Point Process Models of ACC and DLPFC during Cognitive Control

Eric Denovellis[1,2], Tim Buschman[3,5], Cinira Diogo[3,4], Daniel Bullock[1,2], Earl Miller[2,3,4]

[1]Grad. Program for Neurosci., Boston Univ., Boston, MA; [2]Ctr. of Excellence for Learning in Education, Sci. and Technol., Boston, MA;
[3]Dept. of Brain and Cognitive Sci., MIT, Cambridge, MA; [4]The Picower Inst. for Learning and Memory, Cambridge, MA; [5]McGovern Inst. for Brain Res., Cambridge, MA

599.12
DDD9

Introduction

Cognitive control allows us to change our response to the world given the situation. Selecting the appropriate response to an external stimulus requires prioritizing internal goals and resisting responses not aligned with the current goal. We call these context-dependent, conditional stimulus-response mappings 'rules.'

Functional imaging and lesion studies have identified the anterior cingulate cortex (ACC) and dorsolateral prefrontal cortex (DLPFC) as brain areas with distinct, but complementary, roles in cognitive control. The DLPFC is associated with directing attention to relevant stimuli while the ACC is associated with monitoring and adjusting behavior, but conflicting evidence from neuroimaging and electrophysiology studies have spawned competing theories involving ACC in detecting conflict (either in the response or the current rule) or response-outcome predictions. Similarly, DLPFC has been associated with directing attention and implementing contextual rules, but how these relate to behaviorally relevant predictors such as the switching of the rule and preparation time is still not well understood.

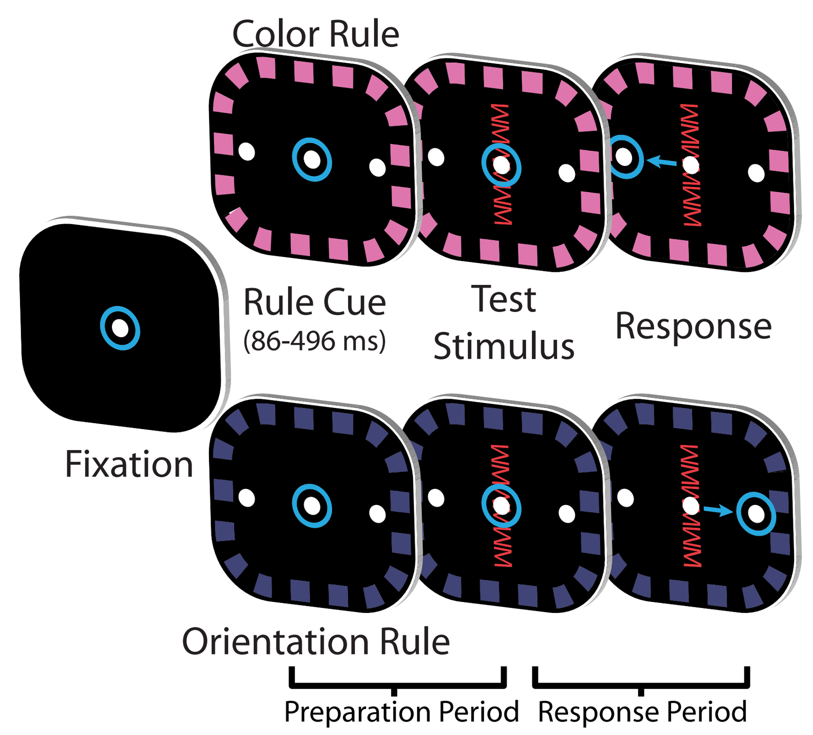
Here, we investigate the respective roles of the anterior cingulate and dorsolateral prefrontal cortex in rule-based task switching by simultaneously recording with multiple electrodes in non-human primates.

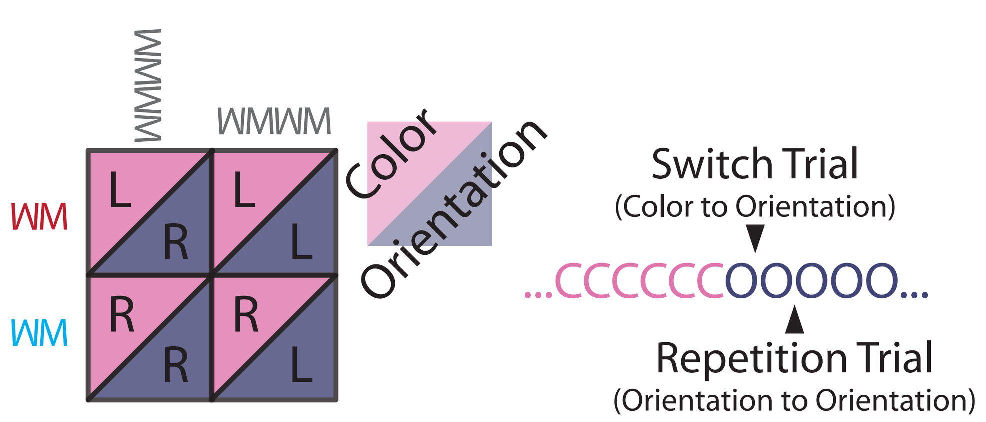
Cued Task Switching in Non-Human Primates

Three monkeys were trained on a cued task switching paradigm. The task began with the presentation of a fixation spot at the center of the screen. After acquiring fixation, a cue bordering the screen indicated one of two rules was in effect – either discriminate color or orientation.

The monkeys continued to fixate for a brief, randomized preparatory period until a test stimulus appeared at the center of the screen. Using the cued rule and the relevant feature of the test stimulus, the monkey saccaded to either the left or right response target to receive a juice reward.

For example, if the rule was color and the test stimulus red, the monkey made a leftward saccade. If the rule was orientation and the test stimulus vertical, the monkey made a rightward saccade.



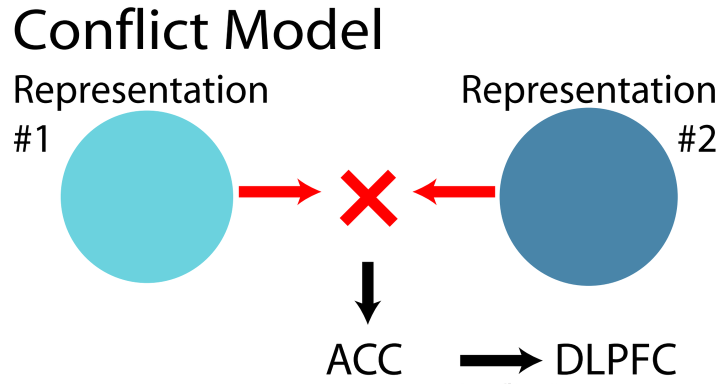


70% of the trials were incongruent – meaning the test stimulus indicated different responses without knowledge of the rule. This made sure the animal consistently applied the rule. The contingency table for all possible combinations of rule and test stimulus is pictured to the left.

Each rule was also repeated for at least 20 trials before a probabilistic switch to the other rule, ensuring the animal could not anticipate the rule switch.

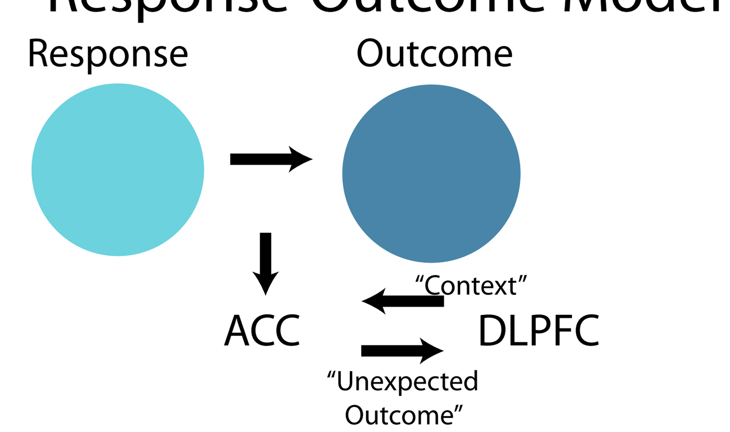
Models of Task Switching

Conflict Model



The conflict model hypothesizes the ACC detects conflict between competing representations and signals the DLPFC to resolve the conflict. Therefore, during task switching, we would expect that ACC activity would increase on rule **switch trials** where rule representations from the previous trial compete with the current rule or on **incongruent trials** where the test stimulus indicates two possible responses.

Response-Outcome Model



The response-outcome model hypothesizes the ACC learns to associate responses and outcomes (reward or non-reward) and signals the "surprise" of unexpected response and outcome combinations -- a prediction error. Importantly, recent models of this type have posited a contextual signal which informs ACC of the expected response-outcome combinations in a given context. Therefore, under this model, we would expect to see greater ACC activity after an error (**previous error trials**) and sensitivity to different **rules.**

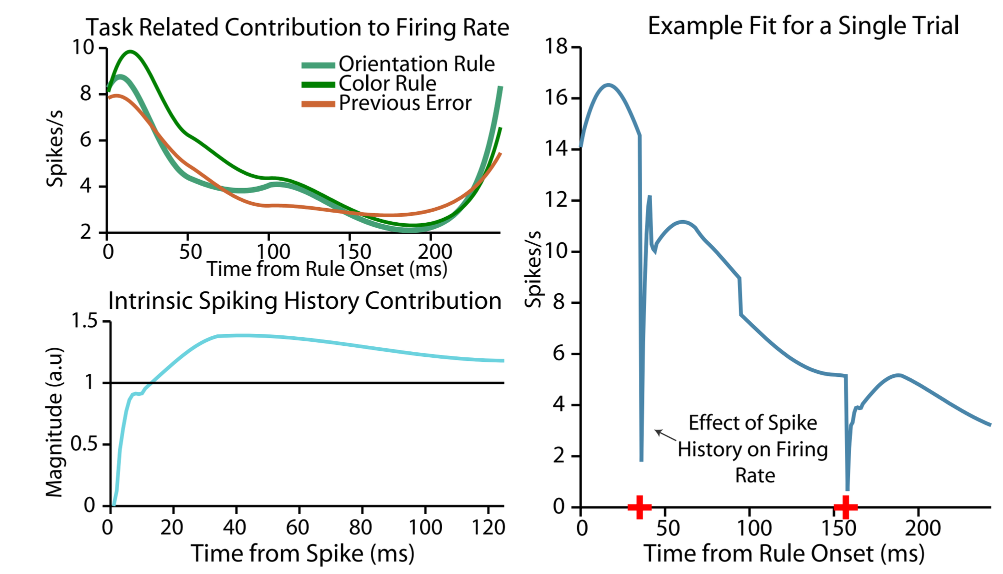
Regression Models: Motivation and Methods

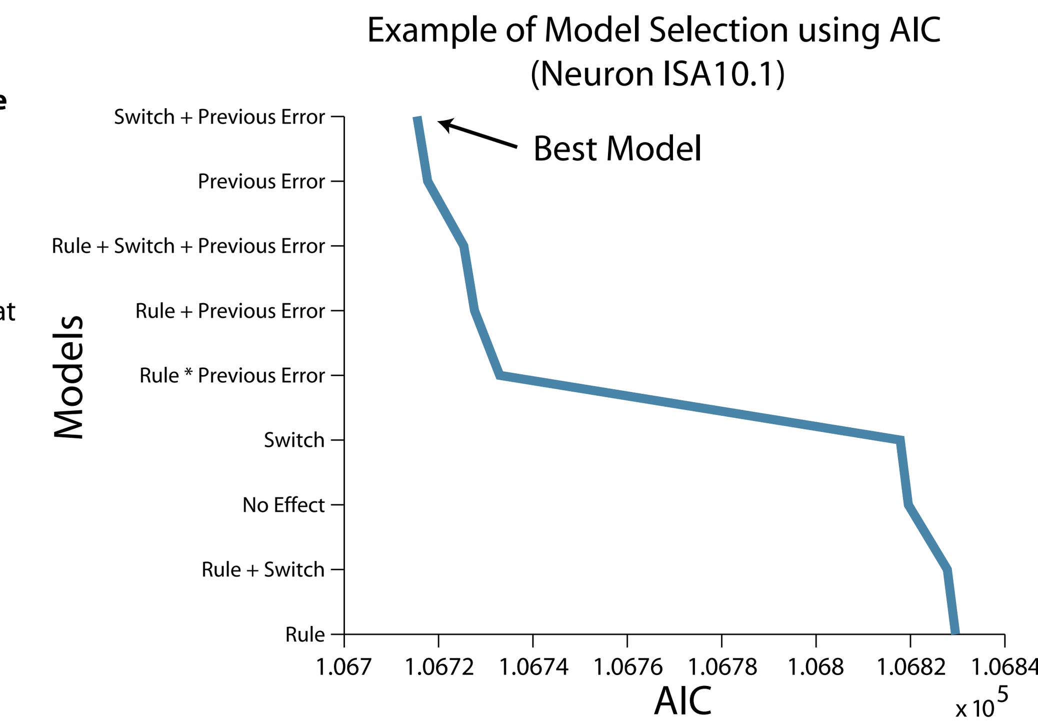
The conflict and response-outcome models make specific, but complex predictions about the behavior of ACC neurons during task switching -- **each model predicts several potential influences on firing rate during the preparation and response periods.** Moreover, prefrontal neurons are known to integrate multiple task parameters, so analysis of any of the potential influences alone might overestimate their effect.

Therefore, in order to compare the conflict and response-outcome models, we modeled each neurons' firing rate as a **point process generalized linear model** that fits a combination of all the potential modulators of firing rate in a particular period of the task. Specifically, we considered a model of the form:

$$\lambda(t) = \lambda_{Conflict}(t) \cdot \lambda_{Response\text{-}Outcome}(t) \cdot \text{Intrinsic Spiking History}$$

where $\lambda(t)$ is the instantaneous spiking rate of a neuron at time t, $\lambda_{Conflict}(t)$ is the contribution of conflict model factors, $\lambda_{Response\text{-}Outcome}(t)$ is the contribution of the response-outcome model factors, and Intrinsic Spiking History is the contribution of the neuron's own spiking history in the previous 125 ms. We used spline basis functions to allow for non-linear functions of time and spiking history.

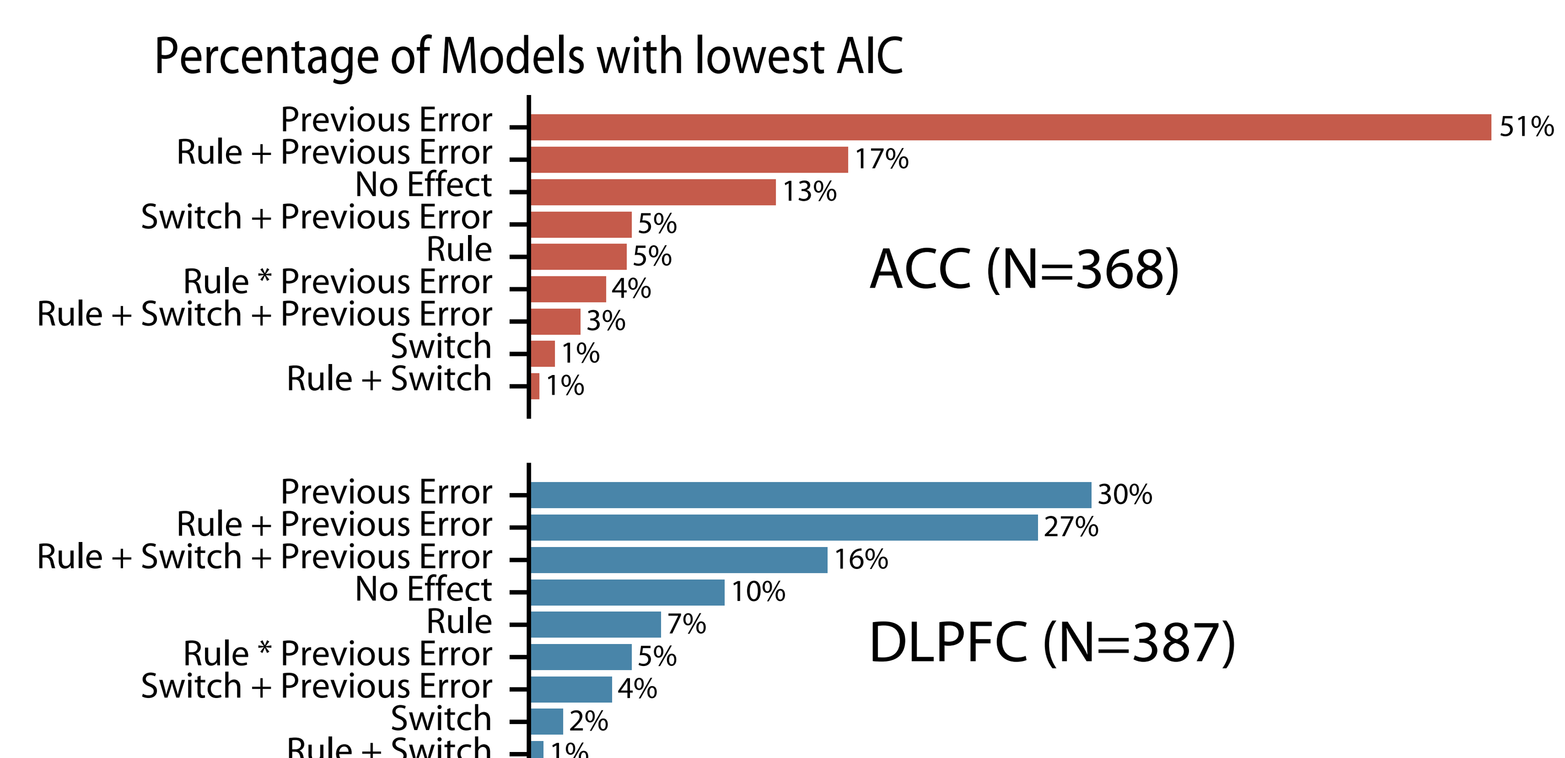


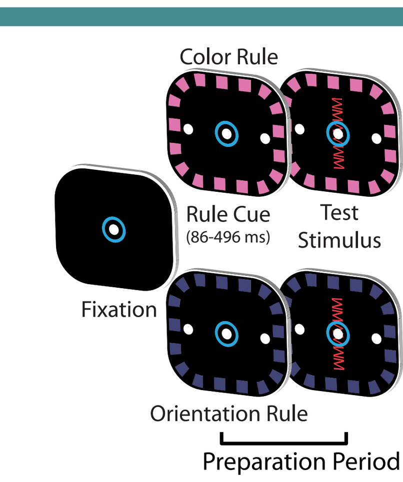


To evaluate the importance of the conflict and response-outcome factors to a neuron's firing rate, we used the **Akaike Information Criterion (AIC).** The AIC is an information-theoretic measure of **how well a model fits the data, subject to a penalty for the number of factors used in a model** -- it is an assessment of the parsimony of a model. Models that are more parsimonious with the data have a lower AIC.

We selectively dropped factors in the models corresponding to the conflict and response-outcome models respectively and assessed which model gave the lowest AIC. **We reasoned that over a population of neurons, the models that most frequently had the lowest AIC were the best models for neurons in a particular area.**

Preparatory Period

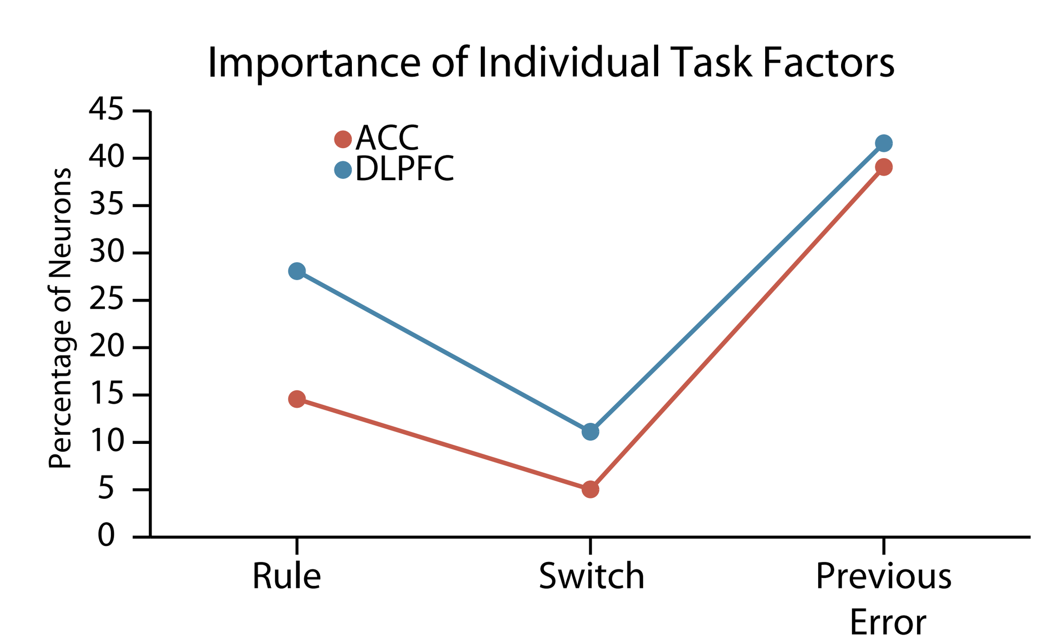




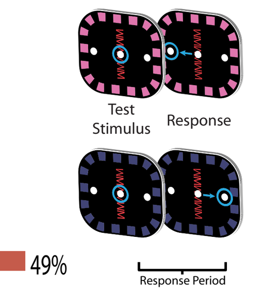
If the conflict model is correct, models that differentiate between conditions with high and low conflict should best fit the data. Therefore, in the preparatory period, ACC neurons should prefer models that take into account the rule switch (**switch trials**).

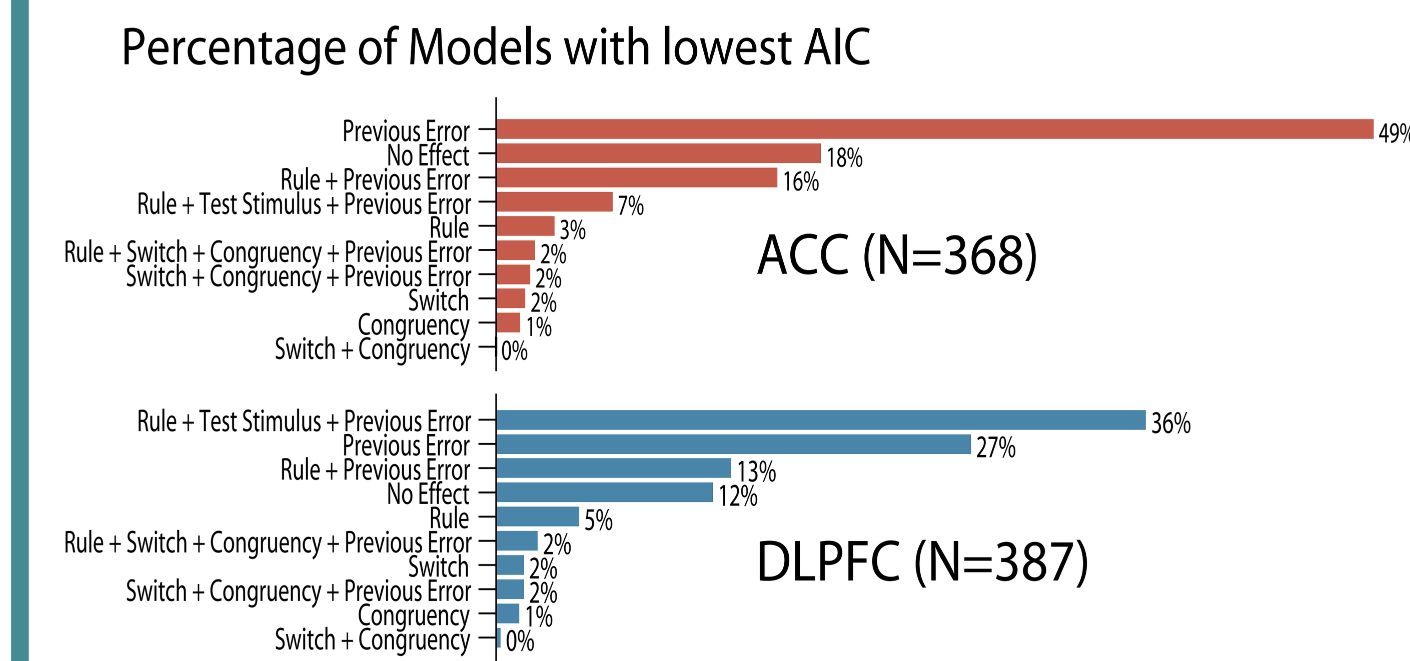
Similarly, under the response-outcome model, models that differentiate between unexpected errors (**previous error trials**) and different contexts (**rule**) should best fit the data.

We find the best models for ACC neurons in the preparatory period are overwhelmingly those that differentiate between unexpected errors and context.



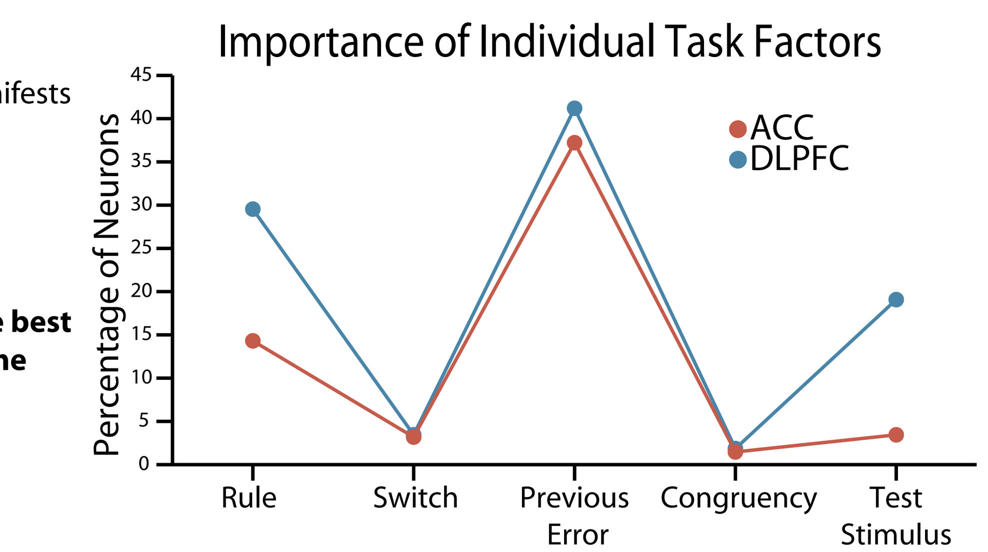
Response Period



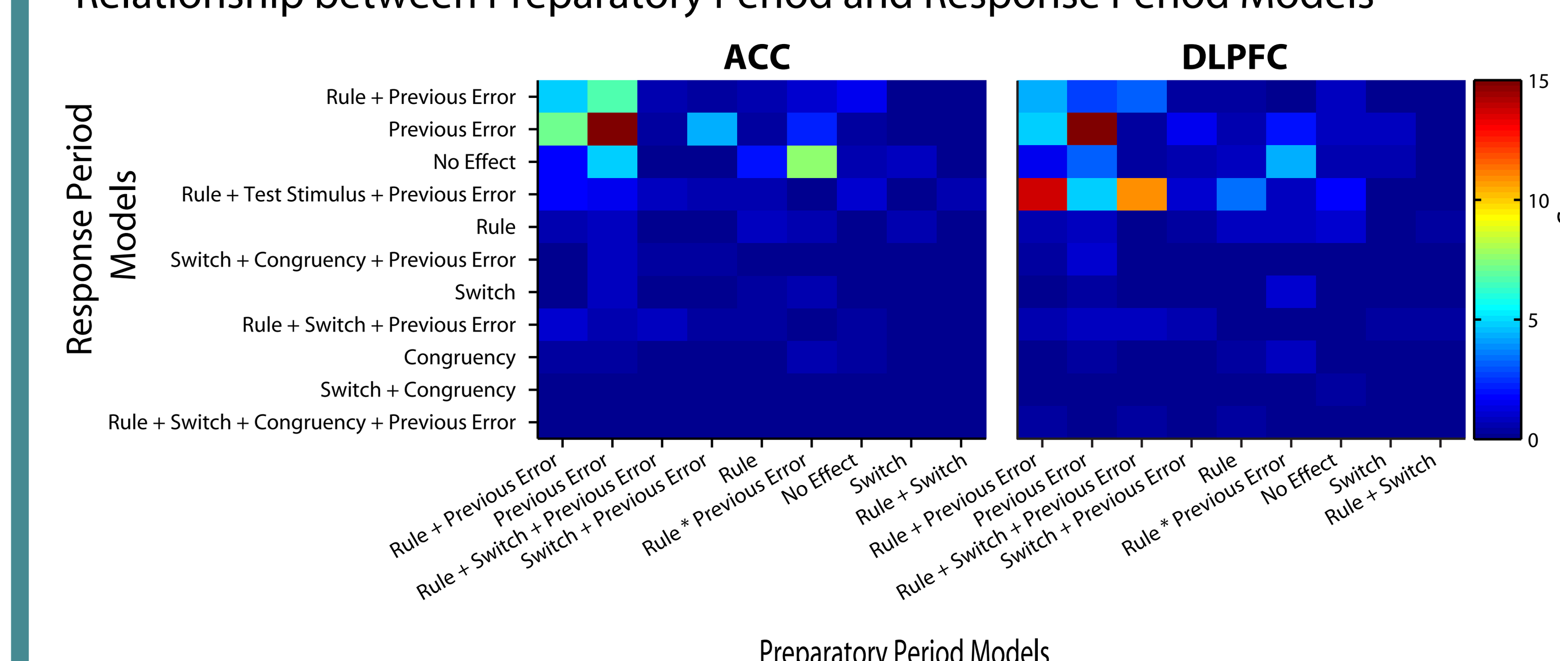


It is possible that conflict activity manifests later during the response period, or is specific to response conflict. Thus, in addition to rule switches, we also considered **incongruent trials.**

Similar to the preparatory period, **the best fitting models for ACC neurons in the response period were those that considered rule or an unexpected outcome** (**previous error**).



Relationship between Preparatory Period and Response Period Models



Summary

1. We considered a complex set of potential models for ACC neurons and find considerable support for the response-outcome model, even when considering a previously unconsidered source of conflict -- the rule switch.
2. Our results are consistent with a division of labor between regions of prefrontal cortex. Although a number of DLPFC neurons are sensitive to unexpected outcomes, they are also highly sensitive to task-relevant parameters such as the rule and test stimulus, while ACC neurons primarily reflected unexpected errors and rules.