nature

Vol 442|13 July 2006|doi:10.1038/nature04970

ARTICLES

Neuronal ensemble control of prosthetic devices by a human with tetraplegia

Leigh R. Hochberg[1,2,4], Mijail D. Serruya[2,3], Gerhard M. Friehs[5,6], Jon A. Mukand[7,8], Maryam Saleh[9]†, Abraham H. Caplan[9], Almut Branner[10], David Chen[11], Richard D. Penn[12] & John P. Donoghue[2,9]

http://www.nature.com/nature/focus/brain/experiments/videoitself1.html

Center-out task

Pong

Email, Browser

Prosthetic hand

Fast forward to 2012…

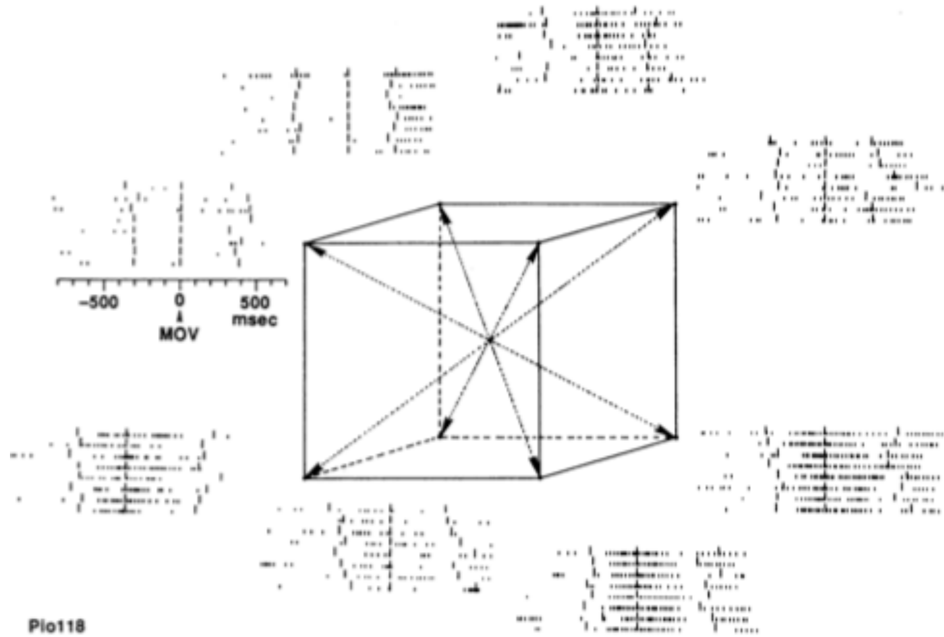
https://www.youtube.com/watch?v=ogBX18maUiM

2015

https://youtu.be/YJMckMIaPrY

Justin Sanchez: Neurotechnology (DARPA "Wait, What?")

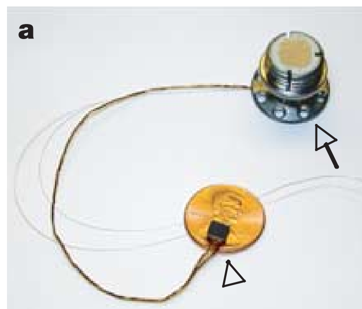
Primary motor cortex neurons



Example neuron in primary motor cortex (from Schwartz & Georgopoulos 1986)

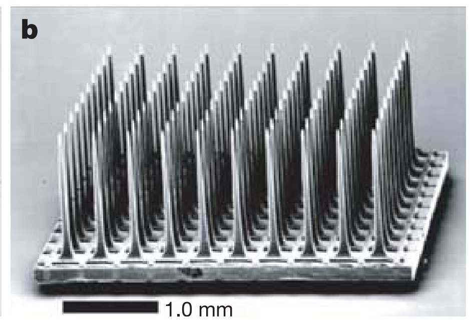
The first participant in the BrainGate trial (MN). The grey box (arrow) connected to the percutaneous pedestal contains amplifier and signal conditioning hardware; cabling brings the amplified neural signals to computers sitting beside the participant. He is looking at the monitor, directing the neural cursor towards the orange square in this 16-target 'grid' task. A technician appears (A.H.C.) behind the participant.

sensor

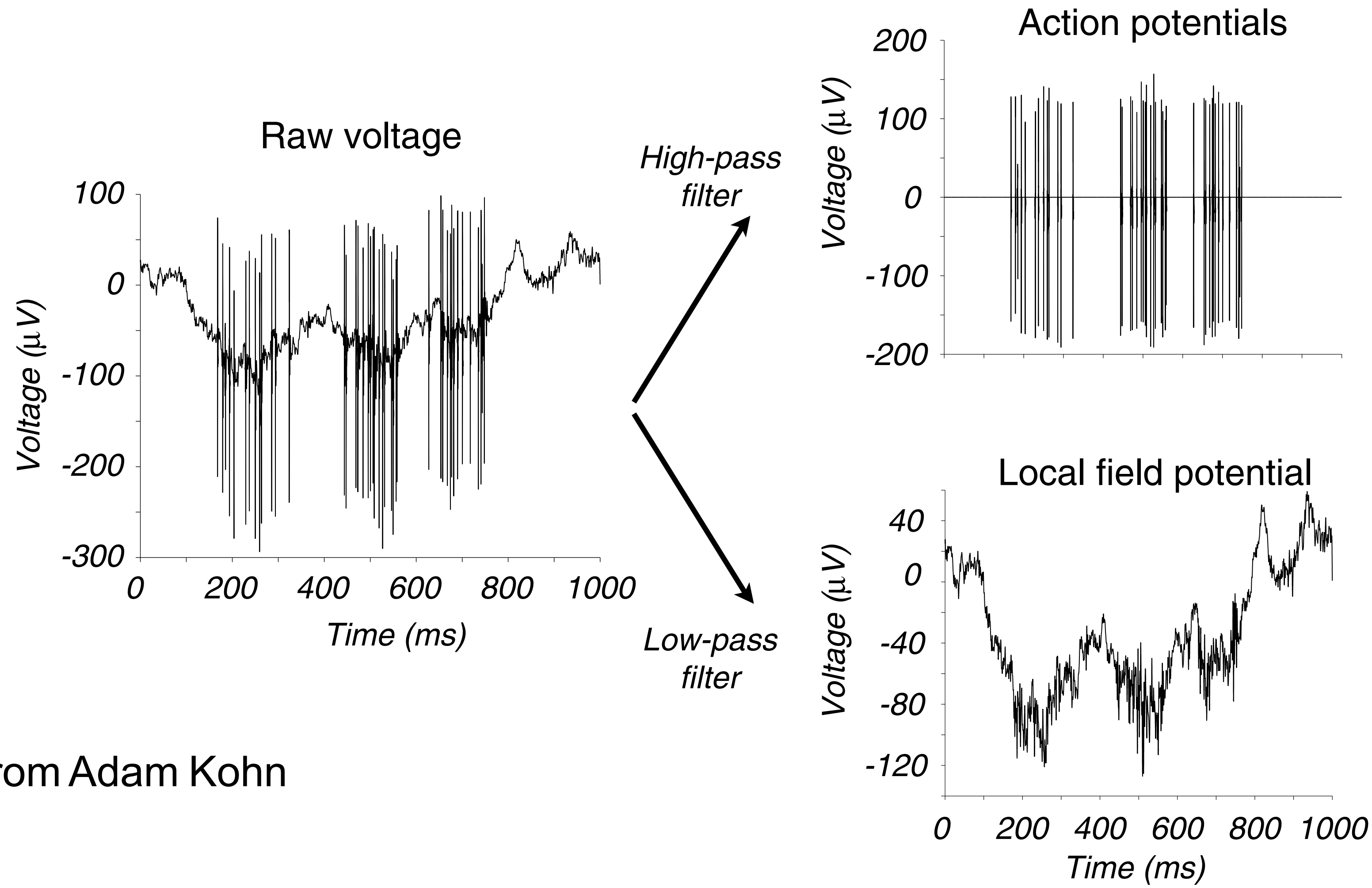


The BrainGate sensor (arrowhead), resting on a US penny, connected by a 13-cm ribbon cable to the percutaneous Ti pedestal (arrow)

100 electrode sensor



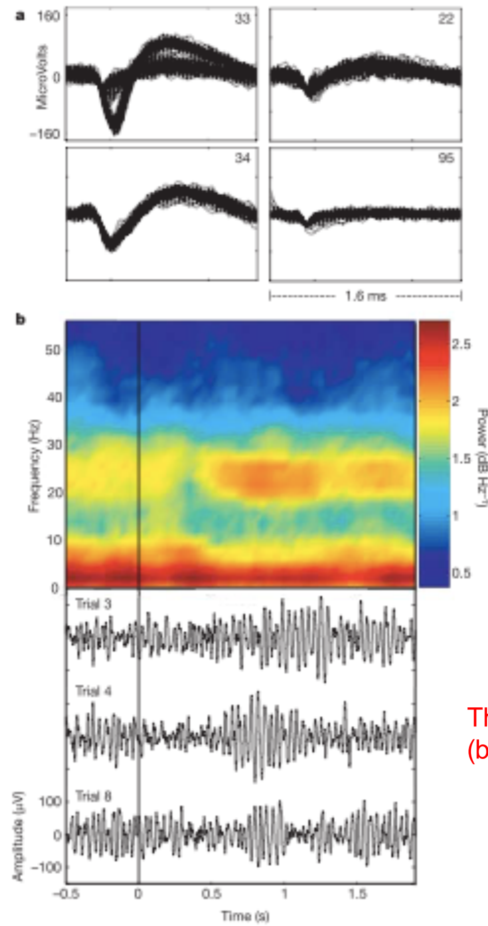
100-electrode sensor, 96 of which are available for neural recording. Individual electrodes are 1-mm long and spaced 400 mm apart, in a 10 by 10 grid.



From Adam Kohn

“Action potentials were readily observable on multiple electrodes, indicating that Primary Motor Cortex neural spiking persists 3 years after Spinal Cord Injury…”

Neural signal persists 3 year after injury!



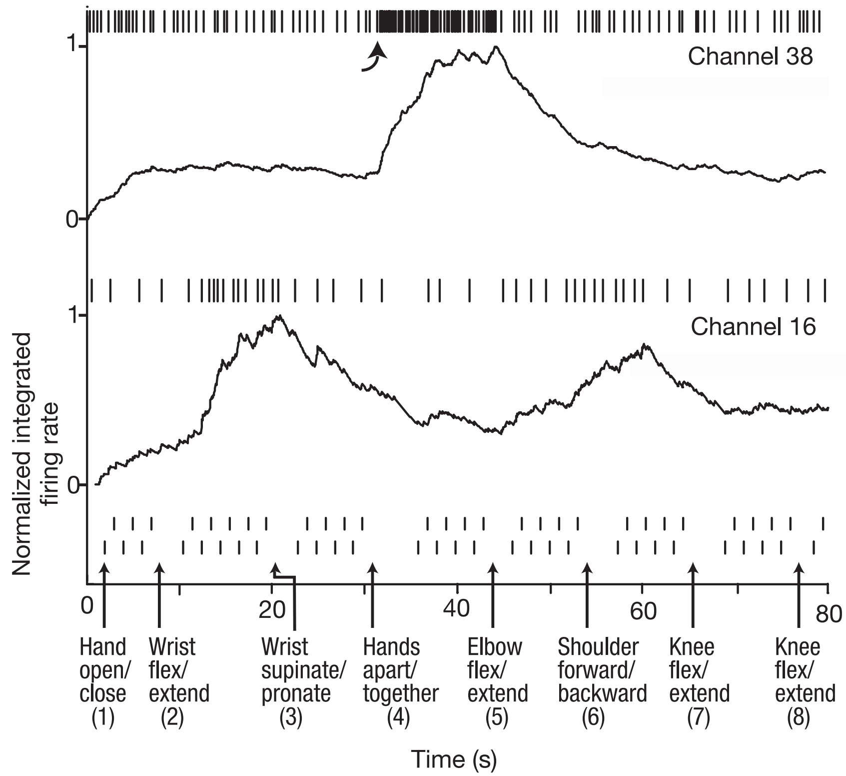
Neural activity in electrodes

Local Field Potentials: Frequency versus time

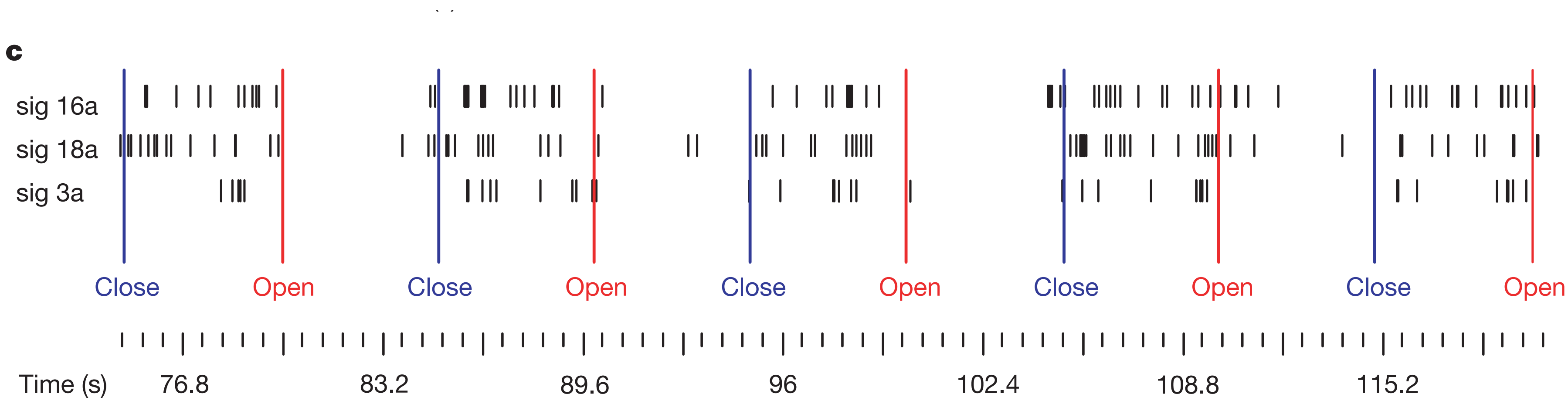
Three trials from one electrode (bandpass 10-100 Hz)

“Imagined limb motions modulated neural firing rate on multiple electrodes… revealed a rich variety of firing modulations largely consistent with patterns observed in monkey Primary Motor Cortex…”

Neuronal selectivity for imagined movements (all imagined except shoulder).

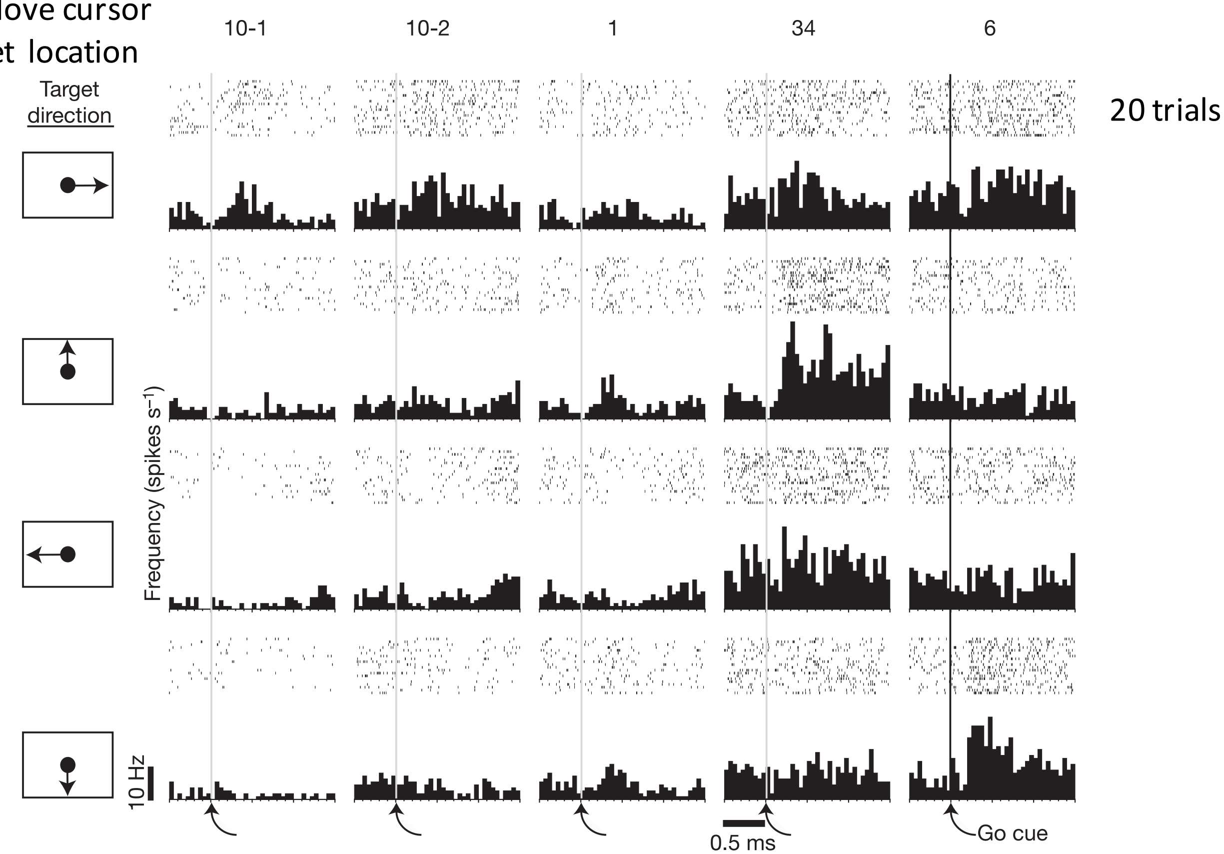


"Over an 80-s period, MN was asked to imagine performing a series of left limb movements (which are described on the abscissa). Movement instruction time is indicated by a vertical arrow…"



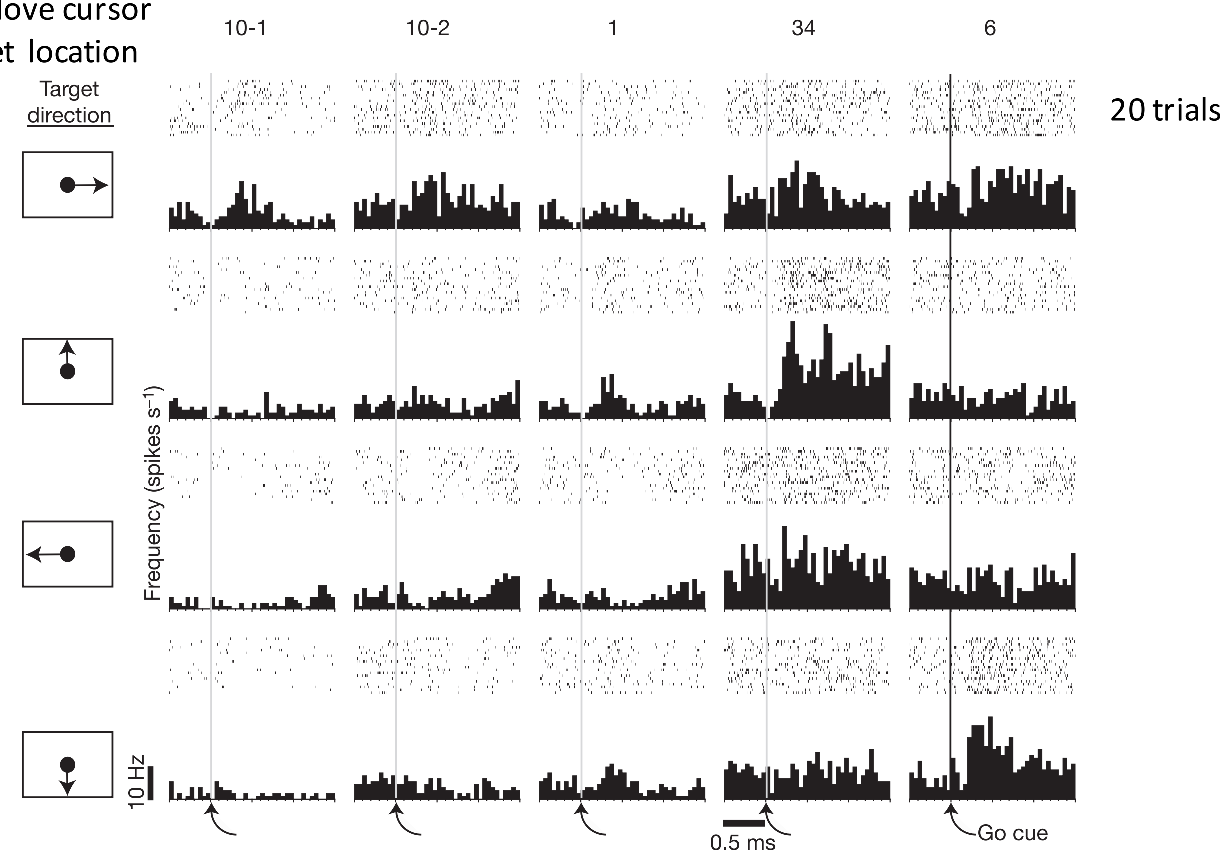
Neuron that increases its firing rate when asked to close the hand (and not for open)

Task: Move cursor to target location



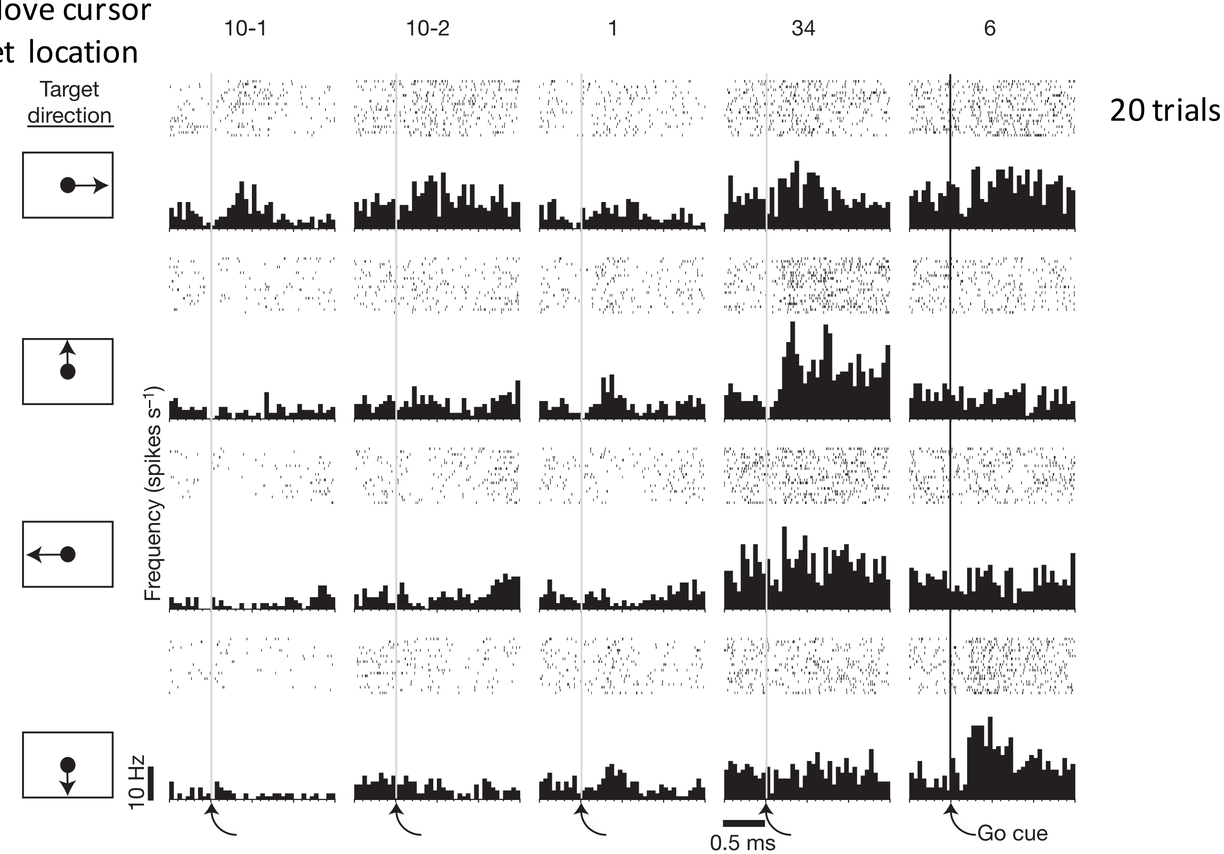
Directional tuning during centre-out task, for 5 neurons (columns)

Task: Move cursor to target location



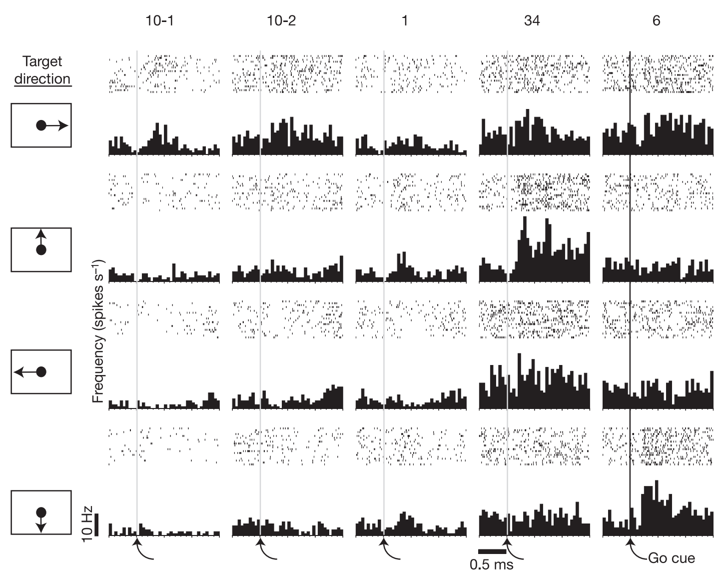
Channel 6: Increased neural activity for what direction?

Task: Move cursor to target location



Channel 6: Increased neural activity for downward movement

Task: Move cursor
to target location



Directional tuning during centre-out task, for 5 neurons (columns)-
“Spike rate modulation occurs soon after the ‘go’ cue … modulation varied by target location as would be predicted for Primary Motor Cortex if actual arm motions were performed … even years after spinal cord injury … can still be actively engaged and encode task-related information during the intention to move the limb …”

Establish transform between firing patterns and intended actions:

Imagine tracking cursor while tracking technician cursor.

Establish transform between firing patterns and intended actions:

Imagine tracking cursor while tracking technician cursor.

Input: ?

Output: ?

Establish transform between firing patterns and intended actions:

Imagine tracking cursor while tracking technician cursor.

Input: firing rate in neural units over time

Output: x, y coordinates of movement

Establish transform between firing patterns and intended actions:

Imagine tracking cursor while tracking technician cursor.

Input: firing rate in neural units over time

Output: x, y coordinates of movement

We would like a transform from input to output… what to do?

Linear filter reconstruction: Imagine tracking cursor while tracking technician cursor.

Establish transform between firing patterns and intended actions:

R = neural response matrix (number neurons by time bins)
K = x,y coordinates of movement
f = filter

$$\boldsymbol{Rf} = \boldsymbol{k}$$

Need to estimate f, and then estimate Rf which reconstructs k

Linear filter reconstruction: Imagine tracking cursor while tracking technician cursor.

Establish transform between firing patterns and intended actions:

R = neural response matrix (number neurons by time bins)
K = x,y coordinates of movement
f = filter

$$\boldsymbol{Rf = k}$$

Need to estimate f, and then estimate Rf which reconstructs k

How??

R = neural response matrix (number neurons by time bins)
K = x,y coordinates
f = filter

$$\boldsymbol{Rf} = \boldsymbol{k}$$

Least squares:

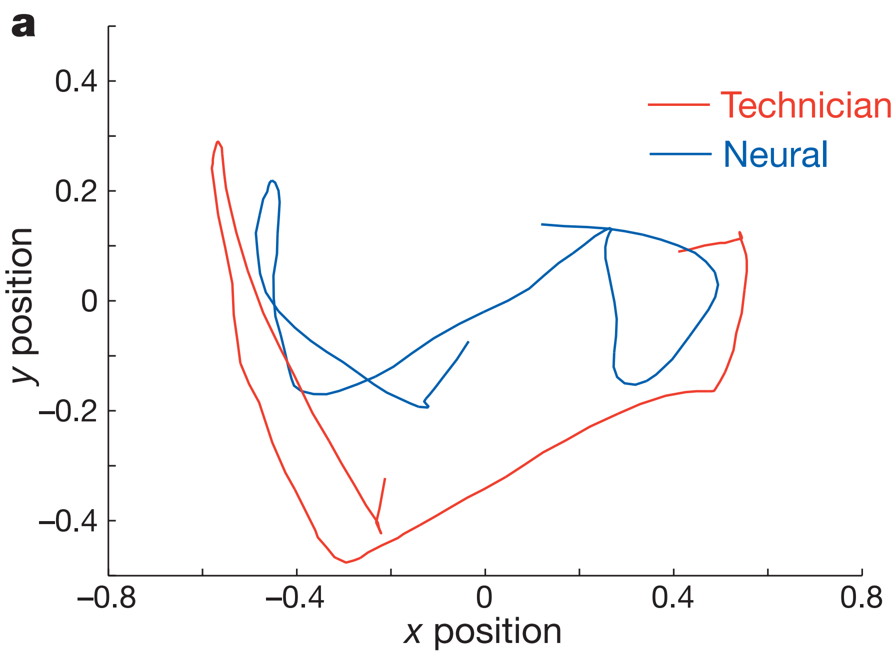
$$\boldsymbol{R}^{T}\boldsymbol{R}\boldsymbol{f} = \boldsymbol{R}^{T}\mathbf{k}$$

$$(\boldsymbol{R}^{T}\boldsymbol{R})^{-1}(\boldsymbol{R}^{T}\boldsymbol{R})\boldsymbol{f} = (\boldsymbol{R}^{T}\boldsymbol{R})^{-1}\boldsymbol{R}^{T}\mathbf{k}$$

$$\boldsymbol{f} = (\boldsymbol{R}^{T}\boldsymbol{R})^{-1}\boldsymbol{R}^{T}\mathbf{k}$$

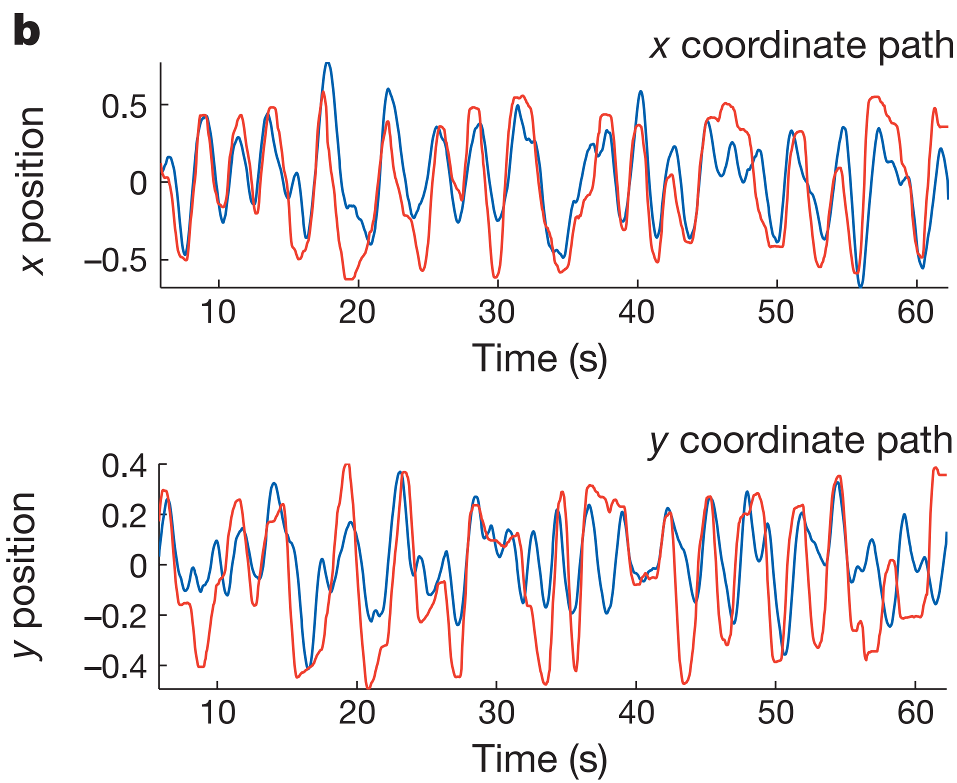
$$\boldsymbol{u} = \boldsymbol{Rf} = \boldsymbol{R}(\boldsymbol{R}^{T}\boldsymbol{R})^{-1}\boldsymbol{R}^{T}\mathbf{k}$$

Comparing technician motion and estimated movement from neural data



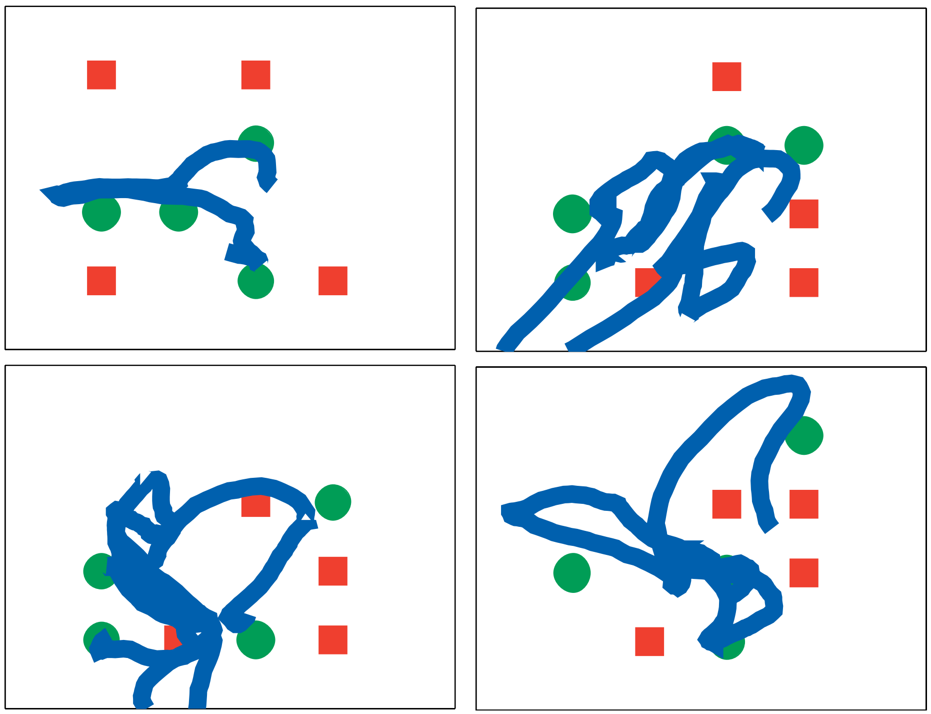
Captures general direction of technician cursor movement but some difficulty overlaying cursor precisely (in neural cursor from imagined movement)

Comparing technician motion and estimated movement from neural data

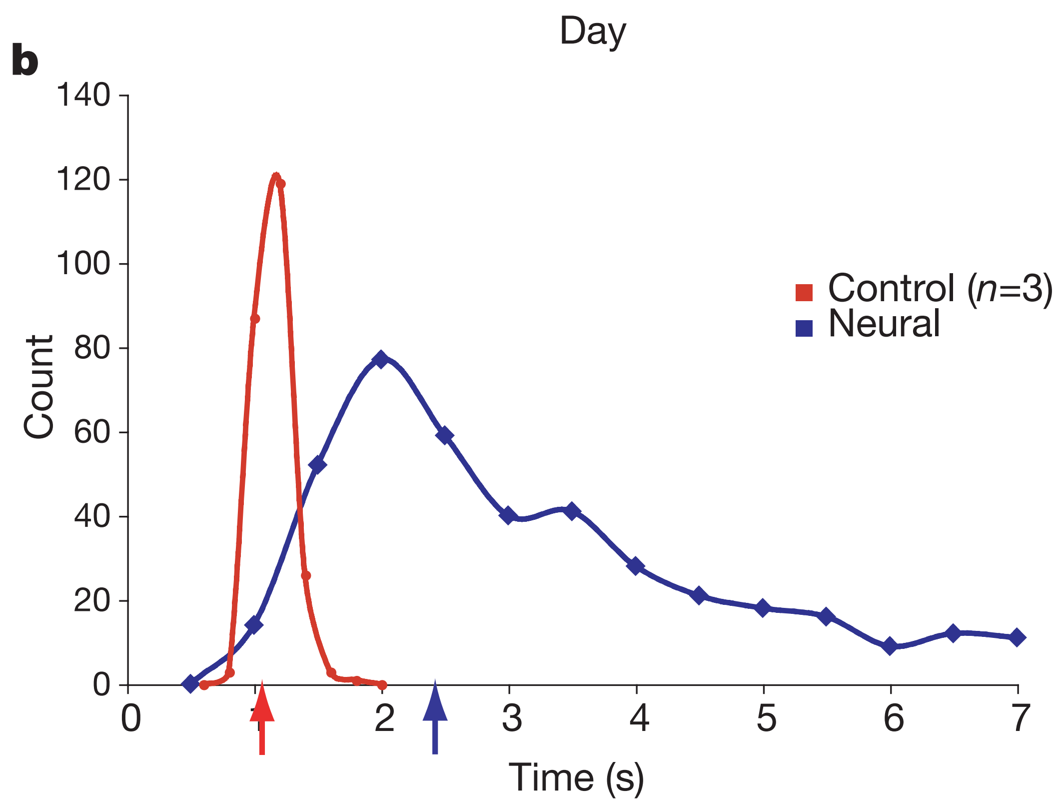


Technician cursor x and y positions (red); and neural cursor position (blue)

c



Neural cursor position in obstacle avoidance task (need to go to green targets and avoid red obstacles)



Centre-out task time to target performance: MN versus control subjects time

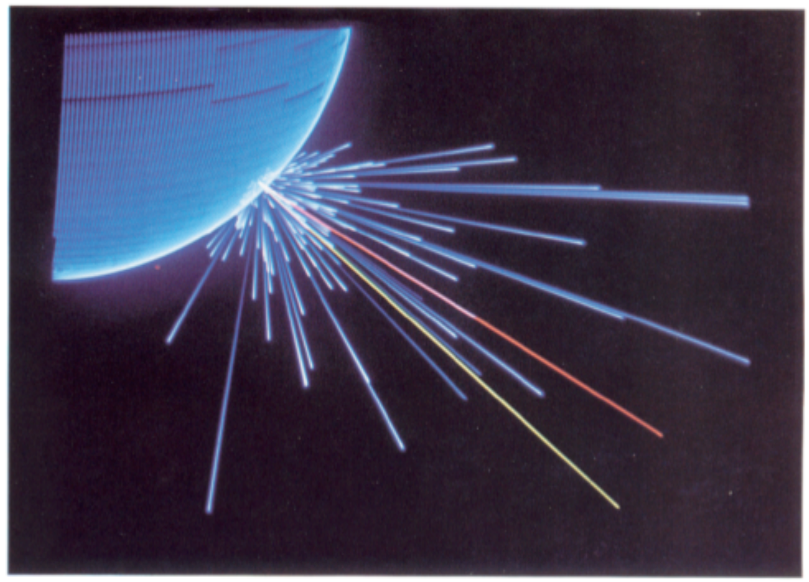
nature Vol 453|19 June 2008|doi:10.1038/nature06996

LETTERS

Cortical control of a prosthetic arm for self-feeding

Meel Velliste[1], Sagi Perel[2,3], M. Chance Spalding[2,3], Andrew S. Whitford[2,3] & Andrew B. Schwartz[1–6]

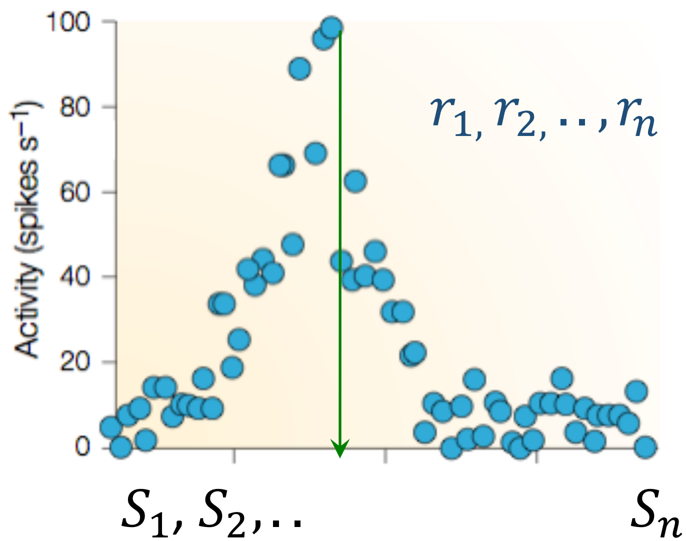
Population coding example



Decoding hand movement direction from primary motor cortex population (from Georgopoulos et al., 1988)

Population vector decoding

Population coding



Population vector: each neuron "votes" for its preferred stimulus

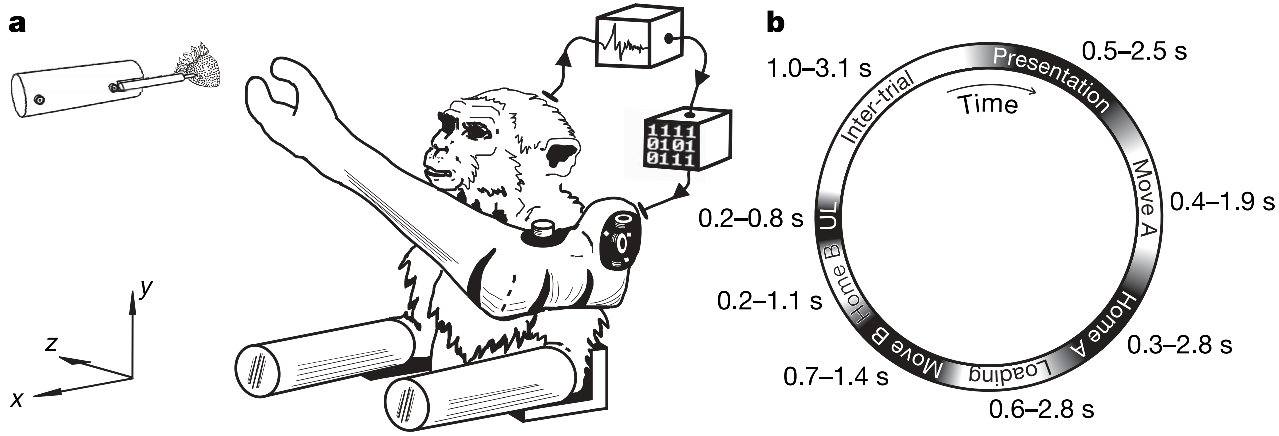
$$\hat{S} = \sum_{i=1}^{n} r_i S_i$$

Has been useful for:
Cercal system
Motor cortex

"… describe a system that permits embodied prosthetic control; we show how monkeys use their motor cortical activity to control a mechanized arm replica in a self-feeding task … in addition to the three dimensions of movement … controlled a gripper at the end of the arm"

Embodied control setup

Self-feeding timeline



(a) “Spiking activity was processed (boxes at top right) and used to control the three-dimensional arm velocity and the gripper aperture velocity in real time. “

(b) “Each trial started with presentation of a food piece, and a successful trial ended with the monkey unloading (UL) the food from the gripper into its mouth … Owing to the continuous nature of the task, there were no clear boundaries between the task periods.”

Self-feeding with robotic arm

https://www.youtube.com/watch?v=Y6fug4pzU4Q

Self-feeding with robotic arm

"For example, the monkey moved the arm to lick the gripper fingers while ignoring a presented food target, and sometimes used the gripper fingers to give a second push to the food when unloading … These behaviours were not task requirements, but emerged as new capabilities were learned, demonstrating how the monkey used the robot arm as a surrogate for its own."

Calibration

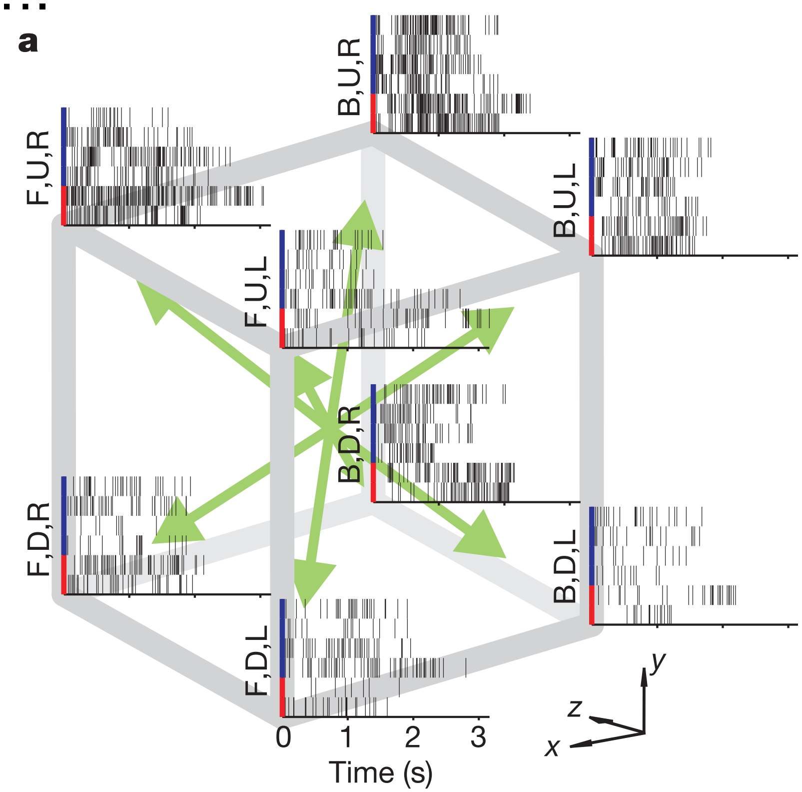
“Population Vector Averaging (PVA) … is dependent on accurate estimates of the recorded units’ tuning properties”

“At the beginning of each day, the tuning properties were estimated in a calibration procedure that did not require the monkey to move its arm.”

“During the first iteration of four trials … the monkey watched the automated performance of reach, grip and retrieval and then received the food. “

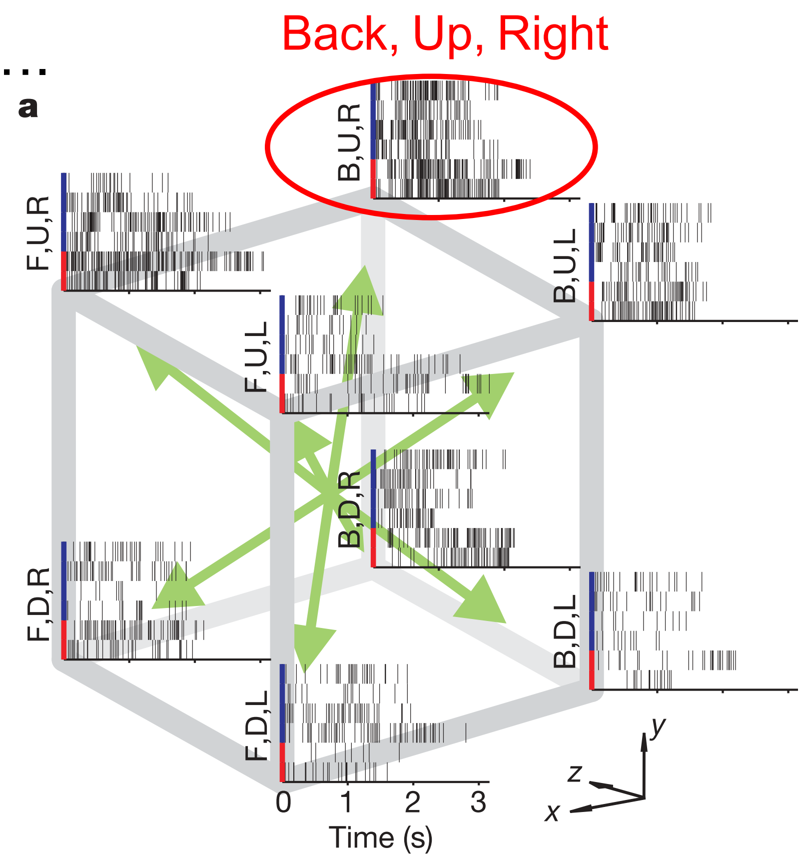
“During the next iteration, these initial estimates were used by the extraction algorithm to generate a signal mixed with automated control”

“gradually decreasing the automated control until both arm movement and the gripper were fully controlled by the monkey’s cortical activity” figure 4….



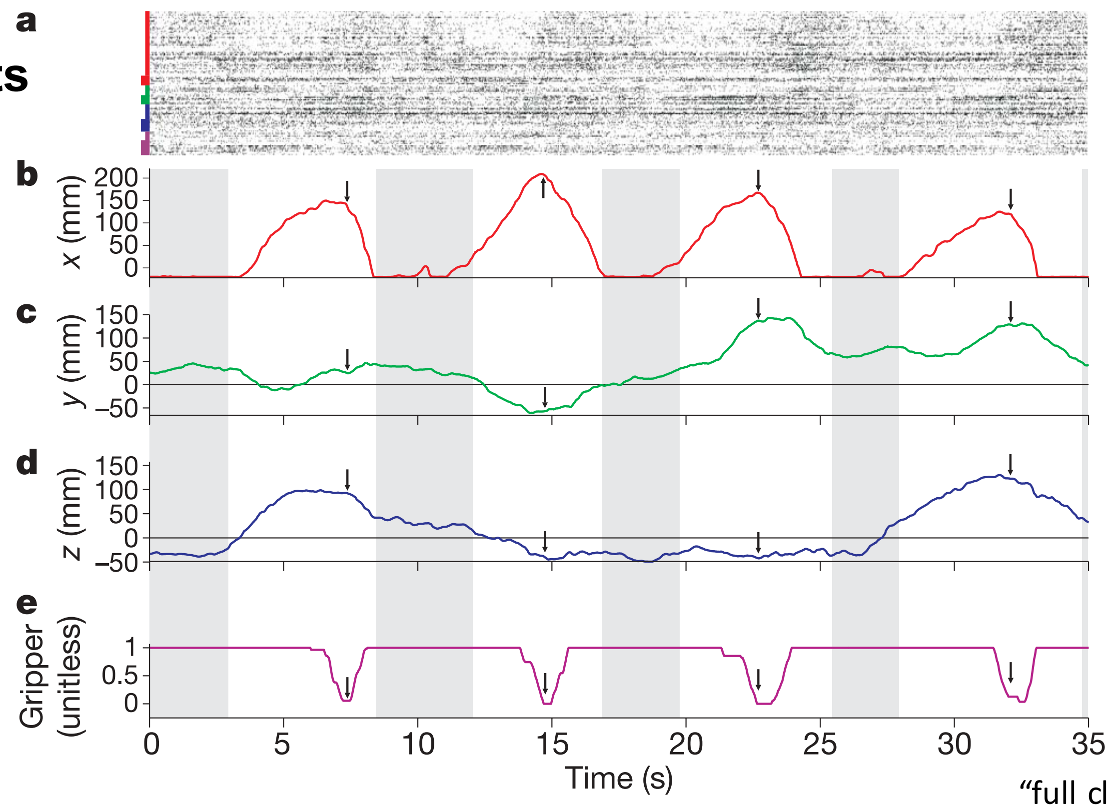
Neuron tuned to direction of movement.
Blue/red: during and after calibration.

figure 4….



Neuron tuned to direction of movement.
Blue/red: during and after calibration.

116 units (rows)



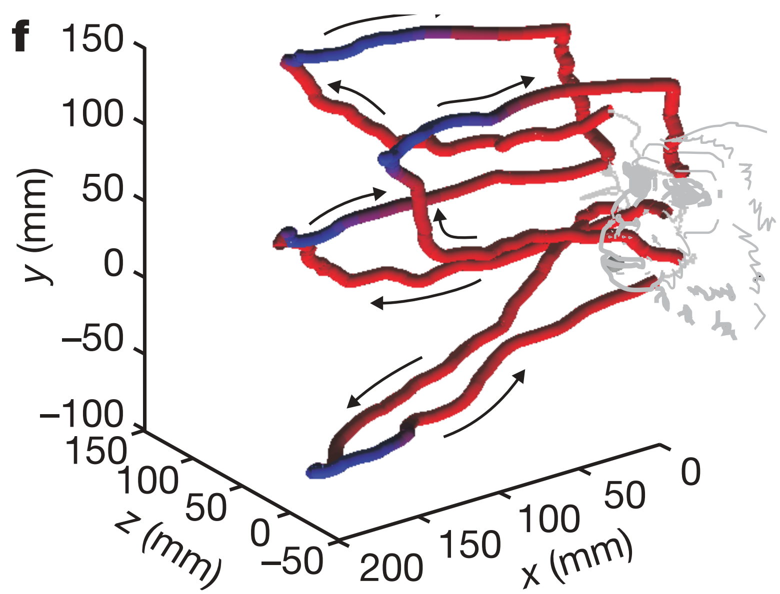
Grouped by major tuning component for x, y, z, gripper (4 colors)

Resulting arm and gripper movement to targets (Arrows: gripper closing At target; Gray is between trials)

1: Open
0: Close

“full closing is required for loading”

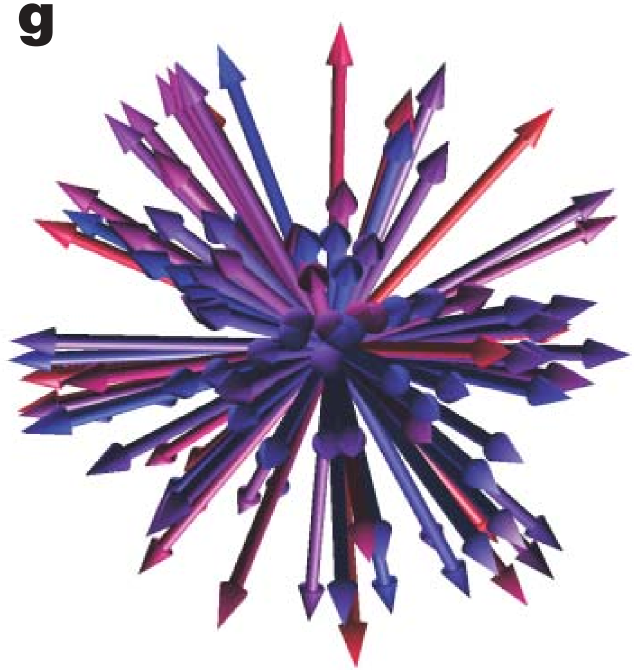
4 Dimensions: X; Y; Z; open/close



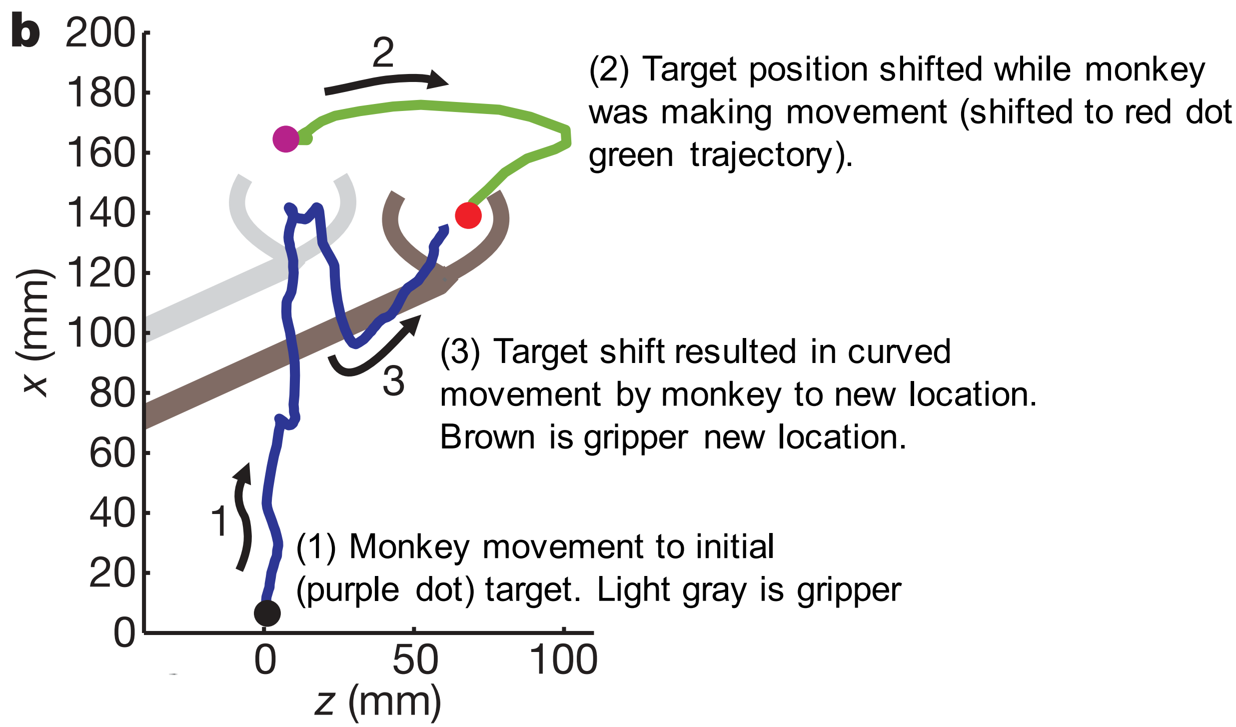
4 Dimensions: X; Y; Z; open/close
blue: closed; purple: half closed; red open.

“Figure 2f reveals a surprising point: after gripping the food and pulling it off the presentation device, the monkey gradually opened the gripper on the way back to the mouth (Move B) and the gripper was typically fully open before it reached the mouth… One might expect the food to have dropped when the gripper was opened, but this was not always the case because marshmallows, and even grape halves to some extent, tended to stick to the gripper fingers.

g



116 units. 4 Dimensions: X; Y; Z;
Distribution of the four-dimensional preferred directions of the 116 units used.
arrow direction indicates x,y,z components
open/close Blue: closed; purple: half closed; red open



Target shift: “The monkey then moved the arm in a curved path (arrow 3) to avoid knocking the food off the presentation device, positioning the gripper (dark grey sketch) to grasp the food.”