

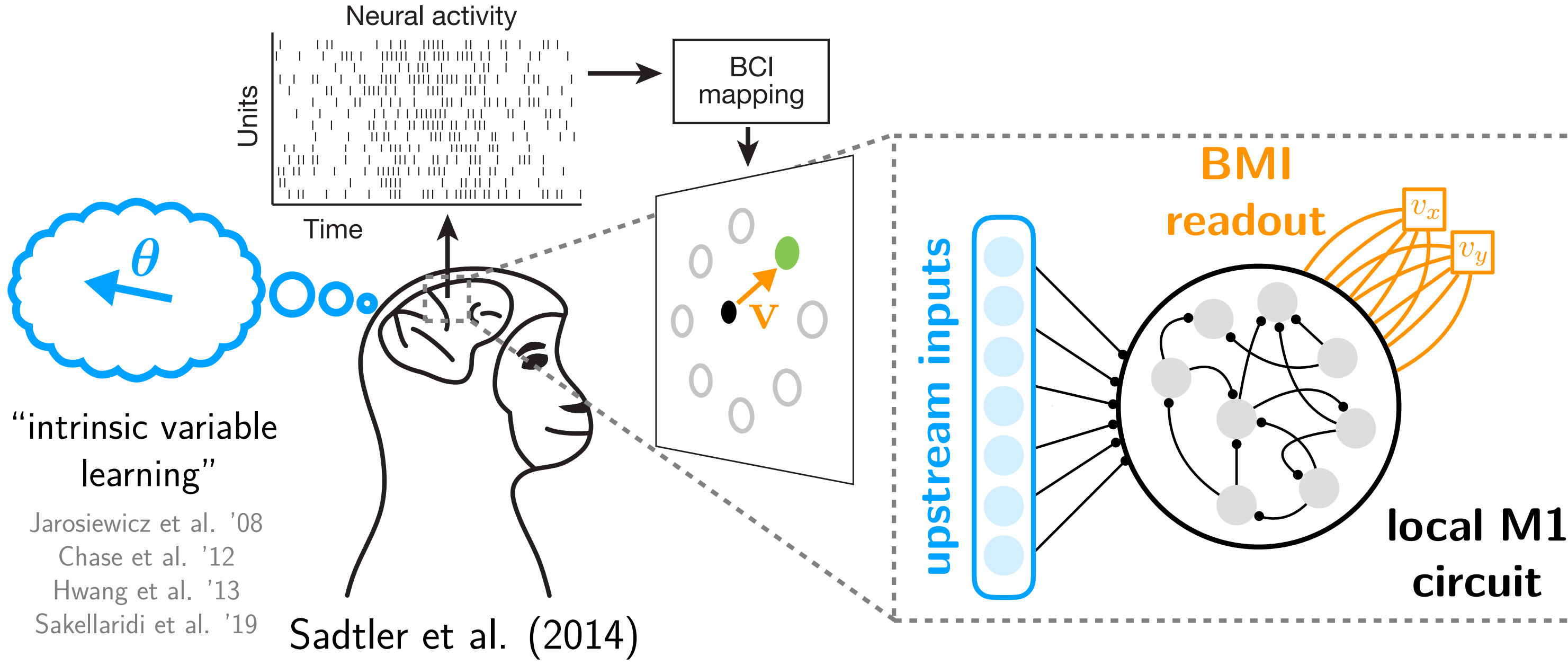
# A motor cortical model of brain-machine interface learning, fast and slow

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## Re-aiming



## Model & Theory

local M1 circuit dynamics  $\tau \dot{\mathbf{x}} = -\mathbf{x} + \mathbf{W}^{rec} \phi(\mathbf{x}) + \mathbf{W}^{in} \mathbf{u}$

upstream inputs  $\mathbf{u} = \phi(\mathbf{M}\boldsymbol{\theta})$ ,  $\boldsymbol{\theta} \in \mathbb{R}^K$

BMI readout  $\mathbf{v}(t) = \mathbf{D}\phi(\mathbf{x}(t))$

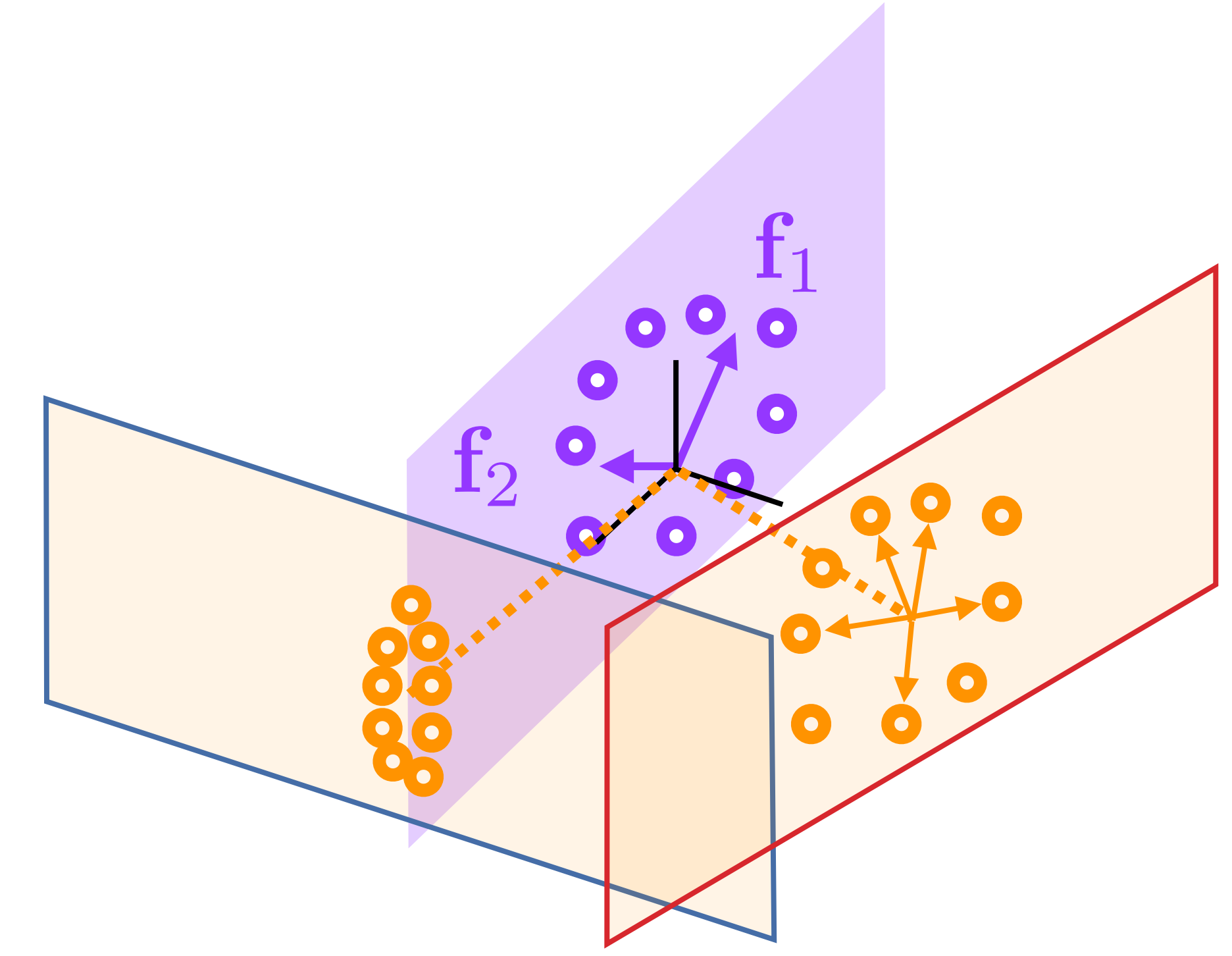
re-aiming  $\hat{\boldsymbol{\theta}} = \arg \min_{\boldsymbol{\theta}} \underbrace{\|\mathbf{v}(t^*) - \mathbf{v}^*\|^2}_{\text{reaching error}} + \underbrace{\gamma \|\boldsymbol{\theta}\|^2}_{\text{metabolic cost}}$

Simple case:  $\phi(\mathbf{x}) = \mathbf{x}$ ,  $\boldsymbol{\theta}$  constant

low-dimensional activity  $\begin{cases} \mathbf{x}(t) = \mathbf{f}_1 \theta_1 + \mathbf{f}_2 \theta_2 + \dots + \mathbf{f}_K \theta_K \\ \tau \dot{\mathbf{f}}_i = -\mathbf{f}_i + \mathbf{W}^{rec} \mathbf{f}_i + \mathbf{W}^{in} \mathbf{m}_i \end{cases}$

optimal average reaching error  $\Rightarrow \mathbb{E}_{\mathbf{v}^*} [\mathcal{E}_{\mathbf{v}^*}(\hat{\boldsymbol{\theta}})] = \frac{1}{2} \sum_{i=1}^2 \frac{1}{(\gamma s_i^2 + 1)^2}$

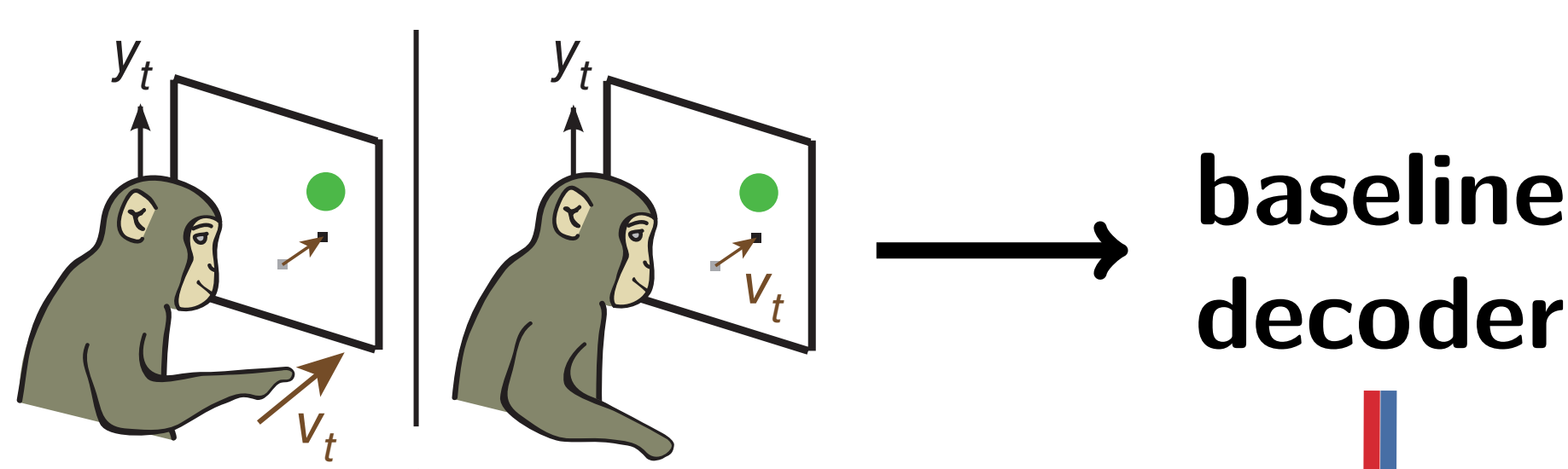
$s_i$  = singular values of  $\begin{bmatrix} \mathbf{D}\mathbf{f}_1 & \mathbf{D}\mathbf{f}_2 & \dots & \mathbf{D}\mathbf{f}_K \\ \vdots & \vdots & \ddots & \vdots \end{bmatrix}$



## Simulations: 2D re-aiming

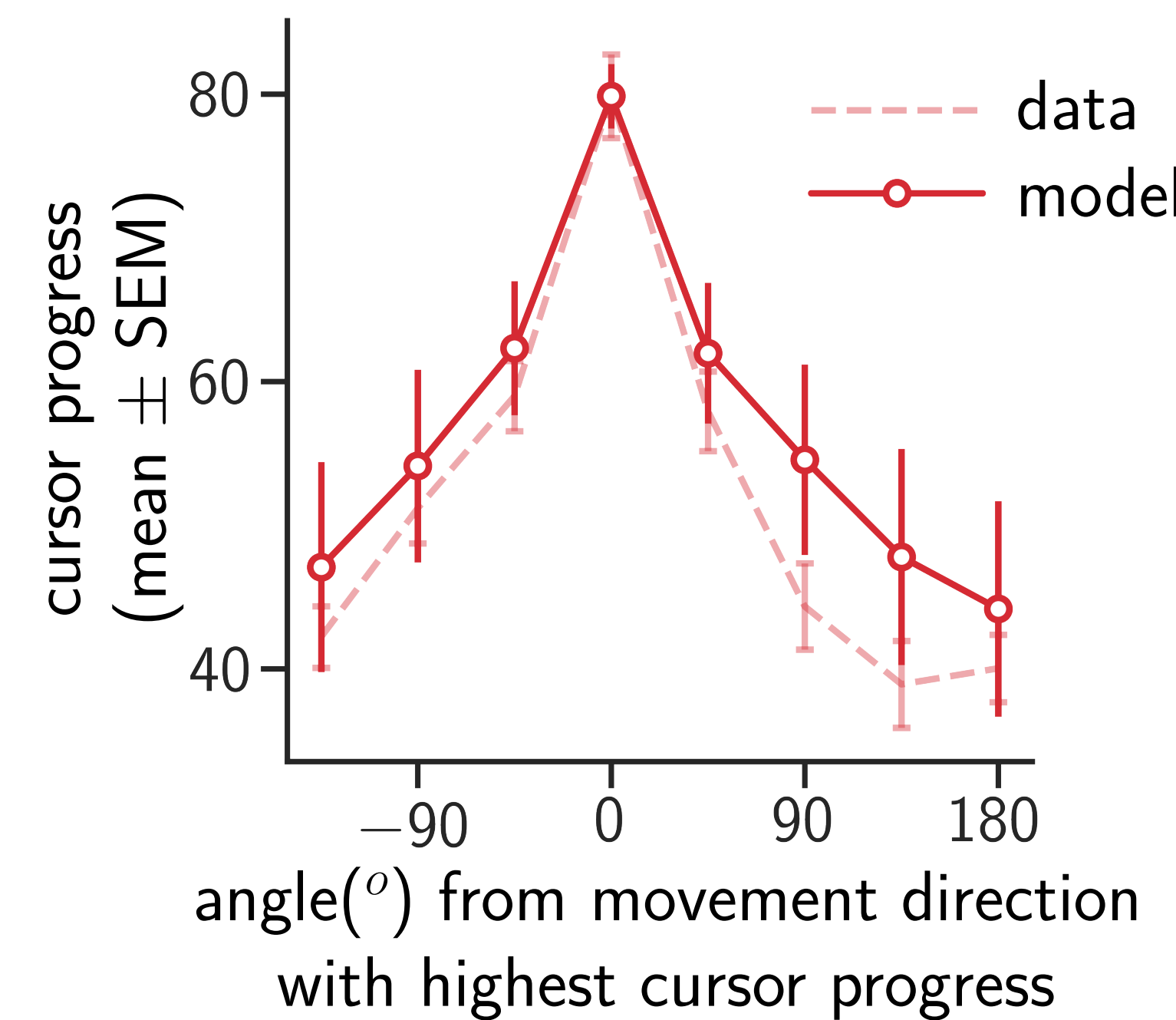
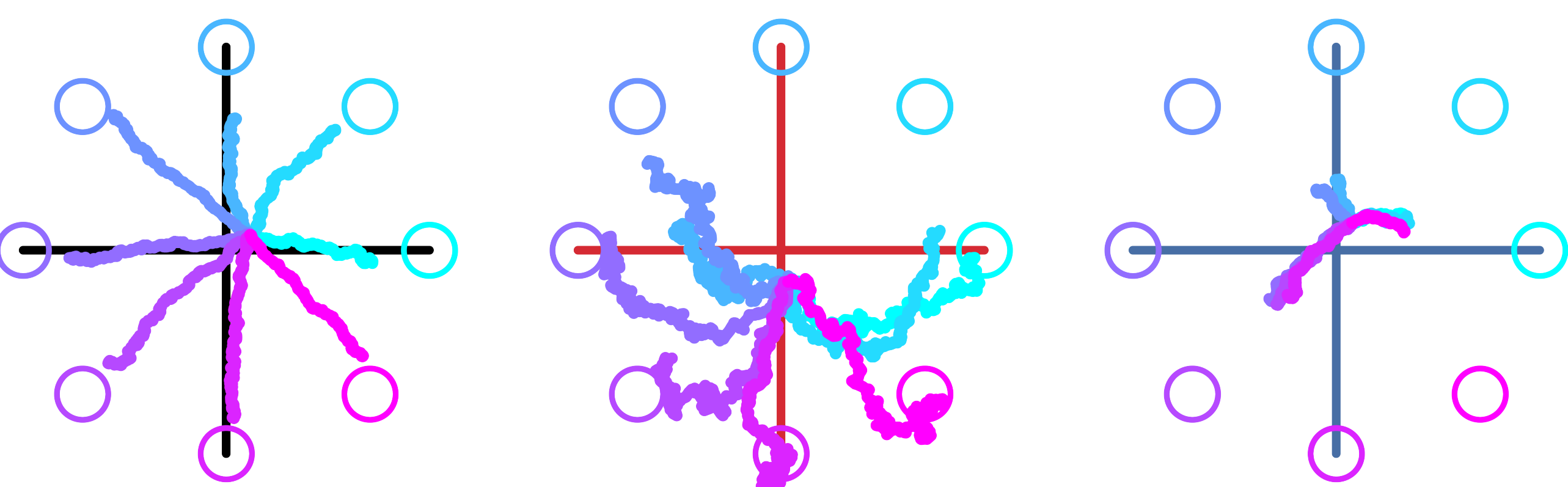
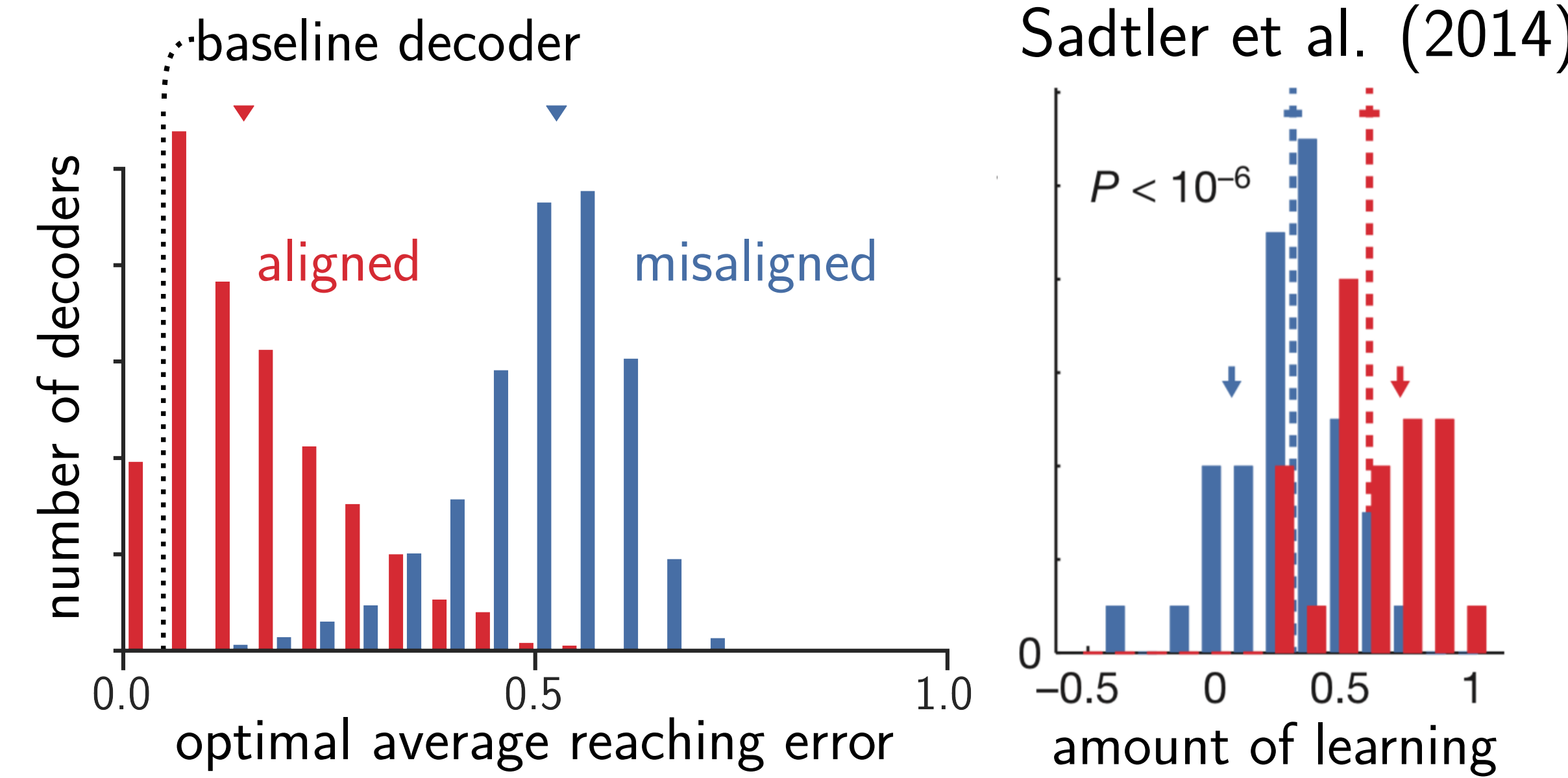
BMI experiment

① calibration task ② decoder fitting

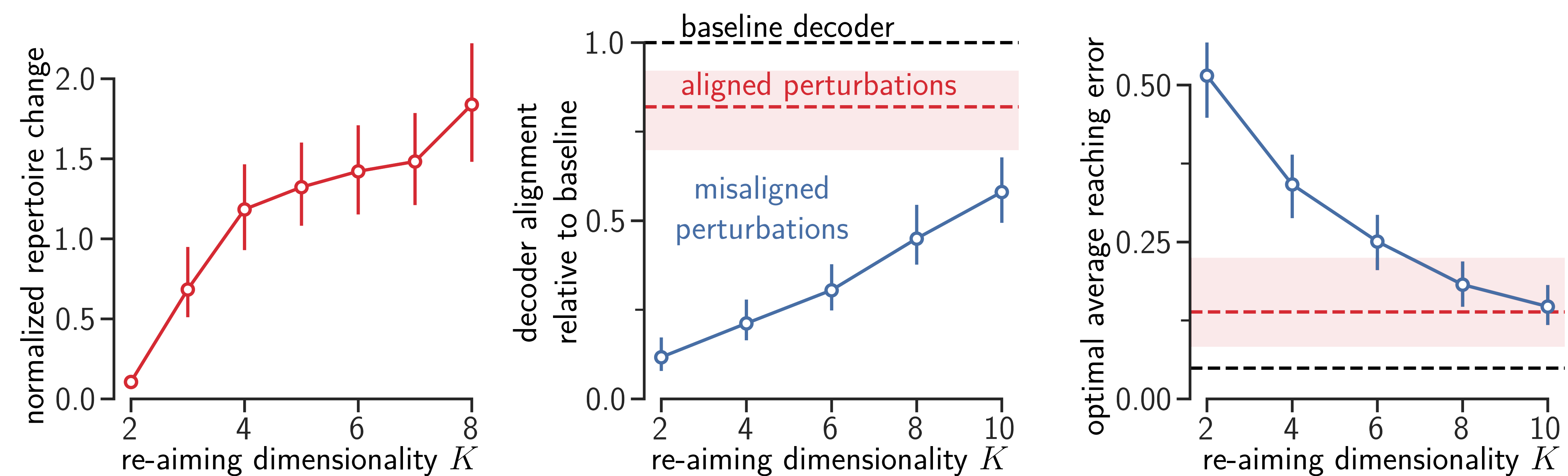


③ decoder perturbation

aligned perturbations misaligned perturbations



## Simulations: $K$ D re-aiming

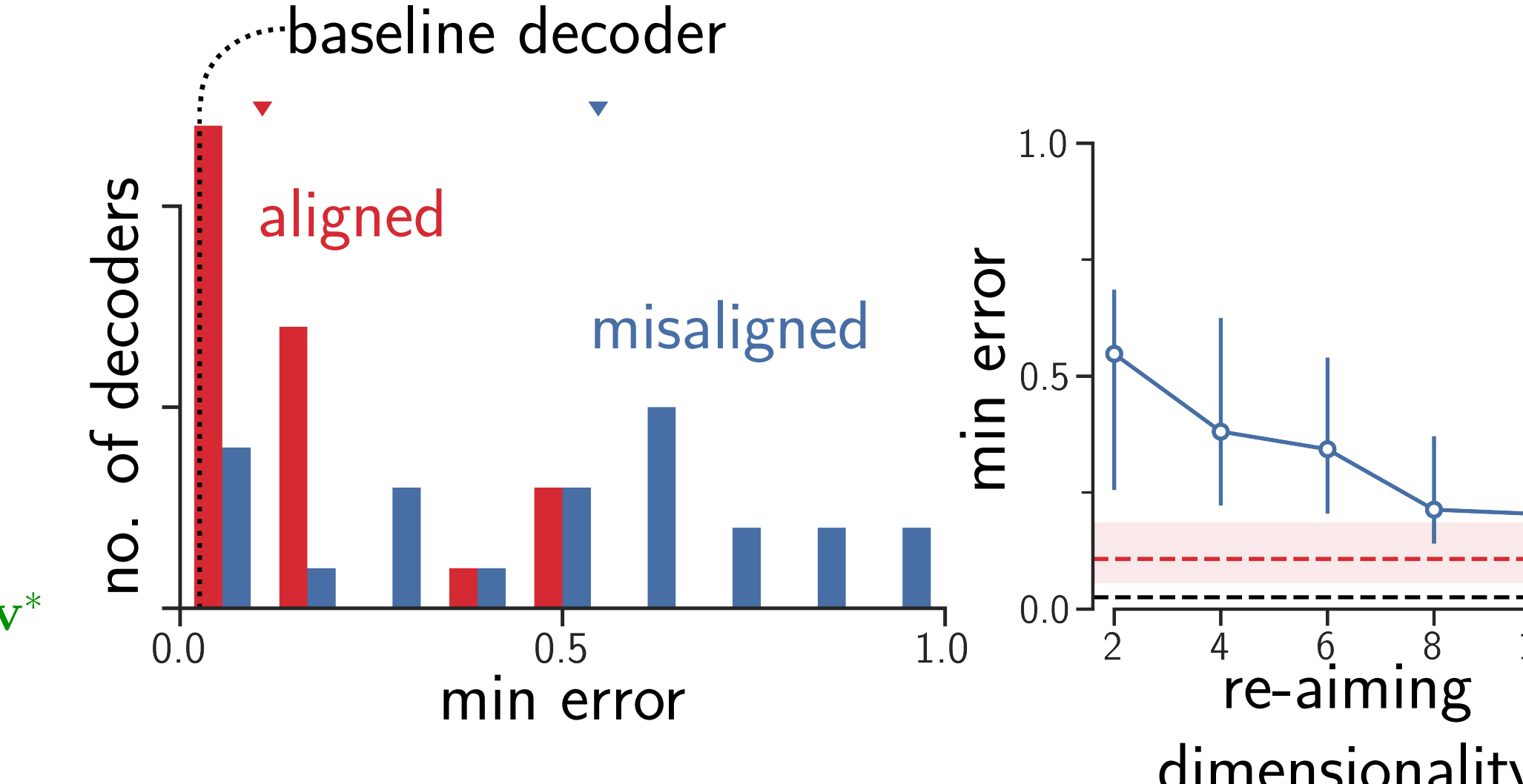
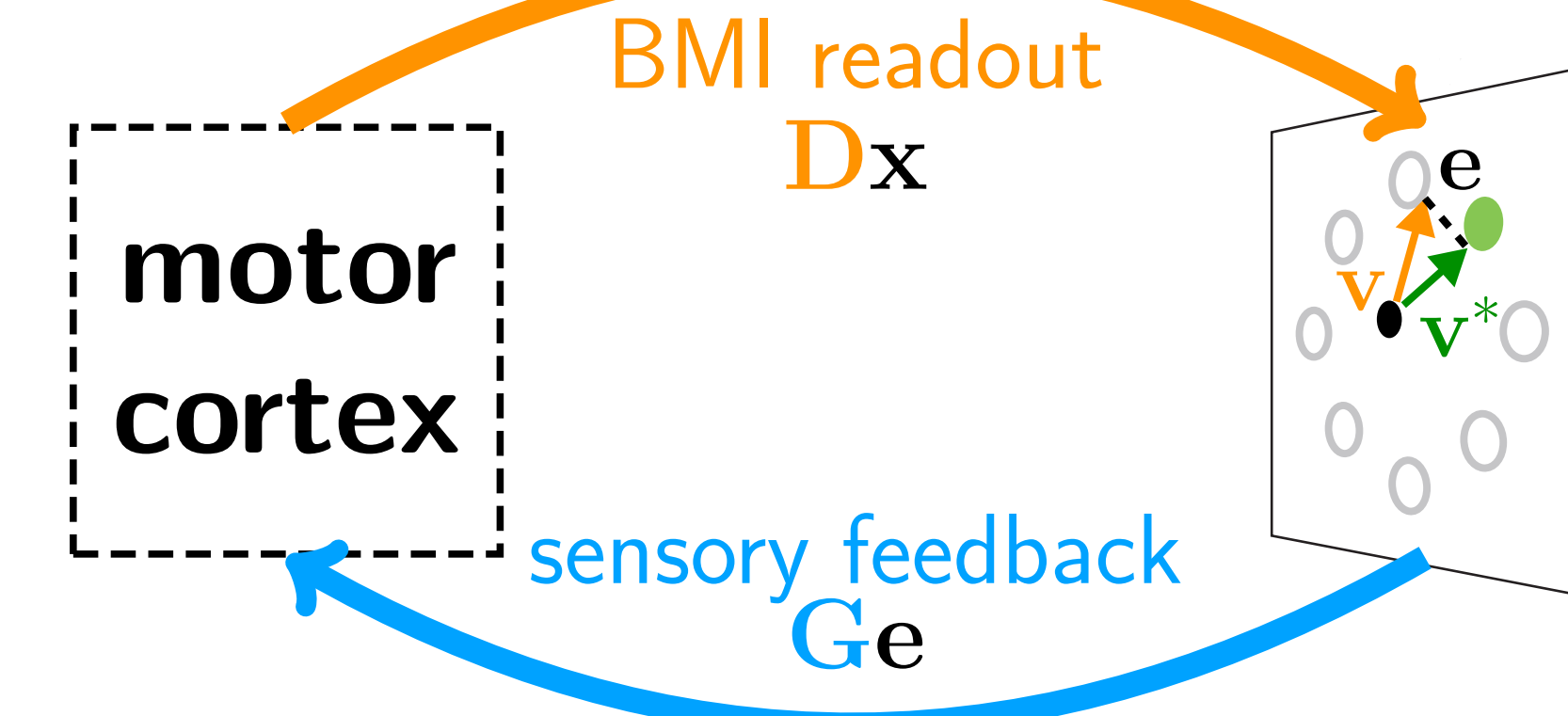
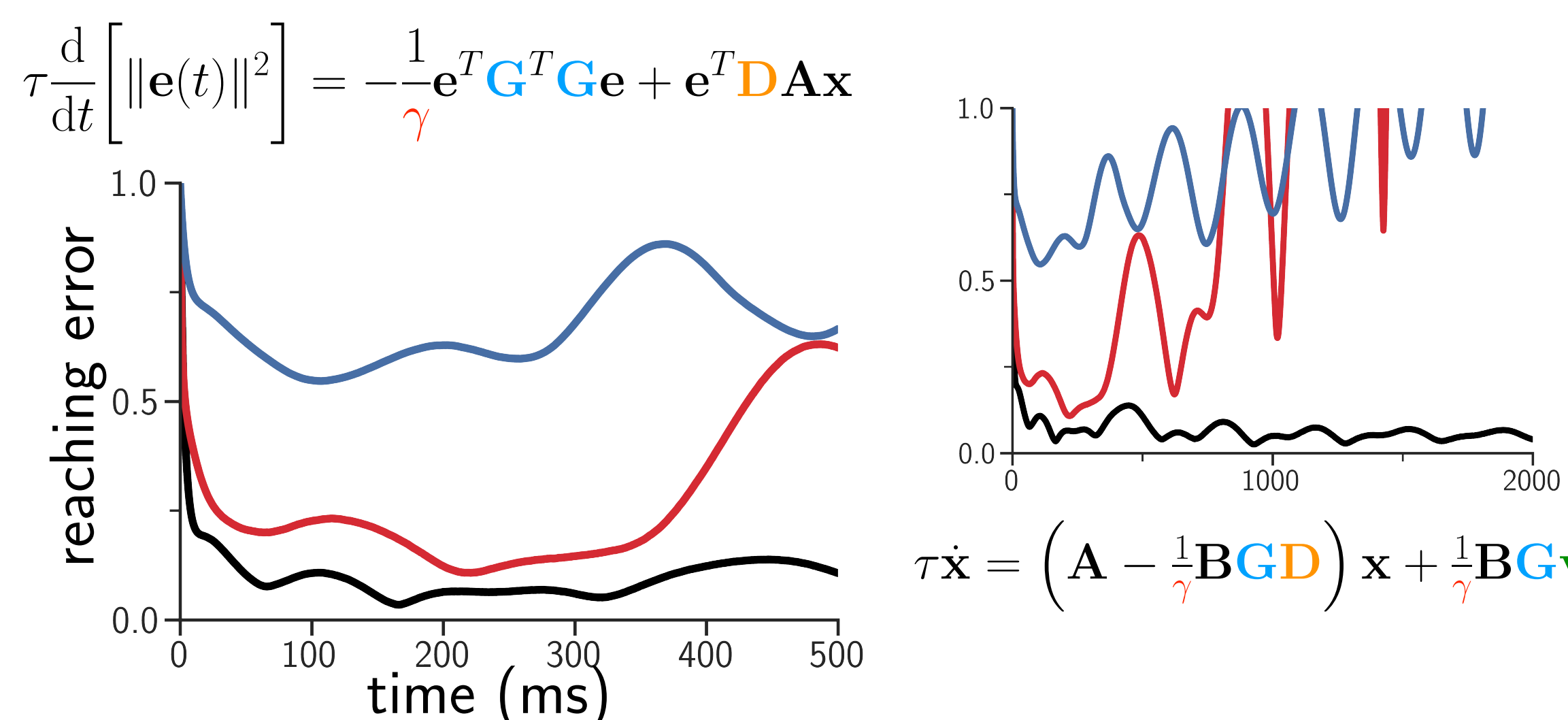


## Limit of $t^* \rightarrow 0$ : myopic feedback control

Consider linear network:  $\tau \dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\boldsymbol{\theta}$

$$\lim_{t^* \rightarrow 0} \boldsymbol{\theta}^*(t) = -\frac{1}{\gamma} \underbrace{(\mathbf{D}\mathbf{B})^T}_{\mathbf{G}} \underbrace{(\mathbf{v}(t) - \mathbf{v}^*)}_{\mathbf{e}(t)}$$

$$= \arg \min_{\boldsymbol{\theta}} \left\{ \frac{d}{dt} [\|\mathbf{e}(t)\|^2] + \gamma \|\boldsymbol{\theta}\|^2 \right\}$$



## Key takeaways

- 1) we build a **neural model** of the **re-aiming** strategy for BMI learning
- 2) the model makes a **novel prediction** about behavior in a BMI learning task, which is verified in a re-analysis of Sadtler et al. '14
- 3) further extensions of the model can explain **neural and behavioral phenomena** over **short and long timescales** of learning

Sadtler, P. T., Quick, K. M., Golub, M. D., Chase, S. M., Ryu, S. I., Tyler-Kabara, E. C., ... & Batista, A. P. (2014). Neural constraints on learning. *Nature*, 512(7515), 423-426.

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