A neurally-constrained process model of prior-informed decision making

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Abstract:

How does the brain exploit prior information about stimulus probability when selecting actions in response to noisy sensory stimuli? Most behavioral modelling studies account for the influence of priors through a single parameter, typically starting point bias, but it is unclear whether these parsimonious models truly reflect the underlying neural computations. Here we make use of recently characterized human scalp potentials reflecting decision formation to construct and constrain a model of prior-informed decision making. We explicitly modelled two decision levels—a motor-independent representation of cumulative evidence feeding build-to-threshold motor signals receiving additional dynamic urgency components. The starting points of the motor-level signals were directly constrained by neural signals, which built to a fixed threshold at response. The model provided a better fit to behavior across three task regimes (easy, time-pressured and weak evidence) compared to the standard diffusion model and, when simulated based on the behavioral fit, recapitulated an array of condition- and outcome-related effects in the neural decision signals. We found that prior biases in the rate of evidence accumulation as well as starting point were needed to jointly account for the neural and behavioral data, elucidating multilevel adjustments that would not be discernible from behavioral modelling alone.

Keywords: sensorimotor decision making; sequential sampling models; electroencephalography; priors.

Introduction

Extensive theoretical and neurophysiological investigations have converged on the principle that timely and accurate decisions can be made by accumulating sensory evidence up to action-triggering thresholds, as described by sequential sampling models. Here we used neural signals that finely trace the evolving decision process to inform, constrain and test models that capture the potentially multifaceted computational adjustments made by the brain in prior-informed sensorimotor decision performance. We recorded EEG data from 20 human subjects performing a motion direction discrimination task with prior cues indicating the likely direction of motion. Because strategies for incorporating prior information might depend on context, we tested three difficulty regimes in separate blocks: easy, difficult due to speed pressure, and difficult due to weak sensory evidence. The task began with a group of dots moving randomly on the screen, which then changed colour to indicate a balanced (50:50) or biased (75:25) probability for leftward vs rightward motion. Coherent motion of the dots then began 836ms after the colour cue. The smooth stimulus transitions ensured that choice-irrelevant EEG signals were minimized, providing a clear view of two distinct decision signals, each of which has been shown to build during decision formation at an evidence strength-dependent rate: the centro-parietal postivitiy (CPP) which traces evidence accumulation independent of sensory or motor task requirements and premotor Mu/Beta activity reflecting preparation of each response alternative (O'Connell, Dockree & Kelly, 2012; Twomey, Kelly & O'Connell, 2016). We drew on these neurophysiological signals to develop a two-level neurally-constrained accumulation-to-bound model.

Model Development

Consistent with previous observations of effector-selective decisions signals (e.g. area LIP), the motor-level Mu/Beta signals (contralateral to response) reached a fixed amplitude just prior to decision reports across all conditions and response times (RTs), consistent with a fixed action-triggering bound set at the motor level. Prior to evidence onset, however, Mu/Beta levels systematically varied across task and prior probability conditions (Figure 1). Using these levels to constrain starting point parameter values, we modelled the motor-level process as the sum of the accumulated evidence fed from the CPP and a linearly increasing urgency signal whose slope was a free parameter for each of the 3 conditions. The bound of the motor-level process was set to 1 for all conditions and was used as the scaling parameter for the model, while the starting points were set to the Mu/Beta levels just prior to evidence accumulation as a proportion of the threshold. The CPP showed no starting-level effects, consistent with our prior work suggesting that it provides a pure index of cumulative evidence independent of strategic motor-level adjustments (Steinemann, O'Connell & Kelly, 2018), and was not used to constrain the model.

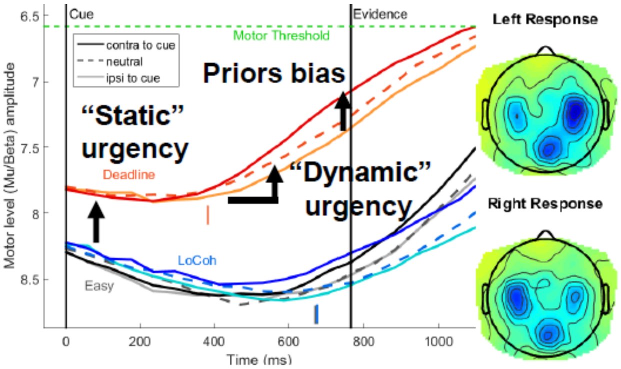

Figure 1: Left: Motor level (Mu/Beta) signal amplitude from cue onset to just after evidence onset in easy (black), low coherence (blue) and time pressured (red) conditions. Right: Topography for Mu/Beta desynchronization for left and right responses.

Results and Discussion

We tested two versions of the resultant neurally-constrained model: one in which prior bias was mediated by starting point alone and another that also incorporated a drift rate bias. We also compared their performance with two similarly parameterized standard diffusion models. The standard diffusion models failed to capture the fast guesses and lack of skew in the response-time distributions for the more difficult conditions (both AIC=200). Both versions of the neurally constrained model did a good job of capturing the major behavioral effects (both AIC=81), except that only the model incorporating drift bias was able to capture the sustained effect of prior bias for long RTs in the low coherence condition. Starting point bias, on the other hand, primarily affects decisions with short RTs as its effect dissipates over time.

While the CPP showed no effect of priors at evidence onset, there was a clear effect at response. The CPP amplitude at response in the time pressured condition was higher for invalid prior cues than for valid cues, reflecting the need to accumulate more evidence in invalid trials to overcome the starting bias that was reflected in the motor-level process. This effect, however, was absent in the low coherence condition despite the clear prior effects in the starting points. We theorized that this could be due to bias in the rate of evidence accumulation which would result in an increase in the CPP level at response for trials with a valid cue. We simulated a "CPP-like" signal for these models reflecting the pure accumulated evidence and found that the model incorporating drift rate bias was better able to reproduce the relative amplitudes of the CPP at response across prior conditions, especially under low coherence. Finally, we introduced term into the objective function for the behavioral fit to penalize divergence between magnitudes of effects of priors on pre-response CPP amplitude and the simulated accumulated evidence. While this naturally resulted in a poorer behavioral fit, the model with drift rate bias emerged as much more dominant.

Our use of neural signals to directly constrain the starting levels and bounds of the decision process has enabled us to develop a more detailed mechanistic model than would have been possible based on behavioral data alone. We were then able to increase confidence in our findings by empirically testing predictions that the new model generated regarding choice-relevant neural dynamics. This work demonstrates a powerful approach for combining neural and behavioral modelling to garner insights into the brain's multi-level decision processing architecture.

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