Rethinking Cortical Organization: Moving Away from Discrete Areas Arranged in Hierarchies

MICHAEL S. A. GRAZIANO and TYSON N. AFLALO
Department of Psychology
Princeton University, Princeton, NJ

One way to understand the topography of the cerebral cortex is that "like attracts like." The cortex is organized to maximize nearest neighbor similarity. This principle can explain the separation of the cortex into discrete areas that emphasize different information domains. It can also explain the maps that form within cortical areas. However, because the cortex is two-dimensional, when a parameter space of much higher dimensionality is reduced onto the cortical sheet while optimizing nearest neighbor relationships, the result may lack an obvious global ordering into separate areas. Instead, the topography may consist of partial gradients, fractures, swirls, regions that resemble separate areas in some ways but not others, and in not a lack of topographic maps but an excess of maps overlaid on each other, no one of which seems to be entirely correct. Like a canvas in a gallery of modern art that no two observers interpret the same way, this lack of obvious ordering of high-dimensional spaces onto the cortex might then result in some scientific controversy over the true organization. In this review, the authors suggest that at least some sectors of the cortex do not have a simple global ordering and are better understood as a result of a reduction of a high-dimensional space onto the cortical sheet. The cortical motor system may be an example of this phenomenon. The authors discuss a model of the lateral motor cortex in which a reduction of many parameters onto a simulated cortical sheet results in a complex topographic pattern that matches the actual monkey motor cortex in surprising detail. Some of the ambiguities of topography and areal boundaries that have plagued the attempt to systematize the lateral motor cortex are explained by the model. NEUROSCIENTIST 13(2):138–147, 2007. DOI: 10.1177/1073858406295918

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The following properties of cortical organization are now nearly universally accepted:

1. The cerebral cortex is divisible into more or less separate areas, each of which tends to emphasize a different type of information.
2. Some areas contain an internal, finer organization of the relevant information such as a retinotopic map of the visual world or a somatotopic map of the body.
3. Cortical areas do not function as separate modules but rather are organized into large, densely interconnected networks that function together, such as the network of extrastriate visual areas or the network of motor areas.
4. Within these larger networks of areas, some areas are hierarchically above other areas, processing information that is more abstract and more removed from the sensory or motor devices of the periphery.

This view of cortical organization, based largely on the visual system of primates (e.g., Felleman and Van Essen 1991; Kaas and Garraghty 1991), is more or less accurate but may be incomplete. It fits the lower levels of visual processing, but the higher levels of visual processing may not fit neatly into the concept of separate areas (e.g., Haxby and others 2001).

The situation becomes even more problematical in the cortical motor system. Published maps of the motor system (see Fig. 1) resemble maps of the visual system, with a topographically organized primary area that is linked to the periphery and a range of higher-order areas that are assigned functions such as "planning" and "sequencing" (e.g., Matelli and others 1985; Wise 1985; Mushiake and others 1990; Luppino and others 1991; Matsuzaka and others 1992; He and others 1995; Preuss and others 1996). Yet the divisions between areas are typically gradients rather than borders, and the hierarchical organization among areas is obscure, given that most of the cortical motor system projects in parallel to the spinal cord (Bortoff and Strick 1993; He and others 1993; Dum and Strick 1996, 2002; Wu and others 2000) and that lesions

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Address correspondence to: Michael Graziano, Department of Psychology, Princeton University, Princeton NJ 08544 (e-mail: Graziano@princeton.edu).

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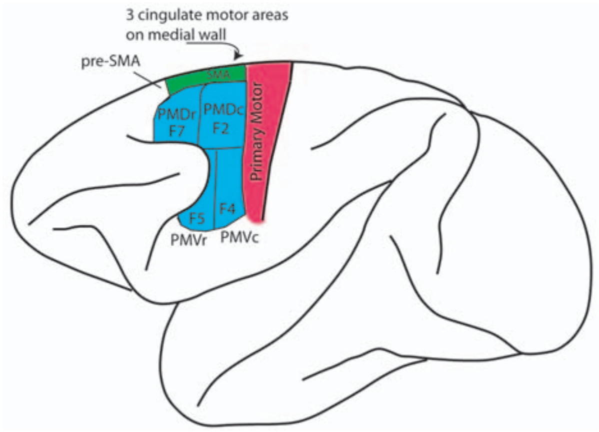

Fig. 1. Some commonly accepted divisions of the cortical motor system of the monkey. PMDr = dorsal premotor cortex, rostral division, also sometimes called field 7 (F7). PMDc = dorsal premotor cortex, caudal division, also sometimes called field 2 (F2). PMVr = ventral premotor cortex, rostral division, also sometimes called field 5 (F5). PMVc = ventral premotor cortex, caudal division, also sometimes called field 4 (F4). SMA = supplementary motor cortex. Pre-SMA = presupplementary motor cortex. These areas fall into three general regions: primary motor (red), lateral premotor (blue), and medial premotor (green).

to the supposed primary area do not permanently abolish movement (e.g., DennyBrown and Botterell 1947; Travis 1955; Rouiller and others 1998; Sherrington 1939). The simple view of discrete areas and hierarchies seems to have done a disservice to our understanding of the motor system and perhaps also of the visual system.

One possible reason for the gap between the standard description of discrete cortical areas arranged in hierarchies and the messy reality is that the standard description is only a convenient rule of thumb, a proxy for a deeper organizing principle that has been recognized for some time. The principle is one of nearest neighbor relationships (e.g., Saarinen and Kohonen 1985; Obermayer and others 1990; Kaas and Catania 2002; Rosa and Tweedale 2005). Similar types of information tend to be processed in adjacent locations in the cortex. One possible explanation for this rule of proximity is that it is a side effect of the normal developmental process; during development, axons are guided to their terminations by chemical gradients, and therefore the connectivity from one brain area to another tends to form a topographic continuity. A second explanation is that it evolved to maximize efficiency in processing; processors that require constant intercommunication have therefore evolved to be near each other in the cortex to minimize wiring length. A third possible reason is that neurons that are near each other tend to share more synaptic connections; as a result, during Hebbian learning, correlated signals tend to become encoded by nearby neurons. Probably all of these reasons contribute and interact with each other. For example, it has been suggested that primary cortical maps are hardwired, and secondary cortical maps grow in a cascade of Hebbian learning from the primary maps (Kaas and Catania 2002; Rosa and Tweedale 2005). Whatever the cause for the local smoothness constraint, whether ontogenetic or phylogenetic, the cortex seems to be organized along this principle of like attracts like.

This principle of organization explains the formation of discrete cortical areas that emphasize specific domains of information. It also explains the formation of topographic maps within cortical areas. For example, adjacent locations on the retina are mapped to adjacent locations in the primary visual cortex in a retinotopic map. Conveniently, both the retina and the cortex are two-dimensional sheets, and therefore the mapping can be accomplished in a topologically exact fashion. The mapping becomes more complex when reducing a higher dimensional space onto the cortical sheet. For example, Obermayer and others (1990) showed that the complex pinwheel arrangement of orientation columns in V1 can be replicated by a model that optimizes nearest neighbor similarity.

V1, with its global retinotopic map and local orientation and ocular dominance columns, still represents a parameter space of relatively low dimensionality. How can the cortex organize around the highly dimensional spaces required for shape recognition, visuomotor integration, or movement control? In these cases, the optimization of nearest neighbor relationships might no longer result in recognizable cortical areas that have discrete borders, distinct functions, and internal topographies. Even more bewildering for the experimenter, if the cortical sheet is examined through the perspective of one set of dimensions, it may appear to take on one type of organization, breaking down more or less into a set of areas; yet when examined through the perspective of a different set of dimensions, its organization may appear suddenly different. In this manner, depending on which glasses one puts on, the same region of cortex might reveal a bewildering range of apparently contradictory organizations, each of which fits the data in a noisy and approximate manner.

This shape-shifting nature of cortical organization may be the case in the cortical motor system. We would argue that it is probably the case everywhere in the cortex where the relevant dimensions of information far outnumber the two dimensions of the cortical sheet.

The following sections focus on the organization of the cortical motor system. We first give a historical perspective on how the cortical motor system came to be seen as a patchwork of hierarchically organized, discrete areas. We then describe some alternative organizations that have been proposed. Finally, we describe a formal model of the topographic organization of the precentral gyrus (Aflalo and Graziano 2006). In this model, several different dimensions of movement compete for space on the two-dimensional cortical sheet. By optimizing nearest neighbor relationships, the model results in a topographic map that in many ways matches the actual maps found in the monkey brain. Many of the apparent contradictions, complexities, and ambiguities described in actual physiology are duplicated in the model.

The main purpose of this review is to try to move away from the description of the cortical motor system as a set of discrete areas that have distinct functions and that fall into a strict hierarchy. Instead, we suggest that the organizing principle is more subtle and results in a topographic pattern worthy of a deranged modern artist. One can squint at the canvas and discern separate areas and even some elements of hierarchy, but these half-imagined patterns miss the underlying truth.

Cortical Motor Areas

Figure 1 shows a common modern view of the organization of the motor cortex. Three general regions of motor cortex are recognized: primary motor cortex (red), lateral premotor cortex (blue), and medial premotor cortex (green) (e.g., Matelli and others 1985; Wise 1985; Mushiake and others 1990; Luppino and others 1991; Matsuzaka and others 1992; He and others 1995; Preuss and others 1996). Some of these regions are further subdivided into halves or quadrants. These municipal boundaries drawn on the cortex are now repeated throughout the literature. The stringent definitions of separate areas applied in the early days of mapping extrastriate visual cortex, however, seem to have been abandoned in the motor system. Throughout the motor cortex, physiological and anatomical properties are clearly nonuniform, but the evidence of discrete areas with borders is scant. In this section, we give a highly selective account, inevitably tinted by our own perspective, of the main experimental steps to date in understanding the organization of the cortical motor system.

1. Fritsch and Hitzig (1870) and Ferrier (1874) described a somatotopically organized motor map on the lateral aspect of the hemisphere.
2. Campbell (1905) proposed that this map could be divided into a posterior strip, the primary motor cortex, and an anterior strip, now called the premotor cortex and originally called the intermediate precentral cortex by Campbell (Fig. 2*A*). In his proposal, the primary motor cortex directly controlled movement through its connectivity to the spinal cord, whereas the premotor cortex controlled higher-order aspects of movement and influenced the primary motor cortex.
3. Penfield and Welch (1951) in the human cortex and Woolsey and others (1952) in the monkey cortex described a second somatotopically organized region on the dorsal surface of the hemisphere and partly on the medial wall (Fig. 2*B*). This second region was termed the *supplementary motor cortex* by Penfield and Welch and *M2* by Woolsey and others.
4. The distinction between the primary motor cortex and the lateral premotor cortex was questioned. In the views of both Penfield and Welch (1951) and Woolsey and others (1952), the division was not correct. Woolsey and others found only one map on the lateral surface, its hands and feet in the location of Campbell's primary motor cortex and its back and neck in the location of Campbell's premotor cortex (compare Fig. 2*A* and 2*B*). Woolsey and others argued that many of the original distinctions between the primary motor strip and the premotor strip, such as the presence of the large Betz cells in the primary motor cortex and the dense projections to the spinal cord from the primary motor cortex, were better described as a gradient across the cortex rather than a boundary. The electrical thresholds were lower for the fingers and therefore lower in the posterior strip, but this boundary of electrical excitability could be attributed to a difference between hand and arm, rather than between primary motor and premotor. In this view, although the lateral motor cortex was nonuniform, with the posterior strip having somewhat different properties from the anterior strip, these differences arose from the cortical representation of different parts of the body rather than from different levels of a processing hierarchy.
5. Rizzolatti and colleagues (Rizzolatti and others 1981a, 1981b, 1988; Matelli and others 1985; Gentilucci and others 1988) revitalized the hypothesis that the lateral motor strip was divided into a primary motor cortex and a lateral premotor cortex. Their most convincing argument was the discovery of a reversal in the map. As they marched their electrode from the posterior edge to the anterior edge of the precentral gyrus, they encountered first a hand representation, then an arm and shoulder representation, and then another hand representation. This second hand representation they assigned to the ventral premotor cortex and labeled field 5 (F5; see Fig. 1). This reversal was strong evidence—one might say conclusive evidence—that the lateral motor cortex did not contain one simple map of the body.
6. Wise and colleagues (Weinrich and Wise 1982; Wise and others 1983; Weinrich and others 1984) established specialized properties of a dorsal premotor cortex (PMD; see Fig. 1). The neurons in this area of the cortex showed an elevated activity during the holding period of a delayed movement task. Wise and colleagues hypothesized that this delay activity reflected the preparation for movement. They showed that this preparation activity was common and robust in the dorsal premotor cortex and less common and less robust in the primary motor area. These results demonstrated a clear nonuniformity across the cortical surface. The evidence for separate areas with clear borders, however, was not strong. The results fit a pattern of complex properties that change in a graded manner, rather than a pattern of discrete cortical areas, each with its own internal organization.
7. Neurons in the caudal part of dorsal premotor cortex (PMDc) were found in many experiments to correlate with reaching (e.g., Hocherman and Wise 1991; Johnson and others 1996; Crammond and Kalaska 1996; Messier and Kalaska 2000; Cisek and Kalaska 2005; Churchland and others 2006). However, the boundary between the PMDc and the primary motor cortex is rarely if ever studied. Whether the distinction is a gradient or a border is still not clear.

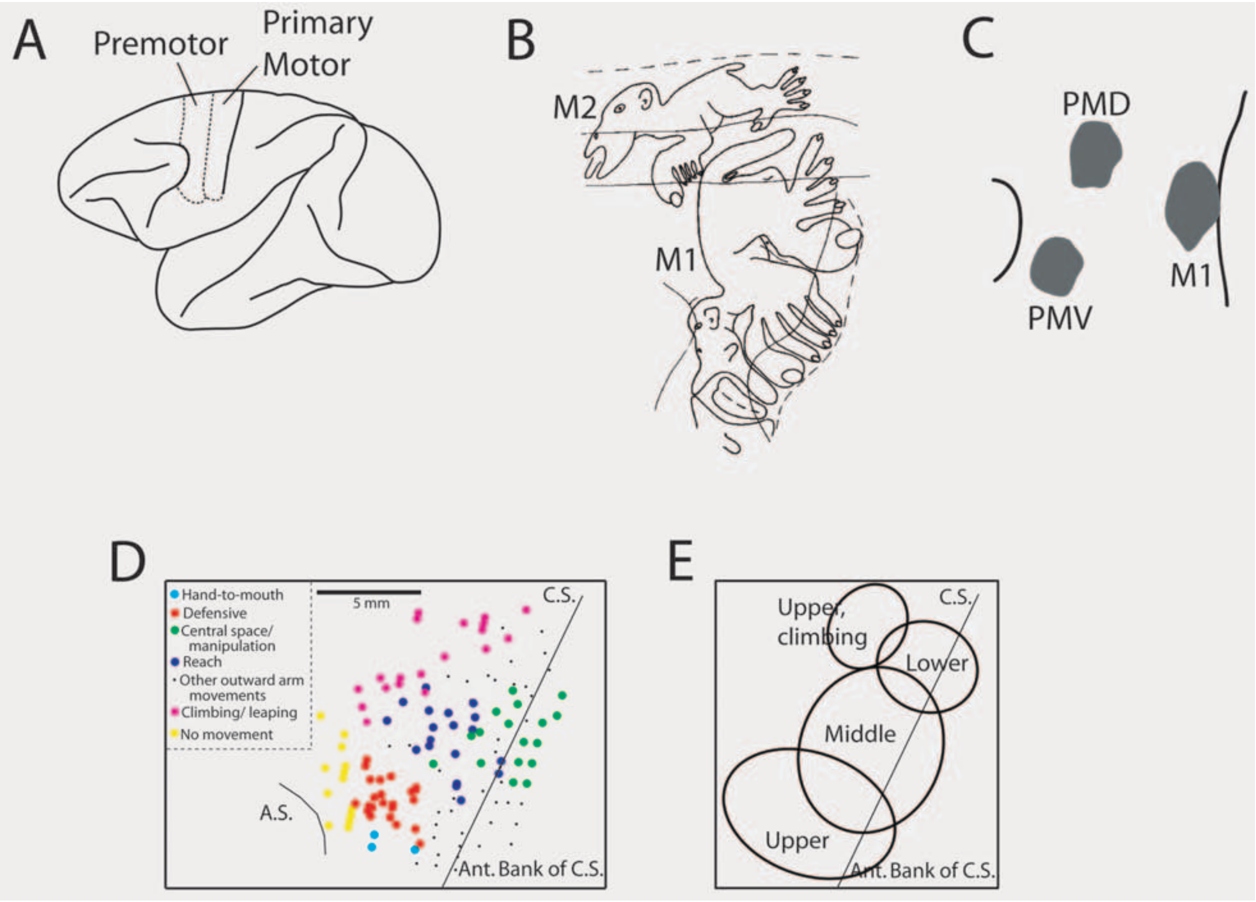

Fig. 2. Changing views of the organization of motor cortex. (*A*) Campbell (1905) divided the lateral motor cortex into a primary motor strip and a premotor strip. (*B*) Woolsey and others (1952) described only one body map in the lateral cortex of the monkey (M1) and one body map in the medial cortex (M2). (*C*) Dum and Strick (2005) described three hand areas in the lateral motor cortex, perhaps located in the primary motor (M1), dorsal premotor (PMD), and ventral premotor (PMV). (*D*) Graziano and others (2005) found that stimulation of different cortical zones evoked different types of behavior. A.S. = arcuate sulcus; C.S. = central sulcus. Each dot shows a stimulation site; color code shows the type of movement evoked. (*E*) Schematic view of hand position map, based on the same monkey as in *D*. Upper = cortical area where stimulation drove the hand into the upper space, such as near the mouth; middle = cortical area where stimulation drove the hand into the middle space, such as in front of the chest; lower = cortical area where stimulation drove the hand into the lower space near the feet. A second representation of upper space (Upper, climbing) was found associated with climbing-like movements.

8. Strick and colleagues (Bortoff and Strick 1993; He and others 1993; Dum and Strick 1996, 2002, 2005) examined the pattern of projections from the cortex to the spinal cord, confirming that most of the cortical motor system projects in parallel to the spinal cord. They suggested that the traditional view of a hierarchy, in which premotor areas control the primary motor cortex, which in turn controls the spinal cord, may require revision. One especially revealing finding was the discovery of three distinct patches within the lateral motor cortex that projected specifically to the hand part of the spinal cord (Dum and Strick 2005). These three hand areas (Fig. 2*C*) may relate to the primary motor hand representation, the ventral premotor hand representation (F5), and the dorsal premotor reaching representation (PMDc). Strick and colleagues found no evidence of a hierarchy among these three areas; all three were mutually connected, and all three projected to the spinal cord.
9. Graziano and colleagues (Graziano and others 2002, 2003, 2004, 2005; Cooke and Graziano 2004) found that electrical stimulation of the motor cortex on a behaviorally relevant timescale can evoke complex, apparently coordinated behavior. These evoked movements are arranged in rough, partially overlapping cortical zones (Fig. 2*D*). Three cortical zones seem to emphasize movements of the fingers. In one zone, stimulation evokes a movement of the hand to a central location in front of the chest and a movement of the fingers that resembles manipulation of an object. This zone roughly corresponds to the primary motor hand area. In a second zone, stimulation evokes a grip-like closure of the hand, a movement of the hand to the mouth, and an opening of the mouth.

This zone roughly corresponds to the ventral premotor cortex. In a third zone, stimulation evokes a reaching-like movement in which the hand opens as if in preparation for a grasp and the arm extends. This zone roughly corresponds to PMDc. It is possible that these three hand-related zones also match the three hand areas defined anatomically by Strick and colleagues (Dum and Strick 2005). In other cortical zones, stimulation evokes defensive-like movements, movements of the arm into lower space as if bracing the body's weight, and climbing-like movements that involve all four limbs. One implication of this work is that the lateral motor cortex may be organized not into separate premotor areas that control a primary motor area but rather into separate clusters that emphasize different ethologically relevant categories of actions.

10. In the same set of electrical stimulation experiments, Graziano and colleagues discerned a map that seemed to encompass the traditional primary motor cortex and part of the lateral premotor cortex, including PMDc, F4, and perhaps F5. Within this map, stimulation of different sites drove the hand to different locations in space. In general, the height of the hand was most consistently mapped, with ventral cortical locations corresponding to upper hand positions and dorsal cortical locations corresponding to lower hand positions (Fig. 2*E*). Also, posterior cortical locations typically corresponded to midline hand locations, and anterior cortical locations typically corresponded to lateral hand locations. No clear ordering was found of the distance of the hand from the body along the line of sight. The map was noisy, containing extensive overlap, yet was statistically present. The authors suggested that the traditional boundaries between the primary motor cortex and lateral premotor cortex (as well as between the subdivisions of the premotor cortex) may have been exaggerated, that these regions may fit together smoothly into a larger organization, and that the differences between subregions may reflect differences in the encoding of different parts of the hand's workspace.

The above 10 points on motor cortex organization present a murky picture. Most of the murk relates to the lateral motor cortex, perhaps because the medial motor cortex has been relatively understudied, and therefore the confusions within it are yet to be fully appreciated. Is the lateral motor strip divisible into two major parts, a primary motor cortex and a lateral premotor cortex? Are the finer subdivisions real areas with distinct boundaries, or are they humps in a set of graded distributions? Do the nonuniformities relate to different stages of processing, such as preparation and execution, or do they relate to different types of ethologically useful actions, such as hand-to-mouth and defensive movements? To what extent is the somatotopic map of the body real, or is it so overlapping and fractured as to be irrelevant? Is there a cortical map of the locations in space to which actions are directed, and how can such a map exist in the same region of cortex that has already been accused of so many other possible organizational schemes?

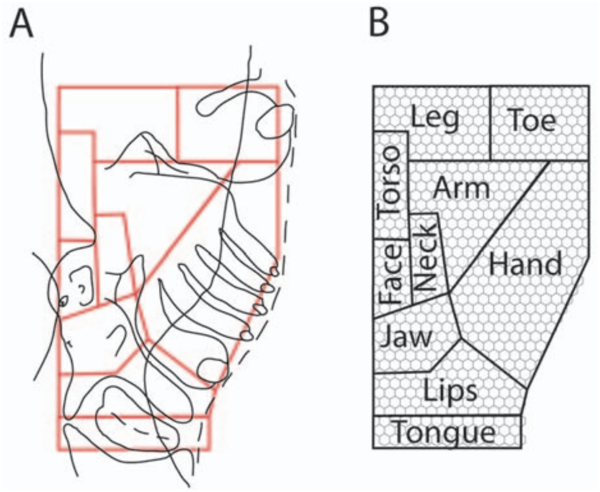

Fig. 3. Initial state of the model. (*A*) Woolsey's map of the somatotopic organization in the monkey motor cortex (Woolsey and others 1952), overlaid with blocked regions showing the schematized somatotopy used in the present motor cortex model. (*B*) Node array used in the present model with initial assignment of body parts to nodes.

Recently, we proposed that this murky and multifarious organization of the lateral motor cortex may be the result of a competition between several different types of organizations fighting for space on the same sheet of cortex. The next section elaborates on this view and describes a formal model that explores the hypothesis.

A Model of the Lateral Motor Cortex

The purpose of the model (Aflalo and Graziano 2006) was to begin with a set of movement dimensions that we believed to be relevant to the monkey motor cortex, to perform a dimensionality reduction to represent those movement dimensions on a two-dimensional cortical sheet, and to compare the resultant map in the model to the actual maps obtained in the monkey brain.

We assigned the map an initial somatotopic organization. We then allowed the map to reorganize under the influence of two additional mapping requisites: hand location in space and ethologically relevant action categories that combine more than one body part. We used five action categories based on the actions commonly evoked by electrical stimulation from the monkey motor cortex: hand-to-mouth movements, manipulation of objects in central space, reaching to grasp, defensive movements, and climbing-like movements. To allow the map to reorganize, we used the Kohonen algorithm (Kohonen 2001), which maximizes local smoothness.

The initial state of the model is shown in Figure 3. The model took the form of an array of nodes, shown here overlaid on Woolsey's map of the motor cortex (Woolsey and others 1952). In the initial state of the model, each

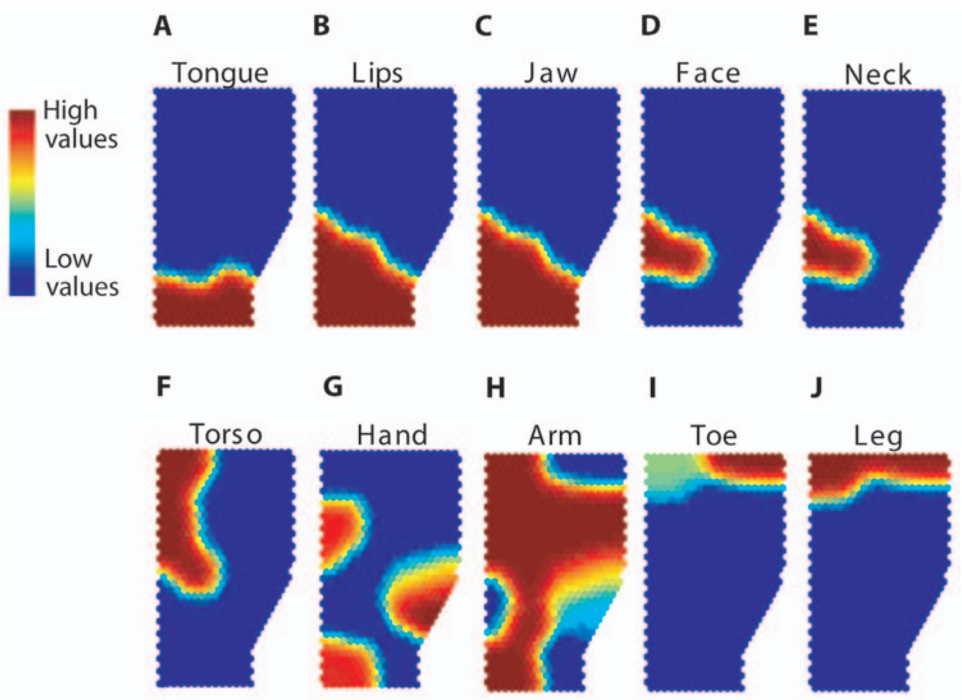

Fig. 4. Final state of the self-organizing map model: somatotopy. (*A*–*J*) Somatotopic arrangement of the 10 body parts after reorganization. Colors show strength of representation of each body part.

node represented movement of a particular body part, and the body parts were arranged in a somatotopic map that matched Woolsey's map. In this initial array, no other movement dimension was systematically mapped. The action category and the position of the hand were assigned small random values to each node and therefore did not form any systematic topography. Our rationale for using a purely somatotopic map as an initial condition was the work of Martin and others (2005). They showed that, in the cat, at least, the motor cortex may begin at birth as a relatively clean somatotopic map and then through experience develop the complexities and overlaps typical of an adult.

The node array was then updated according to the method of a Kohonen neural network (Kohonen 2001). In this method, the network is trained on a set of example movements. Our training set included 12,800 movements that included movements of single body parts and complex movements of multiple body parts that fell into one or another of the five action categories. During training, the network updated such that neighboring nodes came to represent similar movements, and therefore local smoothness was optimized. In this manner, the multidimensional space of movements was reduced onto the two-dimensional array.

Figures 4 through 6 show the result of this dimensionality reduction. In Figure 4, each panel shows the final state of the map, with the representation of a different body part highlighted. For example, the first panel shows the representation of the tongue, mainly in the ventral part of the map; the second panel shows the representation of the lips, largely overlapping the tongue representation. Figure 5 shows more results of the same model. Here the representations of the five different ethological action categories are plotted. Finally, Figure 6 shows the representations of hand position across the map model. This topography, generated by the artificial model of the motor cortex, is similar to the actual motor cortex of the monkey in the following five ways.

1. As a result of the dimensionality reduction, the initially discrete somatotopy was turned into an extensively overlapping somatotopy, much more similar to the actual maps obtained in physiological experiments.
2. The model developed a distinction between a posterior strip of the map and an anterior strip. Along the posterior strip (the right edge of the array), a relatively discrete progression can be seen (Fig. 4). This progression includes a mouth representation at the bottom, then a region that emphasizes the hand but also weakly represents the arm, then a region that emphasizes the arm but also weakly represents the hand, then a region that represents the foot and leg. A classical motor somatotopy is displayed. Along the anterior strip of the map (the left edge of the array), the somatotopy is much more overlapping and fractured, and a classical motor somatotopy is not as evident. The reason for this trend in the self-organizing map is clear: some of the movements in our model were especially complex in that they required coordination among different body parts. For example, reaching involved action of the hand,

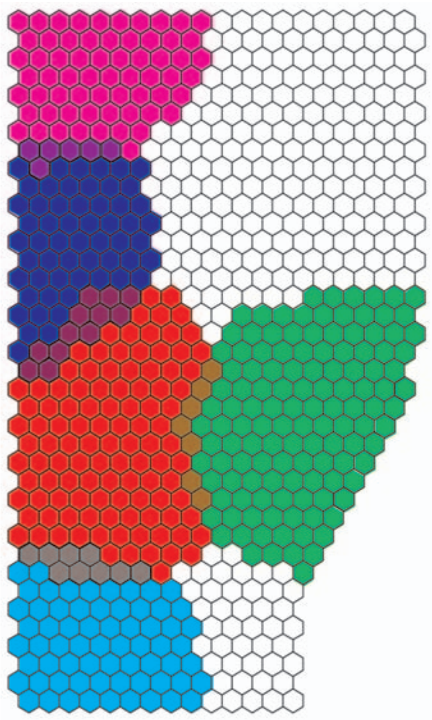

Fig. 5. Final state of the self-organizing map model: action zones. Light blue = hand to mouth; dark blue = reach; red = defense; green = central space/manipulation; pink = climbing. Regions of overlap have intermediate colors.

arm, and torso. Defensive movements involved action of the face, rotation of the head, movement of the torso, and movement of the arm. Climbing was perhaps the most integrated, involving the arm, torso, and leg. These movements involved the axial musculature because the trunk and neck form the connecting links between different body segments. The initial somatotopy was arranged with the axial musculature in an anterior region and the distal musculature in a posterior region. As a result, during learning, the complex movements that link more than one body segment gravitated to the anterior regions of the map. Thus, in our model, in its final state, one can distinguish a posterior strip that is "primary like" in that it contains a relatively discrete somatotopy, representing body segments in a separate manner, and an anterior strip that is "premotor like" in that it contains a more integrated, blurred somatotopy and represents movements of greater intersegment complexity. However, no processing hierarchy is implied by the map. The anterior strip does not control the posterior strip.

3. The hand representation became divided into three regions (Fig. 4*G*). One hand representation was located in the posterior part of the array, as if corresponding to the primary motor hand area; the second hand representation was located in an anterior region within the dorsal half of the array, as if corresponding to the dorsal premotor hand area; and the third hand representation was located in an anterior region at the ventral edge of the array, as if corresponding to the ventral premotor hand area. These three hand areas also resemble the three hand areas described by Dum and Strick (2005) on the basis of projections from the cortex to the spinal cord. The reason why the model developed three distinct hand areas is that it was trained on three distinct categories of action that included the hand: manipulation in central space, reaching to grasp, and hand-to-mouth movement.
4. The five ethological categories of movement became focused into five cortical zones that were relatively discrete, with minimal overlap (Fig. 5). The topographic arrangement of the zones in the self-organizing map closely resembled the arrangement observed in the actual monkey brain. This arrangement of ethological zones resulted from the initial somatotopy and the subsequent attempt of the network to optimize nearest neighbor relationships. For example, the hand-to-mouth movements converged on a ventral location where the mouth, hand, and arm representations could develop a region of overlap. The climbing movements converged on a region where the arm, leg, and torso representations could develop a region of overlap. In this manner, the topography of these action zones on the cortex was highly constrained. These specialized areas that developed in the model may help to explain the cortical subregions with specialized physiological properties described in the literature. The model contains a posterior, primary-like strip and a collection of more anterior, premotor-like areas, in some ways similar to the standard parcellation of the motor cortex shown in Figure 1. However, an essential feature of the model is that this parcellation into relatively separate areas is not a complete description. It would be misleading to characterize the final state of the model as a simple division among specialized areas. Instead, the model contains a multidimensional, complex organization, only one aspect of which is reflected in the ethological action zones.

5. The model developed noisy maps of hand location that approximated the findings in the monkey motor cortex (Fig. 6). The height of the hand was most consistently mapped, with upper hand positions in a ventral location in the map and lower hand positions in a dorsal location. A second upper hand location formed in a dorsal, anterior region of the map, overlapping the representation of climbing-like movements, again roughly matching the findings in the monkey brain. The lateral position of the hand was less clearly ordered in the map, and the forward distance of the hand along the line of sight showed no consistent topography.

These results of the model support our hypothesis that the organization in the lateral motor cortex can be partially understood as an initial, underlying somatotopy that is reorganized under the competing influences of other mapping requisites, including a cluster map of

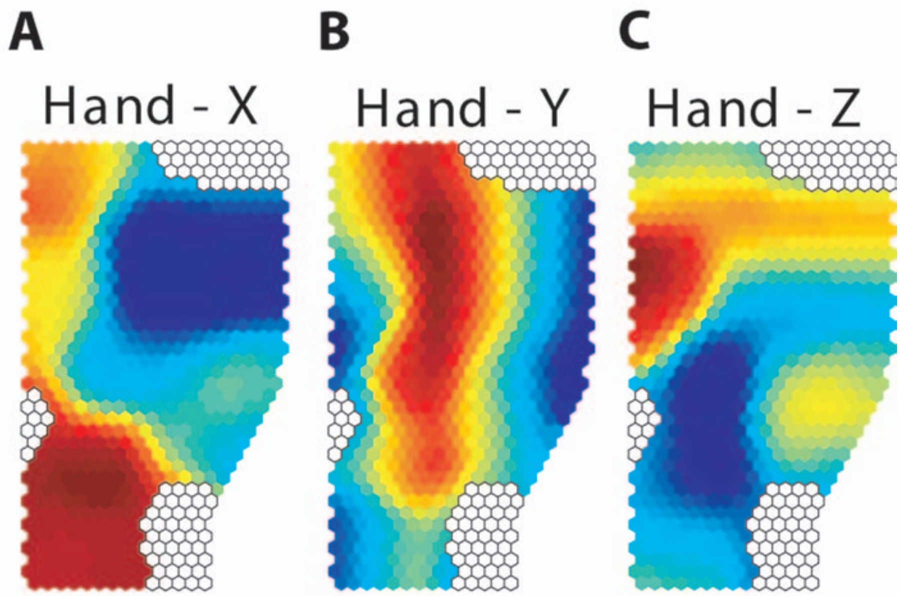

Fig. 6. Final state of the self-organizing map model: hand location. X = hand height, warm colors = greater height; Y = lateral location of hand, warm colors = more lateral locations; Z = distance of hand from body along line of sight, warm colors = more distant locations.

ethologically relevant movements and a topographic map of hand position in space. Other variables relevant to the animal's movement repertoire might of course also influence the topography within the motor cortex.

"Like Attracts Like" as a General Principle of Cortical Organization

The maximization of local smoothness automatically imposes a topographic organization on the cortex. The large-scale division of the cortex into visual, somatosensory, auditory, and motor areas follows this principle. The division of these larger chunks of real estate into smaller areas that represent different types of information also emerges from the same principle. The well-ordered maps within areas, such as retinotopic, tonotopic, or somatotopic maps, all naturally emerge from a nearest neighbor principle. The micro-organization revealed in some cortical areas, such as the maps of orientation tuning in V1 (Hubel and Weisel 1962) or the maps of movement direction in MT (Albright and others 1984), follows the same principle. This principle, however, does not always generate a clear global order. When the dimensionality of the parameter space far exceeds the two dimensions of cortex, the resultant cortical arrangement, although still maximizing local smoothness, may form a confusing mash of gradients, partial maps, swirls, and misleading boundaries. In these cases, rather than attempting to shoehorn the cortex into a traditional set of areas arranged in hierarchies, a more accurate approach may be to accept the global disorder as an emergent property of a deeper principle.

We suggest that the lateral motor cortex in the monkey brain can be understood in this manner. Squinting at the model one way, the map contains separate areas with fuzzy borders (Fig. 5), consistent with a traditional approach of dividing the cortical motor system into distinct areas. Squinting another way, however, the same cortex is a single, albeit noisy, map of the body (Fig. 4) consistent with Woolsey's conception (Woolsey and others 1952). Squinting from yet a third perspective, this region of cortex is a noisy map of hand position in space (Fig. 6) consistent with our initial report using stimulation on a behaviorally relevant timescale (Graziano and others 2002). All of these seemingly contradictory descriptions make sense within the context of a reduction of many dimensions onto the cortical sheet.

The same principle may help explain the organization of other cortical areas. For example, some controversy has emerged over the organization of the ventral temporal cortex. This area of cortex is known to process the identity of visual stimuli. Whether it is uniform, with all shapes represented in a distributed fashion over the cortical area (Haxby and others 2001), or whether it is separated into discrete areas that represent faces, places, body parts, and other categories (Spiridon and Kanwisher 2002), is in dispute. One senses that the space of shape recognition is highly dimensional and therefore probably cannot be easily rendered onto the cortical sheet in a simple topography. A dimensionality reduction model of this region of cortex might help to shed light on its organization.

Another area of cortex that has defied separation into clear subareas is the lateral prefrontal cortex. In one attempt to bring order to this region, Funahashi and others

(1990, 1993) proposed that the dorsal-lateral prefrontal cortex contained a map of space. When monkeys performed a memory-guided spatial task, neurons in different parts of the map appeared to participate in the memory of different spatial locations. In a further attempt at order, the dorsal-lateral prefrontal cortex was proposed to specialize in spatial memory, and the ventral-lateral prefrontal cortex was proposed to specialize in object memory (Wilson and others 1993). However, these maps and separations were not robust. Miller and colleagues found that neurons in the lateral prefrontal cortex, whether in the dorsal or ventral subdivision, appeared to encode the parameters relevant to any task that the monkey had learned, whether spatial or object, memory, matching rule, categorization of shapes into cats and dogs, or recognition of the number of objects in a display (Rao and others 1997; Asaad and others 2000; Freedman and others 2001; Wallis and others 2001; Nieder and others 2002). The neurons appeared to be multitalented, trainable on almost anything, and therefore unlikely to break down into discrete cortical areas dedicated to separate information domains. It is probably not correct to infer that the lateral prefrontal cortex is a homogeneous region of equipotential neurons, but certainly no neat boundaries or topographies are evident. One possibility is that different parameter spaces can be rendered onto the prefrontal cortex, depending on the task performed by the animal, and that these dimensionality reductions result in different complex, murky organizations. A two-dimensional cognitive task such as remembering locations on a projection screen may indeed result in a map of space on the cortical surface, but other tasks may result in no recognizable global topography.

In summary, the traditional view of separate cortical areas—each one with its own internal topography, all of them arranged in hierarchies—is probably not the real organizing principle of the cortex. Although it may serve as a good approximation in some cases, it may also be misleading or plain wrong in other cases. A more fundamental principle of cortical organization may be that "like attracts like," resulting in a spatial rendering of high-dimensional spaces onto the cortex. This principle can account for the discrete areas and simple maps but may also be able to account for the regions of cortex that lack any clear global ordering.

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