Chapter 6
Neuroscience for an Artist; a Beginning

Emilio Bizzi and Robert Ajemian

Abstract In this essay we describe some of the brain processes that are engaged when artists produce drawings and paintings. Two brain structures have been recently identified as key locations where the abstract neural signals representing the intention to move are transformed into patterns of neural activity suitable for activating the muscles. The first of these locations is the putamen, a section of the basal ganglia, the second is in the spinal cord. It is interesting that different types of modules and combinatorial activities characterize both structures. Finally, we discuss the ability of experts to generalize their learning across radically different contexts.

At the June 2018, meeting "Space-time geometries in the Brain and movement in the Arts' held in Paris, Dr. Bizzi described the processes in the brain that are engaged when artists produce drawings and paintings. The drawing shown in Fig. 6.1, by the highly regarded Andrea del Sarto, a Florentine artist active in the mid 1500's, is an example of a piece of art work combining exceptional technical skills and high artistic value. The drawing shown in Fig. 6.1, is a preparatory study representing the head of St. John the Baptist.

The purpose of the study was to facilitate the making of a full body painting of the saint which is now in Florence (at Palazzo Pitti).

Del Sarto, like all artists of that time in Florence, went through a rigorous and protracted training in the art/skill of design. Giorgio Vasari, a contemporary of Del Sarto who chronicled the life and work of Italian painters from medieval times to the late renaissance, emphatically stressed that the practice of drawing was the foundation of the visual arts; painters achieved perfection by careful, protracted practice with preparatory sketches. As a consequence of this practice, an abundance of drawings were produced, some of which have happily survived.

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T. Flash and A. Berthoz (eds.), *Space-Time Geometries for Motion and Perception in the Brain and the Arts*, Lecture Notes in Morphogenesis,
https://doi.org/10.1007/978-3-030-57227-3_6

Fig. 6.1 Andrea Del Sarto - preparatory study representing the head of St. John the Baptist

On the basis of Vasari's prescriptions, coupled with what we know about the functional organization and plasticity of the nervous system, we can now be confident that intense sensory-motor practice must result in changes of the cognitive state of painters' central nervous system. In this essay, we will describe the cortical and subcortical changes that result from artists' intense practice. It is the ambitious goal of this essay to show how these changes might facilitate the expression of the artist's ideas.

Figure 6.1, which is a drawing made during Del Sarto's mature years, shows how the skills he acquired through years of practice made it possible to express the complex, conflicting feelings represented on the Baptist's face. The pensive, slightly sad expression of the saint's face reveals his awareness of being a precursor of Christ and a martyr. Del Sarto used his skill to convey something that touches our emotions; he captured the saint in a moment of foreshadowing the glory of his life as one close to God's son and the inevitable doom of an impending cruel death.

In the last 100 years neuro-scientists and clinicians have focused on understanding voluntary movements and discovered that the neural processes that subserve even the simplest everyday actions are incredibly complex and only partially understood. In this essay, we will not try to summarize the large amount of data related to movements' production, but will focus instead on a few key discoveries of the last 20–30 years that have made it possible to gain a deeper, albeit still incomplete, understanding of how an evanescent wish to move is translated into actions (Brincat et al. 2018).

6.1 Preliminary Preparatory Neural Events

Let us now imagine that we could peek into Del Sarto's brain as he begins to draw the face of the handsome, but here inconsequential boy of Fig. 6.1. We would then witness the simultaneous appearance of two sets of neural events: sensory visual activity in the occipital cortical areas and motor related activity in the cortical/subcortical areas.

On the sensory side, as the artist's eyes scan the model's features, retinal cells become active and transmit signals to the visual cortical areas. These signals flow in a rostro-frontal direction and they make contact with the neurons of the middle temporal cortical areas, the posterior inferior temporal and the lateral prefrontal cortex (Heyworth and Squire 2019). What happens at these areas is a gradual transformation of the sensory signals into sequences of "categorical abstractions" that precisely reflect the artist's depiction of what he is seeing. This activity eventually becomes the input to the motor system.

On the motor side, as the artist persists in drawing the model over and over in search of perfection, the relevant neural circuitry is reshaped to embody sensory-motor learning or "traces". These traces are gradually established in all the major components of the motor circuitry, like the premotor and prefrontal cortices as well as the medial temporal cortex.

6.2 The Formation of Motor Memories

From a neural cell perspective sensory-motor learning involves changes in synaptic connectivity—and indeed new synapses are formed between cells that are activated at the same time; basically, memories are established through this correlative process. Described in this way memory formation seems a straightforward process, but, as often happens in neuroscience new peculiar features have emerged which indicate an unexpected degree of complexity, and most importantly, the need to rethink some basic assumptions about how memories are formed. The surprising, paradoxical problem is that synapses have a short life—because they are proteins they are churned over every few days—while, of course, memories remain throughout life.

Recent modelling work has provided an alternative explanation of this quandary. Ajemian et al. (2013) developed a neural network characterized by synapses that are constantly changing even during learning a variety of skills (Ajemian et al. 2013). This type of network would be highly redundant with each neuron contacted by a large number of synapses originating from the circuit's other neurons. Ajemian et al. (2013) showed that in this type of neural circuit many different synapses can give rise to the same input- output processing and this network can perform the same function even if its synapses undergo changes. Thus, memory is not specified by a fixed pattern of synapses, but by patterns of input—output processing. In short, the artist's brain keeps changing, but the artistic expertise remains.

6.3 Basal Ganglia Modularity: The Transformation of Cortical Preparative Activity

Del Sarto in his drawings often made use of models that provided an external representation. Of course, many artists do not always utilize external models; they paint or draw by relying on internal representations. An example of a painting whose representation is not dependent on external models is the famous Autumn Rhythm by Pollock (Jiang et al. 2018). It is certainly interesting that Pollock began by drawing a grid on the canvas lying on the floor. In this way he created a structure that constrained the dripping paint. The resulting painting has rhythm and dynamic energy; the seemingly chaotic contorted lines create a tension that makes this painting a masterpiece of abstract expressionism (Fig. 6.2).

As Del Sarto and Pollock begin drawing and painting they would summon to the forefront their artistic expertise, an action which begins a mode of processing across their landscape of cortical activity. These landscapes represent intention—related preparatory activity, that is, neural activity that acts like a command for the motor system. One of the key areas where preparatory activity is formed is the frontal cortex which is a point of convergence for neural signals emanating from different sensory areas as well as memory-related and attention-related cortical areas (Churchland et al. 2010; Guo et al. 2017; Inagaki et al. 2018; Waskom and Wagner 2017). From

Fig. 6.2 Jackson Pollock-Autumn rhythm

the prefrontal cortex the “preparatory” activity reaches a key subcortical structure: the putamen—a subcortical region that is part of the basal ganglia (Graybiel 1998) (Fig. 6.3).

Two important papers have recently contributed to our understanding of the process that are taking place in the cortico-striatal loop. Markowitz et al. (2018) and Wiltschko et al. (2015) used a confluence of machine learning techniques to detect a finite library of sub-movements represented in basal ganglia of freely moving mice. These sub-movements embody recurring behavioral modules or motifs that exist at the sub-second time scale (350 ms), a scale sufficient to act as building blocks for volitional movements that occur on the scale of seconds. In essence, one can think of these modules as kind of micro pattern generators representing recognizable action segments. As a consequence of the arrival of cortical signals at the putamen, the sub-movements are connected to each other in a non-uniform way with each sub-movement preferentially linked to some modules and not others, depending on existing behavioral constraints. This process of concatenation leads

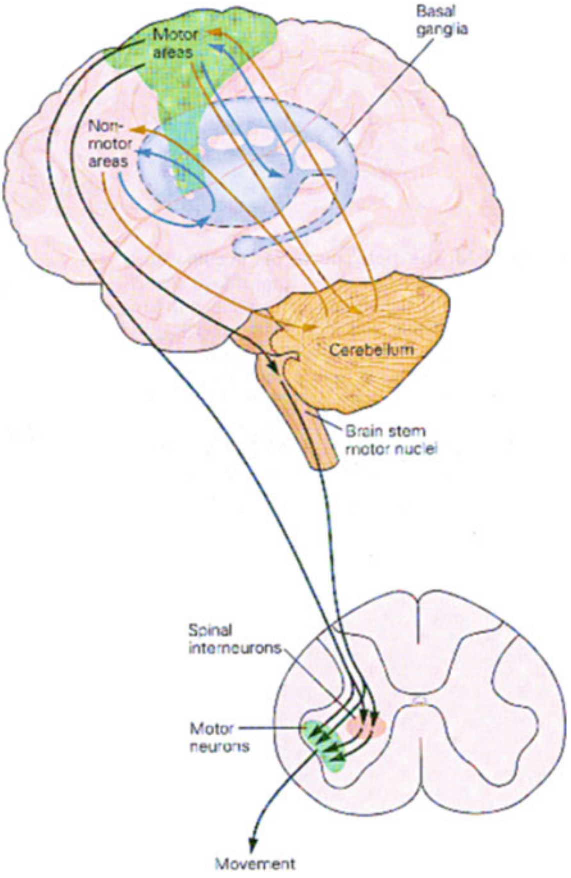

Fig. 6.3 Schematic—central nervous system

to the formation of full movements and movement sequences. When new behaviors are expressed, new combinations of modules are observed simply by reusing of the same modules without forming any new ones. It is then tempting to conclude that this loop is involved in beginning to implement the sensorimotor transformation by converting abstract movement commands embodied by prefrontal cortical signals into a sequence of movement segments with some "motor" character.

The output of the putamen connects with the cells of the Globus pallidus via D1R and D2R fibers, which connect respectively to the internal/external segments of the Globus Pallidus (Sheng et al. 2019). The Globus pallidus, in turn, connects to the ventro-lateral thalamus and, finally, from there the loop ends on the motor cortex. While the steps from the putamen to motor cortex via globus pallidus and thalamus are meant to make the signals in cortico-striatal loop progressively more "motor like", it is not yet clear whether and how "motor tuning" processes occur at these stations.

The discovery of the putamen's functional properties is certainly an important step; it demonstrates the presence of two neural circuits: a special type of modularity as well as the combinatorial propensity of the micro pattern generator. However, to gain further insight into this region and to firm up what we can consider an important, but initial beginning, much more information about the loop and the putamen should be gathered. The following questions are just an example of what we need to know in order to get an in depth view on the loop and putamen.

1. What kinds of neural patterns are conveyed by the fibers that connect the prefrontal area to the putamen modules? Do these fibers specify a "code" or does the specification emerge after contacting the putamen modules?
2. Does each prefrontal fiber carry a slightly different signal? And if it is so, are the different patterns a variety of motor solutions to be shaped by feedback at some point along the way to the spinal cord?
3. Are the preparatory signals carrying a continuous stream of neural activity from the beginning of the movement to its end or a sequence of segments? (Graybiel 1998; Kadmon et al. 2018).
4. If so, from where are the segments originating? (Abeles et al. 1995; Wymbs et al. 2012).

6.4 Spinal Cord Modularity: The Key Role of Muscle Synergies

To sum, we are fairly confident that the neural signals representing the intention to move are transformed by a loop which begins at the prefrontal cortex and ends at the motor cortex. The end point of the loop are the neurons of the descending cortico spinal tracts; these fibers convey motor signals to spinal motorneurons and interneurons, which ultimately lead to the muscles of the artist hand, arm and body (Dum and Strick 1991).

As mentioned before modularity and combinatorial activity of micro patterns generators are the main functional feature of the putamen. The surprising outcome of recent spinal cord investigations is that modularity and combinatorial activities have also been found to be a spinal cord functional feature (Bizzi et al. 2008; Caggiano et al. 2016).

The neural origin of spinal cord modules rests on studies in several vertebrate species. These studies have demonstrated that a spinal module is a functional unit of spinal interneurons that generates a specific motor output by imposing a specific pattern of muscle activation (muscle synergies). Muscle synergies are neural coordinative structures that function to alleviate the computational burden associated with the control of movement and posture. Anatomically, the modules are made up of groups of spinal interneurons whose efferent fibers make contact with a distinct set of motor neurons (Caggiano et al. 2016; Fetz et al. 2002). It follows that whenever these motor neurons are activated by descending cortico-spinal impulses and/or reflex pathways from the periphery a distinct muscle synergy becomes active. This process leads to the formation of muscle “synergies” which represent kind of functional building blocks whose combination leads to the “construction” of voluntary movements (Bizzi et al.2008; Caggiano et al. 2016). A factorization algorithm that takes as input all the recorded muscle EMG data is utilized to extract muscle synergies and activation coefficients. The factorization procedure essentially performs a dimensionality reduction by grouping muscles that tend to co-vary in the data set into individual synergies.

In the last few years many investigators have examined motor behaviors in humans and animals. The results show that combining a small set of muscle synergies appears to be a general strategy that the central nervous system utilizes for simplifying the control of movements (Bizzi et al. 2008).

All in all the following important points have emerged from spinal cord investigations: (1) the same synergy may be utilized in different motor behaviors, and (2) different behaviors may be constructed by linearly combining the same synergies with different timing and scaling factors, and (3) the development of new skills over long periods of time leads to the formation of new specialized task synergies.

With respect to the question of cortical control of muscle synergies the study of Overduin et al. (2015) demonstrated that intra cortical stimulation in monkeys elicited EMG patterns that could be decomposed into muscle synergies. Importantly, these EMG patterns were found in a few cases to be similar to those evoked during the same animal’s voluntary movements. Whether this finding indicates that the cortex “encodes” muscle synergies remains to be determined.

At this point our knowledge of the supraspinal machinery involved in synergy activation is inadequate. We need to know how the signals elaborated by the supraspinal loop play into the spinal modules.

On the bright side, the experimental evidence summarized above indicates that the spinal cord operates as a discrete combinatorial system. In a way, the motor system is like language, a system in which a discrete elements and a set of rules for combining them can generate a large number of meaningful entities that are distinct from those of their elements. And just as with language, the combinatorial system can accommodate different levels of expertise.

6.5 Generalization

While we can reasonably assume that progress will eventually be made on some of the questions discussed in this essay, there are certain aspects of motor behaviors that seem harder to understand. Motor generalization is a case in point and Michelangelo Figs. 6.4 and 6.5 illustrate an example of this behavior.

Figure 6.4 is a preparatory study of a nude male which Michelangelo utilized for the painting of a section of the ceiling of the Sistine Chapel. Note that the male represented in Fig. 6.5 was painted while Michelangelo was hoisted parallel to the chapel's ceiling. Because the postural changes lead to changes in the influence of gravity on Michelangelo's brush strokes, the motor output needed to implement the same artistic vision has changed entirely! Yet Michelangelo, as an expert, effortlessly

Fig. 6.5 Michelangelo—Ignudo—ceiling of Sistine Chapel

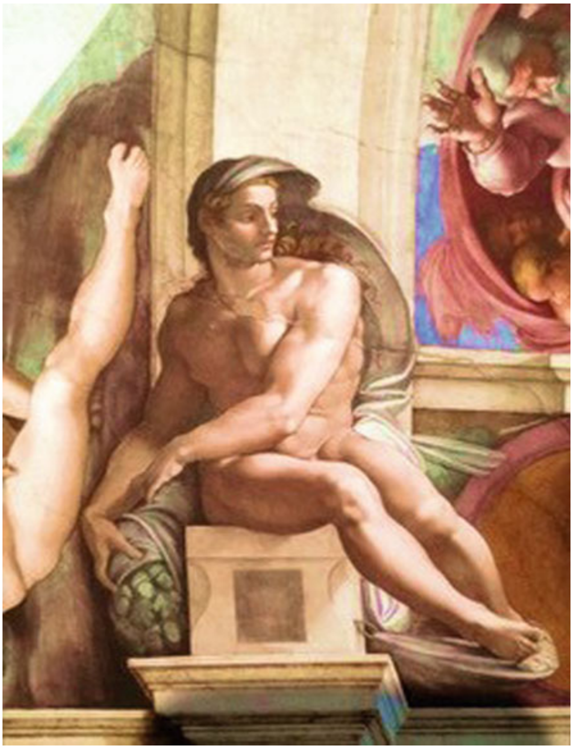

Fig. 6.4 Michelangelo—seated nude and two studies of an arm, about 1510-12

accomplishes the task. This is known as generalization, because learning in one set of circumstances applies more generally to other circumstances.

To paint in that awkward and uncomfortable posture requires, at the minimum, a radical re-programming of most of Michelangelo's muscles. Whether the reprogramming was initiated by a massive change of proprioceptive feedback is no more than an educated guess. But, for neuroscientists interested in pursuing complex and certainly challenging questions of how experts generalize, this motor behavior might be an opportunity to explore neural complexity through creative computer modelling.

Broad generalization embodies the highest form of expertise in any sort of skill learning—and one which as of yet still eludes current approaches in Artifical Intelligence. Michelangelo's extraordinary artistic ability involves multiple forms of generalization, many of which involve his ability to utilize highly sophisticated mental models of the geometry of both space and time. Here we categorize multiple types of mappings across which Michelangelo generalized to produce his art.

Artistic concept to 2-D image: Michelangelo invariably has a 3-D model in his head of body shape and form. Yet the rendering takes place on a 2-D surface. In order to make this transformation from a 3-D idea to a 2-D form, Michelangelo possesses complete mastery of projective geometry and linear perspective, as formally articulated by Filippo Brunelleschi at the onset of the Renaissance.

Temporal motion to curvilinear static form: More so than in the case of most works of art, the frescoes of the Sistine Chapel are bursting with a latent dynamic energy of motion, perhaps most famously illustrated by the finger of God reaching out to touch Adam in the *Creation of Adam.* Here, Michelangelo is able to masterfully convey the dynamics of human movement through curvilinear static forms.

Motor intentions to motor output in a completely novel posture: Michelangelo painted the Sistine Chapel while standing on a scaffold with his head uncomfortably tilted back and his arms reaching upwards. To paint in that awkward and uncomfortable posture requires, at the minimum, a radical re-programming of most of Michelangelo's muscles. Part of this reprogramming may have been initiated by a massive change of proprioceptive feedback to provide feedback guidance for his brushstrokes. Still, even these feedback signals would be of an unfamiliar form; yet without any specific practice of painting in this posture and even with the acute time constraints of having to finish each fresco while it is wet, Michelangelo nonetheless managed without requiring any "do-overs".

These are just some of the many mappings which were integrated by Michelangelo and across which he generalized adeptly in order produce a masterful work of art. For neuroscientists interested in pursuing complex and certainly challenging questions of how experts generalize, the skills of an artist might be an opportunity to explore neural complexity underlying sophisticated sensorimotor control.

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