

## Comments and Controversies

## Conflict, error likelihood, and RT: Response to Brown &amp; Yeung et al.

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We would like to thank our reviewers and the authors of the commentaries on our paper. Though we may have scientific differences, the criticisms raised in the commentaries will undoubtedly improve our understanding of the neural basis of decision making and provide a springboard for future experiments. In our response, we clarify why our data are incompatible with both the error likelihood and the conflict monitoring models presented by Brown and by Yeung et al., respectively.

## The error likelihood model

Brown (2011) argues that time on task is not a likely confound in the experimental design of previous error likelihood studies that activated the dorsal medial frontal cortex (dmFC, often referred to as “anterior cingulate”; Brown and Braver, 2005, 2007). Specifically, in the countermanding task used by Brown and Braver, differences in RT between conditions were small or non-existent and, when present, were controlled by incorporating the RTs into the general linear model used to analyze the BOLD data. However, even in the absence of RT differences between conditions, the critical issue in countermanding tasks is the “time on task” as measured by the time the subject is actively monitoring for the countermanding cue. When the cue is delayed in these tasks, working memory and attentional demands are extended for longer durations, which should result in larger BOLD responses. When the cue is not delayed, shorter cognitive demands should result in smaller BOLD responses. RTs may or may not be related to this duration depending on factors such as the subject’s speed/accuracy tradeoff, motivation, and strategy. This example illustrates how error likelihood could be confounded with time on task despite the lack of RT differences

between conditions. Moreover, we welcome Brown et al.’s Prediction of Response Outcomes (PRO) model and are interested to learn whether it is consistent with our finding that, in the Stroop task, no relationship between error likelihood and dmFC activity exists.

## The conflict monitoring model

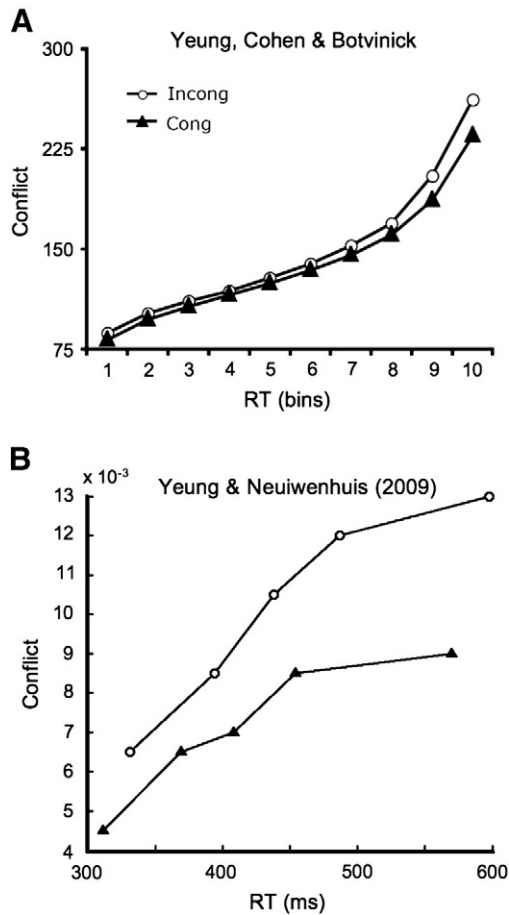
The goal of our study was to critically evaluate the predictions of the conflict monitoring model. Thus, we started with the definitions provided by the original authors of the model. For example, Carter et al. (1998) stated that “response competition arises when a task elicits a prepotent but inappropriate response tendency (manifested as activity in the incorrect response channel) that must be overcome to perform correctly. These conditions are also more likely to elicit incorrect responses.” Similarly, Botvinick et al. (2001) defined conflict as the “simultaneous activation of mutually inhibiting [response] units” and predicted that “ACC activation would be greater on incompatible trials, as this is where conflict is greatest.” Such statements suggest that conflict (1) involves the co-activation of competing response options; (2) is greatest when stimulus features are associated with incompatible responses; and, critically, (3) is linked to increased error likelihood under most conditions, particularly on incompatible trials. These descriptions of the conflict monitoring model assert that conflict and error likelihood are correlated.

To test that the computational model of conflict we used was compatible with these predictions, we simulated the effects of conflict on RT and error likelihood. We used Matlab code written by Matthew Botvinick (Botvinick et al., 2001) and applied by Siegle et al. (2004) to simulate conflict differences in depression. The model (Fig. S2 of Grinband et al., 2011) makes predictions that appear consistent with the conclusions made by Botvinick et al. (2001), Carter et al. (1998), and Botvinick et al. (1999). Specifically, it predicts that both RT and error likelihood are greater on incongruent trials and that these effects are due to the presence of conflict.

In their commentary on our article, Yeung (2011) present a conflict monitoring model (a variant of the basic model discussed previously, but presumably with different parameter settings) that makes different predictions from the Botvinick model. They simulate a case in which conflict closely tracks RT on both incompatible and compatible trials, and shows no effect of congruency (Fig. 1A). Thus, for any given RT, it predicts that congruent and incongruent trials will have equal levels of conflict, a result that appears consistent with our data.

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**Fig. 1.** Predictions of Yeung and Nieuwenhuis (2009) model. (A) Model replotted from Yeung (2011) reply to our article. There are no differences in conflict between congruent and incongruent trials. (B) Data replotted from Fig. 2A of Yeung and Nieuwenhuis (2009). Large differences in conflict exist between congruent and incongruent trials even after controlling for RT differences. Each point represents an RT quantile. Because bin position was different between conditions, data was plotted against ms rather than bin number.

Although there may exist conditions under which compatibility effects are completely mediated by RT, as in Yeung et al.'s simulation, it is not clear that such conditions hold in a wide variety of experimental situations. For example, Yeung et al.'s simulation appears to contradict results from another previously published conflict monitoring model (Yeung and Nieuwenhuis, 2009; Fig. 1B). Unlike the simulations by Yeung et al. (Fig. 1A), the Yeung and Nieuwenhuis model estimated conflict to be substantially greater for incongruent than congruent trials (Fig. 1B). The relationship between stimulus congruency and conflict appears to depend entirely on which implementation of the model is used. Given that the Botvinick et al., Yeung and Nieuwenhuis, and Yeung et al. models all make different predictions, it is unclear whether a single unified model of conflict monitoring exists.

A second feature of the Yeung et al. model (Fig. 1A) is its prediction that greater activation of the incorrect response results in fewer errors. Though this appears counterintuitive, Yeung et al. claim it can be easily explained. Conflict can stem not only from the stimulus but also from a variety of independent sources, such as sensory noise, attentional fluctuations, and momentary response biases. In fact, they claim that variance from these types of sources dwarfs congruency-related conflict effects, which explains why "conflict" can be as strong or stronger on compatible trials as on incompatible ones. Thus, their model does not differentiate conflict effects that arise from situations with clear competing responses – which the incongruent- vs. congruent-trial comparison was designed to identify – from speed/

accuracy trade-offs due to fluctuations in sensorimotor noise, changes in task goals or rules, motor readiness, and other processes.

Insofar as conflict is defined as "any sensorimotor or cognitive process that lengthens RT", as Yeung et al. appear to do, their model is compatible with our data. However, we believe this definition trivializes the idea of conflict. Conflict is no longer defined as competition between response options, but rather arises from a less well-specified set of processes. This definition leads to strange conclusions, for example: RT variability in a simple signal detection task, with only a single response option, is due to the "conflict" created by sensory noise. Most studies of conflict monitoring, including the earlier studies by Cohen, Carter, Botvinick, and colleagues (Botvinick et al., 1999; Botvinick et al., 2001; Carter et al., 1998), explain RT variability due to incompatible stimulus-response relationships, not the speed/accuracy trade-offs present in all reaction-time tasks. If neither the stimulus conditions (i.e. congruent vs. incongruent), nor the internal causes, that generate 'conflict' can be specified precisely, the ability to test and falsify the conflict account of dMFC is diminished.

### Alternative models of dMFC activity

Electrophysiological studies (Deco and Rolls, 2003; Histed and Miller, 2006; Olson, 2003) have demonstrated that dMFC neurons encode spatial and sensorimotor task demands consistent with a role in working memory and spatial attention. All tasks requiring a response from the subject place a load on the working memory/attention systems from the onset of a stimulus until a response is made. Thus, it is possible that dMFC stores task-related stimulus/response parameters or maintains attentional focus on the stimulus.

To test this hypothesis we asked 17 subjects to view a flashing checkerboard of variable duration and press a button when the stimulus disappeared. In this paradigm, the stimulus was unambiguous, only one response was possible, no choice decision was required, and no errors were made. Thus, error likelihood was uniformly zero and no competition between response alternatives existed. The only common feature between the checkerboard and Stroop tasks was an identical temporal structure. Nevertheless, the checkerboard task produced the same pattern of neural activity in dMFC as the Stroop task (Fig. S3 of Grinband et al., 2011). Specifically, the dMFC response was proportional to the duration of each checkerboard (i.e. time on task). To explain this result in the context of the conflict monitoring model, one would need to postulate that long duration checkerboards generate greater conflict than short checkerboards. We believe this is not a parsimonious account.

### Summary

The fundamental problem in the original studies of conflict is the lack of an adequate null hypothesis, specifically, that the dMFC is driven by task general processes (e.g. working memory, spatial attention) rather than conflict. Tested against this null hypothesis, we found no evidence in favor of dMFC's role in conflict monitoring – dMFC activity was uncorrelated to stimulus congruency or error-likelihood. The Yeung et al. model (2011 – current issue) proposes that conflict is independent of stimulus congruency and highly correlated to RT; that is, when RT is held constant, congruent and incongruent trials have equal conflict. However, if conflict is independent of congruency, then tasks that manipulate congruency, such as those used in the original conflict studies (Botvinick et al., 1999; Botvinick et al., 2001; Carter et al., 1998), are neither necessary nor relevant for arguing in favor of this model. The model further implies that the large differences in error likelihood between congruent and incongruent trials are unrelated to conflict, an implausible assertion. Finally, this model makes identical predictions for dMFC activity whether it is specialized for detecting conflict (alternative hypothesis)

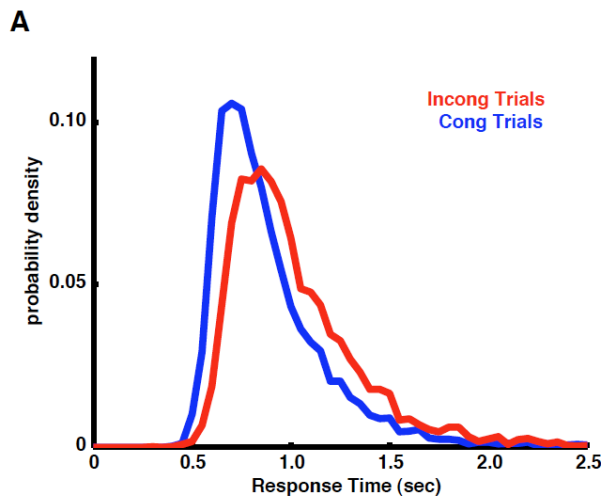
or involved in task general processes (null hypothesis), making it impossible to test using standard fMRI methods.

Conflict was first defined as the competition between mutually exclusive response options. This definition helped explain greater RT and error likelihood on incongruent vs. congruent trials in a wide variety of experimental paradigms. Yeung et al.'s definition of response conflict does not clearly differentiate conflict from other sensorimotor, memory, and attentional processes, weakening its usefulness as a psychological construct. The notion that dMFC is a conflict detector is difficult to maintain unless one accepts this diffuse definition. We welcome further discussion on these issues.

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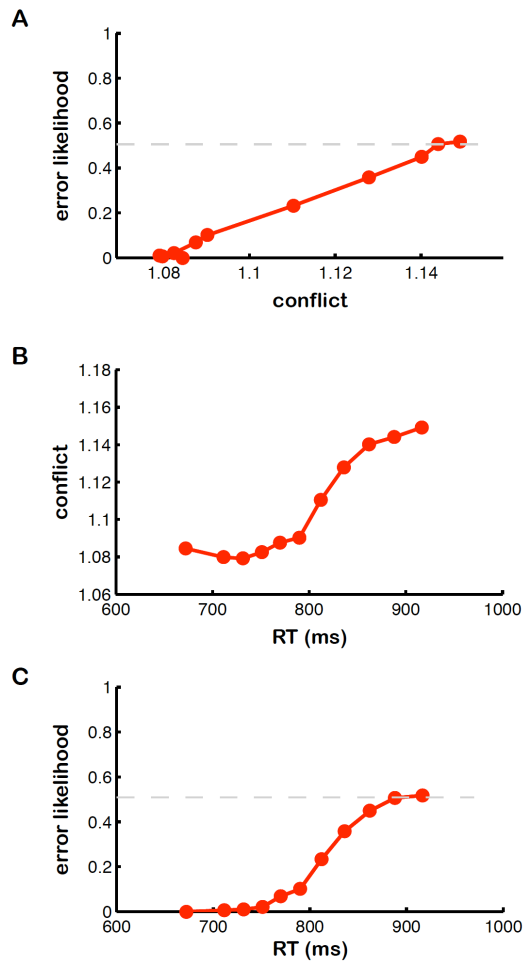
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## Supplementary Materials

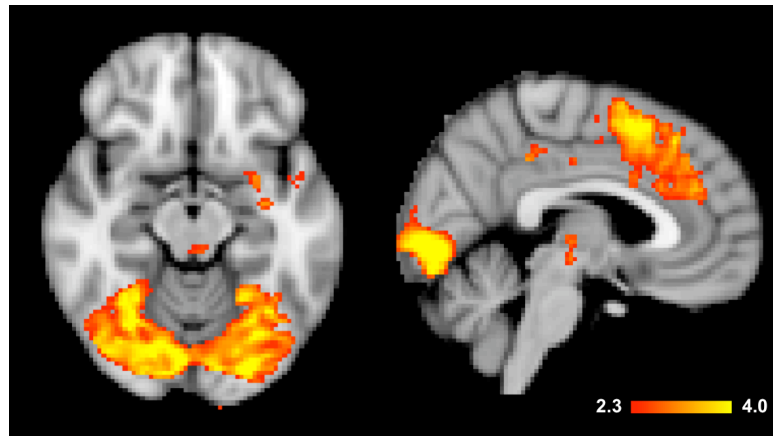


**Figure S1 – RT probability density.** Incongruent trials have longer mean response times than congruent trials. Both the conflict monitoring and the time on task accounts predict increased neural activity on incongruent trials, either from increased conflict or longer time on task. When differences in the shape of the distributions are not considered, conflict and time on task become confounded.

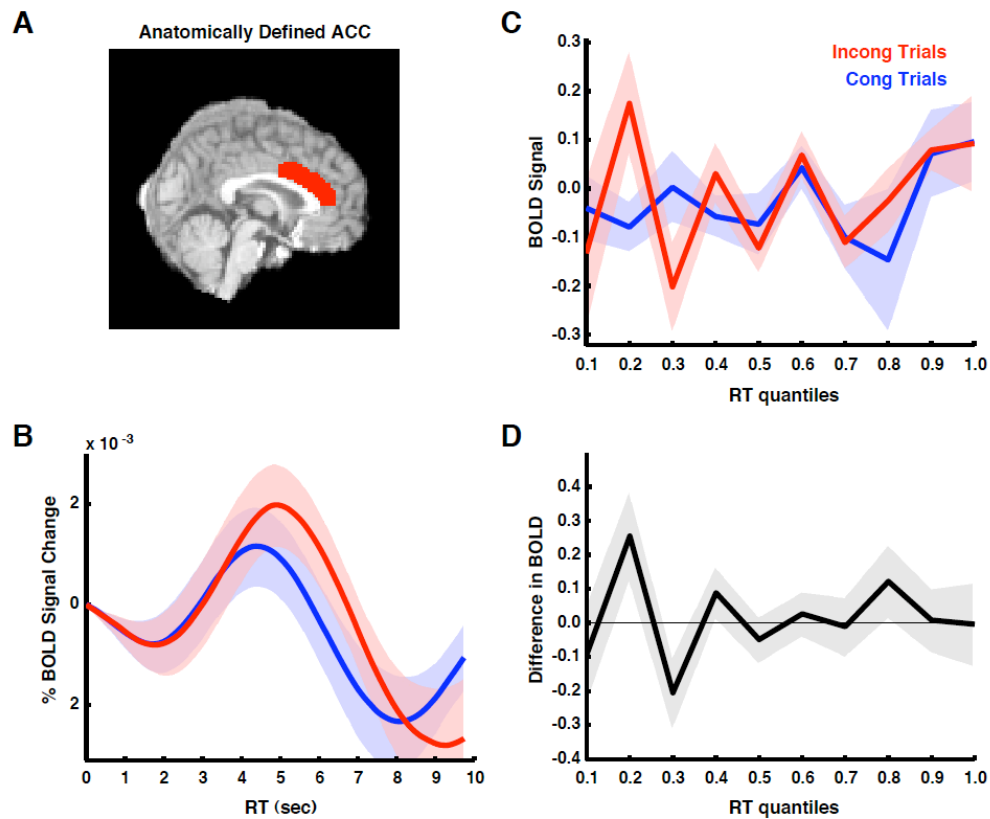
To determine the relationship between conflict, error likelihood, and RT, we performed simulations using the conflict monitoring model (Botvinick et al., 2001; Siegle et al., 2004). Parameters were set to those used in Botvinick et al (2001): tau (rate of propagation through network) = 0.1; std dev of noise = 0.015; response threshold = 0.6; task input strength = 0.5; task unit gain = 1; bias vector = [0 0 -4 -4 -4 -4 -4 -4 0 0]. The unit weighting were a = -2, b = 4, c = 1.5, d = 2.5, e = 2, f = 2, m = -2, n = -2, where a = stim layer inhibition, b = color to color-task unit, c = color to color-response unit, d = word to word-response unit, e = word to word-task unit, f = colors to color-task unit, m = response layer inhibition, n = task layer inhibition. The network was primed with 1000 iterations.



**Figure S2– Conflict monitoring model.** We executed 10,000 iterations of the conflict monitoring model to determine the relationship between conflict, error likelihood, and RT. (A) Error likelihood is linearly related to conflict. Thus, error likelihood can be used to determine if conflict is present after equating RT between congruent and incongruent trials. (B) Conflict is sigmoidally related to RT. (C) Error likelihood is sigmoidally related to RT. Our behavioral data does not show this sigmoidal relationship (see Fig. 4A). Furthermore, contrary to predictions of the conflict monitoring model, the relationship between error likelihood and RT changes with congruency.



**Figure S3 – Flashing checkerboard.** To determine whether the dmFC can be activated in the absence of response conflict we asked a new group of subjects ( $n = 17$ ) to view a flashing checkerboard and press a button whenever the stimulus disappeared. The stimuli were presented with random inter-trial intervals (0.1 – 7.1 sec) and randomly generated stimulus durations (gamma distributed, mean = 800 ms, min = 500 ms – these are RT values typically found in the Stroop task). In this task, no choice decision is made, no errors can occur, and only a single response is possible; thus, response conflict cannot exist. A GLM analysis was performed using a single regressor that modeled the checkerboards as a set of variable duration boxcars with onset and offset times that matched the actual stimuli. The task activated visual cortex and dmFC, consistent with the time on task account.



**Figure S4 – BOLD activity for anatomically defined ACC.** (A) The ACC was defined as the cortex between the cingulate sulcus and corpus callosum posterior to the genu and anterior to the collosal midpoint. (B) The hemodynamic responses for correct congruent and incongruent trials are about two orders of magnitude smaller in the anatomically-defined ACC than in the functionally defined dMFC mask. (C) The BOLD signal was integrated over 10 sec and plotted as a function of RT quantile. (D) No significant differences were present between congruent and incongruent trials ( $p < 0.05$ ).

The voxels used in the model-free analysis (Fig 3) were identified using a functional contrast of the two conflict conditions (i.e. the region of interest in Fig 2A). This ROI is located above the cingulate sulcus. Since previous studies have focused on the anterior cingulate cortex (ACC) as the region involved in conflict monitoring, we repeated the quantile analysis using an anatomically defined ACC mask. The ACC was defined as the cortex between the corpus callosum and the cingulate sulcus, posterior to the genu of the corpus callosum and anterior to the rostro-caudal midpoint of the corpus callosum (Mansouri et al., 2009). There were no significant differences in ACC activity between congruent and incongruent trials (Fig S4). This analysis was repeated using an ACC mask derived from a meta-analysis of 47 conflict-related studies (mask centered on MNI152: 0/20/40) (Nee et al., 2007). This mask also showed a monotonic relationship with RT but no significant differences between conditions.