The Motor System: Lecture 6
Disorders of the parietal cortex
The motor cortex

Reza Shadmehr

Encoding of a movement plan during a delay period

Slide 2. The evidence that the posterior parietal cortex is involved in planning of movements comes from experiments where monkeys prepare to make a reaching movement to a target, that target disappears, and then after a wait period, they reach to the location where they remember the target to be. In one of these experiments, Donald Crammond and John Kalaska recorded from the dorsal region of area 5 (called area 5d) in the monkey posterior parietal cortex in a task where the animal was given instructions about where to reach to, but had to wait until a "go" signal appeared. In the experiment, the target cue stayed lit for only 500 ms, and then disappeared. The monkey waited for a go signal, which could come much later. Trials were directed either toward the cell's preferred direction or in the opposite direction. They found that during the delay period, the directionally tuned activity in the trials where the cue was only briefly visible was essentially the same as when the cue was visible during the entire period. Therefore, the presence of the cue was not necessary to sustain the delay period response. This is consistent with the idea that the neural discharge in PPC reflects something about the planning of the movement and not merely a passive response to the information that is currently available on the retina.

Human PPC neurons code for target location in fixation centered coordinates

Slide 3. Recall that when you fixate a point, the image to the right of fixation goes to the left visual cortex, and the image to the left of fixation goes to the right visual cortex. In this experiment, Doug Crawford and his colleagues used fMRI to test the idea that in human, targets of reaching are represented as vectors with respect to fixation. They asked participants to fixate a central point and flashed a target on either left or right side of the fixation point ("delayed pointing" task). After a delay period, the participant reached to the remembered location of the target. They found that if the target was to the left of fixation, the right PPC was activated, and vice versa. In a subsequent experiment ("delayed pointing with intervening saccade"), the participant fixated a point when the movement target was flashed to one side, say the right side of fixation, thus activating the left PPC. However, before reaching, a second fixation point appeared so that now the remembered target fell on the left side of the fixation point. As the saccade moved the fovea from one fixation point to another, the remembered location of the target moved from right side of fixation point to left. Coincident with this, the activity in PPC shifted from the left hemisphere to right. Therefore, despite the fact that no target was visible, movements of the eyes caused a remapping of the remembered reach target with respect to fixation point. This finding again illustrates that reach targets are encoded as a vector with respect to the fixation point.

In this figure, the participant fixates a central location, where a letter indicates the task to perform (S, saccade to a target; P, point to a target; or F, continue fixating the center of the screen). For the "delayed-pointing" task, the target appears and, after a delay, the participant points to the remembered location of the target. In the "delayed-pointing, with-intervening-saccade" task, the fixation point changes locations before the pointing takes place. The PPC region that shows "activity", i.e., changes in blood flow, switches hemispheres when eye movements place the remembered target to the left of the fixation point, as opposed to when they place it to the right of that point. The "activated" regions appear as enclosed areas on an "inflated" map of the cortex.

PPC neurons encode the relevance of the visual stimulus with respect to action

Slide 4. In most of the experiments explained above, the animal is sitting in a dark room and a light flashes. If the flash is in the receptive field of a PPC cell, it shows an increased discharge.

However, in the real world, visual stimuli are constantly falling on our retina. Are the PPC cells in our brain constantly on?

In this experiment, Gottlieb, Kusunoki, and Goldberg (1997) tried a more natural setting. They had a monkey fixate a peripheral fixation point (15 deg left). The receptive field of this cell is drawn by the gray circle in part A. So at the start of the task, there was nothing in the receptive field of the cell. Just above the fixation a cue appears (in this case, a circle). The fixation point moves to the center (first saccade). Now the circle falls in the receptive field of the cell. The animal saccades to the circle (second saccade). Notice that just before the first saccade, in anticipation of the cue falling in the receptive field of the cell, the cell increases its discharge.

Now compare this with the results shown in part B. In this case, the cue is a "+". After the first saccade, the circle is once again in the receptive field of the cell, but the cell's discharge is unchanged. The cell only cares about the visual input if that input is relevant for future action. In a sense, these cells encode the salience or value of the visual world with respect to action.

PPC neurons code for movement kinematics and not dynamics

Slide 5. What does the term "planning a movement" really mean when we say that the posterior parietal cortex appears to be coding a movement's plan? Is the plan limited to the kinematics of the task (target location), or does it also involve issues of dynamics (forces necessary to do the movement)? To answer these questions, John Kalaska and his colleagues performed an experiment where a monkey held on to a handle and reached to a target while loads were imposed on the arm. Therefore, the idea was to make the monkey reach to the same target along the same trajectory, but with each load, the monkey would have to activate different muscles and produce different kinds of torques on the joints. This dissociated the movement kinematics from its dynamics.

Kalaska and his colleagues found that activity of area 5 cells were relatively unaffected by the presence of the load or its direction but during the time that the animal was holding the manipulandum and waiting for the go signal and during the time when the monkey was making the movement. This was in sharp contrast to a somatosensory area (area 2). Both in this area and in the primary motor cortex (area 4), discharge was strongly affected by the dynamics of the task.

Lesion of the right parietal cortex can result in neglect

Slide 6. Damage to the <u>right parietal cortex</u> does not produce simple sensory deficits such as blindness or loss of tactile senses. Rather, damage results in **agnosia**, an inability to act on objects despite normal sensory processes. A particular striking form of agnosia is neglect. Neglect is a failure to respond or orient to stimuli that are presented contralateral to a brain lesion, when this failure is not due to elementary sensory or motor loss. For example, in the line bisection tack, the patient is given a long line and asked to indicate its midpoint. The neglect patient will cross the line to the far right. In the cancellation task, a paper contains targets and the patient is asked to mark out (cancel) all the targets. The neglect patient will cross out only the targets on the right side. In the copying test, the patient is asked to copy a line drawing. The neglect patient will draw only the right part of the figure.

Although neglect can be associated with both right and left hemisphere lesions, it is much more severe and frequent with right hemisphere damage. The asymmetries appear to be related to asymmetrical representation of visual space. Whereas the left hemisphere primarily attends to visual information on the right of fixation, the right hemisphere attends to both sides.

Coding object position with respect to the hand takes place in the premotor cortex

Slide 7. Neurons in the posterior parietal cortex encode target and hand position in fixation centered coordinates. In the premotor cortex, these two vectors are compared and a new vector is computed: a vector that points from the hand to the target. Finally, in the primary motor cortex, this vector is transformed into the motor commands needed to move the arm.

Slide 8. To test the idea that in the premotor cortex, cells encode target position with respect to the hand (i.e., kinematics of the movement, not the forces), an experiment examined the neuronal activity in the ventral premotor region (PMv) in a task where the animal fixated a point and objects were brought close to the arm. A neuron's tactile receptive field was mapped by touching various parts of the arm. The tactile receptive field for one PMv neuron is shown in B.

On each trial, the animal fixated one of three lights. A 10 cm white sphere served as a visual stimulus that was advanced along one of four trajectories toward the arm. The response of this cell to the visual stimulus is shown in C. The cell discharged strongly only when the stimulus was presented at a location that was on the side of the tactile response. As the fixation point was changed, the discharge did not vary significantly. Therefore, the visually evoked response remained fixed to the position of the visual stimulus with respect to the arm, not the fovea. When the arm was moved to the left side, the response was now strongest for trajectory III. That is, the visually evoked response appeared to move with the arm, and not the eyes. This is what would be expected if the position of an object were coded with respect to the position of a limb.

Neurons in the premotor cortex are sensitive to location of the target with respect to the hand and not forces

The results describe above suggest that the ventral premotor cortex might be a good place to look for cells that represent planning of reaching movements. The hypothesis is that if one is planning to reach for an object, cells in this region might code for where the target is located with respect to the hand, that is, the displacement vector. Importantly, if the location of the target remains invariant with respect to the location of the hand, the representation of the vector should also remain invariant. This would predict that if a monkey were to make reaching movements from different start positions of the hand, what matters is where the target is located with respect to the hand and not where the arm is located in the workspace, or where the arm is located with respect to point of fixation.

Slide 9. To test for this, discharge of cells in PMv were recorded in a task where a monkey was trained to move a cursor on a video monitor by moving its wrist. The monkey held a device in its hand that was connected to a computer that translated the stick's motion to cursor motion. When a target was shown on the screen, the animal moved his wrist to bring the cursor to the target. The interesting point was that the movements were performed in three different initial wrist configurations. When the wrist was in the pronated position, the muscles that were activated to move the cursor to the target at 45^o were quite different than the muscles that were activated to make the same cursor movement with the wrist in the supinated position. So if the cells somehow reflected the muscle commands that were needed to make the movement, then their activity should change considerably when the wrist configuration was changed. On the other hand, if the cells were coding the target direction with respect to the current position of the end-effector, where the end-effector now is not hand position but the cursor position, then their discharge might be invariant to changes in arm configuration. Indeed, among nearly all the task related PMv cells that were found, discharge was related to the direction of the target with respect to the cursor and not affected significantly by changes to the arm's configuration.

Neurons in the motor cortex are sensitive to forces that are involved in making a reaching movement

Slide 10. Cells in PMv as a population appear to encode a movement in terms of a displacement vector with respect to the hand. Such cells are rare in the primary motor cortex (M1). In M1, most cells change their discharge as the configuration of the arm is changed, despite the fact that the cursor on the screen is moving the same way as before. Therefore, in M1 cells begin to transform the plan of the movement from a displacement vector with respect to the hand to patterns of activity that are necessary for activating the muscles and moving the limb.

Some cells in M1 have a discharge that correlates with forces produced by arm muscles

Slide 11. In this experiment, a constant torque was applied to elbow and shoulder joints of the monkey's arm. The animal is trained to maintain constant arm position. Therefore, muscles produce activity to counter the imposed torque. Discharge for two neurons is shown as a function of torque imposed on the arm.

During a movement, activity in the premotor cortex precedes activity in M1

Slide 12. Consistent with the idea that the premotor cortex represents the movement plan with respect to the hand and the motor cortex represents the movement commands in terms of activities needed to guide the muscles, the activity in premotor cortex tends to precede the activity in M1.

Stimulation of the motor cortex results in twitch-like movements

Slide 13. High intensity stimulation of almost any part of the cerebral cortex produces a movement. However, the primary motor cortex produces movements with the lowest levels of stimulation. During brain surgery, the cortex may be stimulated and the resulting movements can be recorded. Stimulation results in discrete, flick-like twitches of a single muscle or small group of muscles on the contralateral side of the body. Movements are never skilled movements. Rather, they are flexion or extension of a single joint. In this slide, we see the notes made by a neurosurgeon regarding the effects that were observed. The dark line is the central sulcus, and the region anterior to it is the primary motor cortex. Note how in the medial aspect of the motor cortex, stimulation causes movements of the arm or the fingers, and that in the lateral aspects stimulation causes mouth and face movements.

Slide 14. There is a somatotopic organization of the body parts in the motor cortex. Body parts that are close to each other (for example, fingers are attached to the hand, which is attached to the arm), are represented by neuron in the motor cortex that are also close to each other. In this slide, we see the movements that are evoked by stimulating an anesthetized monkey. There is a general trend for somatotopy: trunk more medial, jaw more lateral. However, movement of a given body part (e.g., digits) is evoked from multiple foci.

Slide 15. This schematic is a summary of the somatotopy in the primary motor cortex. The amount of neural tissue dedicated to control of a particular body part is drawn to scale. Therefore, much more neural tissue is concerned with control of shoulder/hand/digits/thumb motion than control of the leg/feet/toes.

Damage to peripheral nervous system causes re-organization of the motor map

Slide 16. Connections between motor cortex and muscles are not fixed. In the adult rat, motor representation in the primary motor cortex can change with in a few hours after a nerve supplying motor axons to the muscles attached to the vibrissae (nose hair, or whiskers) is sectioned. This branch contains no sensory fibers. With in hours after cutting of the motor nerve, the motor map adjacent to the vibrissae region grows and takes up the region which used to evoke vibrissae movement.

Mechanism of reorganization of the motor map

Slide 17. There is a system of excitatory intracortical connections between motor cortical output neurons. This connection is not usually functionally expressed because of the intracortical fibers also stimulate local inhibitory neurons. Adjacent cortical regions expand when preexisting lateral excitatory connections are unmasked by decreased intracortical inhibition. We don't know how cutting a peripheral nerve or changes in sensory inflow might influence this intracortical inhibition.

Amputation reorganizes the motor map

Slide 18. An individual was involved in an accident and his right arm above the wrist had to be amputated. A year after the surgery, the motor cortex in each hemisphere was stimulated and muscle activity was recorded in the contralateral biceps. Note that the motor map for biceps on the left hemisphere is larger than the right hemisphere. This is because the biceps motor map in the left hemisphere has grown to take over the hand/finger regions that are no longer needed.

A stroke in the motor cortex results in reorganization of the motor map

Slide 19. After a stroke in the primary motor cortex, there is weakness and paralysis in the contralateral musculature. A gradual return of some abilities often occurs in the following weeks or months. In humans, there is rarely complete recovery of function in distal musculature. In this slide, we see the motor map in the motor cortex of a monkey. The lesion destroyed 21% of digit and 7% of wrist areas. After 3 months, the area for digits has been reduced further. This is probably because after a stroke, the affected limb is used less. It is possible that this reduced use itself affects representations in the brain, resulting in further loss of limb regions in the motor cortex. Therefore, it may be possible to reverse some of the effects of the damage through a movement therapy that "forces" the patient to use the affected limb.

Rehabilitation through forced use of the affected limb restores some of the lost motor map regions

Slide 20. Rehabilitation can prevent loss of motor cortical zones outside the region of infarct: the animal in this study received extensive training after the infarct and we see that there was a prevention of the loss of hand territory adjacent to the infarct region. Functional reorganization in the undamaged motor cortex was accompanied by behavioral recovery of skilled hand function. Therefore, the undamaged motor cortex can play an important role in motor recovery by reorganizing itself and compensating for the damaged areas.

Constrained motion rehabilitation can restore function in humans long after a stroke

Slide 21. Volunteers who were on average 5 years post stroke had their non-affected arm put in a splint for 90% of waking hours during a 2 week period. On 8 days during this two week period they came into the laboratory and were asked to perform movements with their affected hand for 6 hours each day. Results showed that the function of the affected hand was significantly improved because of the therapy, and the improvement lasted for months after the splint was removed.

Motor learning produces change in the motor map

Slide 22. Learning to make a skilled grasping movement results in changes in the motor cortex. Adult monkeys were trained to grasp small food pellets. The motor cortex was mapped using microstimulation both before and after training. Regions of cortex that evoked movements in a particular limb part were noted. After training in the hard task (small well training), there was an increase in the size of the motor map associated with the digits. However, if the task was easy (large well), there was no change.

Summary of functions of PPC, PM, and M1:

Slide 23. Posterior parietal cortex is important for spatial localization of our body and objects around us. Here, neurons align proprioception of arm with vision of hand and compute hand position in eye-centered coordinates. Neurons also compute object position in eye-centered coordinates.

In the premotor cortex, the location of an object that is the goal of the reaching movement is represented with respect to position of the hand. Here, neurons subtract target position with respect to hand position and code the desired movement in terms of displacement of the hand.

In the primary motor cortex, neurons transform the desired movement to muscle activity patterns and send this command to the spinal cord.