Stable Long-Term Neural Decoding with Minimum Adaptation

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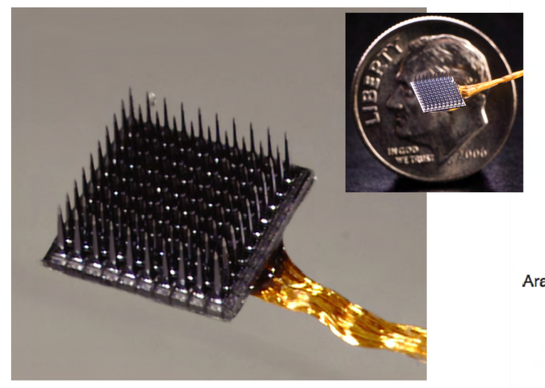
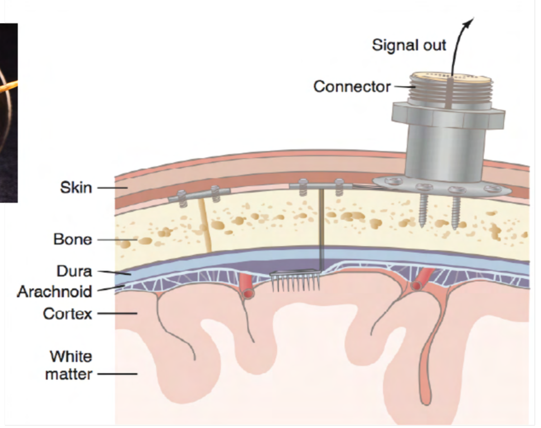
INTRODUCTION

- Intracortical brain-computer interfaces (iBCIs) have enabled people with tetraplegia to control external devices via decoding movement intentions from neural recordings.
- iBCI is a practical technology for restoring communication through rapid point-and-click cursor control for applications such as typing, web browsing, and navigating apps on a tablet.
- However, current iBCI systems require frequent decoder re-calibration due to instability in neural recordings. Biological and technological instabilities could interfere with neural control performance when a previously trained decoder no longer describes the relationship between neural activity recordings and movement intention as this relationship can vary over time.
- Rather than explicitly re-calibrating the decoder, a better option is to develop an continuously adaptive decoder that is robust against within-day instability, but also converges to be more stable and maintain high performance as more training data become available.
- We showed in offline that this training procedure produces a decoder capable of maintaining cursor control with less data needed for same-day adaptation.

BACKGROUNDS



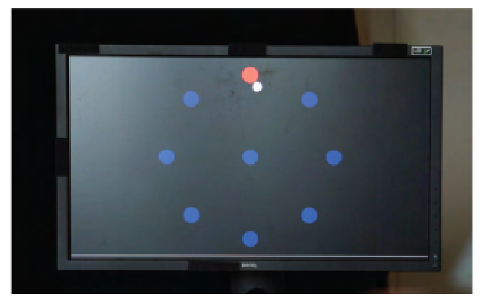
Microelectrode Array (Blackrock Neurotech)



Participant T11

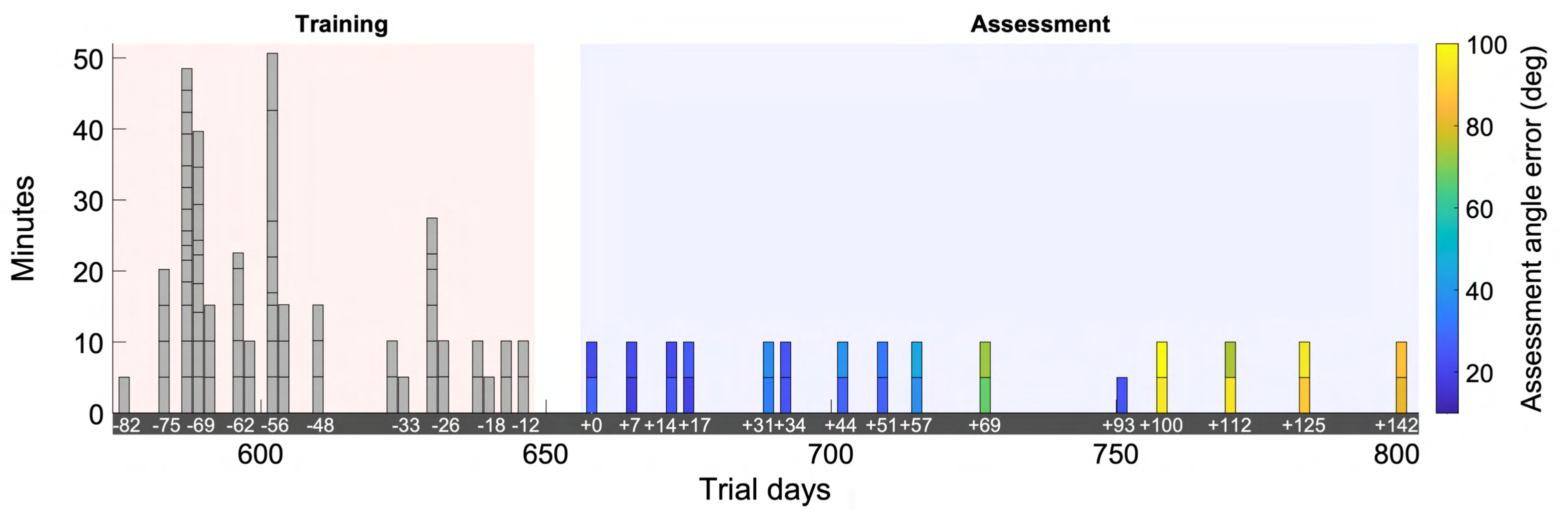
Participant T11 (Enrolled in BrainGate2 pilot clinical trial, IDE*)

- 37 year-old male with tetraplegia due to C4 AIS-B spinal cord injury
- Two 96-channel microelectrode arrays implanted into left (dominant) precentral gyrus
- Intracortical neural recordings via a wireless broadband iBCI (Simeral et al, IEEE, 2021)
- Extracted threshold crossing events and power in the spike band (250 - 5000Hz) binned every 20 ms



Center-out-and-back (radial-8) task on a monitor screen.

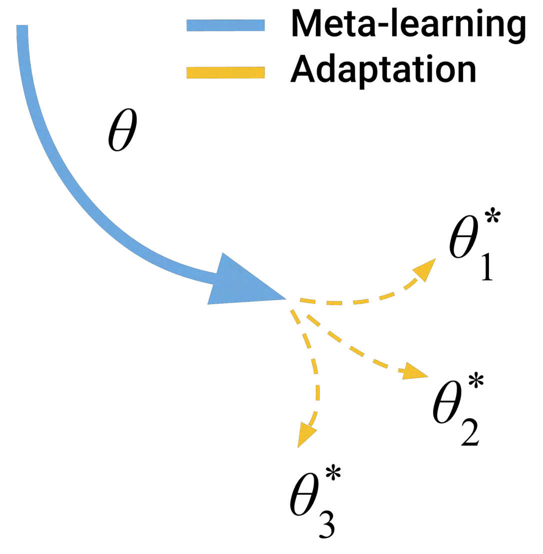
LONG-TERM FIXED DECODER DATASET



Data for training a RNN decoder and its online assessment. An single-layer LSTM was trained on concatenated historical data from various cursor tasks on trial days 576-646, then evaluated online for 15 sessions spanned from day 658-800, on a radial-8 task (Pun et al, NER, 2023).

META-LEARNING AND RAPID ADAPTATION WITH KF

- We hypothesize that there is a stable neural latent space governing consistent low-dimensional behaviors, which is easier for a linear dynamic model to learn on each day.
- To parameterize this space, each new session day is treated as a new task, and we train the model episodically sampled from these days.
- The feature extractor (a nonlinear LSTM model) aims to discover a stable neural latent space. Extracted features are then used in the adaptation head (a Kalman filter).



Feature Extractor

$$z_t = \phi_\theta(y_t)$$

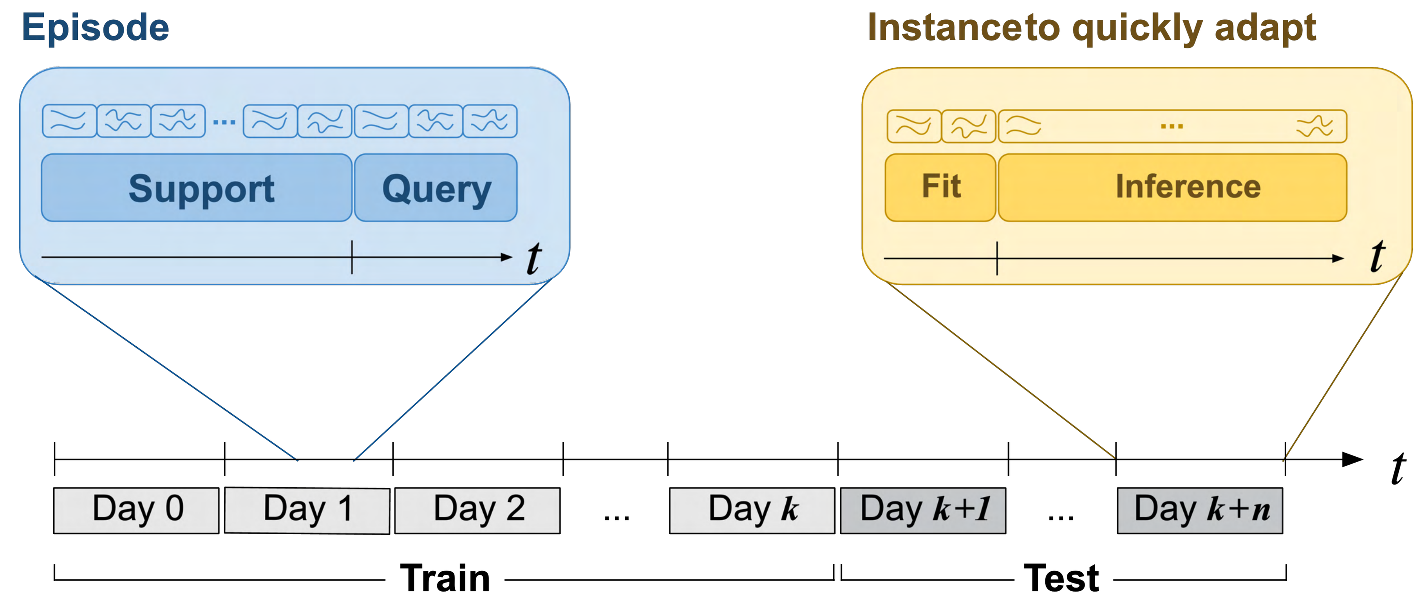
Adaptation head

$$\begin{cases} x_{t+1} = Ax_t + w_t, & w_t \sim \mathcal{N}(0, Q) \\ z_t = Cx_t + v_t, & v_t \sim \mathcal{N}(0, R) \end{cases}$$

Loss

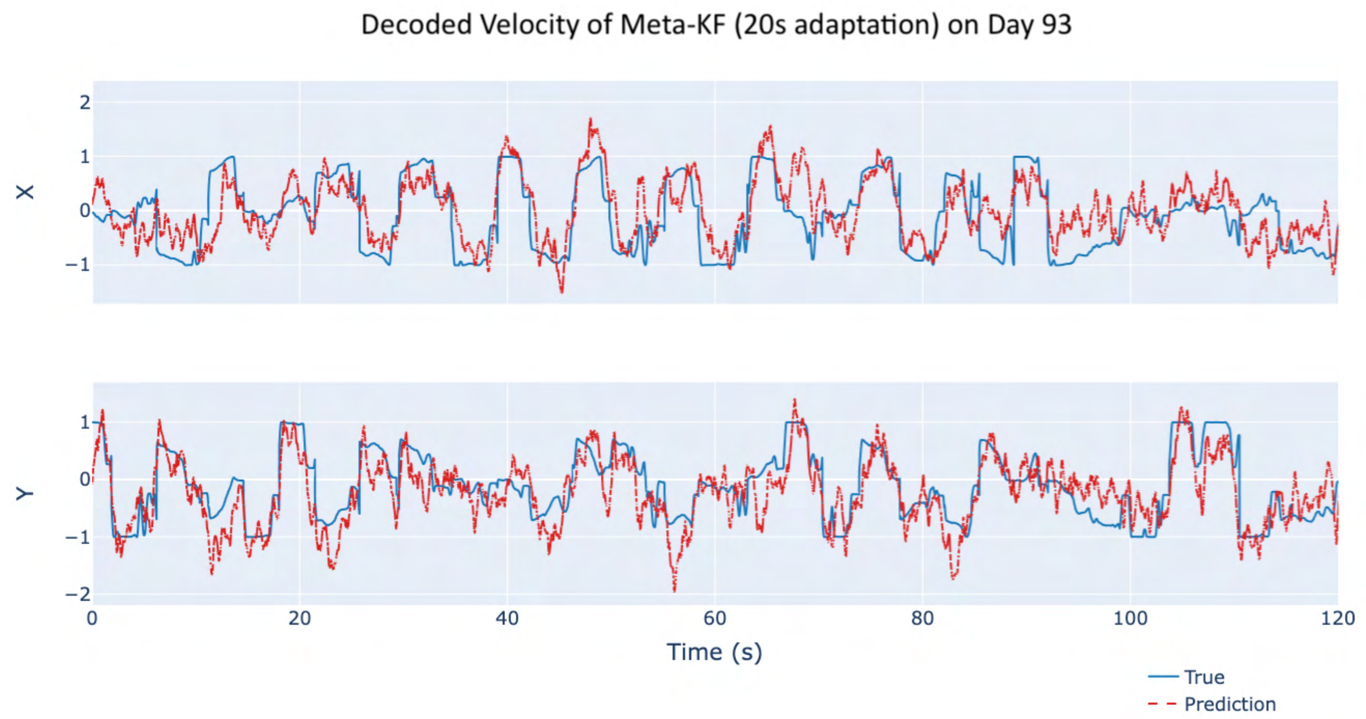
$$NLL = -\sum_{i=1}^{N} (x_i \cdot \log(p(x_i)))$$

Diagram of the meta-learning setup. It optimizes for a representation θ that can quickly adapt to new tasks ($\theta_1^*, \theta_2^*, \theta_3^*$, ...)

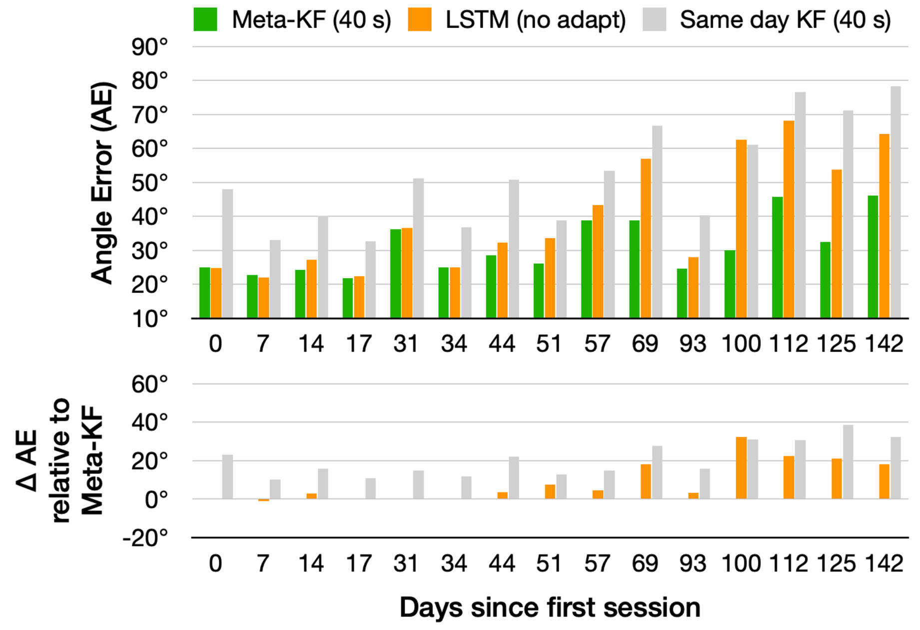


Episodic training and testing. Episodes are sampled from a block on a session day, where the model is trained on a support set and evaluated on the query set. During adaptation, the feature extractor is not updated and a short support is used to quickly adapt by a Kalman filter. Once trained, the model is applied for inference for until another instance where quickly adapt is needed (e.g. a new task).

META-KF DECODES CURSOR VELOCITY

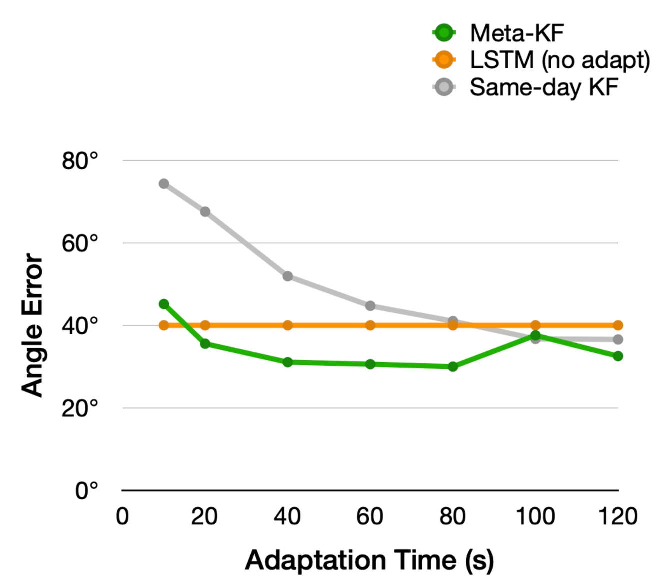


META-KF ENABLES SAME-DAY RAPID RECALIBRATION



Top: Median angle error per assessment day. For each day, the first 40 seconds of neural data was used for rapid adaptation in Meta-KF, and for training a same-day Kalman filter. Just LSTM doesn't adapt.

Bottom: Angle error improved by the Meta-KF compared to the other decoders. There is bigger improvement on later assessment days.



Mean angle error over all assessment days versus the amount of training time used in rapid adaptation. Meta-KF enables same-day adaptation and is faster to adapt.

CONCLUSION AND FUTURE WORK

- Episodic training offers benefit of quick adaptation during test time, and greatly reduce the need for recalibration.
- Large volume of previously collected neural data can be useful for training the feature extractor to find the stable latent space.
- Next, we will evaluate the model online with our current participants.
- Effective continuous learning remains an open question especially when the movement intentions are not readily available.

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