Neural Dynamics of Reaching Following Incorrect or Absent Motor Planning

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Introduction

Neural prostheses aim to restore movement to individuals with paralysis or lost limbs. Activity from the patient's brain is recorded and used to decode their intended movements, allowing the user to naturally control a prosthetic arm or computer cursor.

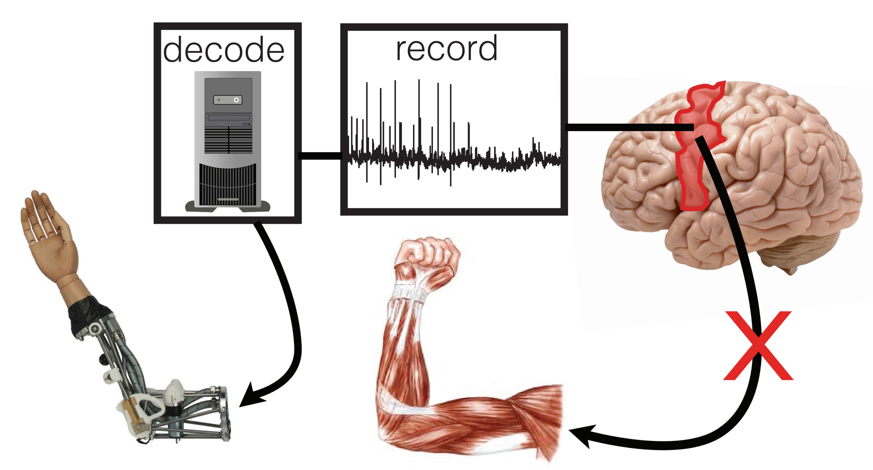
Current neural prostheses assume that all of the observed neural activity relates to the immediate movement being controlled. However, this simplistic assumption is inadequate for doing more complex tasks such as planning a movement before starting it or simultaneously executing one action while planning a subsequent one. To enable next-generation neural prostheses, we set out to understand how movement planning relates to movement execution.

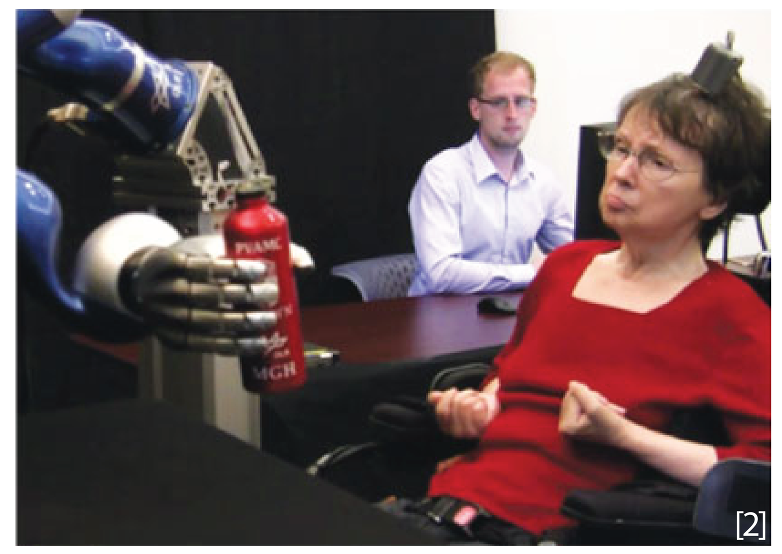
It is known that when given time to plan a reach, neural activity achieves and holds a distinct pattern of firing rates called the **plan state** which is specific to the upcoming movement. Evidence suggests that this plan state is beneficial for making the reach and reduces reaction time [1,3].

Is planning necessary for generating movement?

Our experiments answer this fundamental question by testing whether the neural state must pass through the plan state before a movement is generated in the cases when 1) there is no time to plan, and 2) a different movement has already been planned.

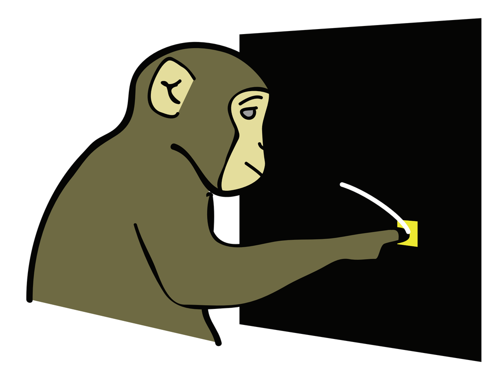
Neural Prosthesis





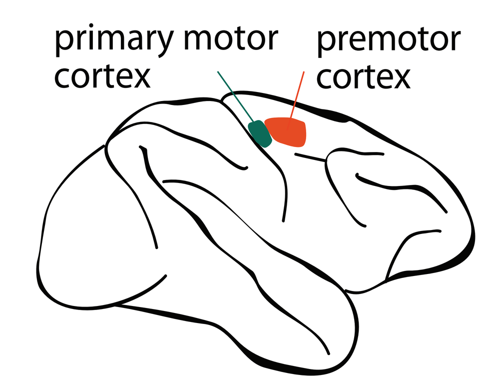
Methods

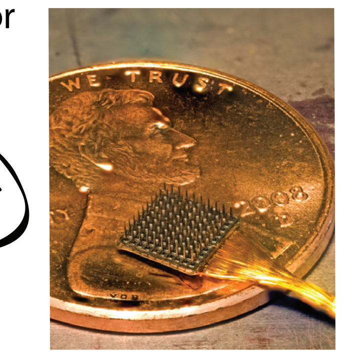
Plan-and-Reach Tasks



Macaques were trained to reach from a start location to an illuminated target on a screen. In delay trials, the monkey must wait after the target appears until a go cue is given. During this time, motor cortex generates a plan to make the instructed reach.

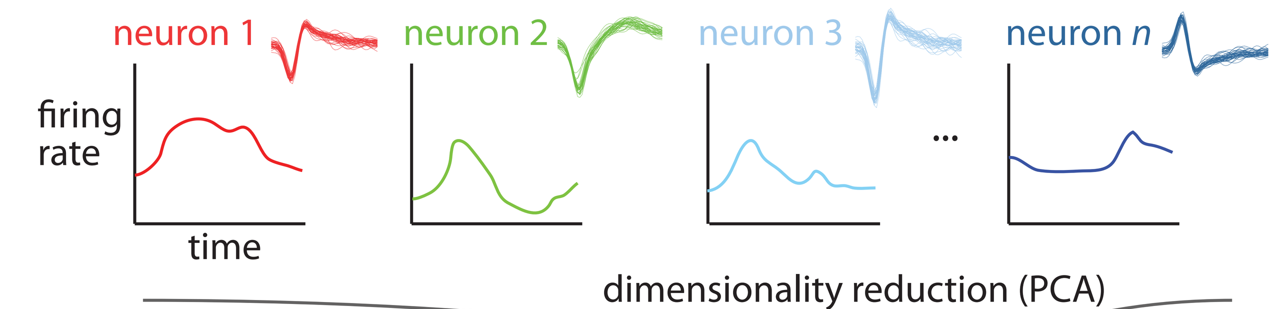
Neural Recording





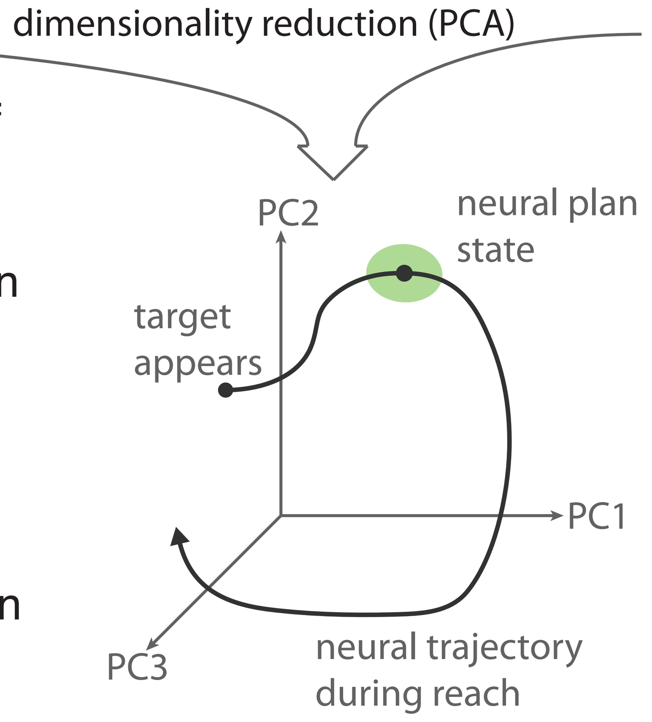
Neural activity from 125 neurons in the primary motor and premotor cortex was simultaneously recorded using a 100-contact multielectrode array in each region.

Neural State Analysis



The simultaneous activity of many neurons during a plan-and-reach trial is summarized as the evolution of a low-dimensional neural state over time.

Since many neurons covary, 80% of the variance is captured in the first three dimensions which are shown to aid intuition.



Results

We performed two experiments. In the first, the monkey was asked to either make a planned reach to a target, or, on **no delay** trials, to make the same reach without having had time to plan the movement.

In the second experiment, the monkey is given time to plan a reach to one target, but on **switch trials** the target was switched at the time of the go cue such that the monkey's previously prepared motor plan was now incorrect.

The plots to the right show the mean neural trajectories for both trial types, averaged over hundreds of trials. In both experiments, the neural trajectory for trials without a proper plan (no delay or switch trials) did not pass through the plan state corresponding to the reach. The planned and unplanned neural trajectories take separate but parallel paths, eventually re-joining soon after movement onset.

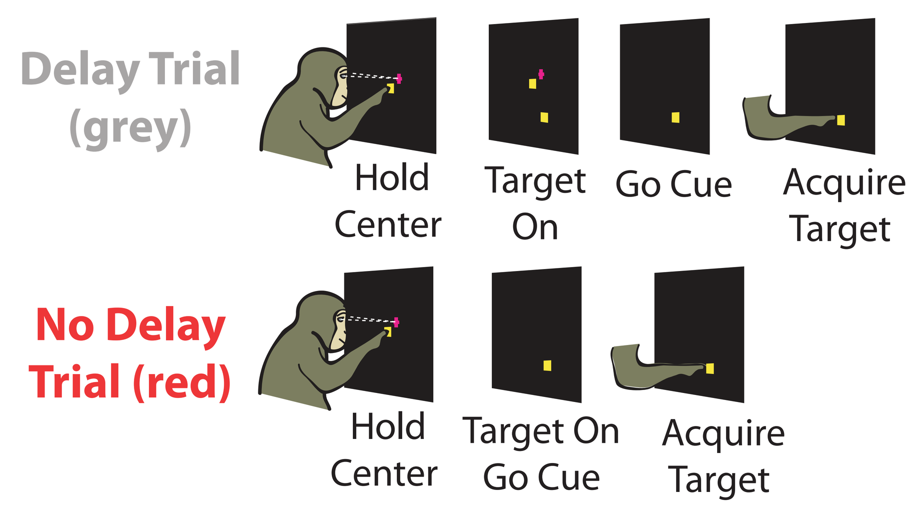
For all conditions, the actual arm movement made during the reach was the same (not shown).

Difference Between Delay and No Delay Trials

The average neural trajectories shown provide intuition that the plan state is not entered during no delay trials. We used a Euclidean state-space distance metric to quantify this difference. Plotted to the right are the minimum distances **(black)** between no delay trajectories and the neural state at four events during planned trials. This distance is compared to the distance expected by chance if the unplanned and planned trajectories were statistically the same **(blue error bars).**

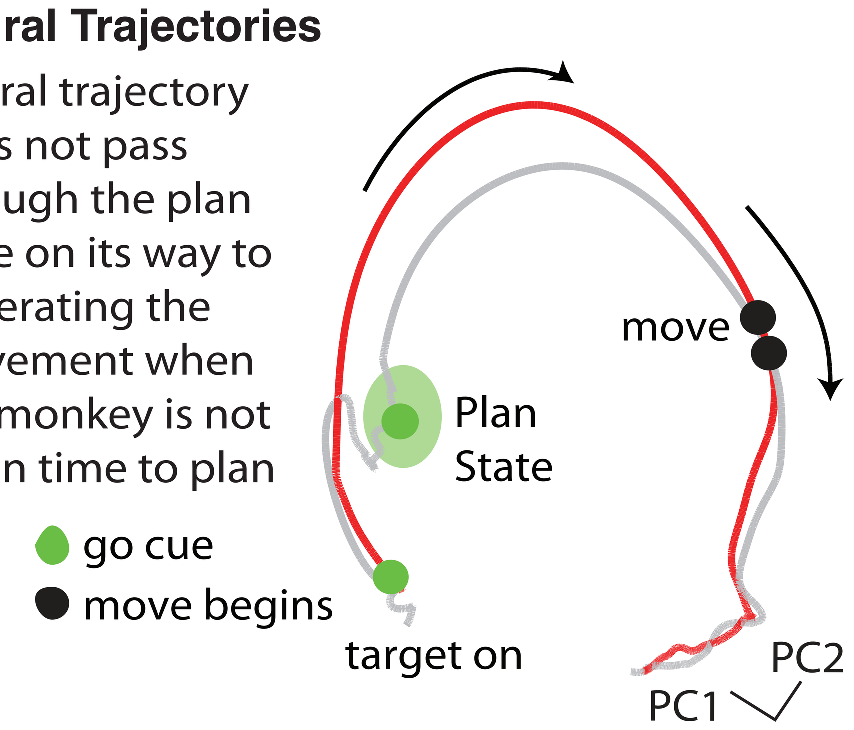
For both conditions, neural activity starts close together (**target on**), but the unplanned trajectory does not come close to the plan state (**go cue**). When the arm starts moving (**move**) the neural states are substantially different, but these two conditions' neural trajectories converge by the time the reach finishes (**end**).

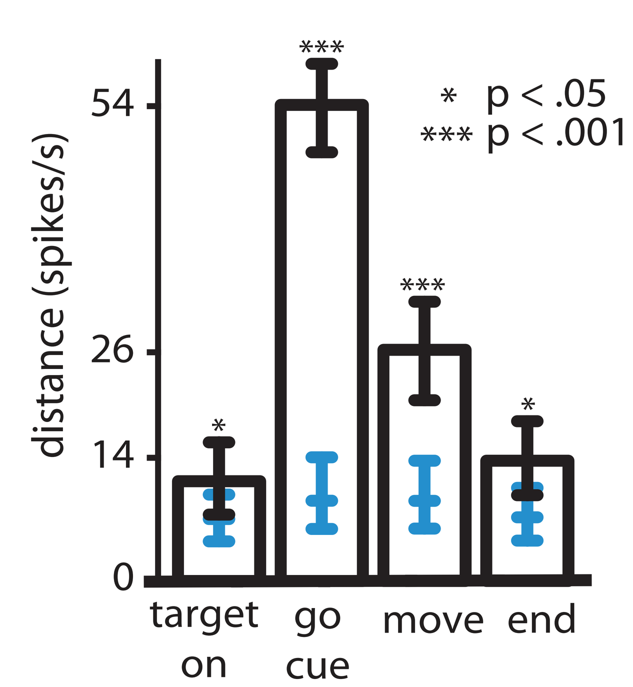
Experiment 1: Reaching Without A Plan



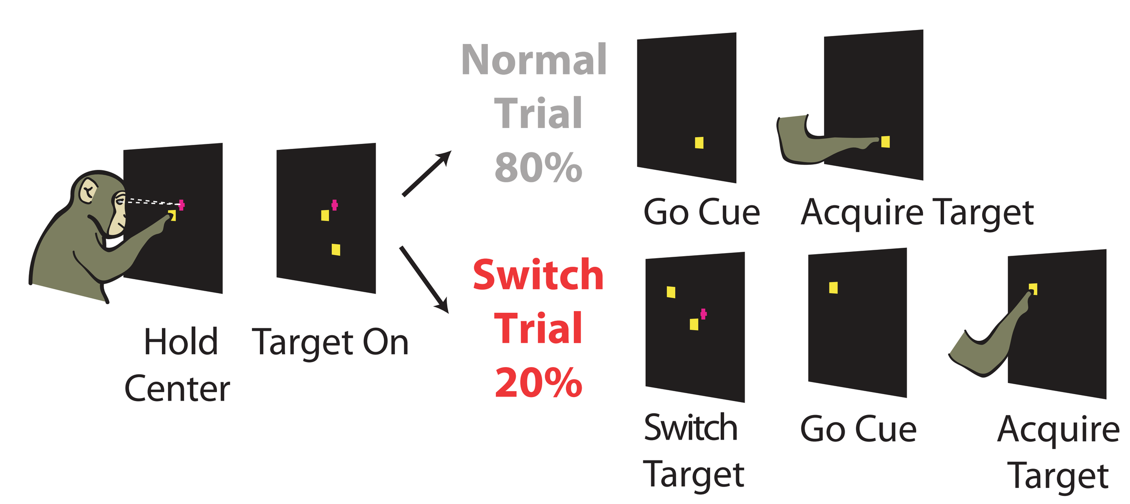
Neural Trajectories

Neural trajectory does not pass through the plan state on its way to generating the movement when the monkey is not given time to plan



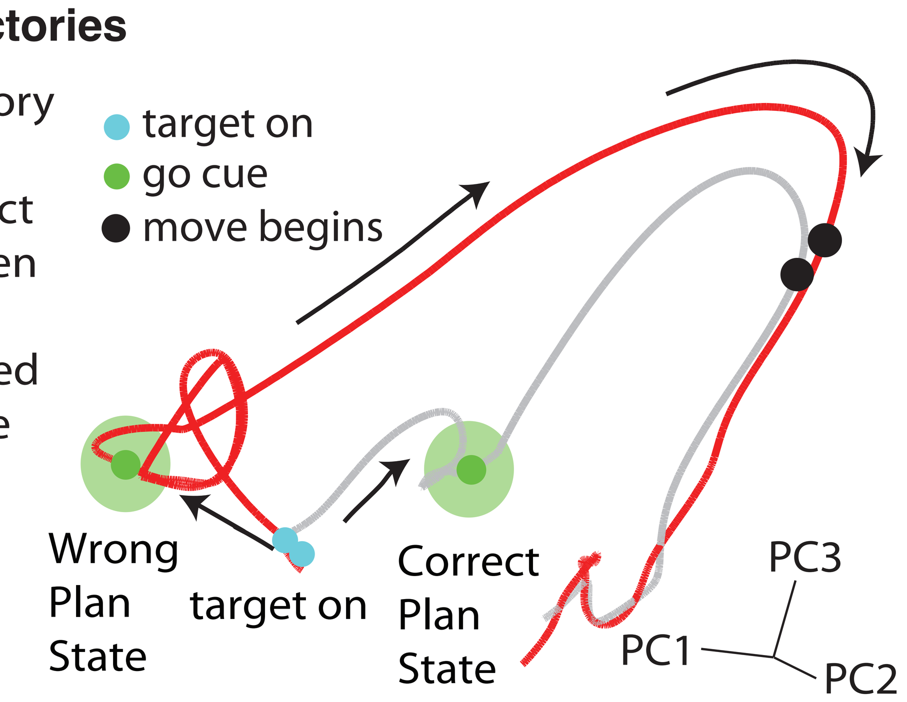


Experiment 2: Reaching With The Wrong Plan



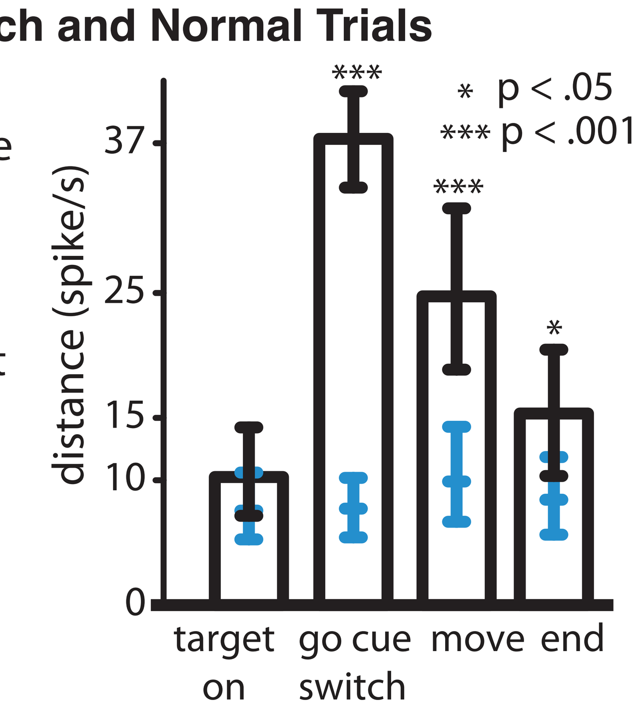
Neural Trajectories

Neural trajectory does not pass through correct plan state when the monkey initially planned to reach to the other target



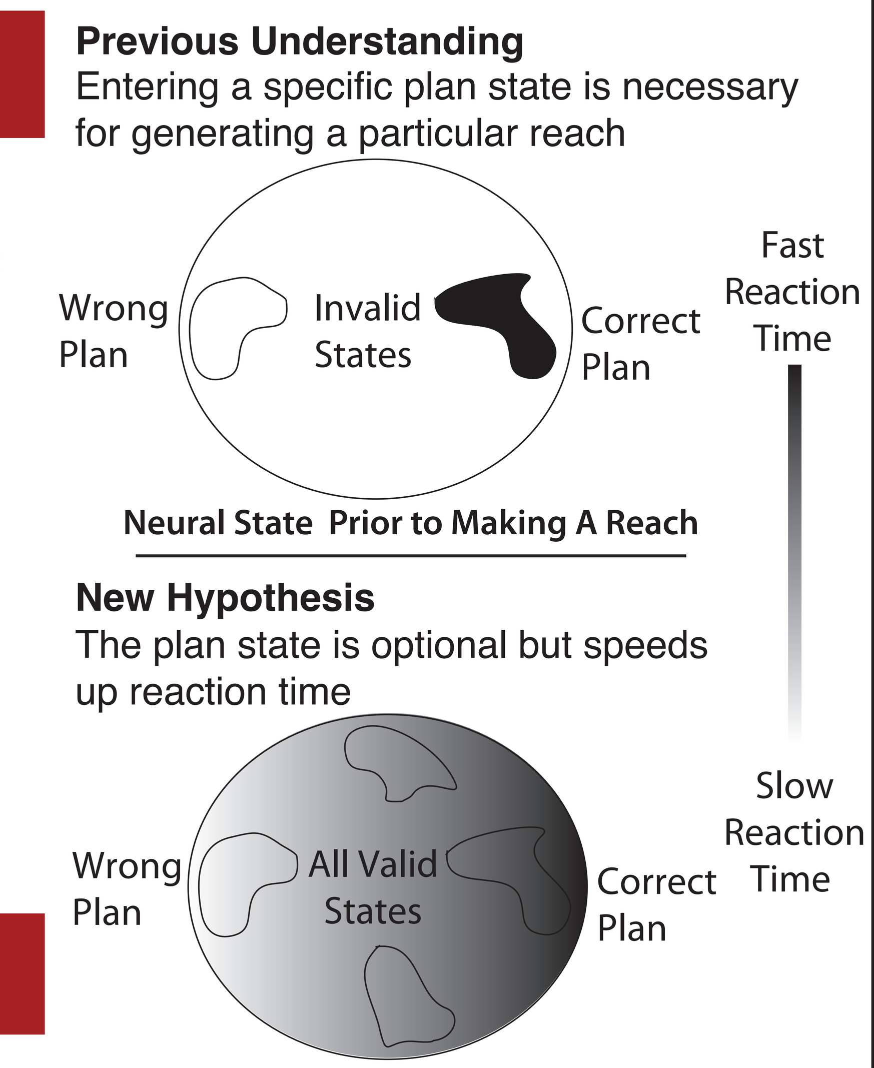
Difference Between Switch and Normal Trials

The neural trajectories for switch and normal trials are similar at the start (**target on**) and end (**end**) of the trial, but the correct plan state (**go cue/switch**) is not achieved during switch trials. Furthermore, the neural states still differ considerably when movement starts (**move**).



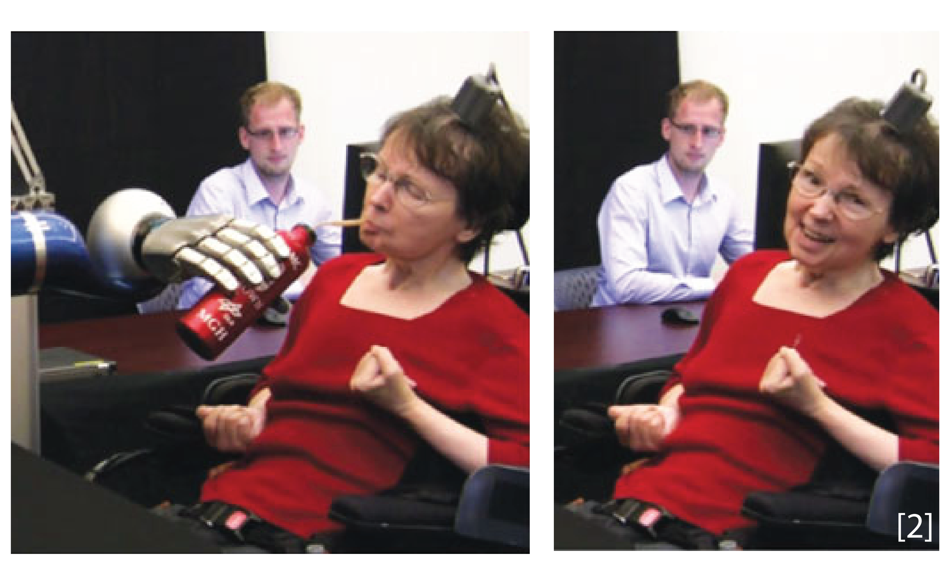
Conclusions

- Neural activity does not need to enter the plan state in order to successfully generate a movement.
- Despite differences in neural trajectory, the movements that result from both planned and unplanned reaches are the same. Unplanned reaches have identical kinematics, but a slower reaction time.
- Differences in initial conditions between neural trajectories are corrected while executing a movement.



Broader Impacts

- Understanding the neural correlates of movement planning may allow us to decode these plan signals to improve the speed, accuracy, and reliability of neural prostheses.
- These results fundamentally revise our understanding of how a motor plan relates to subsequent movement. They establish a basis for further experiments to understand how motor plans adapt to changing goals and inputs.



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References

[1] Churchland et al., Neurophys. 2006
[2] Hochberg et al., Nature 2012
[3] Shenoy et al., Prog. Brain Res. 2011