



Comments and Controversies

Medial prefrontal cortex activity correlates with time-on-task: What does this tell us about theories of cognitive control?

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ABSTRACT

A paper by Grinband et al. (this issue) argues that dorsal medial prefrontal cortex (mPFC) activity reflects time-on-task rather than conflict or error likelihood. In this commentary, Brown suggests that the findings are consistent with a new model in which mPFC learns to predict the nature and timing of action outcomes. The new model predicts that time-on-task effects coexist with distinct error likelihood effects, a result which is consistent with other recent findings from fMRI and monkey neurophysiology.

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The medial prefrontal cortex (mPFC) and especially anterior cingulate cortex (ACC) has been the subject of intense study especially in the last 15 years. Empirical findings as well as theoretical and computational models have abounded, but the controversy remains. In this issue, Grinband et al. (2011) provide an important contribution to the range of known effects in mPFC, focusing on the positive correlation between reaction time (RT) and mPFC activity. Their results are striking and yet in many ways consistent with prior findings showing greater activity with longer time on task (Burle et al., 2008; Yeung and Nieuwenhuis, 2009).

The question that arises from these findings is what the results mean for our theories of mPFC. While arguing strongly against conflict and error likelihood accounts, the paper offers little in the way of specific theoretical proposals, aside from passing references to possible general functions of planning, switching, and inhibitory control. This is symptomatic of a larger issue with mPFC research in that theoretical development has been strong overall but has not kept pace with the even greater number of new effects reported. Empirical results from mPFC have multiplied and fractured across species to such a degree that many have questioned whether a unified theoretical account is even possible (Cole et al., 2009).

When we introduced the error likelihood model of ACC six years ago (Brown and Braver, 2005), I hoped that it would provide a way forward to reconcile a larger body of findings. The error likelihood proposal continues to generate much healthy debate. The present Grinband et al. paper argues that in the countermanding task originally used to test the error likelihood hypothesis, RTs are longer in the high vs. low error likelihood conditions, so that general correlations between RT and mPFC activity could in principle

account for the apparent error likelihood effect. This was in principle a possibility, but it was not in fact the case. There was a slightly longer average RT in high error likelihood trials, but we were aware of this as a potential confound and performed additional analysis to covary out the RT. The error likelihood effect remained even when controlling for RT (Brown and Braver, 2005). In a follow-up study, there was actually *no difference* between high and low error likelihood RTs, for the critical correct trials with no countermand signal. Again, the error likelihood effect remained and furthermore correlated with risk avoidance traits (Brown and Braver, 2007). Thus error likelihood effects cannot be accounted for solely on the basis of time-on-task.

Nonetheless, the error likelihood computational model turned out to be limited in that it could not account for various data, such as the larger error effects when error likelihood is low (Brown and Braver, 2005), and it is not clear how it could account for the present finding of positive correlations between time-on-task and mPFC activity. We have therefore proposed a new model that casts mPFC as learning to predict the outcomes of actions (Alexander and Brown, 2010, submitted for publication). We refer to this as the Prediction of Response Outcomes (PRO) model, of which the error likelihood model is a special case. In the PRO model, the probabilities of all possible outcomes (good as well as bad) are represented, and these predictions are compared against the actual outcomes.

Of particular relevance here is that in the PRO model, the outcome probabilities are *temporally structured*, so that cell activities representing the outcome probabilities grow larger as the timing of the expected outcome approaches. If the expected outcome is unexpectedly delayed, then the activity predicting the outcome will continue to increase until the outcome actually occurs, at which point the prediction activity will cease. This leads necessarily to a positive correlation between mPFC activity and the time interval until the outcome occurs, whether it is a movement or some external feedback from the environment (Alexander and Brown, submitted). We have

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tested this model prediction with fMRI and found that not only does greater RT lead to greater mPFC activity, but delayed external feedback about a correct action also leads to greater mPFC activity (Forster and Brown, 2011). Also, this proposal is consistent with previous monkey neurophysiology findings of supplementary eye field cells that show increasing activity toward predictable events such as movement initiation (Amador et al., 2000; Shidara and Richmond, 2002) yet paradoxically do not control the movement (Stuphorn et al., 2010). More strikingly, our simulations show that this positive correlation between time-on-task and mPFC activity coexists with both error likelihood effects and the effects of incongruent stimuli that have previously been interpreted as reflecting response conflict (Alexander and Brown, submitted), as well as a large body of other reported effects in mPFC.

Given the above, we welcome the findings of the Grinband et al. paper, as they provide useful and strong constraints on candidate theories of mPFC function.

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