Toy MT-LIP integrator

To explore what would be expected from canonical two-stage feed-forward models of sensory decision making – both in terms of the signal response and the inter-areal noise correlation – we simulated neurons that integrated populations of *m* idealized spiking MT neurons. The simulated MT populations consisted of two pools of neurons that were tuned for the two possible directions and connected through limited-range connections only. Correlated spiking was simulated using conditionally Poisson neurons with causal coupling filters. The spiking of each MT neuron, *i*, at time *t* was generated from a Poisson process:

$$\mathbf{r}_i(t) \sim \mathrm{Poisson}(\lambda_i(t)\Delta)$$

where the binning, Δ, was 1ms. The conditional intensity, λ_i, was given by:

$$\lambda_i(t) = \exp\left(\mathbf{k}_i \cdot \boldsymbol{x}(t) + \sum_{j=1}^{m} \boldsymbol{c}_{i,j} \cdot \mathbf{r}_j(t-1)\right)$$

Where $\mathbf{k}_i \cdot \boldsymbol{x}$ denotes the convolution of the stimulus filters for neuron *i* with the stimulus $\boldsymbol{x}$ and $\boldsymbol{c}_{i,j} \cdot \mathbf{r}_j(t-1)$ denotes the convolution of the coupling filter for neuron *i* with the recent history from neuron *j*. When *i*=*j*, this is the history filter.

Stimulus filters for each MT neuron consisted of a temporal filter that convolved with the contrast of the stimulus and a temporal filter that convolved with the time-varying direction (as in the main text). Both temporal filters were constructed as α functions:

$$\mathbf{k}(t) = \exp\left(\frac{-t}{\tau}\right)\left(1 - \exp\left(\frac{-t}{\tau}\right)\right)$$

Where *t* is time and $\tau = 10\mathrm{ms}$. K was then normalized to have a maximum of 0.08 (Supplementary Math Note Figure 1). The coupling filters **c** were generated from a Toeplitz matrix that decayed exponentially away from the diagonal such that only neighboring neurons had strong coupling. This level of coupling produced weaker noise correlation than we observed in our data (Supplementary Math Note Figure 2). Our results regarding MT-LIP coupling depend on the magnitude and type of correlations in MT. If all MT neurons are independent, we would fail to detect MT-LIP coupling for indirectly connected pairs. We chose to simulate weaker correlations than were observed in the data to provide a conservative estimate on the type of correlations that are present, and because our recordings sampled from neurons that were in the vicinity of each other (typically < 1mm), thus it is possible we sampled largely from the higher end of correlations. Importantly, these simulations did not include shared variability across large populations due to latents (Ecker et al., 2014) or large gain fluctuations (Goris et al., 2014) that are often observed in cortex. If these types of correlations were shared across areas, we would more easily detect MT-LIP dependencies.

The idealized LIP integrator neurons were simulated by taking the cumulative sum of a specified fraction of the MT population and normalizing by the number of neurons being integrated:

$$\lambda_{\mathrm{LIP}}(t) = \mathbf{r}_0 + \frac{1}{n}\int_1^t \mathbf{r}_{\mathrm{MT}} dt$$

where *n* is the number of MT neurons directly projecting to this integrator neuron. Spikes were generated as a Poisson process:

$$\mathbf{r}_{\mathrm{LIP}}(t) \sim \mathrm{Poisson}(\lambda_{\mathrm{LIP}}(t))$$

Choices were generated by comparing $\mathbf{r}_{\mathrm{LIP}}$ at the time of the go signal plus additive Gaussian noise to a threshold. Noise was added to ensure that our simulated LIP neuron had a choice probability in the range observed (and thus did not perfectly predict the choice on each trial).

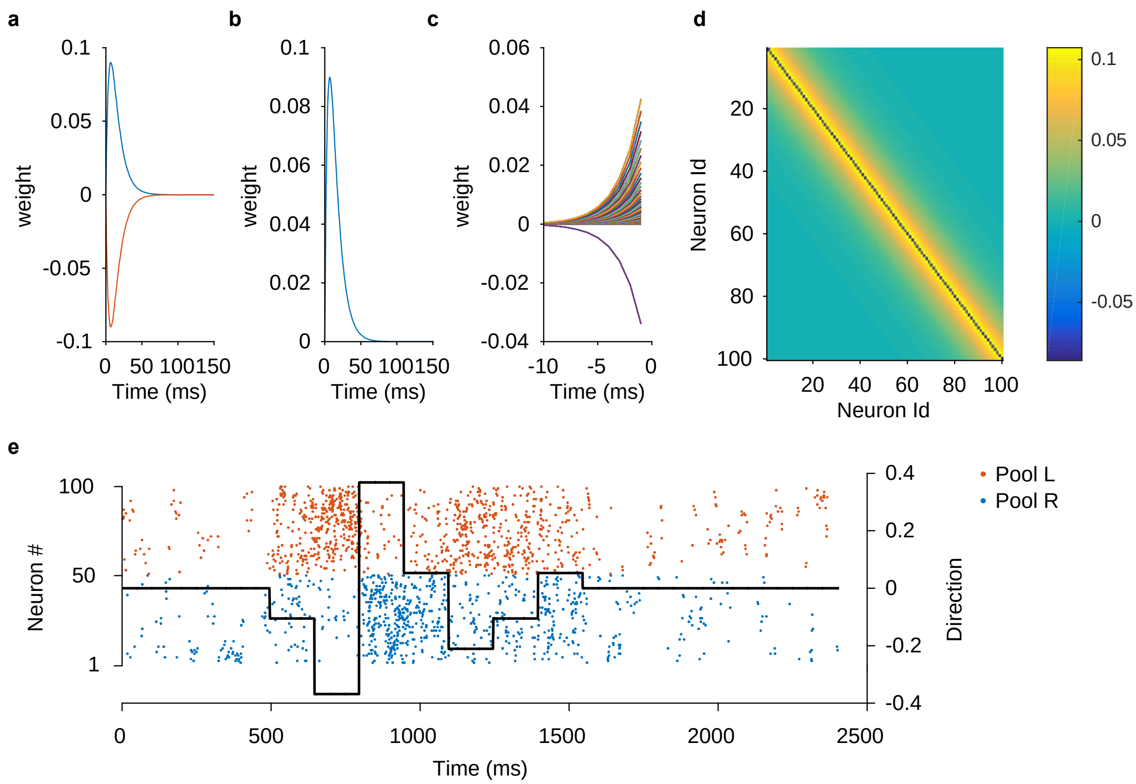
We then ran our GLM analysis on the toy MT-LIP integrator neurons. The first observation is that the GLM with no choice term did not vastly undershoot the choice-dependent ramps of the Toy MT-LIP integrator (Supplementary Math Note Figure 3). This contrasts with the need for the choice-dependent terms to be added for fits to the real LIP data, and likewise confirms that a GLM is capable of returning fits that capture the average dynamics of a true integrator.

We compared an uncoupled model to one with included coupling terms (as in the main text). To ensure that this comparison wasn't biased by directly connected MT-LIP pairs, we included only indirectly connected MT neurons. We simulated an integrator for different fractions of projecting neurons and then estimated coupling kernels for 3 indirect MT neurons – 3 was the median number of simultaneously recorded MT neurons for each LIP neuron in our dataset. Evaluating the likelihood ratio per trial of a model with MT coupling compared with an uncoupled model shows that the GLM correctly identified the dependence on MT (Supplementary Math Note Figure 4)

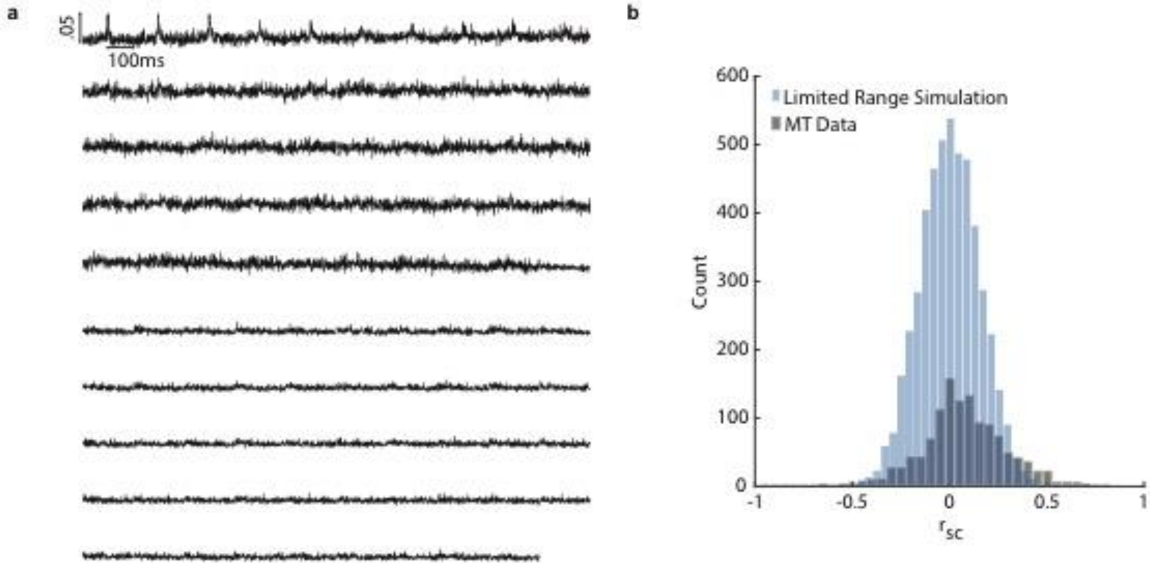
References

Ecker, A. S., Berens, P., Cotton, R. J., Subramaniyan, M., Denfield, G. H., Cadwell, C. R., Smirnakis, S. M., Bethge, M., and Tolias, A. S. (2014). State dependence of noise correlations in macaque primary visual cortex. *Neuron*, 82(1):235–248.

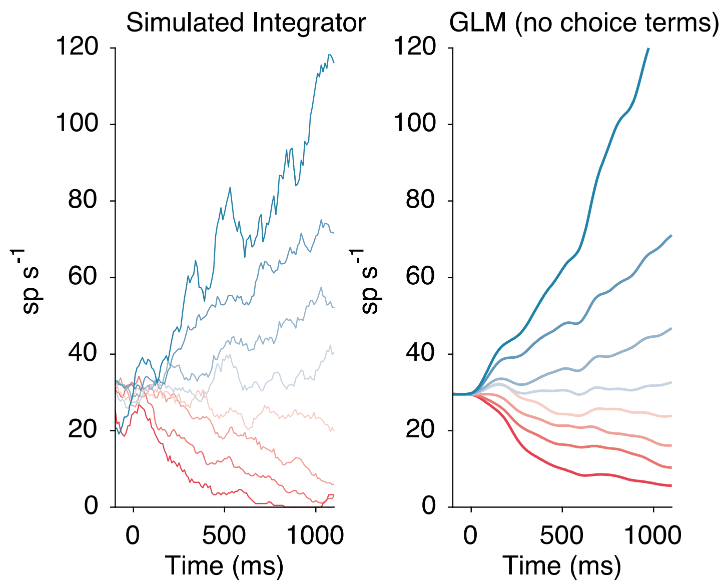
Goris, R. L. T., Movshon, J. A., and Simoncelli, E. P. (2014). Partitioning neuronal variability. *Nature Neuroscience*, 17(6):858–865.



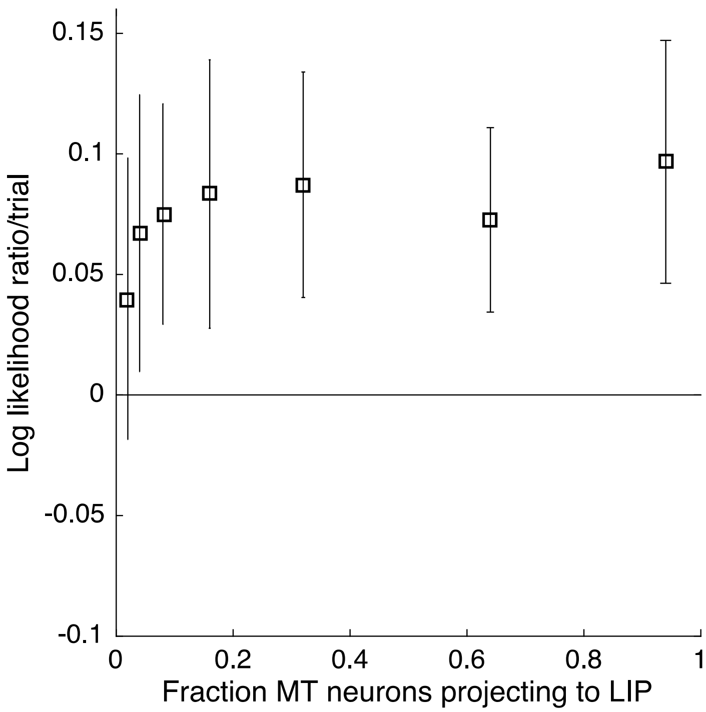
Supplementary Math Note Figure 1: Parameters for simulated MT neurons. (a) direction kernels for simulated “Pref” (blue) and “Anti” (red) pools of neurons. (b) contrast kernel to generate motion onset and plateau (c) Plot of all coupling and history filters from the simulation (d) strength of coupling (sum of the coupling filter) for all pairwise connections. The off-diagonal structure shows that only limited-range correlations were included in this simulation. (e) Example trial from the two simulated pools (spikes overlaid with the direction stimulus for that trial).



Supplementary Math Note Figure 2: Interneuronal correlations in the MT simulations. (a) Cross-correlations for a single simulated MT neuron and the other simulated MT neurons. Correlations were fine time-scale and fell off with distance between the pairs. (b) Spike-count correlations for simulated population (blue) overlaid with measured correlations from our MT dataset (gray). Measured correlations were larger than simulated correlations to simulate a conservative estimate for correlations.



Supplementary Math Note Figure 3: Visualization of simulated integrator neuron next to GLM fit. (left) Motion- and choice-dependent PSTH of a simulated integrator neuron. Red and Blue are the two possible choices. The strength of motion is depicted by the strength of the color. (right) Same analysis for simulations generated by a GLM neuron fit to the simulated integrator. This neuron did not include choice terms or history. In this model neuron, the integration comes from the stimulus filter.



Supplementary Math Note Figure 4: Model comparison for coupled vs. uncoupled model for simulated LIP integrator neurons. We fit the fully-coupled MT-LIP model to simulated MT and LIP units, excluding all directly connected MT-LIP pairs. We ran the simulation with different fractions of the MT population projecting to LIP. Error bars are the standard deviation across cross-validation folds.