Trends in Cognitive Sciences

Review

Ethological Action Maps: A Paradigm Shift for the Motor Cortex

Michael S.A. Graziano[1],*

The map of the body in the motor cortex is one of the most iconic images in neuroscience. The map, however, is not perfect. It contains overlaps, reversals, and fractures. The complex pattern suggests that a body plan is not the only organizing principle. Recently a second organizing principle was discovered: an action map. The motor cortex appears to contain functional zones, each of which emphasizes an ethologically relevant category of behavior. Some of these complex actions can be evoked by cortical stimulation. Although the findings were initially controversial, interest in the ethological action map has grown. Experiments on primates, mice, and rats have now confirmed and extended the earlier findings with a range of new methods.

Trends

For nearly 150 years, the motor cortex was described as a map of the body. Yet the body map is overlapping and fractured, suggesting that it is not the only organizing principle. In the past 15 years, a second fundamental organizing principle has been discovered: a map of complex, meaningful movements.

Different zones in the motor cortex emphasize different actions from the natural movement repertoire of the animal. These complex actions combine multiple muscles and joints.

The 'action map' organization has now been demonstrated in primates, prosimians, and rodents with various stimulation, lesion, and neuronal recording methods.

The action map was initially controversial due to the use of electrical stimulation. The best argument that the action map is not an artifact of one technique is the growing confirming evidence from other techniques.

Beyond the Body Map

In 2002, my laboratory reported an unexpected organization of the primate motor cortex [1]. The motor cortex appeared to contain functional zones, each of which emphasized a complex, ethologically meaningful category of behavior. The categories included interactions between the hand and the mouth, actions that defend the body surface, reach-to-grasp actions, and other species-typical behavior. These complex actions could be evoked by electrically stimulating sites within the cortical action zones. Although the ethological action map resembled no traditional account of the motor cortex, it also did not directly contradict previous views: it coexisted with the standard, blurred map of the body arranged along the motor cortex.

Over the next several years, we studied this map of ethological actions using various techniques [2–16]. Initially, few other researchers joined the pursuit. The work was controversial. Since then, especially in the past 5 years, interest in the map of ethologically relevant actions has grown. The action map has now been studied in rats, mice, prosimians, monkeys, humans, squirrels, and cats, using a great range of methods including electrical and optogenetic stimulation, chemical manipulation, lesions, single neuron recording, functional imaging, anatomical tract tracing, behavioral analysis, and computational modeling. The ethological action map appears to be a fundamental, previously overlooked organizing principle of the motor cortex that cuts across mammalian species. Here I review the current state of research on action maps in the motor cortex and reassess some of the original claims and controversies.

Discovering the Ethological Action Map

Our initial discovery of a map of complex actions in the motor cortex depended on transplanting a standard experimental method into the monkey motor cortex where it was not typically used. In this method a train of electrical pulses is applied through a microelectrode to a site in the brain for an extended, behaviorally relevant time scale. The directly stimulated neurons, through their connectivity, are assumed to influence a larger network. The network then produces a

[1]Princeton Neuroscience Institute, Princeton, NJ 08544, USA

*Correspondence:
graziano@princeton.edu
(M.S.A. Graziano).

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coordinated effect on the animal's behavior. This approach has a long history of use; for example, to study eye movements [17–20], perceptual decision making in visual and somatosensory cortex [21,22], and the control of motivated states such as hunger and sexual arousal in the hypothalamus [23–25].

In the study of the motor cortex, however, a different milieu of ideas prevailed [14]. In the traditional perspective, the motor cortex works through a descending pathway from cortex to muscles. To study this pathway, researchers applied brief bursts of electrical stimulation to the cortex, no more than 50 ms in duration and often much less, evoking muscle twitches [14]. The greatest concern was that the stimulation might accidentally spread through connections within the motor cortex or among other parts of the motor system, thereby blurring and contaminating the investigation of the descending pathway [26,27]. The idea of stimulating on an extended timescale and expecting meaningful actions to emerge as a result of signal ramifying through the motor network was not part of the standard discussion.

When we extended the stimulation of the monkey motor cortex to half a second, roughly the timescale over which macaque monkeys perform common actions such as reaching and grasping, a cornucopia of complex movements emerged [1,2]. For example, at sites within one cortical zone, stimulation caused a hand-to-mouth action. During stimulation, the hand closed in a precision grip posture, the forearm rotated thus aiming the grip toward the head, the elbow and shoulder rotated, thus bringing the hand to the mouth, the mouth opened, and the neck turned to orient the mouth toward the approaching hand. The first time we found a hand-to-mouth cortical site and realized that we could trigger the movement on demand with the press of a button, we were so surprised that we ran out of the experiment room and tried to find someone else in the building, anyone, to watch and make sure that we were not crazy.

At other sites we evoked apparent defensive movements. We had previously studied a cluster of neurons in the motor cortex known to respond to sensory stimuli [28–32]. These multimodal neurons responded to visual, tactile, and sometimes auditory stimuli. The sensory responses emphasized the space near the body. For example, a neuron might respond to a touch on the right side of the face, to the sight of objects within 20 cm of the right cheek, and to auditory stimuli with an especially strong response to nearby sounds on the right. Electrical stimulation of a cortical site with this type of sensory response evoked closure of the right eye, pursing of the facial musculature around the right eye, flattening of the ears against the head, turning the head to the left, shrugging the right shoulder, lifting the right hand to a blocking position beside the face, and even a characteristic centering movement of the eyes unique to defensive reactions [1–4]. The action was fast and reliable and ended as soon as the stimulation train ended. It made little obvious impression on the monkey, who continued to feed himself fruit snacks with the other hand.

Stimulation of other cortical sites evoked other, equally complex actions that appeared to come straight from the animal's normal repertoire. The actions were reliable on repeated stimulation and could be evoked in awake or anesthetized animals, although the nuances were easier to study in the awake case. The same actions could also be evoked by chemical stimulation of the cortex. Defensive movements could be evoked by chemical stimulation of the defensive zone and the monkey's natural defensive movements could be suppressed by chemical inhibition of the same cortical zone [3]. When the monkey's spontaneous movements were tracked, individual motor cortex neurons were more active during some movements than others, and those movements preferred by the neurons tended to match the action evoked by stimulating the same cortical site [4–6]. The stimulation-evoked movements also matched the general behavioral repertoire of macaque monkeys in both the kinds of movements and their relative proportions [7–9,14].

We reported three overarching properties of the action map in the motor cortex of monkeys [15]. First, it was organized in zones. Each cortical zone emphasized a different ethologically relevant type of action. Stimulation anywhere within the zone usually evoked some variant of that action. Figure 1 summarizes the action zones that we found in the monkey motor cortex.

A second property of the action map was that arm movements targeting upper space were typically evoked from more ventral cortex and arm movements targeting lower space were evoked from the dorsal cortex. This map of extrinsic space was statistically present but noisy.

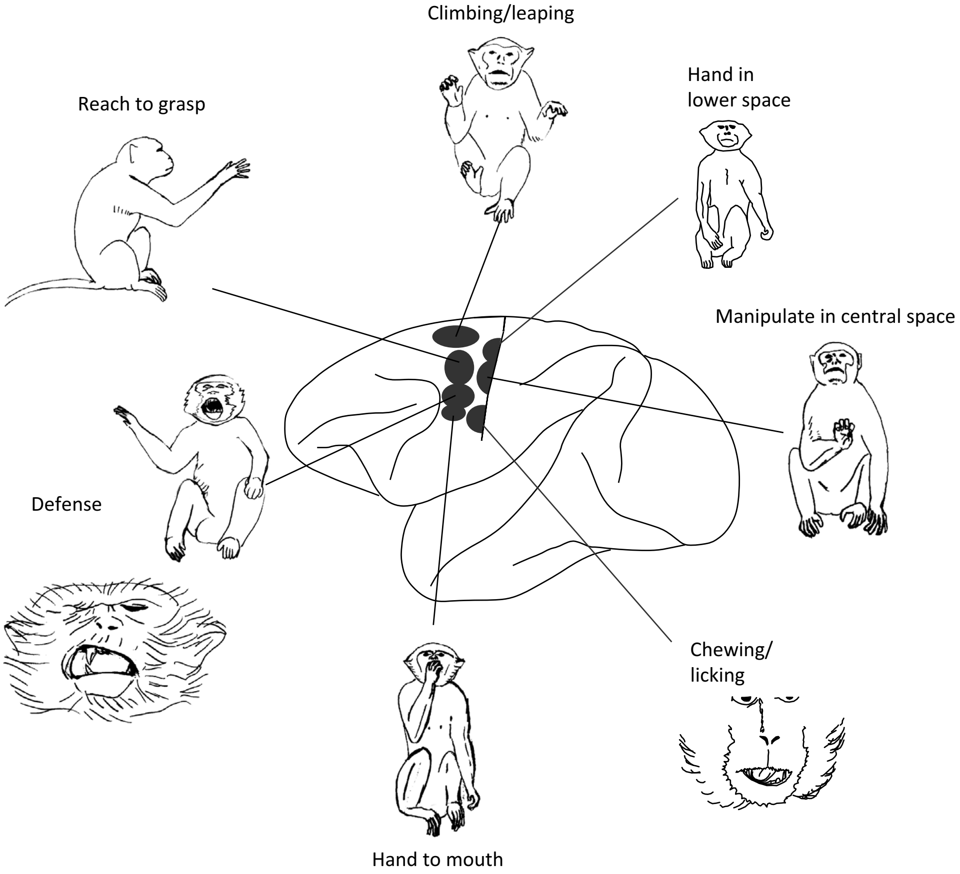

Figure 1. The Action Map in the Macaque Motor Cortex. Intracortical stimulation for 500 ms evoked complex, ethologically meaningful actions [1–4,14]. Different actions were evoked from different cortical zones. Hand-to-mouth actions involved shaping the hand into a grip posture, orienting the grip toward the head, moving the hand to the mouth regardless of starting position, opening the mouth, and turning the head to align the mouth to the hand. Defensive actions involved closing the eyes, pursing the skin around the eyes, folding the ear against the head, turning the head, shrugging the shoulder, turning the torso, and raising the hand to a blocking posture. Reaching involved movements of the torso, shoulder, and arm to project the hand, pronation of the forearm to orient the hand, and postures of the hand as if to preshape for grasping. Climbing and leaping postures involved bilateral postures of the legs and arms with the feet and hands partly curled as if in preparation to grasp branches and sometimes deflection of the tail as if to maintain balance during locomotion. Hand-in-lower-space actions involved postures of the arm that brought the hand to the space near the feet or laterally to the side of the feet and often brought the hand to a palm-down posture as though to brace the body's weight against the ground. Manipulation in central space involved complex postures of the wrist and fingers that resembled typical actions during the manipulation of objects and often movements of the arm that brought the hand to the central space in front of the chest or stomach where monkeys typically manipulate acquired objects. Chewing and licking movements were evoked from the classical primary motor oral area. Huang *et al.* [61] reported chewing movements in 1989, before the larger action map was discovered.

A third, surprising property of the action map was that it appeared to span the primary motor cortex and the caudal premotor cortex, areas that are traditionally thought to form a processing hierarchy. We suggested that these areas may operate at a similar hierarchical level and may instead differ in their properties because they emphasize different types of actions in the movement repertoire.

The action map may at first seem incompatible with the classical motor homunculus (Figure 2). How can complex, multijoint actions be reconciled with representations of individual parts of the body? However, the homunculus is not a punctate, orderly map of muscles or body parts. It contains considerable overlap. That apparent disorder provides a clue: the mapping of the body is not the only influence on motor cortex organization. The map is influenced partly by the structure of the body and, evidently, partly by common actions in the behavioral repertoire.

One way to conceptualize these multiple influences on the map is that many different mapping parameters are in competition for space on the 2D cortex. We constructed a formal mathematical model of this competitive mapping, essentially flattening the statistics of the macaque behavioral repertoire onto the cortical surface in competition with a map of the body [10,11]. Based on these mapping principles, the model was able to reconstruct the ethological action zones in correct topographic order on the cortex, as well as to reconstruct many of the otherwise confusing quirks, fractures, and overlaps of the body map spanning the primary motor cortex and much of the premotor cortex. The success of the model gave us some confidence that we had finally begun to understand the principles behind the motor cortex organization. It is part map of the body and part map of actions.

Further Studies of the Action Map: Primates

The discovery of the cortical action map was understandably controversial. It broke with 130 years of tradition. Now, however, cortical action maps have been extensively confirmed. This

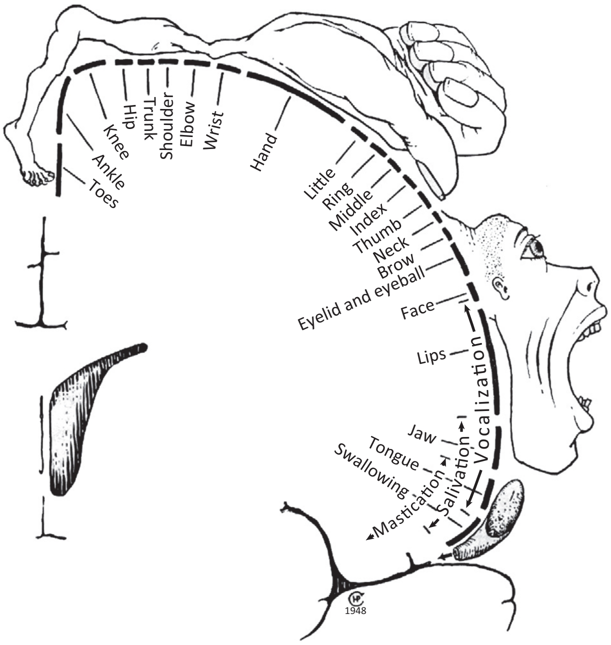

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Figure 2. The Motor Homunculus as Drawn by Penfield and Rasmussen [44]. Although the drawing shows an orderly progression of body parts, Penfield warned that the drawing was not to be taken literally. He described the cortical map as extensively overlapping. One of the few researchers to propose a discrete map of body parts at the level of individual muscles was Asanuma [26]. Almost all other accounts over the 145-year history of motor cortex physiology describe the map as overlapping with some fractures and reversals [14]. The ethological action map may explain why. The topography is influenced both by the structure of the body and by the structure of the movement repertoire.

section summarizes the developments in the primate literature and the next section summarizes the even more extensive work in rats and mice.

One of the first laboratories to join in the study of the cortical action map was that of Jon Kaas. In 2005, Kaas and colleagues [33] reported using half-second stimulation trains to evoke complex, ethologically relevant actions in the galago, a species of prosimian. The evoked actions matched many that we had reported, including hand-to-mouth and defensive actions. Different cortical zones emphasized different ethologically relevant actions. Galagos had at least two action maps, one in the parietal cortex and one in the motor cortex [33–35], consistent with our findings in macaques [13,16].

Kaas and colleagues detailed action maps in the galago, squirrel monkey, owl monkey, and macaque monkey [33–38]. They studied the connectivity between the parietal and frontal maps and found specific connectivity between matching action zones [35–37]. Chemical inhibition of an action zone in the parietal map subtly altered the movements evoked from the matching zone in the frontal map, suggesting that the frontal map depended at least partly on interactions with the parietal map [38]. Inhibition of an action zone in the frontal map often abolished the movements evoked from the matching zone in the parietal map, suggesting that the parietal map operated mainly through its influence on the frontal map. This body of work has greatly expanded our knowledge of the cortical action maps in primates.

Bizzi and colleagues applied half-second stimulation to the hand region of the macaque motor cortex [39,40]. For each cortical site, a unique postural shaping of the hand was evoked. The muscle patterns observed by Bizzi and colleagues matched the muscle synergies found in normal hand action and these stimulation-evoked synergies were arranged in cortical clusters or zones. These results suggest that action zones can be resolved even within the more specialized category of hand actions.

Cheney and colleagues [41,42] used half-second stimulation in the motor cortex of macaques to replicate many of the complex actions reported by us and others. It is only fair to report that this group offered an alternative interpretation in which the evoked complex movements are coincidental collections of muscle contractions and do not reveal the natural function of the cortex. Their studies appeared to differ from ours in focusing on a smaller, posterior part of the area that we studied, thereby potentially missing the more anterior ethological action zones. They may have missed more characteristic actions such as defensive movements. Although they describe movements of the hand toward the mouth, they may have missed the hand-to-mouth zone. Within the area studied, their results seemed to correspond to ours, despite their different interpretation.

The human motor cortex may also contain an ethological organization. The original, famous studies of Penfield and colleagues [43,44] used surface stimulation and therefore the results are difficult to interpret in a modern context, although some complex actions were reported. Recently, Desmurget and colleagues [45] used long-train (1–3 s) intracortical stimulation in the human motor cortex and obtained complex movements including hand-to-mouth actions.

Taken together, these findings show the reliability of the action map across a range of primate species. Similar ethological actions evoked from the motor cortex have also been reported in cats [46] and squirrels [47]. An even greater range of techniques has been used to study the action map in the motor cortex of mice and rats, as reviewed next.

The Action Map in Rodents

Arguably, the focus of motor cortex research in the past several years has shifted from the primate model to rats and mice. This work, in turn, has focused mainly on the discovery of an ethological action map in the rodent motor cortex similar to the one found in primates. Initial work focused on a cortical zone that emphasized whisking [48,49]. Subsequent reports [50–56] described zones related to defensive-like movements, reaching, grasping, chewing, and other complex actions from the normal behavioral repertoire of rodents (Figure 3).

The action map in the mouse motor cortex was confirmed using optogenetic stimulation [52]. Finding the same type of map with a third method of stimulation (electrical, chemical, and now optogenetic) lends greater confidence to the results.

Cortical action zones were also confirmed through lesion studies. In one of the most thorough series of studies, Ramanathan *et al.* [51] mapped action zones in the rat motor cortex. They surgically lesioned the cortical zone from which reaching could be evoked and the rats were no longer able to reach. Over time the rats relearned the behavior. When mapped again, the motor cortex had reorganized to develop a new zone from which reaching could be evoked. That new zone was larger in rats that had relearned the skill better.

Brown and Teskey [55] studied the action map in rats using reversible deactivation. They used long-train electrical stimulation to define a grasping zone and a reaching zone in the motor cortex. Temporary deactivation of each zone impaired the corresponding action while the rat was gathering food pellets. The impairment was specific not to particular forelimb muscles but instead to the particular action performed by the limb. The results argue for an ethological map rather than a strict muscle map.

Budri *et al.* [56] found that restricting limb movement in rats for 30 days caused changes in the action map. The result suggests that action zones are partly shaped by experience, an effect predicted by our computational model of motor cortex topography [10].

Dombeck *et al.* [57] used calcium imaging to measure the activity of individual neurons in the mouse motor cortex during two different actions that involve the forelimb: running and grooming. They found that neurons active during the two behaviors were not fully intermixed but instead tended to cluster into adjacent cortical zones.

These many findings provide broad support for the action map as a fundamental principle of motor cortex organization across many mammalian species.

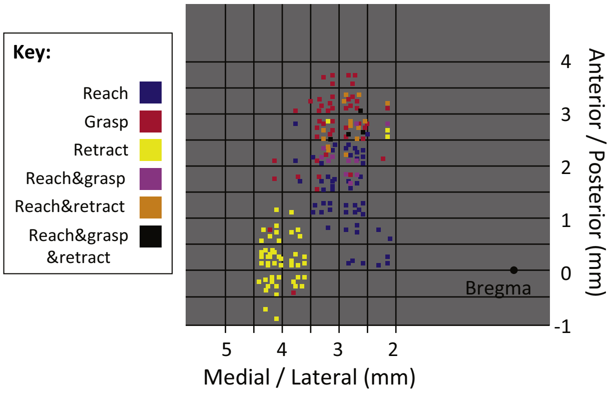

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Figure 3. The Action Map in the Rat Motor Cortex Based on Ramanathan *et al.* [51]. Different categories of forelimb action were evoked by long-train electrical stimulation of different sites in the cortex. Composite of 11 animals. Bregma, standard midline skull feature.

Reassessing the Action Map

Given the enormous amount of work in the past 14 years on ethological action maps, it is possible now to reassess some of the most basic questions and controversies raised from the beginning. The following sections reconsider the three key properties first proposed for the action map.

Does the Motor Cortex Contain a Map of Ethologically Relevant Actions?

Many techniques have now converged on the same answer. The motor cortex contains zones that emphasize complex, ethologically relevant categories of behavior. At least some of the most common species-typical behaviors are represented. Presumably more remain to be detailed. This ethological map appears to be a fundamental organizing principle across many mammalian species.

The ethological action map was so different from traditional views that controversy was inevitable. The controversy centered almost entirely around the use of electrical stimulation on an extended, behaviorally relevant timescale. Although the method was commonly used in many brain systems [17–25], it was not traditional in motor cortex studies. Critics of the action map tend to focus narrowly on the caveats of electrical stimulation. The stimulation technique does have its caveats and the evoked movements are not perfect mimics of real behavior. Yet, as in other brain systems where it has been used, the method provides insight that can be confirmed and extended through other methods. The action map has since been confirmed through so many other methods that the controversy has somewhat subsided.

Cheney and colleagues [41,42] argue that the evoked complex movements are artifacts of electrical stimulation. They call the process ‘neural hijacking’ [41,42]. In that perspective, the stimulation may spread in the cortex, activating groups of neurons that are not naturally linked. A collection of muscles represented separately but near each other in the cortex may become co-contracted as the stimulation imposes a sustained and unnatural plateau of activity.

This counter-hypothesis is likely to be partially correct. Of course stimulation is not a perfect mimic of real behavior, and to the extent that it deviates from real behavior the concerns of Cheney and colleagues are likely to be the cause. Yet there is reason to believe that these are not crippling problems, that neural hijacking is not the primary explanation for the evoked movements, and that the method still provides fundamental insight.

One argument against a major problem with miscellaneous co-contraction is that the evoked actions do not look like chance collections of muscles. They match ethologically valid actions, sometimes in astonishingly elaborate detail [1,2,7–9]. The limb moves to a spatial location that is appropriate for other aspects of the action, suggesting that the limb posture is not an accidental equilibrium. Moving the electrode to different sites within a cortical action zone does not fractionate the movement into its components, suggesting that the components are not the result of separate, adjacent cortical representations. During stimulation, when the spread of signal in the cortex is measured through various brain imaging methods, the signal follows physiological pathways rather than spreading indiscriminately [58–60]. The evidence suggests that stimulation on a behavioral timescale, despite the very real caveats, tends to recruit meaningful, connected networks rather than cobbling together unrelated components.

The example of defensive actions illustrates the experimental tension between generating meaningful results and acknowledging some artificiality. Stimulation of the defensive zone can evoke up to eight specific action components that precisely match natural defensive behavior, including a unique, curved centering movement of the eye that occurs under no other known circumstance [4,7]. Moreover, the evoked action matches the properties of the stimulated neurons: the action defends the specific part of the body where the sensory receptive fields of the neurons are located. Chemical disinhibition of the area can evoke spontaneous defensive movements and exaggerate defensive reactions to air puffs [3]. Chemical inhibition of the area reduces defensive reactions to air puffs without muting other actions that use the same facial muscles [3]. Superficially, the results seem a perfect match to the real behavior. Yet when muscle activity is examined, the artificiality of stimulation begins to emerge. During a stimulation-evoked defensive action, the muscle activity rises abruptly to a plateau, remains high during stimulation, and abruptly falls when stimulation ends [3,4]. The timing is square like the stimulation and unlike the complex pattern in a natural defensive movement [7]. It is worth noting that chemical disinhibition of the same cortical zone evokes a more realistic muscle activity pattern [3]. Is the electrically evoked movement ‘real’ or an artifact? The likely answer is both. The cortical zone helps coordinate defensive actions and stimulation of it with an artificial signal evokes an imperfect approximation to a defensive action. Cheney and colleagues [41,42] find that electrical stimulation evokes an unnatural plateau of muscle activity, much as we reported [3,4,12]. There is little if any disagreement on the data. The difference is in the interpretation: whether the stimulation-evoked movements reflect an underlying action map or an artifact.

In the end, the best argument that the action map is not an artifact of one technique is the confirming evidence from other techniques, including optogenetic stimulation [52], chemical stimulation [3], chemical inhibition [3,38,55], surgical lesions and cortical reorganization during recovery [51], the specific match between stimulation-evoked actions and neuronal response properties [4–6], the specific match between stimulation-evoked and natural behaviors (Box 1) [1,2,7–9], and mathematical models that show that the most efficient way to map the behavioral repertoire onto the cortex matches the actual action map [10,11]. As more techniques confirm the action map, attempts to explain it away as an artifact become less plausible.

Does the Motor Cortex Contain a Map of Limb Position?

We reported that the motor cortex contained a map of spatial locations to which the hand was directed [1,2]. Ventral sites corresponded to elbow flexion and the upper space around the head (such as in the hand-to-mouth cortical zone) whereas dorsal sites corresponded to elbow extension and the lower space around the feet. The primary motor hand area mainly emphasized hand locations in or near the central space. This organization was statistically present but noisy. We argued that the spatial location to which actions are directed was one of several parameters competitively influencing the cortical layout [10,11].

A recent study of stimulation-evoked postures in the monkey motor cortex [41] did not report an overarching map of hand locations, although it confirmed some of the findings such as a dominance of central hand locations in much of the classical primary motor hand area and a tendency for upper hand locations to be evoked from more ventral cortex. One possible reason why the study failed to find a larger map of hand locations may be that it was limited to testing only part of the map. Within the range tested, the results seemed consistent with ours. Only with sufficient coverage of action zones, each zone emphasizing a different part of extrinsic space, can the map of hand locations emerge. The coverage must extend beyond the classical primary motor cortex and include some of the premotor cortex, as discussed in the next section.

In the rat motor cortex, a rough map of action space was confirmed by Bonazzi and colleagues [54] and Budri and colleagues [56]. Adjacent cortical action zones emphasized different paw locations, resulting in a spatial topography.

Taken together, the evidence suggests that forelimb posture or hand location is one contributing factor shaping the overall topography of the motor cortex. Since the movement repertoire is

Box 1. How Do Stimulation-Evoked Postures Relate to Direction Tuning?

In 1982, Georgopoulos and colleagues [62] reported that neurons in the monkey motor cortex are broadly tuned to the direction of the hand during a reach and that, in principle, populations of such neurons could specify hand direction. The next 30 years were replete with studies, counter-studies, and controversies regarding the tuning properties of motor cortex neurons [6,63–70].

Our initial report of complex gestures evoked from the monkey motor cortex matched none of the positions staked out in the tuning literature. Neurons tuned to hand speed, velocity, direction, or force could not explain a hand-to-mouth gesture or a protective flipping of the hand to the side of the face. The evoked movements spanned the natural repertoire and did not resemble the trained reaching or lever-pulling tasks typical of the tuning-curve literature. The stimulation results appeared to conflict with the tuning curves.

To try to reconcile the stimulation-evoked actions of the arm with the previous reports that motor cortex neurons are tuned to relatively simple movement parameters, we studied the activity of single neurons during spontaneous complex movement [5,6]. We found that each neuron in the motor cortex was tuned to a great range of movement parameters simultaneously, as might be expected if the neurons help control natural actions. They were partially direction tuned, speed tuned, and posture tuned – more tuned to posture than to any other tuning model we tried – and to the extent that they were posture tuned, the preferred posture matched the arm posture evoked by stimulation from the same cortical site. Neurons in the defensive movement zone not only responded during movement but were also tuned to sensory stimuli approaching or touching the defended part of the body [3,4]. The neuronal properties seemed to match the stimulation-evoked actions.

The map of actions, in the end, did not help resolve the debate over different types of tuning curve. A hand-to-mouth action necessarily ends up with the hand near the mouth. It is not evidence for a universal end-point code or against a directional code. Instead, final postures and end points are common in the behavior of primates and are therefore commonly represented in the cortex. Direction, speed, force, and other variables are also important parts of natural behavior. It is unlikely that the control of one movement variable underlies most movement. The findings suggest that whatever output variable needs to be controlled for a given behavior, the system will control it.

defined by a large number of dimensions and the cortical surface contains only two, the map is necessarily complex, fractured, and overlapped [10,11]. No one type of map – body map, map of action zones, or map of hand locations – is perfectly organized. Instead, many factors are in competition with each other for topographic space.

What is the Relationship between the Primary Motor and Caudal Premotor Cortex?

Based on the distribution of cortical action zones, we suggested that the monkey primary motor cortex and some areas of the premotor cortex are not related hierarchically but instead emphasize different subsets of the movement repertoire. These premotor zones include the caudal dorsal premotor cortex (PMDc) (sometimes called F2), the caudal ventral premotor cortex (PMVc) (sometimes called F4), and even parts of the supplementary motor cortex. The proposal was controversial because it contradicted a more traditional view in which the premotor cortex is hierarchically above the primary motor cortex [14].

In our interpretation [11,14], the premotor areas appear more complex because they emphasize actions that coordinate among more body parts. These movements include, for example, hand-to-mouth actions, defensive actions that coordinate the head and arm, and reaching actions that involve the shoulder, torso, and arm. These actions, by their nature, require more extrinsic spatial processing. For these reasons, these areas of the brain were assumed to be higher order despite their direct projections to the spinal cord.

By contrast, the primary motor cortex appears less complex because it emphasizes actions that focus on individual body parts. These movements include, for example, actions of the tongue and jaw during chewing and actions of the fingers during manipulation of objects. These actions, by their nature, necessarily rely on intrinsic variables such as individuated control of hand muscles and finger joints. For these reasons, this area of cortex was assumed to be lower order.

In this view, the hierarchy is a misinterpretation. The caudal premotor zones and the primary motor zones differ because they emphasize different, equally important parts of the movement repertoire that have radically different control requirements. It makes no sense to suppose that one controls the other – that a defensive movement zone controls a digital manipulation zone.

The proposal does not reject all hierarchy. It reinterprets the status of the caudal premotor cortex. Other cortical areas such as the rostral premotor cortex and parietal cortex are undoubtedly part of a larger cortical hierarchy.

It is fair to say that this proposal about the relationship between the primary motor and caudal premotor cortex has not been embraced in the primate literature. The numerous differences between the two cortical regions are almost always interpreted in a hierarchical framework instead of in the framework of differing action categories. By contrast, in the rodent literature reviewed above the distinction between primary motor and caudal premotor cortex was never made. The action map is typically interpreted as encompassing the motor cortex as a whole with no assumption that one action zone might be hierarchically above another. Thus the rodent literature is more aligned with our original proposal.

Outstanding Questions

What structures, other than the motor cortex and the parietal cortex, contain a map of complex, ethologically relevant movements?

How are these structures interconnected and how do the maps depend on each other?

When complex movements are evoked from the motor cortex, do those movements depend mainly on the direct descending activation of the spinal cord or do they depend on recruiting other motor structures such as the midbrain, cerebellum, or thalamus?

Is the action map largely fixed after development or does it continuously change with learning?

Concluding Remarks: Next Steps

The discovery of an action map in the motor cortex is an opportunity to understand the motor system as an interactive whole. Traditionally, motor physiology focused on the cortical–spinal–muscle axis. Is the pathway a one-to-one map of cortical points to muscles? Is it a many-to-many map, resulting in topographic overlap? Does activity at one point in the cortex trigger activity in six muscles, twenty muscles, just the hand, or the hand and the shoulder? Does the hand area overlap the face area? Can the map become more punctate, more one-to-one, if tested with a more refined method? Since the discovery of the motor cortex in 1870, the same questions of mapping from cortex to muscles have been asked and asked again [14]. Tracing that one pathway through a larger network has led to simplistic thinking. After all, a single pathway has almost no computational complexity or ability to coordinate meaningful behavior. The reality is that the motor cortex is part of an interactive network and yet has almost never been studied in that manner.

The action map may finally provide an opportunity to study that network. Stimulation-evoked movements that involve temporal patterning, like chewing or whisking, probably recruit subcortical structures such as the facial nucleus. Other movements, like reaching or putting the hand to the mouth, require less temporal sequencing and more of a simultaneous coordination among many muscles. Yet even these movements might depend on subcortical timing circuits. One possibility is that the cerebellum shapes the timing for stimulation-evoked movements. The midbrain may also play a role in coordinating these complex movements. The mechanism behind the action zones remains largely unknown but is experimentally approachable.

Stimulation of an action zone in the motor cortex on a behavioral timescale is like finding a button in the brain that reliably prompts the whole motor network to produce an action. That action is an approximation to a coordinated piece of behavior, a species-typical fragment of great complexity that the system has specifically evolved to produce. Having found a way to trigger that action, one can then deconstruct the system. By modifying or inhibiting different parts of the system – parietal lobe, rostral premotor cortex, cerebellar deep nuclei, intermediate layers of the superior colliculus, putamen – one can ask, how do the pieces contribute to coordinating so complex an action? One has the sense that motor physiology can finally escape its obsession with the mapping from cortex to muscles and begin to tackle the 'system' part of the motor system.

Acknowledgments

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