News & views

Neuroscience

Map redrawn for the human motor cortex

David A. Leopold

The human brain's motor cortex is often regarded as a linear map with discrete sections, each controlling different parts of the body. The discovery that portions of the motor cortex have other functions points to a different type of map. **See p.351**

How does our brain control everyday behaviours, such as grasping a cup of coffee or telling a joke? A century of experimental neurology testifies that a thin strip of motor cortex running sideways down the outer surface of the brain translates voluntary actions (the decision to take a sip, for instance) into muscle movements. This strip is usually thought of as representing a continuous map of the human body, with separate sections each containing neurons that contact the spinal cord to operate a particular group of muscles. 'Higher' regions of the brain act as puppeteers, orchestrating movements by creating appropriate spatio-temporal sequences of neuronal activity in the motor-cortex map.

On page 351, Gordon *et al.*[1] provide a modified portrait of human motor-cortex organization, showing that the cortex is a composite of two distinct and spatially interleaved systems, only one of which is devoted directly to bodily movements.

In the 1930s, the neurosurgeon Wilder Penfield conducted a series of experiments in which he electrically stimulated regions of the motor cortex in awake people[2]. He found that the position of stimulation determined which part of the body moved. This led him to produce a map of motor-cortex organization that many are familiar with today. It is illustrated as a homunculus – a cartoon of oddly proportioned body parts overlain on the cortical surface (Fig. 1a).

Over the years, this homunculus model has been questioned – in part because individual brains differ in their details, and also because of concern that the precision and continuity of the motor map had been overstated[3]. A large-scale replication of Penfield's findings in 2020 provided some reassurance[4]. But, curiously, more than half of the sites of stimulation did not lead to any bodily movements, suggesting that some regions of the motor cortex have other roles.

In support of this idea, several facts indicate that the primate motor cortex is far from a singular map governing bodily movements. First, some body parts are controlled by two distinct regions of the motor cortex, one of which bypasses the internal spinal-cord circuitry to permit direct cortical control over individual muscles[5]. The evolution of this direct pathway greatly enhanced refined motor behaviours, such as dexterous hand movements, in humans and other primates. Second, rather than being linear in its layout, the monkey motor cortex has a concentric organization (for example, the hand region is flanked on both sides by regions controlling the wrist, elbow and shoulder)[6,7].

Third, some motor-cortex subregions participate in decidedly non-motor actions – the regulation of arousal signals for fight-or-flight behaviours[8], for instance. Fourth, stimulation from a single point in the motor cortex can sometimes elicit complex,

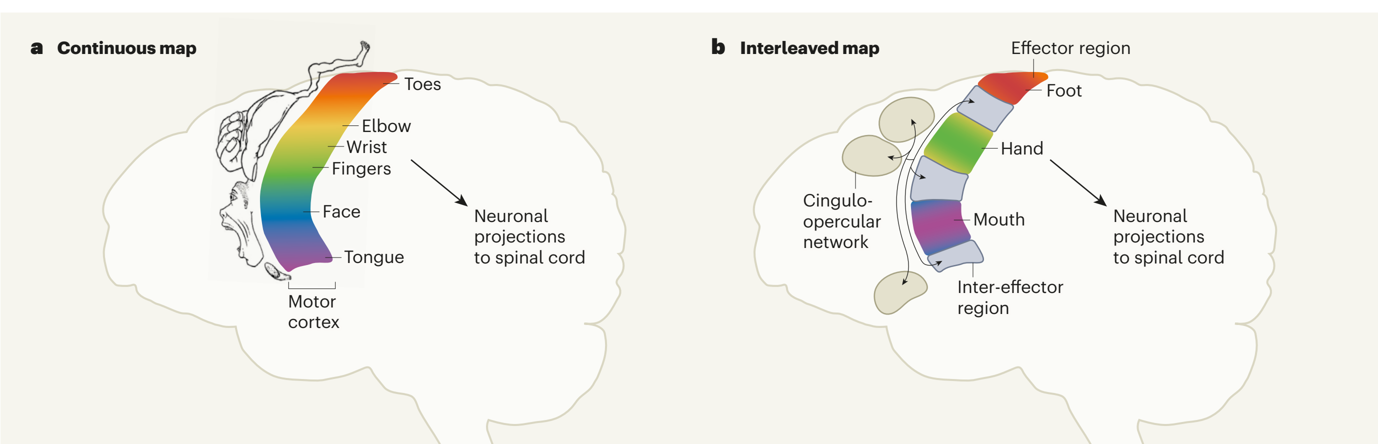

Figure 1 | Two models for the motor cortex. a, In conventional models of the human brain, discrete portions of the motor cortex send neural projections to particular regions of the brainstem or spinal cord to control certain parts of the body (colour coding reflects motor-cortex regions that control different body parts). As a result, the motor cortex can be thought of as a continuous map of the regions that it controls, often illustrated as a homunculus (shown to the left of the motor cortex). **b**, Gordon *et al.*[1] propose an alternative model. Here, the movement map is centred around three effector regions (coloured segments), each with a concentric organization (so in the hand region, for instance, neurons controlling the fingers are sandwiched between those controlling the wrist, then the elbow). The effector regions are interleaved with inter-effector regions involved in action coordination. These inter-effector regions lack the body-part specificity of the effector regions, are interconnected with the cingulo-opercular network (which controls action initiation) and have the potential to regulate a range of body functions beyond basic movements.

stereotyped behavioural sequences that involve multiple body parts, such as bringing the hand to the mouth in a gesture that resembles eating a piece of food[9].

Gordon and colleagues re-examined motor-cortex organization in humans using a brain-imaging technique, called functional magnetic resonance imaging (fMRI), that indirectly measures neural activity through regional changes in blood flow. The authors imaged spontaneous activity in the brains of people lying motionless at rest. They also analysed subjects performing motor tasks (bending limbs in particular ways, for instance, or making certain noises in response to a cue), carefully mapping the topography of body movements to activity on the cortical surface. Their findings reconcile and build on previous observations.

Their main discovery is that, in contrast to the conventional depiction of the homunculus, the motor cortex is divided into alternating subregions that serve different functions (Fig. 1b). Most recognizable are the three 'effector' motor regions representing the foot, hand and mouth. Gordon *et al.* provide some evidence that — as in monkeys — these regions have a concentric arrangement. Lying in between them are three 'inter-effector' regions, which are very different from the effector regions.

The authors showed that, unlike effector regions, inter-effector regions are functionally interconnected, seemingly operating as a unit. Their activity is coupled with a set of brain regions called the cingulo-opercular network that is involved in goal-oriented cognitive control. During subject-initiated actions, inter-effector regions responded to the movement of various body parts — particularly during movements linked to visceral functions, such as swallowing, and to postural changes, such as shoulder movements. These regions even responded to the planning of movements that were never executed. The researchers observed none of these features in the effector regions.

On the basis of these findings, Gordon and colleagues hypothesize that inter-effector regions contribute to the preparation and implementation of actions, and effector regions to performing those actions. They dub the inter-effector regions collectively the somato-cognitive action network (SCAN).

This hypothesis will raise eyebrows and could spur a broad reconsideration of the homunculus model. Some researchers might question whether results based on fMRI — a blood-based imaging signal for which the precise neural basis is never clear — should override a model of the motor cortex based on direct cortical stimulation. This is a legitimate concern. However, Gordon *et al.* address this criticism by drawing together diverse lines of support.

For example, the authors reanalysed data from the 2020 electrostimulation study[4], and discovered that a sizeable region of the motor cortex from which no body movements could be elicited matched one of their inter-effector subregions. They replicated their main findings in large, publicly available fMRI data sets. They also found evidence for the inter-effector regions in infants, indicating an early developmental origin, and to some degree in macaques, indicating evolutionary conservation in primates. Finally, it is worth noting that a human electrophysiological study published on the preprint server bioRxiv[10] has described an area embedded in the motor cortex where neural responses to body movements resemble those seen in the inter-effector regions reported by Gordon and colleagues.

The work also has implications beyond the need to revise the functional layout of the motor cortex. Unlike in laboratory experiments, where studies of motor actions often involve simply flexing individual joints, real-world behaviours involve highly orchestrated movements that take into account gravity, energetics, social context and more. It is interesting to speculate that the connections that expand primates' control over their motor system[5,11] are matched by a parallel expansion of projections from inter-effector regions that control postural and visceral functions during the execution of behaviours.

There is perhaps some irony in deriving principles of natural movement control from the brains of subjects lying supine and motionless. But Gordon and colleagues have done just that. Their identification of the SCAN and its selective communication with the cingulo-opercular network opens the door to new ways of thinking about how the brain's motor circuits keep our entire body in mind as we carry out our daily activities.

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Quantum information

Superconducting qubits cover new distances

Marissa Giustina

Superconducting quantum bits, a promising platform for future quantum computers, have been entangled over a separation of 30 metres, with a performance that enabled the demonstration of a milestone in quantum physics. **See p.265**

Of the many physical platforms being explored for quantum computing, superconducting quantum bit (qubit) processors have stood out over the past decade for increases in their qubit number and system performance. For example, researchers have built superconducting quantum computers with up to a few hundred qubits, and have used superconducting qubits to run a number of quantum algorithms, including modelling physical systems and correcting quantum errors to pave the way for useful quantum computing. However, these qubits encode quantum information in tiny amounts of energy stored in circuit elements that must be cooled to millikelvin temperatures, and transferring quantum information between processors is challenging.

On page 265, Storz *et al.*[1] report a superconducting qubit set-up that operated over a 30-metre distance with high fidelity. Their approach involves a quantum property known as entanglement, which is a key ingredient in a possible strategy for transferring quantum information. The authors also show fast readout of the qubits' states, enabling them to demonstrate an experimental feat known as a 'loophole-free' Bell experiment, in the first successful attempt