Continuous encoding of intent and error in the human motor cortex

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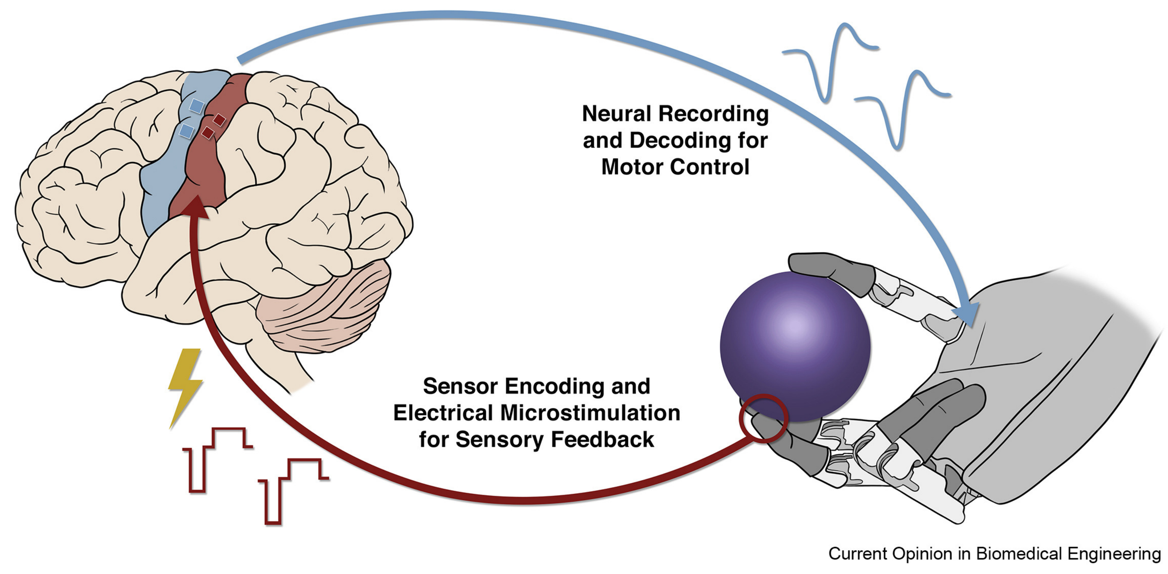
Abstract

1) How is M1 cortical activity impacted during erroneous movement control?
2) Can we leverage neural signature of erroneous control to detect errors?
3) Are the changes in M1 activity endogeneous (i.e. caused by spontaneous changes of neural state) or exogeneous (i.e. caused by visual feedback of the error)?

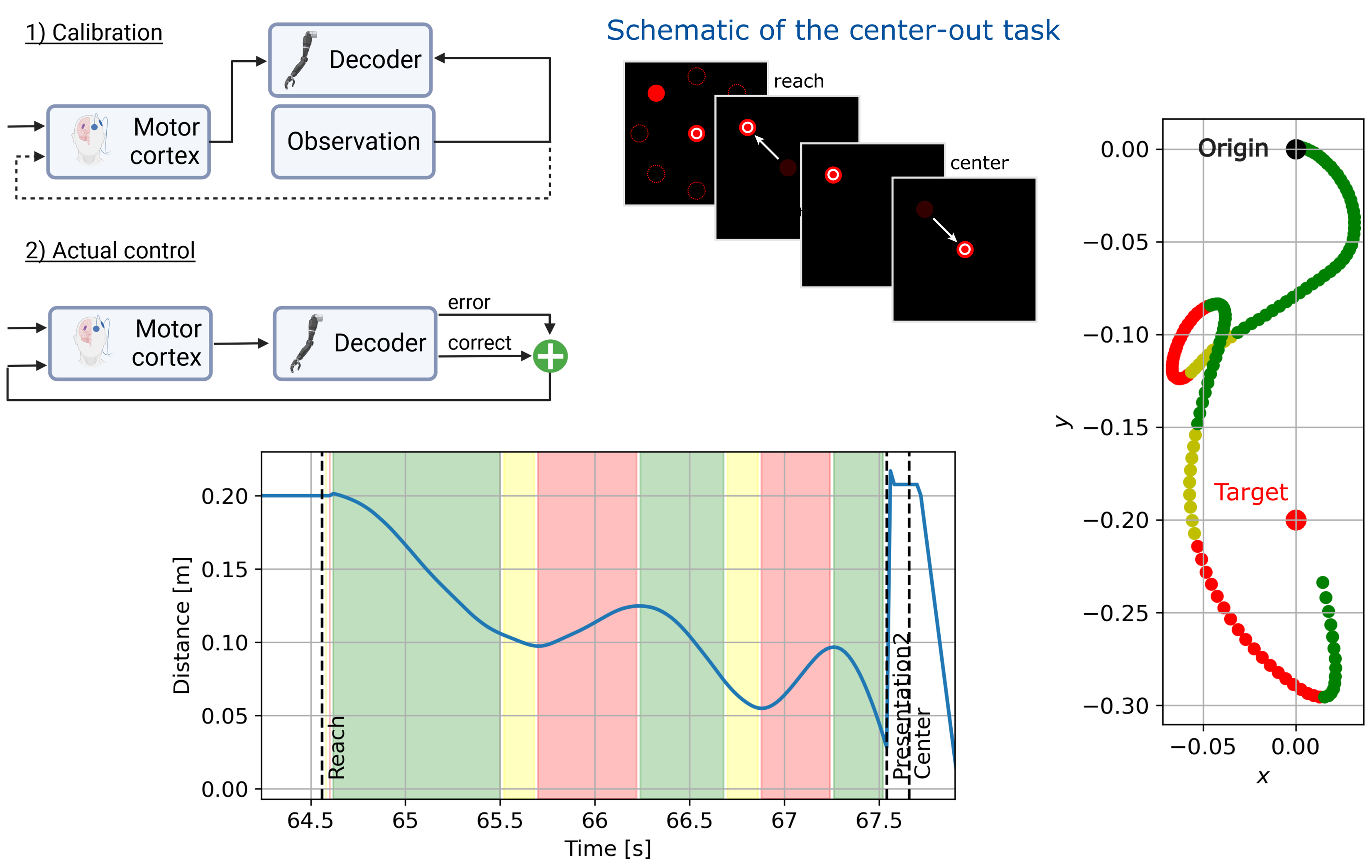
Methods

Data were recorded from one human participant. Cursor velocity was linearly decoded from the binned threshold crossings recorded on 2 intracortical electrode arrays implanted in M1 (Blackrock Microsystems, Inc.) Spiking activity was binned in 20ms epochs.



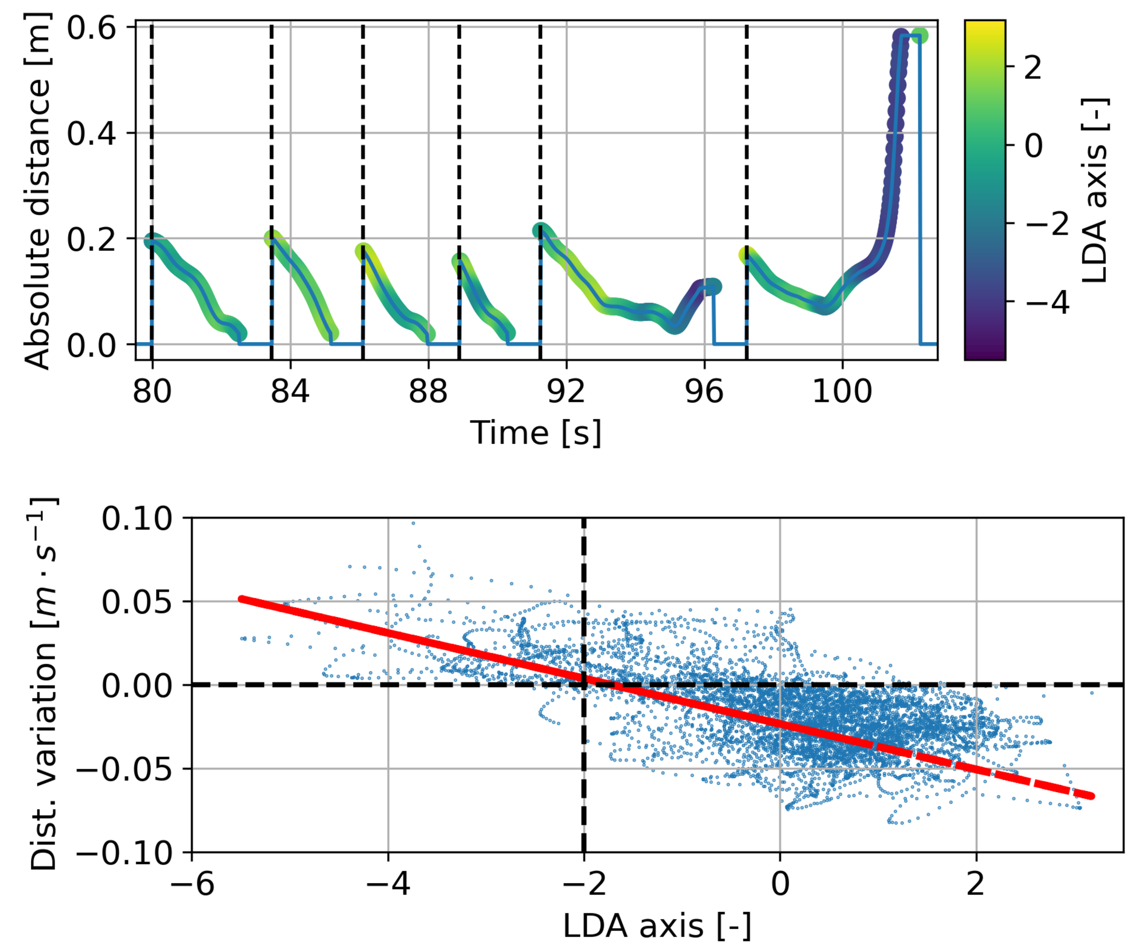
Schematic of Brain-Computer Interfaces (BCIs) which are used for movement decoding

Experimental setting



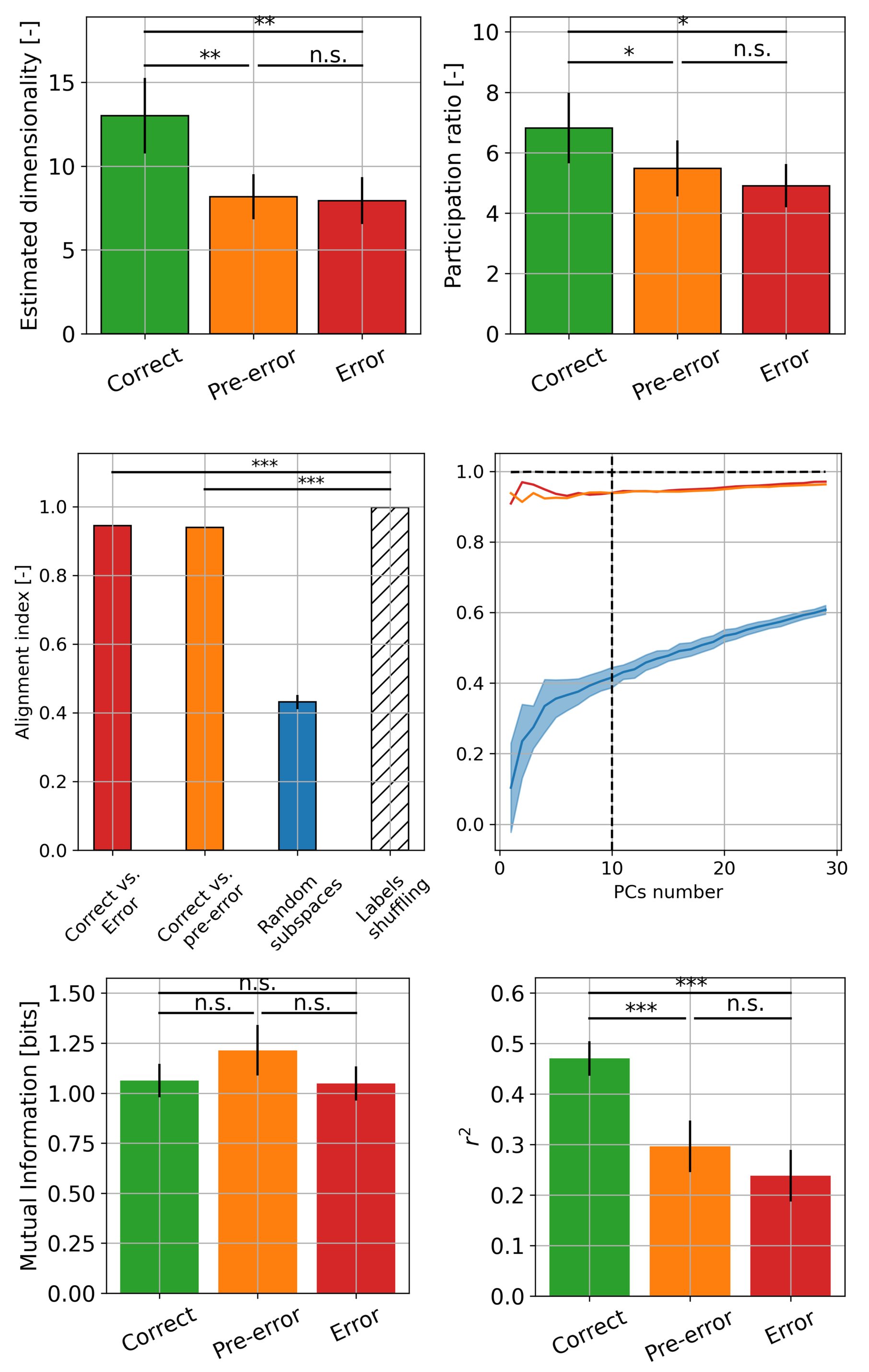
Absolute distance between target and current cursor position (blue line) for an example trial. Epochs of correct (green) and erroneous (red) control feedback are defined based on whether the controlled cursor appears to move on or off-target.

M1 activity during erroneous control is separable from activity during correct control



Neural activity corresponding to each epoch is projected using an LDA classifier; the resulting LDA components are separable between correct and erroneous control.

Data structure suggests an endogeneous origin of M1 activity modulation



$$\frac{(\sum_i \lambda_i)^2}{\sum_i \lambda_i^2}$$

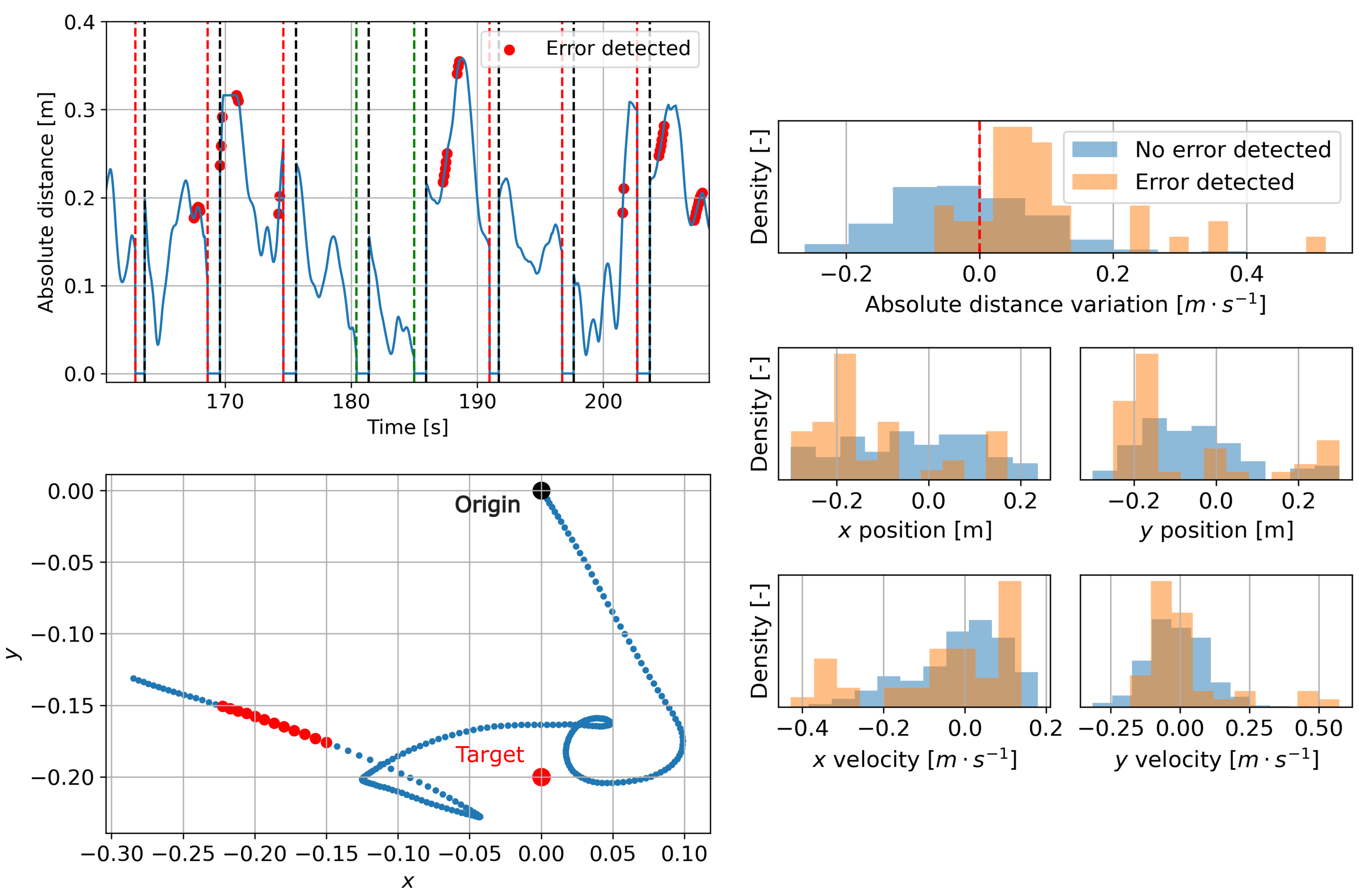
Participation ratio

Top: Dimensionality of both subspaces for each session, as well as in the 200ms windows preceding error onsets (Pre-error).

Middle: Alignment index (Elsayed et al., 2016; Hasnain et al., 2023) between the Correct and Error subspaces, between random subspaces having the same covariance as real data (Random subspaces), and with random reshuffling of epoch labels (Labels shuffling).

Bottom: mutual information between M1 activity and motor intent.

This neural signature can be leveraged to detect error during BCI control



Using these activity changes as a neural signature of ongoing error, we trained a classifier to detect them; this allows us to perform online error detection during BCI control to stop ongoing errors without any specific action from the participant.

Conclusion

We highlight significant differences in the population activity of M1 between periods of correct and erroneous control: including a dimensionality collapse, akin to what has been observed in the PFC during cognitive tasks (Rigotti et al., 2013).
These changes tend to precede the onset of control error, supporting the hypothesis that these errors are caused by endogenous changes in the population activity of M1. This is in agreement with previous results, which have shown that neural activity is temporarily confined to an outputnull subspace following an artificial perturbation (Stavisky et al., 2017) and that demultiplexing visual feedback and motor intent does not improve BCI control (Stavisky et al., 2018).
Based on our results, our next step will be to leverage the possibility to perform online error detection (Even-Chen et al., 2017; Wallace et al., 2023).

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