

Figure 34-6 Some neurons in the parietal cortex of the monkey have receptive fields that dynamically expand once a tool is grasped. (Adapted from Maravita and Iriki, 2004. Copyright © 2003 Published by Elsevier Ltd.)

A. The orange area on the hand (*left*) indicates the somatosensory receptive field for a neuron. The purple area (*middle*) indicates the neuron's visual receptive field (vRF) region around the hand. The vRF is anchored to the hand and changes spatial location whenever the monkey moves its arm. The vRF expands

when the monkey grasps a rake after it has learned how to use the rake to reach for objects in the workspace (*right*).

B. A single neuron that has a shoulder-centered bimodal somatosensory (orange) and visual (purple) receptive field is illustrated. The vRF for this neuron (*middle*) is larger than the one shown in part A, possibly reflecting the potential workspace related to whole-arm function. The vRF also expands to incorporate the extended workspace permitted by use of a rake (*right*).

state estimation will depend on the origin of its pre-movement activity. If it is mainly generated within the parietal cortex itself, this will strongly implicate the parietal cortex in the planning of intended movements. In contrast, if it is primarily driven by an efference copy relayed from precentral motor areas, this would strongly implicate the parietal circuits in state estimation, including predicting how the arm should move in response to the motor command.

Premotor Cortex Supports Motor Selection and Planning

As outlined at the beginning of this chapter, a decision to act in a particular way in a given situation is shaped by many factors, including sensory information about objects, events, and opportunities for action from the

environment, body position and motion, internal motivational states, prior experiences, reward preferences, and learned arbitrary rules and strategies linking sensory inputs to motor actions. There can be many reasons why you want to drink some coffee, and that desire can be fulfilled by actions ranging from simply reaching out to your full coffee cup to making coffee at home or going to a café.

Frontal premotor cortical regions just rostral to M1 play an important role in early movement planning or task-selection processes. Many neurons in those areas, such as the PMd neurons shown in Figure 34-4, generate activity during instructed-delay tasks that reflect the motor intentions of the monkey and even the factors that influenced those action choices. The different premotor cortical regions are presumed to make different but overlapping contributions to motor selection and planning. For instance, the lateral premotor

cortex, including PMd and PMv, have traditionally been implicated in actions initiated and guided by external sensory inputs. In contrast, medial premotor areas, including SMA, pre-SMA, and CMA, have been implicated in the control of self-initiated movements as well as the suppression of actions. However, the distinction between their respective contributions is not absolute.

Medial Premotor Cortex Is Involved in the Contextual Control of Voluntary Actions

Clinton Woolsey's pioneering electrical stimulation studies showed that, in addition to the motor map in M1, the medial wall of the frontal cortex contains an array of neurons that also regulate body movements. This medial motor map, now called the supplementary motor area (SMA), includes the entire contralateral body but is coarser than the detailed map in M1, as described later. Strong stimulus currents are required to evoke movements, which are often complex actions such as postural adjustments or stepping

and climbing and can involve both sides of the body. Today, there is agreement that this region contains two areas that have distinct cytoarchitectonic characteristics, axonal connections, and functional properties: a more caudal SMA proper and a more rostral presupplementary motor area (pre-SMA), which we will collectively call the supplementary motor cortex (SMC).

The SMC has been implicated in many aspects of voluntary behavior, although its contribution remains controversial. Several lines of evidence support a role in self-initiated behavior. In humans, electrical stimulation of SMC below the threshold for movement initiation can evoke an introspective sense of an urge to move that does not arise during M1 stimulation. Lesions of SMC produce problems initiating desired movements or suppressing undesirable movements (Box 34–2). Moreover, recordings of slow cortical potentials at the surface of the skull during the execution of self-paced movements show that the initial potential arises in the frontal cortex as much as 0.8 to 1.0 second before the onset of movement. This signal, named the *readiness*

Box 34–2 Lesions of Premotor Cortex Lead to Impairments in the Selection, Initiation, and Suppression of Voluntary Behavior

Lesions of the supplementary motor area (SMA) and presupplementary motor area (pre-SMA) and the prefrontal areas connected with them produce deficits in the initiation and suppression of movements. Initiation deficits manifest themselves as loss of self-initiated arm movements, even though the patient can move when adequately prompted. This deficit can involve movement of parts of the body (*akinesia*) contralateral to the region and speech (*mutism*).

Deficits in movement suppression, in contrast, include the inability to suppress behaviors that are socially inappropriate. These include compulsive grasping of an object when the hand touches it (*forced grasping*), irrepressible reaching and searching movements aimed at an object that has been presented visually (*groping movements*), and impulsive arm and hand movements to grab nearby objects and even people without conscious awareness of the intention to do so (*alien-hand* or *anarchic-hand syndrome*).

Another striking syndrome is *utilization behavior*, in which a patient compulsively grabs and uses objects without consideration of need or the social context. Examples are picking up and putting on multiple pairs of glasses or reaching for and eating food when the

patient is not hungry or when the food is clearly part of someone else's meal.

These deficits in the initiation and suppression of actions may represent opposite facets of the same functional role for SMA and especially pre-SMA in the conditional or context-dependent control of voluntary behavior.

Lesions affecting premotor cortex also lead to impairments in the selection of motor actions. For example, when a normal monkey sees a tasty food treat behind a small transparent barrier, it readily reaches around the barrier to grasp it. However, after a large premotor cortex lesion, the monkey may persistently try to reach directly toward the treat and so repeatedly strikes the barrier with its hand, rather than making a detour around the barrier.

More focal lesions or inactivation of the ventral premotor cortex perturbs the ability to use visual information about an object to shape the hand appropriately for the object's size, shape, and orientation before grasping it. Focal lesions of the dorsal premotor cortex affect the ability to learn and recall arbitrary sensorimotor mappings or conditional stimulus–response associations, whereas supplementary motor cortex lesions impede the ability to learn and recall temporal sequences of movement.

potential, has its peak in the cortex centered in SMC. Because it occurs well before movement, the readiness potential has been widely interpreted as evidence that neural activity in this region is involved in forming the intention to move, not just in executing movement.

Neurons in both SMA and pre-SMA discharge before and during voluntary movements. Unlike M1 neurons, the activity of most SMA neurons is less tightly coupled to particular actions of a body part and appears instead to be associated with more complex, coordinated motor acts of the hand, arm, head, or trunk. Compared to SMA neurons, pre-SMA neurons often begin to discharge much earlier in advance of movement onset and are less tightly coupled to the execution of movements.

The SMC has been implicated in the so-called *executive control* of behavior, such as operations required to switch between different actions, plans, and strategies. For example, in monkeys, some SMC neurons discharge strongly when a subject is presented with a cue instructing it to change movement targets or to suppress a previously intended movement. The

SMC may therefore contain a system that can override motor plans when they are no longer appropriate.

The SMC has also been implicated in the organization and execution of movement sequences. Some SMC neurons discharge before the start of a particular sequence of three movements but not before a different sequence of the same three movements (Figure 34–7). Other neurons discharge only when a particular movement occurs in a specific position in a sequence or when a particular pair of consecutive movements occurs regardless of their position in the sequence. In contrast, some other SMC neurons discharge only when the monkey makes the movement that occurs in a particular ordinal position of a sequence (eg, only the third) irrespective of its nature or how many movements remain to be executed in the sequence.

These seemingly disparate functions may reflect a more general role of the SMC in *contextual control* of voluntary behavior. Contextual control involves selecting and executing those actions deemed appropriate on the basis of different combinations of internal and external cues as well as withholding inappropriate actions in

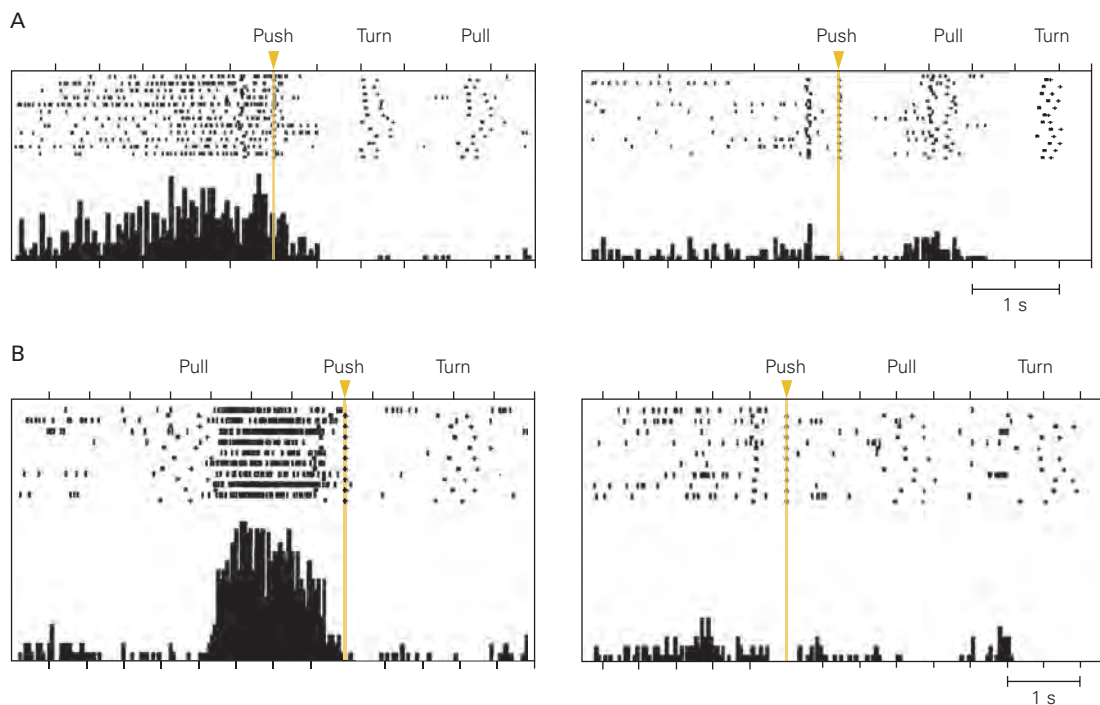


Figure 34–7 Some neurons in the supplementary motor complex of monkeys encode a specific sequence of motor acts. (Adapted, with permission, from Tanji 2001. Copyright © 2001 by Annual Reviews.)

A. A neuron discharges selectively during the waiting period before the first movement of the memorized sequence push-turn-pull (*left*). When the sequence is push-pull-turn (*right*), the cell remains relatively silent, even though the first movement in

both sequences is the same (push). Triangles at the top of each raster plot indicate the start of the push movement.

B. Records of a neuron whose activity increases selectively during the interval between completion of one motor act, a pull, and the initiation of another act, a push. The cell is not active when a push is the first movement in the sequence or when pull is followed by turn.

a specific environmental or social context. It also can involve organizing the sequence of actions required to achieve a particular goal. Contextual control likely also involves contributions from other neural circuits such as regions of the prefrontal cortex and the basal ganglia.

The cingulate motor areas (CMA) may also contribute to the contextual control of behavior. CMA appears to be involved in selecting alternate actions following motor errors or in response to changing reward contingencies. For example, monkeys were trained to push or turn a handle in response to a noninstructive trigger signal. Initially, the monkeys received a large reward if they made the same movement (pushing or turning the handle) in sequential trials. After several trials, the reward size began to decrease. If the monkeys then switched to the other movement, the reward size returned to maximum once that movement was repeated for several trials. The best strategy for the monkeys, therefore, was to switch between repetitions of either pushing or turning the handle as soon as they detected a reduction in reward size.

In this task, some neurons in the rostral CMA responded during the interval between the reception of reward and the start of the next trial. On trials with a reduced reward, task-related activity in these neurons did not change when the monkeys made the same movement in the next trial; their activity only changed when the monkeys switched to the other movement in the next trial. Importantly, those same neurons did not show the same response change when a visual cue instructed the monkeys to change movements in the next trial. This suggests that these rostral CMA neurons were preferentially involved in the voluntary decision to switch and move to the alternate goal based on action outcomes (reward size), but not by visual instructions to switch.

Dorsal Premotor Cortex Is Involved in Planning Sensory-Guided Movement of the Arm

Some of the first neural evidence that the lateral premotor cortex, including PMd and PMv, plays a crucial role in the selection and planning of sensory-guided motor actions came from recording studies by Ed Evarts, Steven Wise, and colleagues in the 1980s. These studies showed that many premotor neurons emitted brief short-latency discharge bursts in response to instructional cues that signaled specific movements, or sustained activity during the instructed-delay period between the appearance of the instructional cue and a second cue that permitted the instructed movement (Figure 34–4).

This activity reflects information about the intended act, including the spatial location of the target, the direction of arm movement, and other

movement attributes. Importantly, PMd delay-period activity can reflect the intention to reach to a particular location with either the contralateral or ipsilateral arm, even though the biomechanical details of the two arm movements are very different. This suggests that PMd activity can signal the intention to generate a motor act independent of the effector used to generate the action, in an extrinsic spatial coordinate framework consistent with a prediction of the sensorimotor coordinate transformation model of motor planning. Imaging studies have likewise found evidence for an extrinsic spatial representation of finger-tapping sequences made with either hand in human premotor cortex.

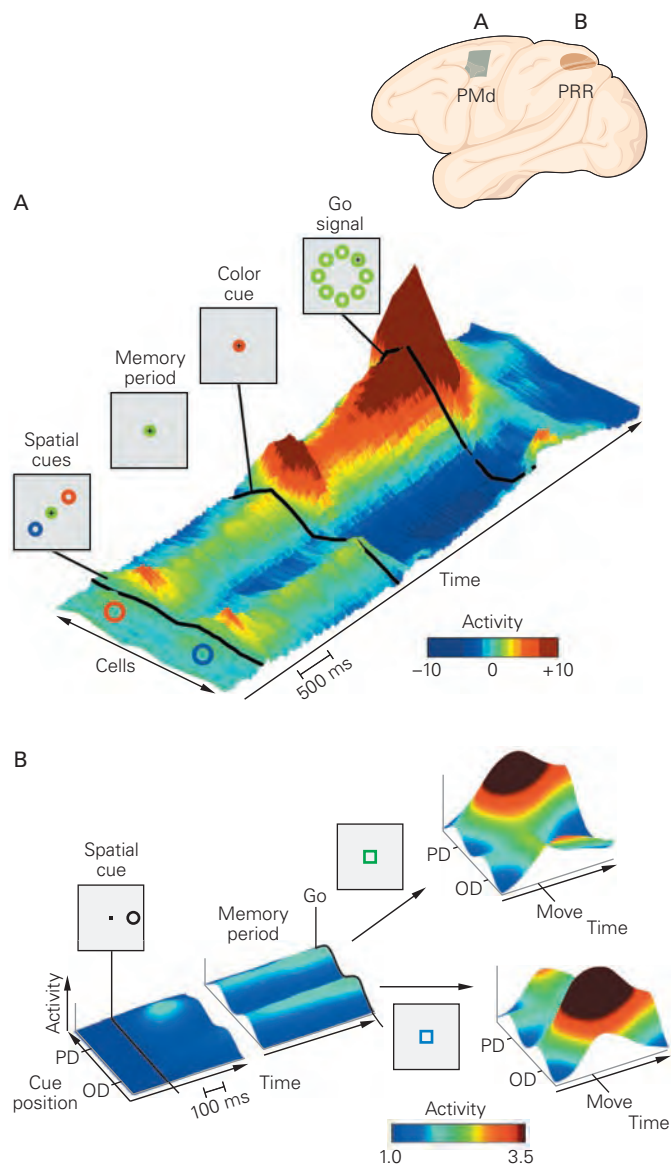
Selection of an appropriate action from among multiple alternatives is a critical aspect of voluntary control. Delay-period activity in PMd can reflect that process. For example, in one experiment, recordings were made from PMd neurons in monkeys during a task in which the animals first received two colored spatial cues that identified two potential targets for reaching in opposite directions. After a memorized-delay period, a new centrally-located color cue informed the monkeys which of the spatial cues was the correct target. Following the first instruction, neural activity in PMd signaled both potential-reaching movements, but immediately after the second instruction, activity in PMd signaled only the monkeys' reaching choice (Figure 34–8A). This showed that PMd can prepare multiple potential motor actions prior to the final decision about which action to take. Subsequent studies suggest that this might be limited to no more than three to four simultaneous potential actions. Reach-related neurons in parietal area PRR also contribute to the preparation for two potential motor actions before the final action decision is made (Figure 34–8B), revealing how this process is distributed across multiple arm movement-related cortical neural populations.

PMd neurons can also signal a deliberate decision not to move. Many PMd neurons generate directionally tuned activity during an instructed-delay period when a colored visual cue at a target location instructs a monkey to reach to the target, but decrease their activity when a different colored cue at the same location instructs the monkey to refrain from reaching to it. This differential activity is an unequivocal signal, seconds before the action is executed, about the monkey's intention to reach in a particular direction or not to move in response to an instructional cue (Figure 34–9). Interestingly, many neurons in the parietal area PE/MIP studied in the same task continue to generate directionally tuned activity during the delay period even after the instructional cue to withhold

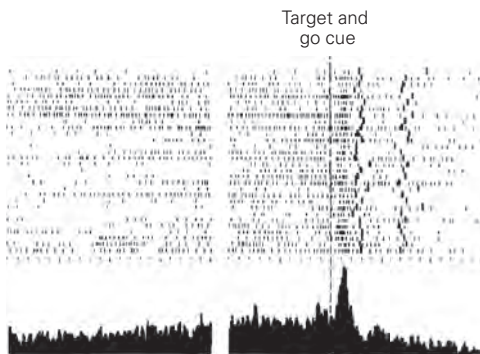
Figure 34–8 Activity of reach-related cortical neurons in monkeys during a target selection task reflects potential movements to different targets as well as the chosen direction of reach.

A. The three-dimensional colored surface depicts the mean level of activity of a population of dorsal premotor cortex (PMd) neurons with respect to baseline in a task in which a monkey must choose one of two color-coded reach targets in each trial. Cells are sorted along one axis (labeled “cells”) based on their preferred movement direction (neurons located at the **red** and **blue** circles prefer movements at 45° and 215°, respectively). Diagrams beside the neural response profile display the stimuli presented to the monkey at different times during the trial. **Red** and **blue** cues provide information about potential actions; **green** cues guide the monkeys through different stages of each trial but provide no information about what reach to make. Shortly after the start of each trial, two potential reach targets (**blue** and **red** spatial cues) appear in opposite locations relative to the starting position of the arm (**green** circle) for 500 ms and then disappear. After a memorized delay period, the color of the starting circle changes to either **red** or **blue** (color cue), indicating to the monkey which is the correct target, in this case at 45°. After a further delay period, the go signal (**green** circles at all eight possible target locations) instructs the monkey to begin reaching to its chosen target. During the period of target uncertainty between the appearance of the two spatial cues and the central color cue, PMd neurons that prefer the two potential reach movements (**red** and **blue** circles) are simultaneously activated, whereas neurons that prefer other movements are inactive or suppressed, so that the entire PMd population encodes the two potential reach actions. As soon as the color cue appears to identify the correct target, the PMd neural activity changes rapidly to signal the reach movement chosen by the monkey. Had the color cue designated the target at 215°, the neurons preferring that target (**blue** circle) would increase their activity, and the neurons preferring the target at 45° (**red** circle) would decrease their activity (not shown). (Reproduced, with permission, from Cisek and Kalaska 2010. Copyright © 2010 by Annual Reviews.)

B. In a second study of neural activity in the parietal reach region (PRR), the format of data is the same as in part **A**. In this study, the monkey is presented with a single spatial cue that instructs it to prepare to reach either to the cue’s location (**PD**) or in the opposite direction (**OD**). After a random memorized delay period, a color cue specifies whether the reach should be to the remembered location of the spatial cue (**green**; **PD**) or in the **OD** (**blue**). PRR neural activity is sorted according to the preferred movement direction of each neuron, as in part **A**. Population activity initially specifies the spatial cue location but then reflects both potential movement directions during the remainder of the memorized delay period. Shortly after the color cue appears, the activity quickly shifts to reflect the chosen reach direction, either the **PD** or **OD**. (Reproduced, with permission, from Klaes et al. 2011. Copyright © 2011 Elsevier Inc.)



A Reaction-time task



B Instructed-delay task

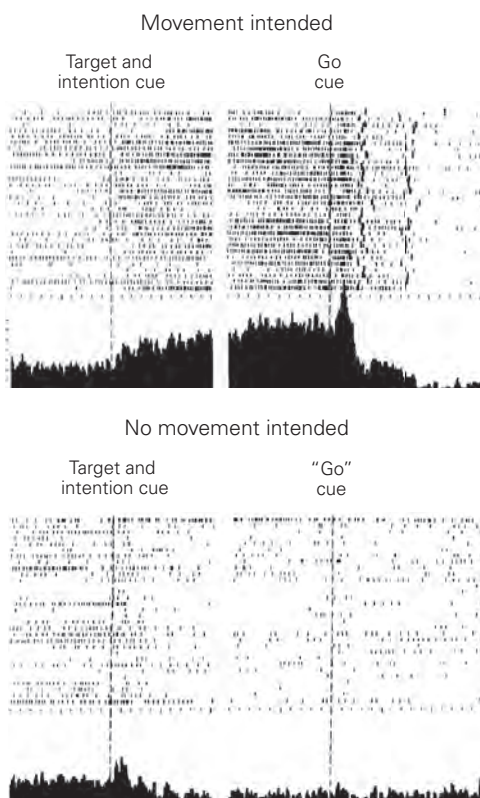


Figure 34–9 Decisions about response choices are evident in the activity of premotor cortex neurons in the monkey. (Reproduced, with permission, from Crammond and Kalaska 2000.)

A. In a reaction-time task (reaching), a cell exhibits gradually increasing tonic firing while waiting for the appearance of a target. When the target appears (go cue), the cell generates a directionally tuned response.

B. In an instructed-delay task, when a monkey is shown the target and instructed to move once the go cue appears, the cell generates a strong directionally tuned signal for the duration of the delay period before the go cue (top). When the monkey is shown the target and instructed not to move when the go cue appears, the cell's activity decreases (bottom).

reaching, suggesting that the parietal cortex retains a representation of potential actions that ultimately are not executed.

Many neurons in premotor cortex also discharge during movement execution. Given this close proximity of planning- and execution-related activity, even at the level of individual neurons, a major question is why planning-related neural activity does not immediately initiate a movement. What prevents the movement from being executed prematurely? It does not appear that planning-related activity simply fails to exceed a minimum threshold required to initiate the movement or that there is a separate overt braking mechanism that must be released to allow the movement to begin.

A different way to interpret neural processing during the planning and execution of reaching that might provide answers to such questions comes from a dynamical-systems perspective. The idea is that cortical motor circuits form a dynamical system whose distributed activity patterns evolve in time as a function of their initial state, input signals, and stochastic neural response variability (“noise”). Activity patterns during different stages of planning and execution thus reflect different states of the network, including a specific state during the delay period that can prepare the movement but not activate muscles (Figure 34–10). The overall similarity of the population-level activity patterns during repetitions of the same movement shows that the entire population undergoes a coordinated pattern of co-modulation of activity during the planning and execution of the movement, determined by the synaptic connectivity within the neural circuit.

Dorsal Premotor Cortex Is Involved in Applying Rules (Associations) That Govern Behavior

Behavior is often guided by arbitrary rules that link specific symbolic cues to particular actions. When driving your car, you must perform different actions depending on whether a traffic light is green, amber, or red. In monkeys that have learned to associate arbitrary cues with specific movements, many cells in premotor areas respond selectively to specific cues. For instance, in order to select the correct target in the two-target study in Figure 34–8, the monkeys had to apply a rule that mapped color to target location provided by the two sequential instructional cues.

The PMd is implicated in the acquisition of new movement-related associations or rules. In one experiment, recordings from PMd neurons were made while the monkeys learned the association between four unfamiliar visual cues and four different movement

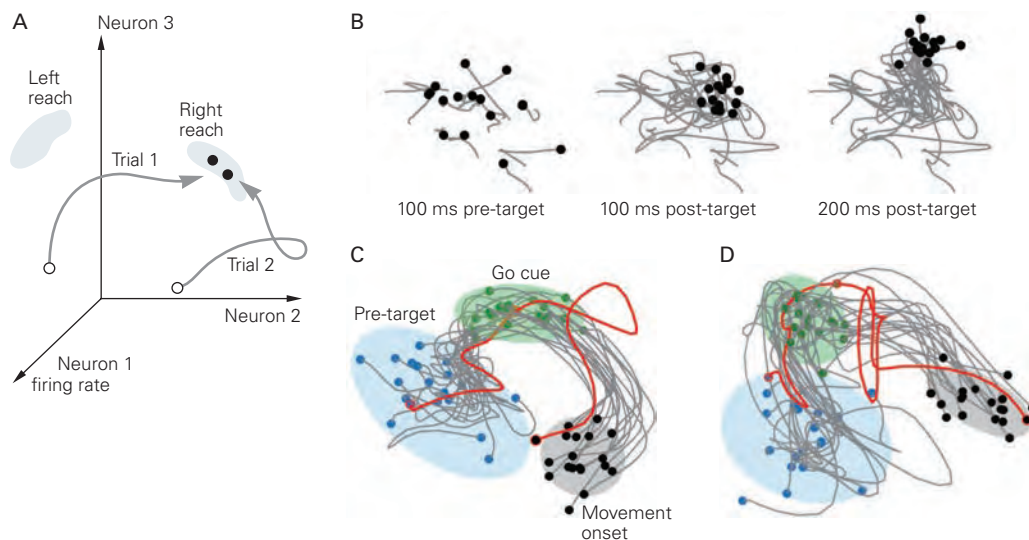


Figure 34-10 The time-varying neural activity in the dorsal premotor cortex of monkeys during different stages of the planning and execution of a movement can be viewed as transitions between different activation states. (Adapted, with permission, from Churchland MM et al. 2010. Stimulus onset quenches neural variability: a widespread cortical phenomenon. *Nat Neurosci* 13:369-378. Copyright © Springer Nature.)

A. A schematic illustration of how the simultaneous activity of neurons can be viewed as a trajectory through a multi-neuron activity “state space.” The time-varying activity level of three simultaneously recorded neurons is represented along three axes, which defines a three-neuron state space. A specific plan (reach left or reach right) requires different combinations of preparatory firing rates for the three neurons (**gray zones**). Prior to the formation of the intention to move left or right, the baseline activity of the three neurons occupies a region in state space that is associated with holding the arm in its current position (**open circles**, for two different trials). When an instruction appears to make a reach to the right, the combined activity of the three neurons changes in a coordinated fashion, creating time-varying “neural trajectories” (**gray arrows**) that converge on the region of state space that is associated with generating a rightward movement (**filled circles** within the “right reach” gray zone).

B. Projection of the simultaneous activity of a large population of dorsal premotor cortex (PMd) neurons onto a two-dimensional state space shortly before (pre-target) and after (post-target) the appearance of a reach target cue in a task in which the reach movement must be delayed until a subsequent go cue is presented. **Gray lines** show the temporal evolution of the neural trajectories during the earliest part of movement preparation from 200 ms before target cue until the specified pre- or post-target time (**black dots**) in 15 different trials to the same target location. Neural activity initially meanders randomly within the region of state space associated with the starting posture of the arm (*left*). It then begins to converge onto a smaller region of the state space shortly after the reach target instruction appears (*center*) and begins to evolve along

the neural trajectory associated with entering the preparatory state for the reach (*right*).

C. A more complete illustration of the neural trajectories recorded during 18 different repeated trials to the same target in this delayed reaching task from the initial pre-target postural state to the onset of movement. **Blue dots** indicate activity while holding the arm in the starting posture 100 ms before appearance of the target instruction onset. Once the target instruction appears, the neural trajectories evolve toward a region of state space associated with the preparatory activity state during the delay period (**green zone**), where it dwells until a go cue appears that allows the monkey to initiate the withheld movement (**green dots**). While in this reach-preparatory part of the state space during the delay period, the arm stays at the start position because PMd activity in that part of state space is not capable of activating muscles (ie, it is “output-null”). When the go cue appears, the neural trajectories unfold toward a different region of state space associated with the initiation of the intended reach movement (**gray zone** and **black dots**). The neural activity can only cause the muscle activity for the intended movement when it enters this “output-potent” zone of state space. The trial-to-trial variability of the neural trajectories can account for intertrial variability in movement kinematics and reaction times. One outlier trial (**red**) had a long reaction time and followed a more complex and time-consuming neural trajectory from the **green** to the **gray** zone. The output-null preparatory (**green**) and output-potent movement-initiation (**gray**) zones for reaches to different target locations occupy different regions of the total population state space distinct from those associated with this reach target.

D. Data are for the same target location as in part **C** but were recorded on a different day. The neural trajectory structure is fundamentally similar for the same movements between recording sessions. Differences in the overall pattern of activity can be explained by interday differences in the activity of individual neurons and differences in the composition of the recorded neural population between sessions.

directions. Although the monkeys' choices were initially random, they learned the rules within a few dozen trials. The monkeys made an arm movement in response to each cue; during the early "guessing" phase of learning, the activity of many PMd neurons was weak but gradually increased in strength and directional tuning as the monkeys learned which cue signaled which movement. Other neurons showed a reciprocal decline in activity as the rules were acquired. These changes in activity during learning reflected both the movement choices and the rising level of knowledge of the rules linking cues with actions.

The nature of the rule can also have a strong effect on neural responses. In monkeys that have been trained to choose between several possible movements based on a spatial rule (a visual cue's location) or a semantic rule (a cue's arbitrarily designated meaning independent of its location), many prefrontal and PMd neurons are preferentially active when the animal chooses a movement using one rule but not the other. This shows that the neural activity is related not just to a particular cue or action but also to the association between them.

Premotor areas are involved in the implementation of even abstract rules. For example, monkeys were trained in a task that required two decisions, one perceptual and the other behavioral, that had no prior association. In each trial, the monkeys first had to decide whether two sequentially presented visual images were the same or different (a *match/nonmatch perceptual decision*). In some trials, a *rule cue* presented at the same time as the sample visual image instructed the monkeys to move their hand if the two images were identical and to refrain from moving if they differed (a *go/no-go motor decision*); in other trials, the rule was reversed—move if the images differ and do not move if they match. Neural activity in PMd after the test visual images were presented was correlated more strongly to the motor decision than the perceptual decision in each trial, but both decisions were expressed in PMd. More strikingly, PMd activity was also correlated with the match/non-match *behavioral rule* during the delay period between the two visual images that guided the motor decision after the test image appeared (Figure 34–11). These results suggest that PMd has a major role in applying rules that govern the appropriateness of a behavior and in making behavioral decisions according to the prevailing rules. Neural recordings in prefrontal cortex during the same task (not shown) found a strong representation of the physical identity of the visual images, but weaker and later correlates of the behavioral rule and the motor decision than in PMd.

Ventral Premotor Cortex Is Involved in Planning Motor Actions of the Hand

The most lateral part of the premotor cortex, area PMv, is reciprocally connected with parietal cortex areas AIP, PF, and PFG and the secondary somatosensory area. Electrical stimulation shows that PMv contains extensively overlapping circuits that control hand and mouth movements.

Like AIP neurons, many PMv neurons appear to contribute to the control of hand actions based on the physical affordances offered by target objects. These neurons tend to fire preferentially during certain stereotypical hand actions, such as grasping, holding, tearing, or manipulating objects. Many neurons discharge only if the monkey uses a specific type of grip, such as a precision grip, whole-hand prehension, or finger prehension (Figure 34–12). Precision grip is the type most often represented. Some PMv neurons discharge throughout the entire action, while others discharge selectively at particular stages of one type of prehension, such as during the opening or closing of the fingers.

Another striking property of PMv neurons is that their discharge often correlates with the goal of a motor act and not with the individual movements forming it. Thus, many PMv neurons discharge when grasping an object is executed with effectors as different as the right hand, the left hand, and even the mouth. Conversely, a PMv neuron may be active when an index finger is flexed to grasp an object but not when the animal flexes the same finger to scratch itself.

Premotor Cortex May Contribute to Perceptual Decisions That Guide Motor Actions

A series of studies provide evidence that cortical motor areas not only represent the sensory information that guides voluntary movements but also express the neural operations necessary to make and act on perceptual decisions. Monkeys were trained to discriminate the difference in frequency between two brief vibratory stimuli applied to one finger and separated in time by a few seconds. The animals had to decide whether the frequency of the second stimulus was higher or lower than the first and to report their perceptual decision by reaching out to push one of two buttons with the other hand.

The decision-making process in this task can be conceived as a chain of neural operations: (1) encode the first stimulus frequency (f_1) when it is presented; (2) maintain a representation of f_1 in working memory during the interval between the two stimuli; (3) encode the second stimulus frequency (f_2) when it is

A Delayed match-to-sample task

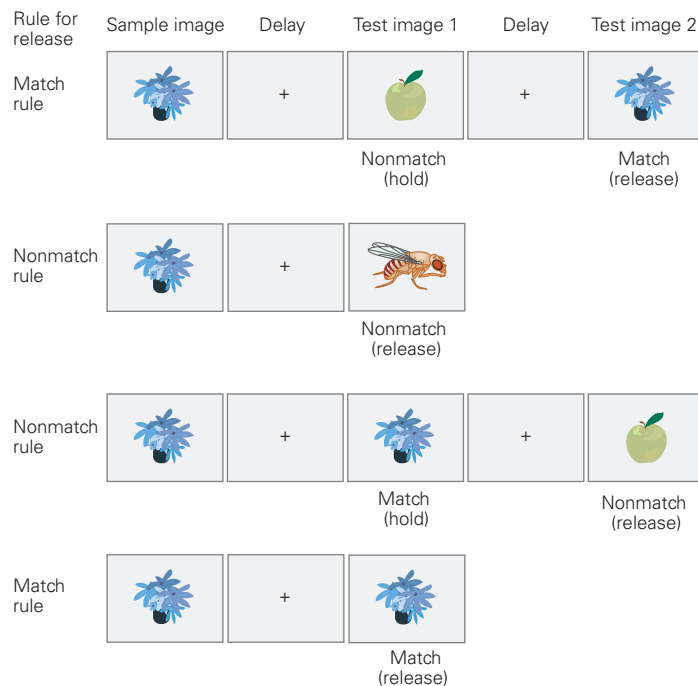


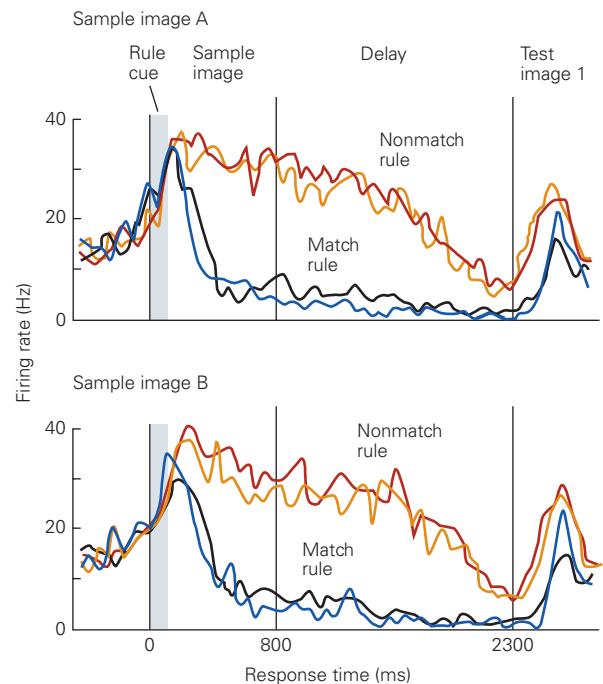
Figure 34–11 Premotor cortex neurons in the monkey choose particular voluntary behaviors based on decisional rules. (Reproduced, with permission, from Wallis and Miller 2003.)

A. A monkey must make a decision about whether to release a lever or keep holding it based on two prior decisions: a perceptual choice, whether a test image is the same as or different from a sample image presented earlier, and a behavioral choice, whether the current rule is to release the lever when the test image is the same as the sample (match rule) or when it is different (nonmatch rule). The monkey is informed of the behavioral rule that applies in each trial by a rule cue, such as an auditory tone or juice drops, which is presented for 100 ms at the same time as the onset of the sample image at the start of the trial.

presented; (4) compare f_2 to the memory trace of f_1 ; (5) decide whether the frequency of f_2 is higher or lower than that of f_1 ; and finally, (6) use that decision to choose the appropriate movement of the other hand. Everything prior to the last step would appear to fall entirely within the domain of sensory discriminative processing.

While the monkeys performed the task, neurons in the primary (S-I) and secondary (S-II) somatosensory cortices encoded the frequencies of the stimuli while they were presented. During the interval between f_1 and f_2 , there was no sustained activity in S-I representing the memorized f_1 and only a transient representation in S-II, which vanished before f_2 was presented.

B Premotor neurons show rule-dependent activity



B. A neuron in the dorsal premotor cortex has a higher discharge rate whenever the nonmatch rule is in effect during the delay between the presentation of the first and second images. The responses to two different sample images (upper and lower plots) were recorded from the same cell, indicating that the rule-dependent activity is not altered by changing the images. Nor, as shown by the pairs of curves associated with each rule, does activity depend on the type of rule cue (auditory tone or juice drops). (Tone cue trials: orange and blue curves; juice cue trials: red and black curves). Other dorsal premotor cortex cells (not shown) respond preferentially to the match rule over the nonmatch rule. The differential activity of the neuron up to presentation of the test image reflects the rule that will guide the animal's motor response to the test image, not the physical properties of the visual stimuli or the motor response.

Strikingly, however, the activity of many neurons in the prefrontal cortex, SMC, and PMv scaled with the frequencies of f_1 and f_2 while they were being delivered. Furthermore, some prefrontal and premotor neurons showed sustained activity proportional to the frequency of f_1 during the delay period between f_1 and f_2 . Most remarkably, many neurons in those areas, especially in PMv, encoded the *difference* in frequency between f_2 and f_1 independently of their actual frequencies when f_2 was delivered (Figure 34–13). This centrally generated signal is appropriate to mediate the perceptual discrimination that determines which button to push. Neurons that encoded the f_2 – f_1 difference were absent in S-I and were far more common in SMC and PMv than in S-II.