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Mechanisms for selection of basic motor programs – roles for the striatum and pallidum

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The nervous system contains a toolbox of motor programs in the brainstem and spinal cord – that is, neuronal networks designed to handle the basic motor repertoire required for survival, including locomotion, posture, eye movements, breathing, chewing, swallowing and expression of emotions. The neural mechanisms responsible for selecting which motor program should be recruited at a given instant are the focus of this review. Motor programs are kept under tonic inhibition by GABAergic pallidal neurons (the output nuclei of the basal ganglia). The motor programs can be relieved from pallidal inhibition through activation of striatal neurons at the input stage of the basal ganglia. It is argued that the striatum has a prominent role in selecting which motor program should be called into action.

Introduction

The only output of the nervous system is the motor system, whether in cognition or action. Nervous systems are equipped with several motor programs along the neuraxis (Figure 1) that serve essential needs such as locomotion, posture, breathing, eye movements, feeding, chewing, swallowing, bowel and bladder functions, and reproductive motor behaviours [1–4]. The networks underlying these different motor behaviours result from innate programming of CNS circuits, combined with epigenetic arrangements that lead to the development of appropriate and fine-tuned motor programs. One simple example of the latter can be taken from the family of withdrawal reflexes. A painful stimulus to a skin region will result in a precise withdrawal reflex, removing the skin region from the stimulus owing to activation of an appropriate combination of muscles. In neonatal rodents, the same skin stimulus will result in the 'correct' withdrawal direction only by chance – programmed learning takes place at the spinal level during the first few weeks after birth, when responses in the incorrect directions are attenuated through synaptic plasticity resulting from activation of touch and pressure stimuli [5,6].

In this review, we will initially consider the general design of the vertebrate motor system and a few of the many different motor programs. We will subsequently discuss the neural mechanisms by which motor programs are called into action – a crucial and less-well-understood aspect of motor behaviour. In particular, we will focus on the prominent but often overlooked role of the basal ganglia in control of brainstem circuits, rather than on the role of the thalamocortical projections, which has received due attention elsewhere and is discussed in countless textbooks. The role of cerebellum in fine-tuning of movements and error-based learning is outside the scope of this review.

Some species stand and walk directly after birth, others take their time

The newborn of some species are very immature, and take a long time to mature; for example, human babies can maintain upright posture (stand) and begin to walk only after around one year. By contrast, species such as horses or antelopes can not only stand but also run on four legs a few minutes after birth, and a chick born around three weeks after fertilization (!) can not only stand but also walk on two legs directly after hatching, and even pick grains from the floor with sufficient visuomotor accuracy to feed [3]. The motor program underlying the basic sequential activation of different muscles that occurs during each step-cycle of locomotion is located in the spinal cord, but it is activated and controlled from command centres in the brainstem in all vertebrates, from cyclostomes to primates (Box 1). Humans thus have a very protracted maturation process, lasting for more than a decade, although the basic motor tasks do not appear significantly more complex than those of our fellow vertebrates such as cheetahs, eagles or squirrels. In fact, primates and especially humans appear to excel rather in the versatility of their motor systems, particularly those of the human hand and the motor coordination underlying speech. Through maturation and learning, control of the hand and fingers is refined, and at around the age of five a child can handle bimanual tasks such as tying shoelaces. Learning capacity is no doubt the largest during childhood and, by extending the maturation process, the ability to acquire more skills will most likely be enlarged at the expense of a longer period of immaturity and dependence on parental care.

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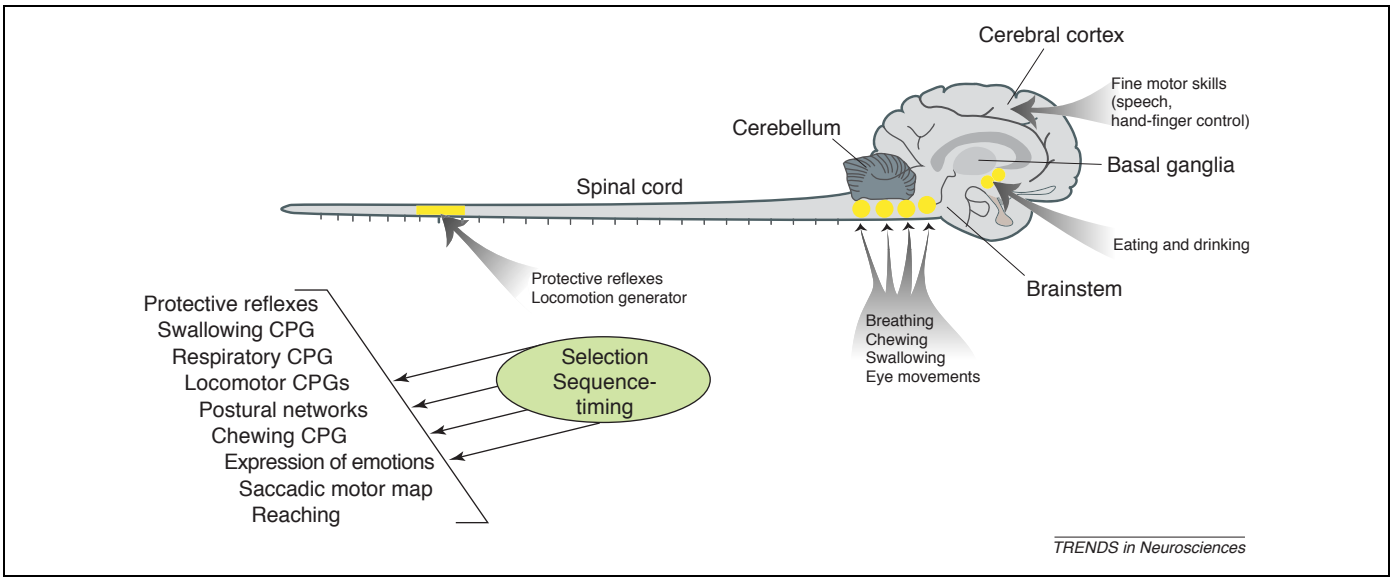

Figure 1. The basic motor repertoire generated by a neuronal toolbox. Along the neuraxis from the spinal cord to the upper brainstem, there are several neuronal networks or motor programs that when activated will produce different types of motor behaviour (drawing, upper right). They are composed of different networks that, for rhythmic motor patterns such as respiration, chewing and locomotion, are often referred to as central pattern generators (CPGs). Likewise, the networks underlying stereotyped single action patterns such as swallowing, coughing or sneezing, and possibly also the expression of emotions, can be referred to as CPGs. The illustration shows some CPGs as yellow circles. Even more complex are the motor maps in tectum (superior colliculus) designed to control saccadic eye movements in different directions and amplitudes. The list on the left represents different motor programs, from the comparatively simple, such as swallowing, to the more complex, such as those generating saccadic eye movements and controlling reaching. These different networks taken together can be considered a neural motor infrastructure or toolbox of the nervous system. Having these different motor programs available, a mechanism is clearly required to determine when a given motor program or network should be called into action (i.e. selecting the appropriate motor program) and to determine how different motor sequences are timed. The basal ganglia are implicated in this control. Inset reproduced from [3].

Orientation movements

At the next level of complexity after basic motor tasks are motor programs that control eye and body orientation towards different objects in the surrounding world. Different senses can contribute to this, such as echolocation in bats, electroreception in some fish and, in most vertebrates, visuomotor coordination. The motor programs elicited from the tectum (superior colliculus) control orientation movements [7,8]. Stimulation of different loci within the superior colliculus results in saccadic eye movements in different directions and amplitudes. Activation of different parts of this tectal motor map thus result in eye movements towards different parts of the surrounding world [9,10] followed, as a rule, by an orientation of head and body towards the point of interest [11]. The same structures are likely to be important during ongoing locomotion, when orientation movements result in steering towards the point of interest, and also during reaching movements.

Motor programs underlying the expression of emotions

Many of the motor programs that we might think of as learnt, such as the expression of emotions, are innate. Adult humans, from all parts of the world, express at least seven different characteristic expressions that are easily interpreted by other humans (crying, smiling, laughter, fear, anger, frowning and dismay). These different emotions are each expressed by a characteristic motor program that activates an innately determined combination of facial muscles [12–15]. All humans are thus able to express the same emotions by using the same motor programs, although individuals from different subcultures will probably laugh at different things.

Vertebrates depend on a basic motor repertoire coordinated from subcortical structures

The basic motor repertoire described here, from withdrawal reflexes and breathing to locomotion, posture and saccadic eye (orientation) movements, is required for survival. These programs rely for their execution to a large extent on command centres and neuronal networks located at a subcortical level [4]. Highly evolved vertebrates such as the cat can perform this basic motor repertoire, even without the involvement of the cerebral cortex. Cats decorticated at birth move around gracefully and display goal-directed locomotion – the uninformed observer would see no or little difference in movement pattern from that of an animal with its cortex intact. Such decorticated cats can successfully search for food and eat, and also use their forelimbs for exploratory movements to determine which path to select from a platform to reach the floor [16]. These findings emphasize the remarkable ability of subcortical structures to process information required for the basic survival motor repertoire without the cerebral cortex. Under these conditions, the thalamic input to the basal ganglia is likely to be particularly important in the interpretation of sensory information and in the selection of appropriate motor behaviour. Of course, these findings from decorticate mammals do not mean that vertebrates do not normally also utilize cortical processing during such motor tasks.

Mechanisms for selection of motor programs – role for the basal ganglia

The nervous system thus contains several different motor programs designed to solve a variety of motor tasks, from 'simple' to complex (Figure 1). These movements are coordinated in the same way by all individuals of a given

Box 1. Neural control of locomotion – an example of the organization of one motor program

The networks underlying locomotion are located at the spinal level – for tetrapods, with one compound network or central pattern generator (CPG) for each limb (Figure I). The limb CPGs can be further subdivided into unit CPGs controlling individual joints [27]. The spinal networks are activated by reticulospinal neurons, which in turn are activated from one of two command centres – the mesencephalic (MLR) and the diencephalic (DLR) locomotor regions (Figure Ia). This organization is conserved throughout vertebrate evolution [4,27,58]. When, for instance, the MLR of a fish is stimulated, the fish starts swimming, and the more its MLR is stimulated the faster it will swim; if the MLR of a mammal is stimulated, the mammal will start walking and with progressively greater strength it will change from walking to trotting to galloping (Figure Ib); in a bird, stimulation of the MLR will induce walking followed by flight. The MLR, in turn, is under tonic inhibition from the pallidal output nuclei [23–27,59] (Box 2), and when this inhibition is relieved, locomotion will be initiated.

Obviously, activation of the spinal locomotor program provides only a template for the type of movement that will be recruited, and various other control signals are required to generate a goal-directed well-adapted pattern of locomotion.

- Supraspinal drive on the spinal CPGs will determine whether the locomotor movements will be slow or fast, and thereby the degree of activation of different motoneurons and muscles.
- Overall direction of the movements is determined by an additional steering command superimposed on the basic locomotor activity (e.g. turn left or right; Figure Ic).
- The motor pattern must be adapted to the terrain (to avoid each stumbling stone), mostly through visuomotor coordination. Such precision walking occurs through tuning of the locomotor movements mediated at least partially through corticospinal pathways. They contribute both to reaching tasks and to the accurate positioning of the feet required during precision locomotion [60–62], when they have a high level of activity; by contrast, corticospinal pathways are not significantly involved when walking over a flat surface.
- Overall posture during locomotion also varies: a cat planning an attack on a prey has a low crouching locomotion, whereas in wet snow it might walk with very stiff straight legs. Humans excel in such adaptations.

All this testifies to the need for highly flexible neural organization.

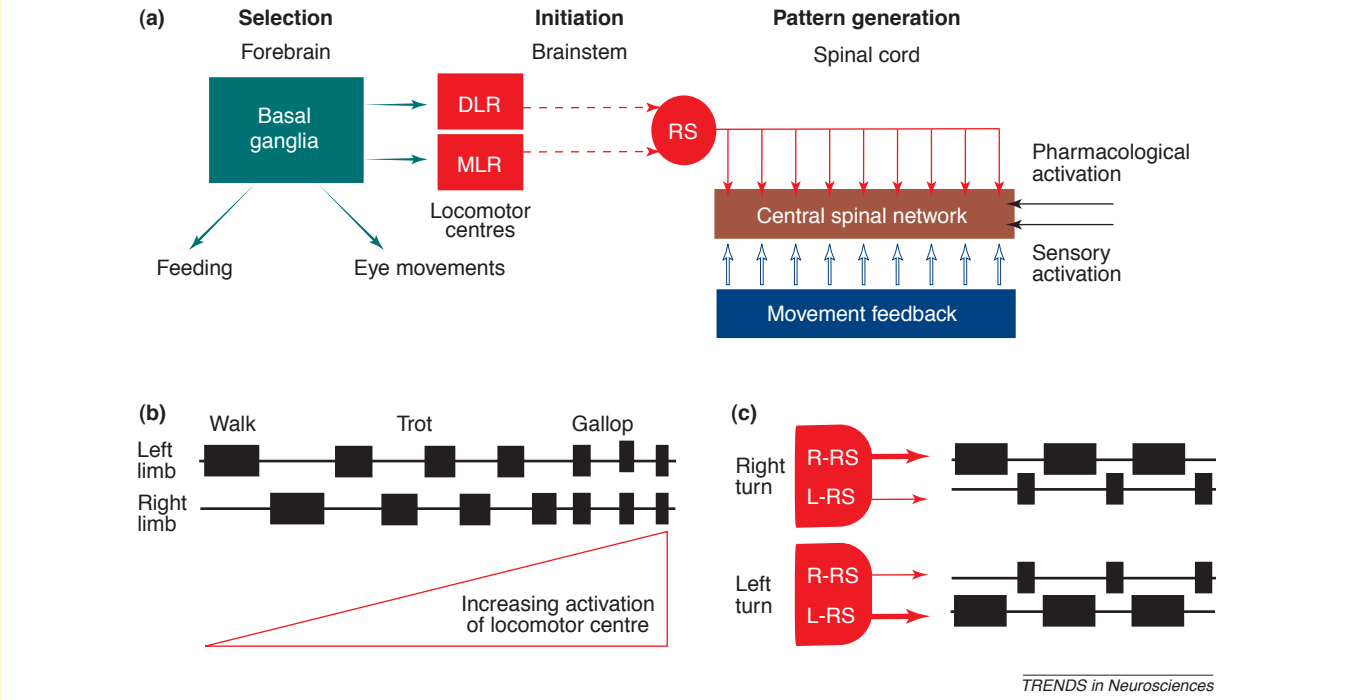

Figure I. General control strategy for vertebrate locomotion. **(a)** Locomotion is initiated by increased activity in reticulospinal neurons (RS) of brainstem locomotor centres [the diencephalic locomotor region (DLR) and mesencephalic locomotor region (MLR)], which activate the central spinal network. This in turn, in close interaction with sensory feedback, produces the locomotor pattern. Experimentally, the spinal central pattern generators can be activated or modulated by different transmitter agonists. With increased activation of the locomotor centre, the speed of locomotion will also increase **(b)**. In quadrupeds, this also leads to a shift in interlimb coordination, from walk to trot and then to gallop. The basal ganglia exert a tonic inhibitory influence on different motor centres, controlling eye movements, posture, locomotion and feeding. Once a pattern of motor behaviour is selected, the inhibition is released, in this case enabling the locomotor centre in the brainstem to be activated. Experimentally, locomotion can also be elicited pharmacologically by administration of excitatory amino acid agonists and by sensory input. **(c)** Asymmetric activation of reticulospinal neurons gives rise to asymmetric output on the left (L) or the right (R) side. This results in a turning movement to one side or the other.

species. The different motor programs form a species-specific toolbox or motor infrastructure [4,17] that can be 'called upon' to initiate a given pattern of motor behaviour (Figure 1).

Most neuroscientists tacitly assume that the cerebral cortex is responsible for the initiation of any goal-directed behaviour. From the preceding paragraphs it follows, however, that a behaviourally meaningful and varied motor pattern can be elicited without the cerebral cortex. There must thus be subcortical structures that can determine when a given motor program should be selected and called into action. By far the most likely candidate structures are the basal ganglia. In intact animals, they – and in particular their input layer, the striatum – have a fundamental role in motor activity. Reduced dopamine innervation of the striatum results in hypokinesia and difficulty in initiating different motor patterns, including facial expressions [15]; conversely, enhanced striatal dopamine activity will instead give rise to hyperkinesia (i.e. premature or unintended activation of motor

programs). These examples in themselves provide convincing evidence that the striatum has a prominent role in the selection of motor behaviour.

Output nuclei of the basal ganglia keep brainstem motor centres under tonic inhibition

The output nuclei of the basal ganglia (the substantia nigra pars reticulata, globus pallidus pars interna and ventral pallidum) will be referred to here as the pallidum (Box 2). These nuclei project to many subcortical motor structures, in addition to the thalamocortical neurons that are the focus of most textbook accounts. The most well-known subcortical example is that of the tectum (superior colliculus), which contains a saccadic motor map within which each local site specifies the direction and amplitude of a given saccadic eye movement [7,18,19]. There are also pallidal projections to the mesencephalic locomotor region (from which locomotion is initiated) and to brainstem areas that control postural tone [20–27]. The pallidal output neurons are inhibitory (GABAergic) and unusual in that they have a high level of resting activity (~90 Hz), thus keeping their target neurons (those of motor programs) under tonic inhibition (Figure 2). In a function-specific way, subpopulations of pallidal neurons project to different brainstem motor centres. During resting-level activity, they appear to keep the different motor centres under tonic inhibition [4,18], thereby preventing them from being activated unless the pallidal inhibitory control is blocked through striatal action.

The input region (the striatum) might have a 'filter' function

In contrast to those in the pallidum, neurons in the input region of the basal ganglia (the striatum) have a high threshold for activation and receive excitatory input from different regions of the cerebral cortex. In addition, they receive a prominent input directly from thalamic nuclei (intralaminar, mediodorsal, ventralis lateralis and anterior nuclei) that has received much less attention [28–32]. The striatal medium spiny output neurons are also inhibitory (GABAergic) and have a low-activity profile during resting conditions. They are essentially silent, and have membrane properties that give them a high threshold for activation. For example, they express inward-rectifier K^+ (Kir) conductances; these remain open at hyperpolarized membrane potentials but close if the cell becomes depolarized. Striatal medium spiny output neurons thus tend to remain in a stabilized, silent hyperpolarized 'down state' [33,34], except when they receive a strong excitatory input. In this case, when Kir conductances are deactivated, a type of plateau depolarization, an 'up state' (close to firing threshold; Figure 3), is induced – this can make them become depolarized for a protracted period. If these neurons receive additional synaptic excitatory drive, they also fire action potentials at a low rate. Dopaminergic innervation (via D_1 receptors) facilitates the transition from the down state to the up state, through action on different ion channel subtypes in the medium spiny neurons. Without dopamine, it is difficult to obtain transition to an up state [34,35]. A striatal neuron in the presence of dopamine thus actually has three possible states [36]: an inactive down state; a depolarized up state, when the neuron can easily be recruited into firing if it receives additional excitation; and a state when it has been recruited into activity and thereby can affect the pallidum (Figure 3 legend).

Box 2. Different structures included in the basal ganglia, as referred to in this review

Input stage

Referred to here as the striatum. Comprises:
- Dorsal striatum: putamen and caudate nucleus
- Ventral striatum: nucleus accumbens

Output stage

Referred to here as the pallidum. Comprises:
- Globus pallidus pars interna
- Substantia nigra pars reticulata
- Ventral pallidum

Nuclei within the basal ganglia
- Subthalamic nucleus
- Globus pallidus pars externa

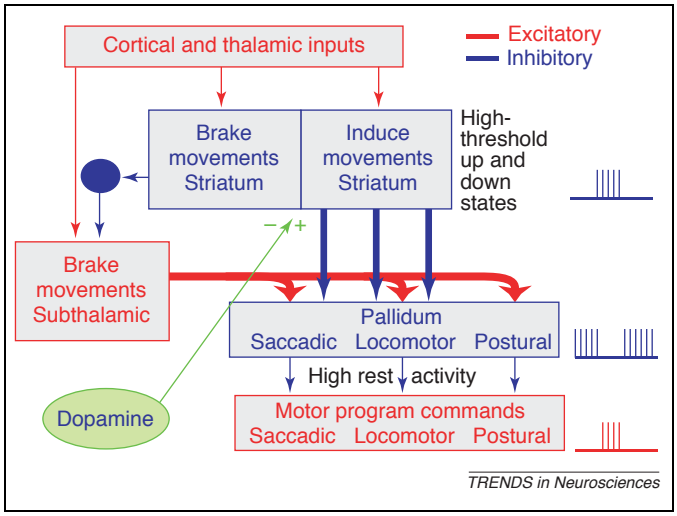

Figure 2. Basic building blocks of the basal ganglia, from a functional perspective. Inhibitory groups of neurons are indicated in blue, excitatory groups in red. The output stage of the basal ganglia is the pallidum, which includes several output nuclei (substantia nigra pars reticulata, and the dorsal and ventral pallidum) all characterized by GABAergic neurons with a high resting level of activity (~90Hz). These pallidal neurons target a large number of brainstem nuclei, in addition to their well-known thalamocortical targets (not illustrated). Subgroups of pallidal neurons project to the command neurons of several different motor programs (those for saccadic eye movements, locomotion and postural tone), and prevent them from being active under resting conditions. When the pallidal neurons in turn are inhibited by the striatum, a motor program can be released (compare spike trains to the right, illustrating correlated activity of striatal neurons, pallidal neurons and neurons of a motor program). The striatal neurons can thus induce activity and release or select a motor program (right half of the blue box representing the striatum). These neurons have a high threshold for activation, and their excitatory input is provided directly from the thalamus and extensively from different cortical regions (upper red box). Their membrane properties stabilize a hyperpolarized level owing to their specific membrane properties (referred to as down state). The transition to an up state due to excitation is facilitated by dopamine (via D_1 receptors). A subgroup of striatal neurons with different properties is indicated on the left. Their activity is depressed by dopamine and they are instead connected to the globus pallidus pars externa, as indicated by a blue connecting neuron to the left, which in turn disinhibits the excitatory subthalamic neurons. These also receive input directly from the cortex, and they add excitation to the pallidal neurons – thus, they can brake or terminate a motor program (or part of a motor program).

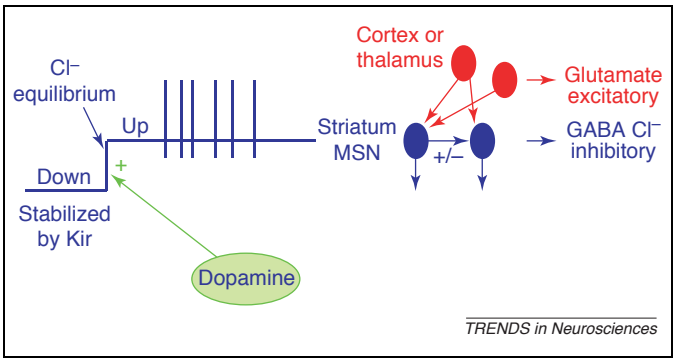

Figure 3. Important factors for the down and up states in medium spiny neurons. To the left is a schematic drawing of the transition from a down to an up state in a medium spiny neuron (MSN) of the GABAergic, substance-P-expressing subtype. The down state is stabilized by K^+ currents of the inward-rectifier type (Kir). An excitatory input from the cortex or thalamus (red, right) can depolarize the MSN so that it is transferred to an up state and Kir will then be turned off. MSNs are unusual in that their Cl^- equilibrium potential is comparatively depolarized and close to the membrane potential of the up state. This could mean that the lateral GABAergic interaction between MSNs can to some degree facilitate the occurrence of an up state. During the up state, an MSN can respond to additional excitation with action potentials; only then can it act on pallidal neurons and possibly disinhibit a motor target. The transition from a down state to an up state is facilitated by dopamine, as indicated. MSN neurons thus have three states: a down state, an up state and, with further depolarization, a state in which they fire action potentials.

Medium spiny projection neurons dominate in striatum (95%), and they interact to some degree through local GABAergic collaterals that activate conventional $GABA_A$ Cl^- channels. In these neurons, however, the Cl^- equilibrium potential is comparatively depolarized [37] and close to that of the up state [37–39], therefore perhaps providing facilitation of this state. Some neurons that do not interact through GABAergic collaterals are instead coupled by gap junctions [40]. There are also intrinsic cholinergic 'aspiny' modulatory neurons that project to the spines of the medium spiny neurons. Within single spines, they oppose the action of D_1 receptors on the glutamatergic input synapses from the cortex. The latter can display long-term synaptic plasticity [34] that is potentiated by dopamine. Finally, there is also a small population of GABAergic interneurons, of three subtypes, that synapse on the striatal medium spiny neurons. The most well characterized of these are fast-spiking interneurons projecting to the soma and proximal dendrites [36,41,42], presumably influencing whether a medium spiny neuron will be active or not [43] (see also [34,35,42]). The connectivity within the striatum has begun to be unravelled, but the integrative significance of the intrastriatal networks, and the subdivision into cellular compartments such as striosomes and matriosomes, remain largely to be elucidated [28,35,44].

Striatopallidal pathway for inducing movements

One major population of striatal spiny neurons (GABAergic neurons, expressing substance P and dopamine receptors predominantly of the D_1 type) projects directly to the pallidal output neurons (Figure 2, right). If a subgroup of such striatal neurons is activated [45], it provides strong inhibition to a subpopulation of pallidal neurons (which have a high resting activity) and thereby disinhibits target neurons in a motor centre (e.g. the superior colliculus, which is responsible for releasing a saccade in a given direction or releasing locomotor or postural control centres) [18]. Thus, when a subpopulation of striatal neurons is activated, it will indirectly remove the tonic inhibition from the particular target motor centre, and thereby activate its motor program. Whether a motor centre will be activated or not could thus be determined by the combined cortical and thalamic input to a particular subgroup of striatal neurons. For instance, focal activation within the ventral striatum (by electrical stimulation or by local application of glutamate agonists or dopamine) will initiate locomotor activity via disinhibition of the mesencephalic locomotor region [46,47]. The relative ease by which striatal neurons can be made to shift to an up state is influenced significantly by the degree of activity in the dopamine system [34]. The dopamine input thus has a gating function in striatum. One can even argue that the striatum functions as a filter for cortical and thalamic excitatory input, and only transmits when sufficient excitatory input and dopamine activation is provided to make the relevant striatal neurons shift to an up state, enabling spike activity.

Pathways for braking or terminating motor activity

The basal ganglia also contain a structure, the glutamatergic subthalamic nucleus, that can rapidly terminate activity in a motor program by exciting the inhibitory pallidal output neurons (Figure 2 left). The subthalamic nucleus receives excitation directly in a somatotopic fashion from the cortex [48], and disinhibition via a so-called indirect pathway from the striatum via the globus pallidus pars externa. The latter is controlled by a separate set of striatal neurons (GABAergic, expressing enkephalin and dopamine receptors predominantly of the D_2 type) with different properties from those that induce motor behaviour. They can thus effectively terminate the activity in a motor centre. Dopamine acts via D_2 receptors on this subset of striatal neurons and has a depressing effect, rather than a facilitating effect, as in the other subgroup of medium spiny cells in the striatum, which express D_1 receptors. The two subtypes of striatal cell are in reality intermingled, but the two circuits with opposite function are drawn separately as two boxes in Figure 2. To terminate a motor act with great precision is often as important as its initiation. Two complementary mechanisms contribute: the one already discussed here and in addition the cessation of activity in the striatal 'on system'.

Neurons in the globus pallidus pars externa are GABAergic and interact in a reciprocal fashion with the glutamatergic subthalamic neurons. Their membrane properties are such that they form a network that easily oscillates [49], and might also contribute to symptoms in Parkinson's disease. In addition the globus pallidus pars externa provides inhibitory input to striatal fast-spiking interneurons that are activated from both the cortex and the thalamus.

Basal ganglia structure and function are conserved throughout vertebrate evolution

From cyclostomes [11,50–52] to mammals, the basal ganglia remain a well-conserved structure [30,31], with the same basic neuronal organization and dependence on

dopamine innervation as a gating mechanism. Reduced dopamine input to the striatum enhances the threshold for eliciting any motor behaviour (hypokinesia), probably owing to an increased threshold for inducing an up state in the striatal medium spiny neurons. Conversely, an enhanced dopamine level (as can occur during L-DOPA treatment) will facilitate the transition to the up state, and lead to hyperkinesias and motor patterns that are released even without any intention of the patient [34,53]. In primates, the basal ganglia have expanded markedly in parallel with the cerebral cortex. The thalamic input to the striatum has received little attention compared with the cortical input, despite its prominence [30]. The thalamic input to striatum might be particularly important in lower vertebrates.

The basal ganglia are here considered to be a crucial element in the process of selecting different motor programs, particularly the striatum, with its wide input from the cerebral cortex and thalamus and its high threshold for being switched from a down state to the transmitting up state (requiring appropriate dopamine tone). Subpopulations of neurons in the striatum determine the activity level in specific subpopulations of neurons in pallidum, which in turn disinhibit their specific target motor program. Thus, reduced or abolished activity of the pallidal neurons (in the substantia nigra pars reticulata) that project to different parts of the superior colliculus motor map contributes to release of a direction-specific saccadic eye movement. Likewise, reduced or abolished activity of pallidal neurons that project to the mesencephalic locomotor region or the pedunculopontine nucleus will initiate locomotor activity [4,26,27] or affect the degree of postural tone [23–25], respectively. Pallidal inhibitory output to the thalamus and back to the cortex might similarly enhance excitability in target areas in the frontal lobe that are involved in cortically derived motor patterns. Thus, a motor program similar to that for locomotion can be released by removal of pallidal inhibition. The activity of this disinhibited motor program might, in addition, be directly influenced by other structures that could contribute to the overall motor outflow.

For the hypothesized function of the striatum in selection of motor programs, a certain level of tonic dopamine activity is required. In addition to this role for dopamine, a vast literature demonstrates that dopamine neurons show a phasic increase in activity in relation to an anticipated or manifest reward, and conversely a decrease in activity when there is a disappointment due to a lack of reward [54]. This enhanced dopamine activity promotes long-term potentiation of the glutamatergic excitatory input synapses on the spines of medium spiny striatal neurons. This dopamine-dependent synaptic plasticity [55] also provides a background for discussing the presumed role of the basal ganglia in reinforcement learning, considering in particular the cortex–striatum–pallidum–thalamus–cortex loop [56,57]. This is, however, outside the scope of this brief review focussing on selection processes and subcortical motor programs.

Concluding remarks

The major inhibitory output from the ventral and dorsal pallidum targets different brainstem motor centres. Under resting conditions, the brainstem motor centres are thus under tonic inhibition. A given motor centre can be recruited into action by disinhibition, due to a striatal inhibition of the appropriate pallidal neurons. It is argued that a major role of the basal ganglia is to select which motor behaviours should be generated in a given instant. Striatal neurons have a high threshold for activation, due to their intrinsic membrane properties, and tend to remain in a down state. Under an appropriate level of dopamine activation, striatal neurons can respond to a sufficiently large excitatory input from the cortex and thalamus, with an up state that permits them to respond with action potentials and to affect their target pallidal neurons. This mechanism could thus be regarded as providing a filter that prevents action, until a sufficient level of excitation has been received. The level required will to a large extent be determined by the level of dopamine activity.

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References

1 Feldman, J.L. *et al*. (2003) Breathing: rhythmicity, plasticity, chemosensitivity. *Annu. Rev. Neurosci.* 26, 239–266
2 Deliagina, T.G. and Orlovsky, G.N. (2002) Comparative neurobiology of postural control. *Curr. Opin. Neurobiol.* 12, 652–657
3 Grillner, S. (2002) Fundamental of Motor System. In *Fundamental Neuroscience* (Zigmond, M.J. *et al*., eds), pp. 753–766, Academic Press
4 Grillner, S. (2003) The motor infrastructure: from ion channels to neuronal networks. *Nat. Rev. Neurosci.* 4, 573–586
5 Schouenborg, J. (2002) Modular organisation and spinal somatosensory imprinting. *Brain Res. Rev.* 40, 80–91
6 Petersson, P. *et al*. (2003) Spontaneous muscle twitches during sleep guide spinal self-organization. *Nature* 424, 72–75
7 Sparks, D.L. (1997) The role of population coding in the control of movement. In *Neurons, Networks and Motor Behavior* (Stein, P.S.G. *et al*., eds), pp. 3–19, MIT Press
8 Lunenburger, L. *et al*. (2001) A possible role of the superior colliculus in eye–hand coordination. *Prog. Brain Res.* 134, 109–125
9 Isa, T. (2002) Intrinsic processing in the mammalian superior colliculus. *Curr. Opin. Neurobiol.* 12, 668–677
10 Sparks, D.L. (2002) The brainstem control of saccadic eye movements. *Nat. Rev. Neurosci.* 3, 952–964
11 Saitoh, K. *et al.* (2004) Coordination of eye and locomotor movement elicited from the lamprey tectum. Program number 882.6. In *2004 Abstract Viewer and Itinerary Planner*, Society for Neuroscience, online
12 Ekman, P. (1973) Cross-cultural studies of facial expressions. In *Darwin and Facial Expressions* (Ekman, P., ed.), pp. 169–222, Academic Press
13 Darwin, C. (1872) *The Expression of the Emotions in Man and Animals*, University of Chicago Press (1965)
14 Russell, J. and Bullock, M. (1985) Multidimentional scaling of emotional facial expressions: similarity from preschoolers to adults. *J. Pers. Soc. Psychol.* 48, 1290–1298
15 Blair, R.J. (2003) Facial expressions, their communicatory functions and neuro-cognitive substrates. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 358, 561–572
16 Bjursten, L.M. *et al*. (1976) Behavioural repertory of cats without cerebral cortex from infancy. *Exp. Brain Res.* 25, 115–130

17 Grillner, S. and Wallen, P. (2004) Innate versus learned movements – a false dichotomy? *Prog. Brain Res.* 143, 3–12
18 Hikosaka, O. *et al*. (2000) Role of the basal ganglia in the control of purposive saccadic eye movements. *Physiol. Rev.* 80, 953–978
19 Hikosaka, O. and Wurtz, R.H. (1983) Visual and oculomotor functions of monkey substantia nigra pars reticulata. IV. Relation of substantia nigra to superior colliculus. *J. Neurophysiol.* 49, 1285–1301
20 Swanson, L.W. (2000) Cerebral hemisphere regulation of motivated behavior. *Brain Res.* 886, 113–164
21 Swanson, L.W. (2003) *Brain Architecture – Understanding the Basic Plan*, Oxford University Press
22 Swanson, L.W. *et al*. (1984) Evidence for a projection from the lateral preoptic area and substantia innominata to the 'mesencephalic locomotor region' in the rat. *Brain Res.* 295, 161–178
23 Takakusaki, K. *et al*. (2003) Basal ganglia efferents to the brainstem centers controlling postural muscle tone and locomotion: a new concept for understanding motor disorders in basal ganglia dysfunction. *Neuroscience* 119, 293–308
24 Takakusaki, K. *et al*. (2004) Role of basal ganglia–brainstem systems in the control of postural muscle tone and locomotion. *Prog. Brain Res.* 143, 231–237
25 Takakusaki, K. *et al*. (2004) Role of basal ganglia-brainstem pathways in the control of motor behaviors. *Neurosci. Res.* 50, 137–151
26 Garcia-Rill, E. and Skinner, R. (1985) The basal ganglia and the mesencephalic locomotor region. In *Neurobiology of Vertebrate Locomotion* (Grillner, S. *et al*., eds), pp. 77–103, Macmillan Press Ltd
27 Grillner, S. (1985) Neurobiological bases of rhythmic motor acts in vertebrates. *Science* 228, 143–149
28 Graybiel, A.M. (1995) The basal ganglia. *Trends Neurosci.* 18, 60–62
29 Nieuwenhuys, R. *et al*. (1997) *The Central Nervous System of Vertebrates*, Springer-Verlag
30 Parent, A. (1986) *Comparative Neurobiology of the Basal Ganglia*, John Wiley & Sons, Inc.
31 Marin, O. *et al*. (1998) Evolution of the basal ganglia in tetrapods: a new perspective based on recent studies in amphibians. *Trends Neurosci.* 21, 487–494
32 Mink, J.W. (1996) The basal ganglia: focused selection and inhibition of competing motor programs. *Prog. Neurobiol.* 50, 381–425
33 Wilson, C.J. and Kawaguchi, Y. (1996) The origins of two-state spontaneous membrane potential fluctuations of neostriatal spiny neurons. *J. Neurosci.* 16, 2397–2410
34 Surmeier, D.J. (2004) Microcircuits in the striatum: cell types, intrinsic membrane properties, and neuromodulation. In *Dahlem Konf* (Vol. 6) (Surmeier, D.J., ed.), pp. 1–21, MIT Press
35 Bolam, J.P. *et al*. (2004) Microcircuits, molecules and motivated behavior: microcircuits in the striatum. In *Dahlem Konf* (Vol. 9) (Grillner, S. and Graybiel, A., eds), pp. 1–24, MIT Press
36 Blackwell, K.T. *et al*. (2003) Quantitative estimate of synaptic inputs to striatal neurons during up and down states *in vitro*. *J. Neurosci.* 23, 9123–9132
37 Plenz, D. (2003) When inhibition goes incognito: feedback interaction between spiny projection neurons in striatal function. *Trends Neurosci.* 26, 436–443
38 Czubayko, U. and Plenz, D. (2002) Fast synaptic transmission between striatal spiny projection neurons. *Proc. Natl. Acad. Sci. U. S. A.* 99, 15764–15769
39 Tunstall, M.J. *et al*. (2002) Modelling inter-segmental coordination of neuronal oscillators: synaptic mechanisms for uni-directional coupling during swimming in *Xenopus* tadpoles. *J. Comput. Neurosci.* 13, 143–158
40 Venance, L. *et al*. (2004) Electrical and chemical transmission between striatal GABAergic output neurones in rat brain slices. *J. Physiol.* 559, 215–230
41 Hellgren Kotaleski, J. *et al*. (2004) The role of background synaptic noise in striatal fast spiking interneurons. *Neurocomputing*. doi: 10.1016/j.neucom.2004.10.068 (http://www.sciencedirect.com/science/journal/09252312)
42 Tepper, J.M. and Bolam, J.P. (2004) Functional diversity and specificity of neostriatal interneurons. *Curr. Opin. Neurobiol.* 14, 685–692
43 Koos, T. and Tepper, J.M. (1999) Inhibitory control of neostriatal projection neurons by GABAergic interneurons. *Nat. Neurosci.* 2, 467–472
44 Gerfen, C.R. (1992) The neostriatal mosaic: multiple levels of compartmental organization. *Trends Neurosci.* 15, 133–139
45 DeLong, M.R. (1990) Primate models of movement disorders of basal ganglia origin. *Trends Neurosci.* 13, 281–285
46 Brudzynski, S.M. *et al*. (1993) Decreases in rat locomotor activity as a result of changes in synaptic transmission to neurons within the mesencephalic locomotor region. *Can. J. Physiol. Pharmacol.* 71, 394–406
47 Mogenson, G.J. (1991) The role of mesolimbic dopamine projections to the ventral striatum in response initiation. In *Neurobiological Basis of Human Locomotion* (Shimamura, M. *et al*., eds), pp. 33–44, Japan Scientific Societies
48 Nambu, A. *et al*. (1996) Dual somatotopical representations in the primate subthalamic nucleus: evidence for ordered but reversed body-map transformations from the primary motor cortex and the supplementary motor area. *J. Neurosci.* 16, 2671–2683
49 Bevan, M.D. *et al*. (2002) Move to the rhythm: oscillations in the subthalamic nucleus–external globus pallidus network. *Trends Neurosci.* 25, 525–531
50 Pombal, M.A. *et al*. (1997) Organization of the lamprey striatum – transmitters and projections. *Brain Res.* 766, 249–254
51 Pombal, M.A. *et al*. (1997) Afferents of the lamprey striatum with special reference to the dopaminergic system: a combined tracing and immunohistochemical study. *J. Comp. Neurol.* 386, 71–91
52 Ménard, A. *et al*. (2003) The role of the basal ganglia in the control of coordination in the lamprey. In *Proceedings of the Sixth IBRO World Congress on Neuroscience*, p.73, IBRO
53 Nicola, S.M. *et al*. (2000) Dopaminergic modulation of neuronal excitability in the striatum and nucleus accumbens. *Annu. Rev. Neurosci.* 23, 185–215
54 Schultz, W. (2002) Getting formal with dopamine and reward. *Neuron* 36, 241–263
55 Picconi, B. *et al*. (2003) Loss of bidirectional striatal synaptic plasticity in L-DOPA-induced dyskinesia. *Nat. Neurosci.* 6, 501–506
56 Brown, J. *et al*. (1999) How the basal ganglia use parallel excitatory and inhibitory learning pathways to selectively respond to unexpected rewarding cues. *J. Neurosci.* 19, 10502–10511
57 Bolam, J.P. *et al*. (2000) Synaptic organisation of the basal ganglia. *J. Anat.* 196, 527–542
58 Orlovsky, G.N. *et al*. (1999) *Neuronal Control of Locomotion. From Mollusc to Man*, Oxford University Press
59 Grillner, S. *et al*. (2000) The intrinsic function of a motor system – from ion channels to networks and behavior. *Brain Res.* 886, 224–236
60 Drew, T. *et al*. (2004) Cortical and brainstem control of locomotion. *Prog. Brain Res.* 143, 251–261
61 Beloozerova, I.N. and Sirota, M.G. (1993) The role of the motor cortex in the control of accuracy of locomotor movements in the cat. *J. Physiol.* 461, 1–25
62 Georgopoulos, A.P. and Grillner, S. (1989) Visuomotor coordination in reaching and locomotion. *Science* 245, 1209–1210