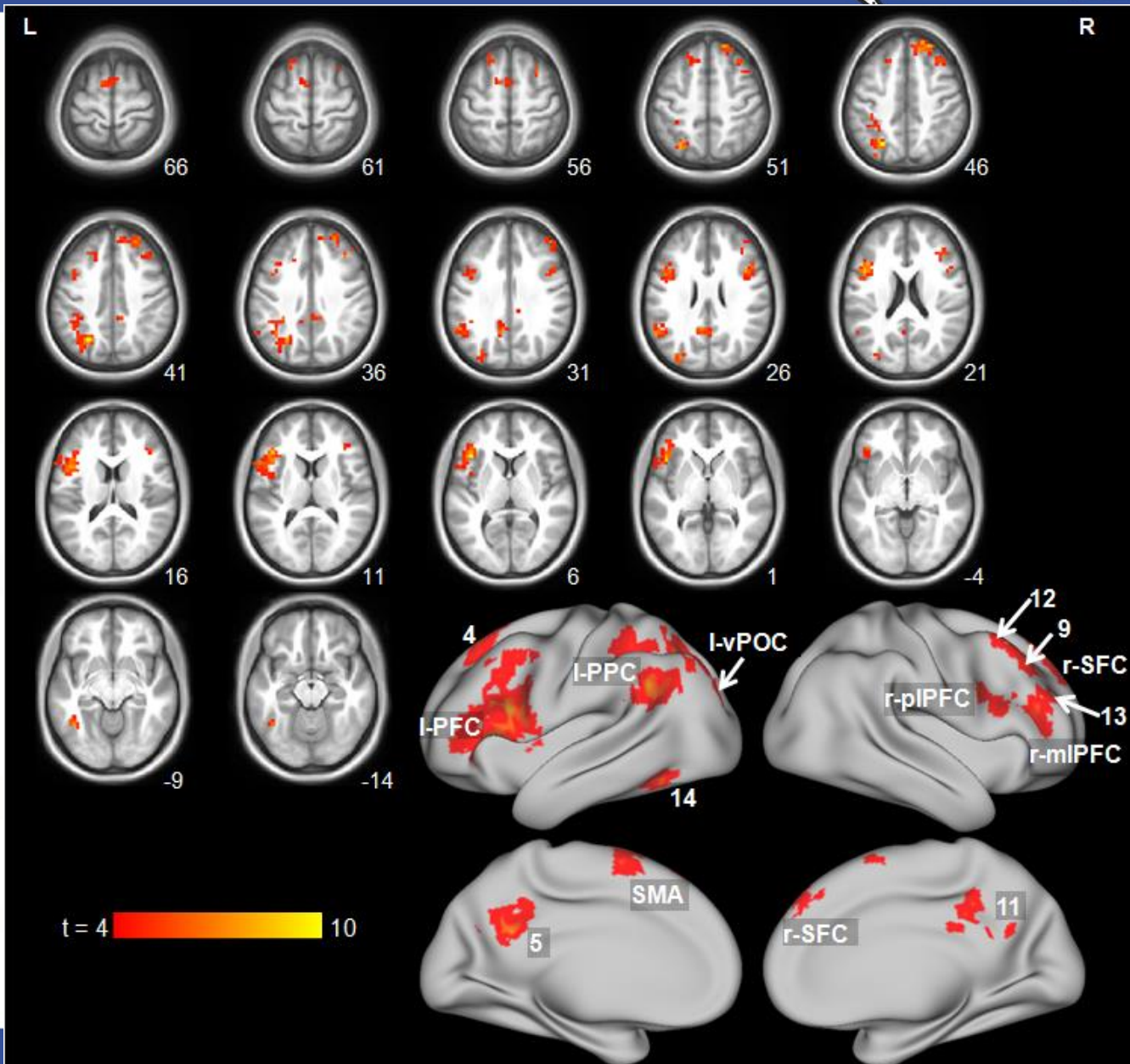
more BOLD on Incentive trials? (post-hoc mass-univariate analysis)  
 Voxels with the largest BOLD incentive effect in canonical reward valuation network.







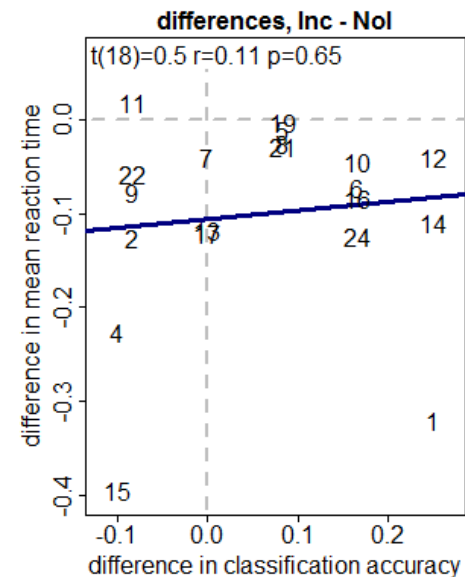
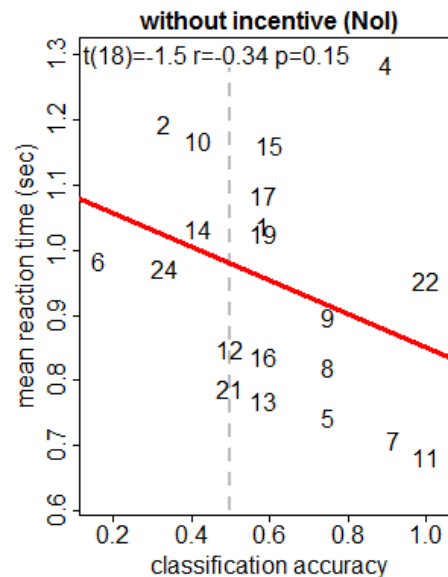
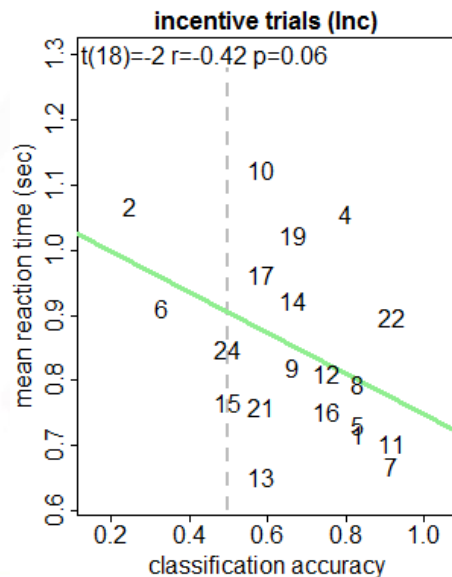
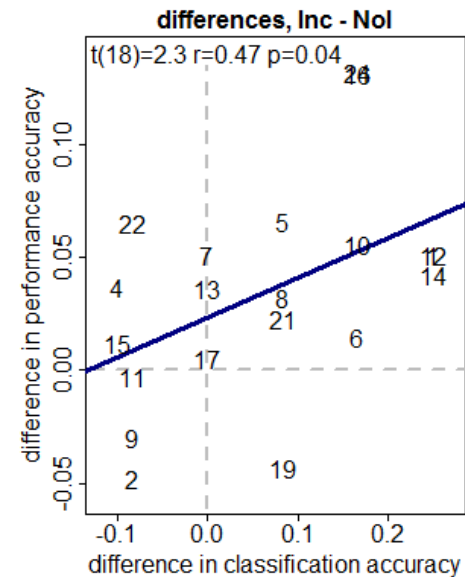
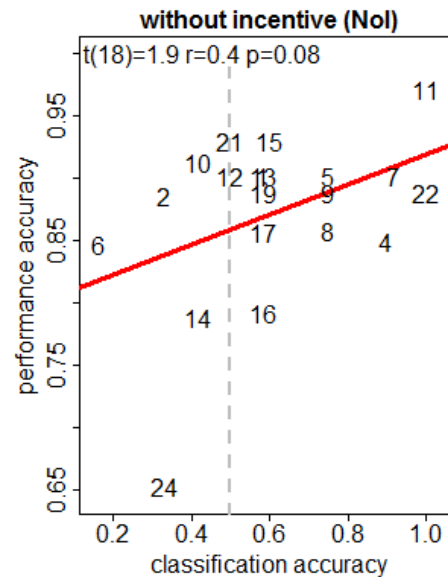
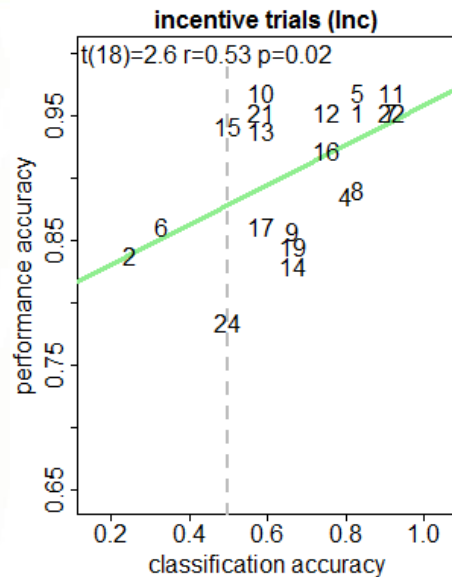
all candidate ROIs.  
validated named, others  
numbered.



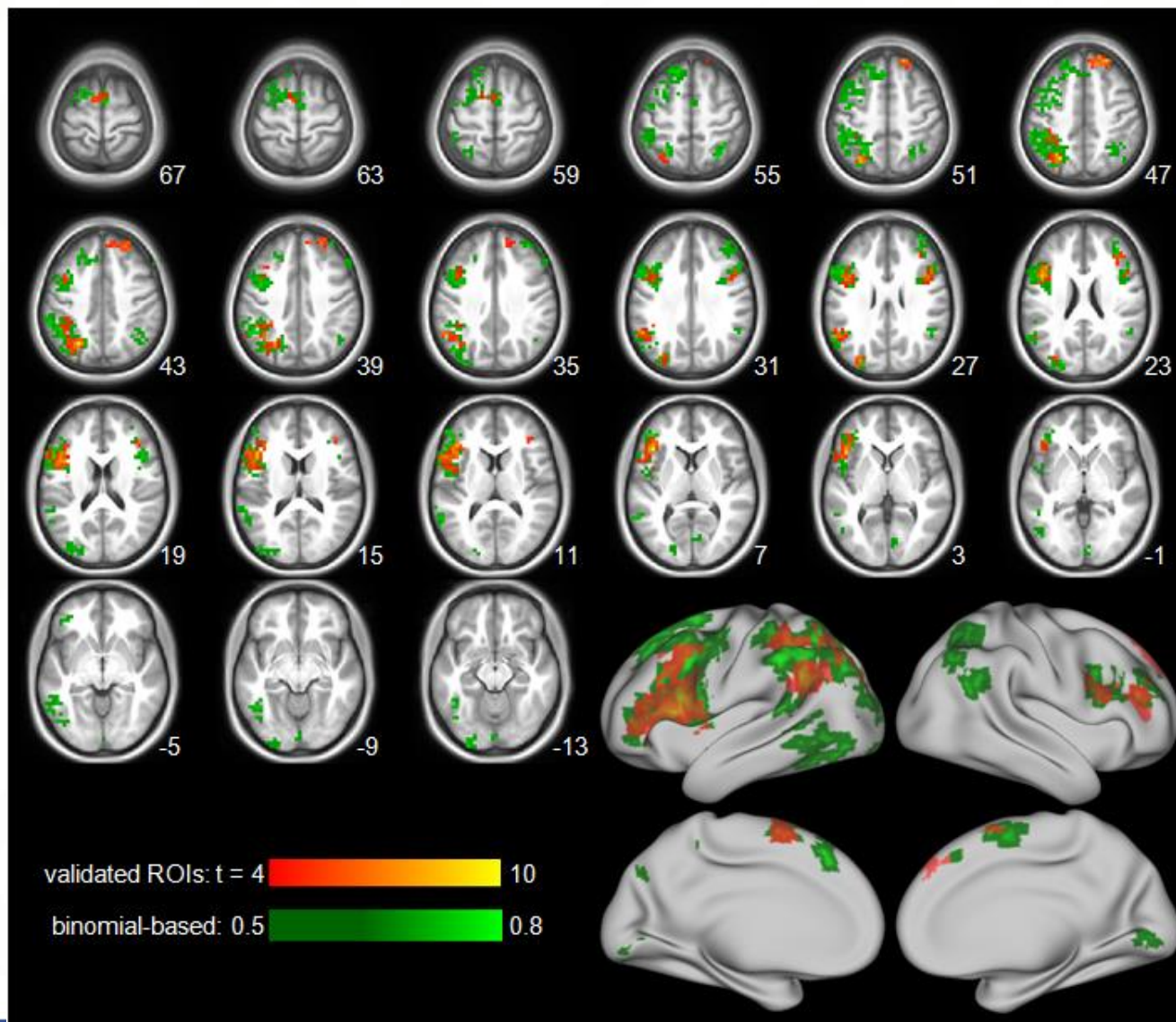




regressions for the mediation analysis, accuracy and reaction time.



Validated ROIs similar with binomial-based group statistic.





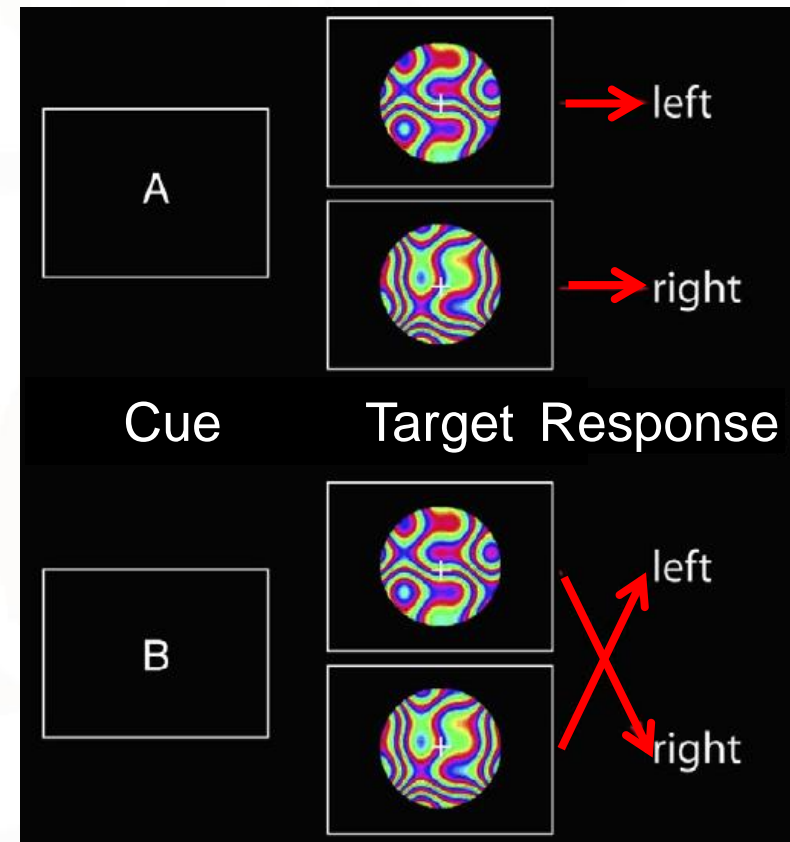
In **cued task-switching** paradigms participants are asked to switch between multiple tasks, depending on the cue starting each trial.

if the trial starts with an **A** cue, move the joystick to the left for the top target;

if the trial starts with a **B** cue, move the joystick to the right for the **same** target.

Cued paradigms give **temporal separation** of task updating and maintenance from task performance.

Since the response cannot be predicted from the target without knowing the cue, task-switching paradigms let us separately analyze task preparation.



Bode & Haynes. Decoding sequential stages of task preparation in the human brain. NeuroImage. 2009.