Cortical Action Representations

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Synopsis

The organization of the motor cortex has been studied and debated for more than 130 years. Although it contains a map of the body, the map is overlapping and fractured and therefore additional principles of organization may be needed to explain the topography. Recently, a growing body of evidence suggests one such principle. The motor cortex appears to be partly organized as a map of complex, behaviorally useful actions that compose the animal's movement repertoire. In the action-map perspective, the statistical complexity of the movement repertoire leads to the complexity of the cortical map.

Introduction: Multiple Perspectives On Motor Cortex

The motor cortex has been studied for more than 130 years. In that time, two major views of the motor cortex have been proposed. In the homunculus hypothesis, the motor cortex is a map of muscles (Penfield and Rasmussen, 1950). In the population-code hypothesis, the motor cortex is a collection of spatially tuned neurons that in aggregate can specify the direction for the arm to reach (Georgopoulos, Schwartz, and Kettner, 1986). In the past decade, a new, third perspective has emerged, the action map view of the motor cortex (Graziano, 2006; Graziano, 2008). In the action map hypothesis, the motor cortex is organized around the common, useful behaviors performed by the animal. The statistics of the behavioral repertoire, including the most frequently used combinations of muscles and body parts, the locations in space to which movements are directed, the broad behavioral purposes of actions, and perhaps other aspects of movement, are reflected in the cortical distribution and overlap of properties. There is a tendency for different categories of action, such as hand-to-mouth actions or defensive actions, to cluster in different areas of cortex. In the action map hypothesis, to understand the motor cortex it is necessary to understand more than the musculature of the animal's body and it is necessary to consider more than one category of behavior such as reaching. One must also understand the structure and complexity of the movement repertoire.

The motor cortex was discovered in 1870 when Fritsch and Hitzig electrically stimulated the surface of the dog brain and obtained muscle twitches. A few years later, Ferrier (1874) published a detailed study of the monkey brain establishing a systematic map of the body along the precentral gyrus with the legs at the top of the brain and the mouth near the bottom. This view of motor cortex as a roster of muscles laid out in topographic order became the standard,

textbook picture of how the brain controls movement. The most iconic images were published by Penfield who used the term "homunculus" and drew a little distorted man stretched across the surface of the human brain (Penfield and Rasmussen, 1950).

The muscle-map view of motor cortex has long been understood to be incomplete (e.g. Ferrier, 1874; Cheney and Fetz, 1985; Penfield and Boldrey, 1937; Rathelot and Strick, 2006; Sherrington, 1939). The motor cortex map is blurred and overlapping. The organization is not a simple segregation of muscles. Although some researchers argued for the segregated control of individual muscles in motor cortex (notably Asanuma, 1975), the consensus among most researchers is that each cortical locus, and even each cortical neuron, contributes to the activity of a range of muscles that cross a range of joints (e.g. Cheney and Fetz, 1985; Donoghue, Leibovic, and Sanes, 1992; Meier et al., 2008; Park et al., 2001; Rathelot and Strick, 2006; Sanes et al., 1995; Schieber and Hibbard, 1993).

One possibility is that the overlapping and complex nature of the map relates in some way to the complex nature of the movement repertoire. Perhaps the motor cortex is an integrative network coordinating among muscles and joints that are most commonly used together, rather than decomposing movements into atomistic units. In support of this perspective, infant cats and monkeys that lack movement experience have less overlap in their muscle representations in motor cortex, and as the animals gain experience with specific complex movements, the muscle map in cortex develops a pattern of overlap that matches the experience (Chakrabarty and Martin, 2000; Martin, Engber, and Meng, 2005; Nudo et al., 1996). Results like these suggest that the complexity and overlap in the cortical map are related to the complexity and overlap in the movement repertoire. But is it possible to study the control of complex movement in a more direct fashion than plotting and re-plotting blurred maps of muscles?

The Cortical Action Map

  Classical studies of motor cortex used brief trains of stimulation, typically a tenth of a second or less in duration, to evoke a muscle twitch. The brief stimulation acts as a tract-tracing method that reveals the mapping from points in cortex to muscles. In contrast, in one recent approach to studying how the motor cortex might control useful combinations of muscles and joints, long-train electrical stimulation was applied to the monkey motor cortex (Graziano, Taylor, and Moore, 2002). When electrical stimulation was applied on a behavioral time scale, such as for the half second of a typical reaching movement, complex and apparently coordinated movements were evoked. A similar method of stimulating on a behavioral time scale had been used for decades in other brain areas to study saccadic eye movements, visual perception, and motivated states, among other aspects of brain function (Graziano, 2008). However, the method has been applied systematically to the motor cortex only within the past decade. As with all methods, electrical stimulation has limitations, and therefore an important aspect of this line of research on motor cortex is the convergent findings from a range of other techniques including chemical manipulation of sites in cortex, optogenetic stimulation of cortex, studies of naturally occurring behavioral repertoire, and single neuron recording, as summarized below.

  Stimulation of the monkey motor cortex on a behavioral time scale evokes complex movements that are typical of the animal's normal repertoire (Graziano, 2008; Graziano, Taylor, and Moore, 2002; Graziano, Aflalo, and Cooke, 2005). Different movements are evoked from different sites in an "action map" that is consistent in its main features from monkey to monkey. The action map is summarized in Figure 1. A crucial aspect of this action map is its diversity of actions. Most previous work on the motor cortex focused on reaching and grasping, clearly

important behaviors that make up part of a primate's normal repertoire. However, the action map obtained through electrical stimulation is more extensive. It includes more of the actions typical of monkeys. When monkeys in the laboratory home cage and in zoos were studied by video analysis and tabulation of movements, the spontaneous movement repertoire corresponded in type and proportion to the repertoire of movements electrically evoked from the motor cortex (Graziano, 2008; Graziano et al., 2004; Macfarlaine and Graziano, 2009).

For example, when cortical sites within one region of the map were stimulated, a hand-to-mouth movement was evoked (Graziano, Taylor, and Moore, 2002; Graziano, Aflalo, and Cooke, 2005). This movement included a closure of the hand into an apparent grip, a turning of the wrist and forearm to direct the hand toward the mouth, a movement of the hand through space to the mouth, an opening of the mouth, and a turning of the head to align the front of the mouth to the hand. The movement occurred reliably on each stimulation trial and could be replicated even when the monkey was anesthetized. Electrical stimulation in this region of the map therefore appeared to generate an approximate version of a common movement. A large part of a monkey's spontaneous repertoire is composed of complex interactions between the hand and the mouth (Graziano, 2008; Graziano et al., 2004).

Other complex movements, evoked from other regions of the map, included reaching into distal space with the hand shaped as if to grasp something; bringing the hand into near, central space with the fingers gripped or otherwise shaped as if to manipulate an object; and moving all four limbs in a pattern that resembled complex locomotion such as climbing or leaping (Graziano, Taylor, and Moore, 2002; Graziano, Aflalo, and Cooke, 2005).

One of the more characteristic actions was a defensive movement. A specific zone in the motor cortex, sometimes called the polysensory zone, contains a high proportion of neurons that

respond to tactile and visual stimuli (Fogassi et al., 1996; Gentilucci et al., 1998; Graziano and Gandhi, 2000; Graziano, Yap, and Gross, 1994; Graziano, Hu, and Gross, 1997; Rizzolatti et al., 1981). Each multimodel neuron has a tactile receptive field on the skin and also responds to visual stimuli in the space near the tactile receptive field. Electrical stimulation of these cortical sites typically evokes a movement that appears to protect the body surface in the area of the tactile receptive field (Cooke and Graziano, 2004a; Graziano, Taylor, and Moore, 2002; Graziano, Aflalo, and Cooke, 2005). For example, if a site in cortex responds to touching the left cheek and to visual stimuli near or approaching the left cheek, then stimulation of that site evokes a squint, a rightward turning of the head, a lifting of the shoulder, and a rapid lifting of the left arm as if to block a threat. The movement is fast, reliable across trials, and can occur under anesthesia. Moreover, chemical inhibition of this cortical region can result in a temporary reduction of a normal defensive reaction, and chemical disinhibition can result in a hypersensitivity to threats to the face and an exaggerated defensive reaction (Cooke and Graziano, 2004b). In the case of the defensive movements, therefore, the evidence shows corroboration among four different sources of data: the neuronal properties, the effect of electrical stimulation, the effect of chemical manipulation, and the animal's natural movement repertoire.

Based on this type of result, a new hypothesis about the organization of the motor cortex emerged. The complex nature of the map might reflect a complex movement repertoire that is flattened onto the cortical sheet. In that hypothesis, the reduction of many movement dimensions onto two cortical dimensions results in a clumping by function, a blurring of borders, and a rough, overlapping, partly fractured body topography. Computational studies show that, indeed, when a statistical description of a monkey's typical movement repertoire is flattened on a sheet,

subject to a local smoothness constraint in which similar movements are mapped near each other, the resulting map is a close approximation to the actual map obtained by physiology (Aflalo and Graziano, 2006; Graziano and Aflalo, 2007). The computational method can reproduce the multiple overlapping maps of the body, the graded borders between areas, and the topographic arrangement of the actions in the action map. In this way a relatively simple underlying principle, a flattening or rendering of the movement repertoire onto the cortical surface, may help explain some of the organization of the motor cortex.

Further Studies Of Cortical Action Maps

Cortical action representations similar to those described above have been found in a range of studies on the primate motor cortex. Huang et al. (1989) obtained rhythmic chewing during long-train stimulation of the mouth representation in the monkey motor cortex. Stepniewska, Fang, and Kaas (2005, 2009) used electrical stimulation to extensively map the parietal cortex and motor cortex of monkeys and prosimians and found action categories in distinct cortical zones. Overduin et al. (2012) found that stimulation in the motor cortex evoked natural synergistic activations of the hand muscles, and that different synergies were emphasized in different adjacent regions of cortex. Van Acker et al. (2013) obtained complex movements of the limbs including hand-to-mouth movements on stimulation of the monkey motor cortex. Caruana et al. (2011) evoked complex social gestures by stimulating the insular cortex of monkeys and found different categories of gestures in adjacent regions of cortex.

Similar effects have also been obtained in rodent models. Haiss and Schwarz (2005) evoked different behaviorally-relevant whisking actions on stimulating different regions of the rat motor cortex, including exploratory whisking from one cortical region and defensive-like

whisker retraction and squinting from another cortical region. Ramanathan, Conner, and Tuszynski (2006) found that stimulation of the rat motor cortex evoked different kinds of forepaw movements from different zones in cortex. When the reaching zone was lesioned, the rats lost the ability to reach. The ability quickly recovered. When the recovered rats were mapped again, their cortex showed a new zone, near the lesioned site, from which reaching movements could be evoked, and the size of the new reaching zone correlated with the extent of the rat's behavioral recovery. Harrison, Ayling, and Murphy (2012) studied the mouse motor cortex. In order to determine whether the effect of electrical stimulation was somehow artifactual, they compared it to the effect of optogenetic stimulation, which is more precise because it specifically induces action potentials in cell bodies in a small target area. They obtained complex, multi-joint movements of the limbs to specific postures. The more precise optogenetic stimulation matched the results of the electrical stimulation. Bonazzi et al. (2013) systematically mapped the rat motor cortex using long-train electrical stimulation and found complex, multijoint movements of the limbs that matched the rat's behavioral repertoire and that were arranged across the cortical surface in an apparent action map.

These findings in primates and rodents demonstrate the usefulness of the action map perspective. To understand the organization and function of the motor system, it is evidently of some use to understand the movement repertoire of the animal. The musculature of the animal is only the most peripheral, simplest aspect of the motor system. The movement repertoire involves complex combinations of muscles and body parts moving in specific ways for specific purposes. It involves a highly dimensional information space that is idiosyncratic to each species and even, to some extent, to each individual animal. The organization of the motor cortex appears to reflect the complexity of the movement repertoire and not merely the layout of the body's muscles.

References

Aflalo TN and Graziano MSA (2006). Possible origins of the complex topographic organization of motor cortex: reduction of a multidimensional space onto a two-dimensional array. J. Neurosci. 26: 6288-6297.

Asanuma H (1975). Recent developments in the study of the columnar arrangement of neurons within the motor cortex. Physiol. Rev. 55: 143-156.

Bonazzi L, Viaro R, Lodi E, Canto R, Bonifazzi C, and Franchi G. (2013). Complex movement topography and extrinsic space representation in the rat forelimb motor cortex as defined by long-duration intracortical microstimulation. J. Neurosci. 33: 2097-2107.

Caruana F, Jezzini A, Sbriscia-Fioretti B, Rizzolatti G, and Gallese V (2011). Emotional and social behaviors elicited by electrical stimulation of the insula in the macaque monkey. Curr. Biol. 21: 195-199.

Chakrabarty S and Martin JH (2000). Postnatal development of the motor representation in primary motor cortex. J. Neurophysiol. 84: 2582-2594.

Cheney PD and Fetz EE (1985). Comparable patterns of muscle facilitation evoked by individual corticomotoneuronal (CM) cells and by single intracortical microstimuli in primates: evidence for functional groups of CM cells. J. Neurophysiol. 53: 786-804.

Cooke DF and Graziano MSA (2004). Sensorimotor integration in the precentral gyrus: Polysensory neurons and defensive movements. J. Neurophysiol. 91: 1648-1650.

Cooke DF and Graziano MSA (2004). Super-flinchers and nerves of steel: Defensive movements altered by chemical manipulation of a cortical motor area. Neuron 43: 585-593.

Donoghue JP, Leibovic S, and Sanes JN (1992). Organization of the forelimb area in squirrel monkey motor cortex: representation of digit, wrist, and elbow muscles. Exp. Brain Res. 89: 1-19.

Ferrier D (1874). Experiments on the brain of monkeys – No. 1. Proc. R. Soc. Lond. 23: 409-430.

Fogassi L, Gallese V, Fadiga L, Luppino G, Matelli M, and Rizzolatti G (1996). Coding of peripersonal space in inferior premotor cortex (area F4). J. Neurophysiol. 76: 141-57.

Fritsch G and Hitzig E (1870). Uber die elektrishe Erregbarkeit des Grosshirns. Arch. f. Anat., Physiol und wissenchaftl. Mediz., Leipzig, 300-332. (On the electrical excitability of the

cerebrum.) Translated by von Bonin G. In: Some Papers On The Cerebral Cortex. 1960. Von Bonin G (Ed). Springfield IL: Charles Thomas Publisher, pp. 73-96.

Gentilucci M, Fogassi L, Luppino G, Matelli M, Camarda R, and Rizzolatti G (1988). Functional organization of inferior area 6 in the macaque monkey. I. Somatotopy and the control of proximal movements. Exp. Brain Res. 71: 475-490.

Georgopoulos AP, Schwartz AB, and Kettner RE (1986). Neuronal population coding of movement direction. Science 233: 1416-1419.

Graziano MSA (2006). The organization of behavioral repertoire in motor cortex. Ann. Rev. Neurosci. 29: 105-134.

Graziano MSA (2008). The Intelligent Movement Machine: An Ethological Perspective on the Primate Motor System. Oxford University Press, Oxford, UK.

Graziano MSA and Aflalo TN (2007). Mapping behavioral repertoire onto the cortex. Neuron 56: 239-251.

Graziano MSA, Aflalo TNS, and Cooke DF (2005). Arm Movements Evoked by Electrical Stimulation in the Motor Cortex of Monkeys. J. Neurophysiol. 94: 4209-4223

Graziano MSA, Cooke DF, Taylor CSR, and Moore T (2004). Distribution of hand location in

monkeys during spontaneous behavior. Exp. Brain Res. 155: 30-36.

Graziano MSA and Gandhi S (2000). Location of the polysensory zone in the precentral gyrus of anesthetized monkeys. Exp. Brain Res. 135: 259-266.

Graziano MSA, Hu XT, and Gross CG (1997). Visuo-spatial properties of ventral premotor cortex. J. Neurophys. 77: 2268-2292.

Graziano MSA, Taylor CSR, and Moore T (2002). Complex movements evoked by microstimulation of precentral cortex. Neuron 34: 841-851.

Graziano MSA, Yap GS, and Gross CG (1994). Coding of visual space by pre-motor neurons. Science 266: 1054 -1057.

Haiss F and Schwarz C (2005). Spatial segregation of different modes of movement control in the whisker representation of rat primary motor cortex. J. Neurosci. 25: 1579-1587.

Harrison TC, Ayling OG, and Murphy TH (2012). Distinct cortical circuit mechanisms for complex forelimb movement and motor map topography. Neuron 74: 397-409.

Huang CS, Hiraba H, Murray GM, and Sessle BJ (1989). Topographical distribution and functional properties of cortically induced rhythmical jaw movements in the monkey (Macaca fascicularis). J. Neurophysiol. 61: 635-650.

Macfarlane NBW and Graziano MSA (2009). Diversity of grip in Macaca mulatta. Exp. Brain Res. 197: 255-268.

Martin JH, Engber D, and Meng Z (2005). Effect of forelimb use on postnatal development of the forelimb motor representation in primary motor cortex of the cat. J. Neurophysiol. 93: 2822-2831.

Meier JD, Aflalo TN, Kastner S and Graziano MSA (2008). Complex organization of human primary motor cortex: A high-resolution fMRI study. J. Neurophysiol. 100: 1800-1812.

Nudo RJ, Milliken GW, Jenkins WM, and Merzenich MM (1996). Use-dependent alterations of movement representations in primary motor cortex of adult squirrel monkeys. J. Neurosci. 16: 785-807.

Overduin SA, d'Avella A, Carmena JM, and Bizzi E (2012). Microstimulation activates a handful of muscle synergies. Neuron 76: 1071-1077.

Park MC, Belhaj-Saif A, Gordon M, and Cheney PD (2001). Consistent features in the forelimb representation of primary motor cortex in rhesus macaques. J. Neurosci. 21: 2784-2792.

Penfield W and Boldrey E (1937). Somatic motor and sensory representation in the cerebral cortex of man as studied by electrical stimulation. Brain 60: 389-443.

Penfield W and Rasmussen T (1950). The Cerebral Cortex of Man. A Clinical Study of Localization of Function. New York, NY: Macmillan.

Ramanathan D, Conner JM, and Tuszynski MH (2006). A form of motor cortical plasticity that correlates with recovery of function after brain injury. Proc. Natl. Acad. Sci. USA 103: 11370-11375.

Rathelot JA and Strick PL (2006). Muscle representation in the macaque motor cortex: an anatomical perspective. Proc. Natl. Acad. Sci. USA 103: 8257-8262.

Rizzolatti G, Scandolara C, Matelli M, and Gentilucci M (1981). Afferent properties of periarcuate neurons in macaque monkeys. II. Visual responses. Behav. Brain Res. 2: 147-163.

Sanes JN, Donoghue JP, Thangaraj V, Edelman RR, and Warach S (1995). Shared neural substrates controlling hand movements in human motor cortex. Science 268: 1775-1777.

Schieber MH and Hibbard LS (1993). How somatotopic is the motor cortex hand area? Science 261: 489-492.

Sherrington CS (1939). On the motor area of the cerebral cortex. In: Selected Writings of Sir Charles Sherrington. Denny-Brown D (Ed). London: Hamish Hamilton Medical Books, pp. 397-439.

Stepniewska I, Fang PC, and Kaas JH (2005). Microstimulation reveals specialized subregions

for different complex movements in posterior parietal cortex of prosimian galagos. Proc. Natl.

Acad. Sci. USA 102: 4878-4883.

Stepniewska I, Fang PC, Kaas JH (2009). Organization of the posterior parietal cortex

in galagos: I. Functional zones identified by microstimulation. J. Comp Neurol. 517: 765-782.

Van Acker GM 3rd, Amundsen SL, Messamore WG, Zhang HY, Luchies CW, Kovac A,

and Cheney PD (2013). Effective intracortical microstimulation parameters for evoking

forelimb movements to stable spatial end-points from primary motor cortex. J.

Neurophysiol. [Epub ahead of print]

Figure legends

Figure 1: Action zones in the motor cortex of the monkey. Adapted from Graziano et al., 2002

and Graziano et al., 2005. These categories of movement were evoked by electrical stimulation

of the cortex on the behaviorally relevant time scale of 0.5 sec. Images traced from video frames.

Each image represents the final posture obtained at the end of the stimulation-evoked movement.

Within each action zone in the motor cortex, movements of similar behavioral category were

evoked.

Climbing/leaping

Reach to grasp

Hand in
lower space
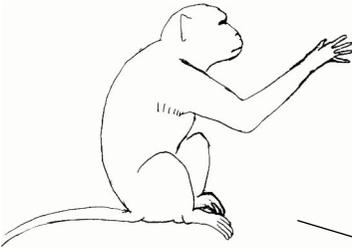
Manipulate in central space
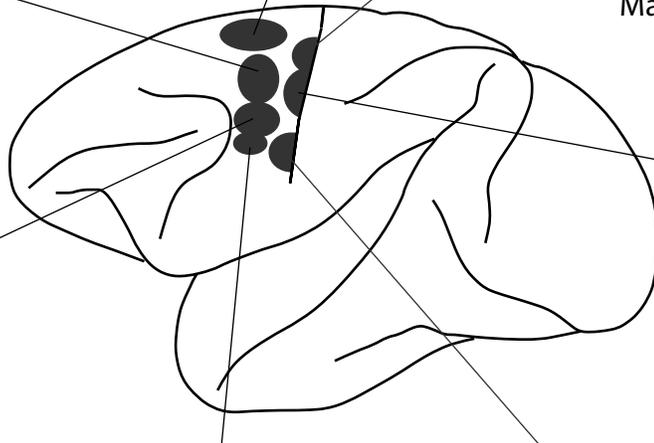
Defense

Chewing/
licking

Hand to mouth