

The basal ganglia: from motor commands to the control of vigor

Joshua T Dudman¹ and John W Krakauer^{2,3}

Vertebrates are remarkable for their ability to select and execute goal-directed actions: motor skills critical for thriving in complex, competitive environments. A key aspect of a motor skill is the ability to execute its component movements over a range of speeds, amplitudes and frequencies (vigor). Recent work has indicated that a subcortical circuit, the basal ganglia, is a critical determinant of movement vigor in rodents and primates. We propose that the basal ganglia evolved from a circuit that in lower vertebrates and some mammals is sufficient to directly command simple or stereotyped movements to one that indirectly controls the vigor of goal-directed movements. The implications of a dual role of the basal ganglia in the control of vigor and response to reward are also discussed.

Addresses

¹ Janelia Research Campus, Howard Hughes Medical Institute, Ashburn, VA, United States

² Department of Neurology, Johns Hopkins University, Baltimore, MD, United States

³ Department of Neuroscience, Johns Hopkins University, Baltimore, MD, United States

Corresponding author: Dudman, Joshua T (dudmanj@janelia.hhmi.org)

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Introduction

To paraphrase the Honorable Potter Stewart, a motor skill is difficult to define, but we know it when we see it. We can agree that a motor skill applies to movements that are either executed precisely or elicit some intended outcome reliably, but are not accessible to a novice. However, it can be difficult to arrive at a definition that captures our diverse conceptions of skill. One aspect of skill is the flexibility of the movements executed in pursuit of a fixed goal. For example, a skilled basketball player reliably hitting a jump shot in the face of variation in initial postures, center of mass, or disrupting contact.

When considering motor skill it is useful to distinguish the intent or goal of a voluntary movement, which we will

refer to as a purposive action, from the execution of the specific movements that constitute an action. The what and how of action. In the more mundane confines of the laboratory one could contrast the action of pressing a lever from the kinematics of the forelimb movement that displaced the lever. From this perspective we suggest a definition of motor skill somewhat distinct from other recent treatments in the literature. Skill is a capacity to execute a purposive action reliably with a broad range of parameters defining its execution. The acquisition of novel motor skills is then a product of both learning actions and the capacity to flexibly parameterize their execution.

A key parameter of movement is its vigor, that is, its speed, amplitude, or frequency. Movement vigor is generally thought of as something that varies with motivation. However, the ability to act over a range of vigor can be considered an essential aspect of skill. A skillful pianist is one who can execute a fixed progression of notes as rapidly *or* as slowly as she chooses. Prior experience, explicit instruction, expected outcomes, and motivational state can all determine the speed with which a particular piece is played. Motivation is usually taken to be an explicit, often declarative, notion that generalizes broadly to appetitive actions directed towards a specific outcome and reward (often described as ‘wanting’). In this review, we use the term in the more abstract and restricted sense of ‘implicit’ motivation [1**] to refer to the state that controls movement vigor. Here we review recent progress understanding the intersection of motivation with motor skill and elaborate a hypothesis about the neural circuits that mediate implicit motivation.

The basal ganglia and motor skill

For the purposes of this review we will focus on the dorsal basal ganglia circuit that is critical for motivated, instrumental³ behavior [2], that is, that component of motor skill that refers to selection of parameterizable action. The role of ventral basal ganglia in related ideas of explicit motivation and response vigor are discussed elsewhere [3*,4,5]. Canonically, the dorsal basal ganglia circuit is defined by its primary input structure, the striatum, and primary output structures, the internal globus pallidus (GPi) and substantia nigra *pars reticulata* (SNr) [6]. The striatum receives input from almost all of the neocortex and diverse thalamic nuclei. Much of the cortical input to the dorsal striatum arises from layer

³ An agent is required to commit actions in order to obtain reward.

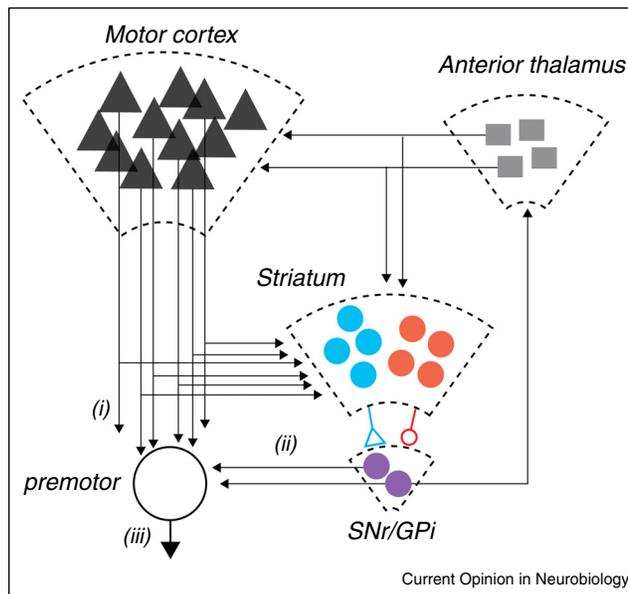
5 projection neurons in the neocortex, both via collaterals of descending corticofugal fibers as well as intratelencephalic projections. Basal ganglia outputs are positioned to shape activity in each of the multiple spinal-targeting pathways that regulate voluntary movement [7,8] via projections to motor thalamus [9], pontine nuclei⁴ [10], and the superior colliculus [11].

The basal ganglia are a critical subcortical circuit that is present in all vertebrates. From lamprey to primates, the neurochemical markers [12], cell types [13], and mesoscopic internal [14] and external [15,16] circuitry of the basal ganglia are highly conserved. However, over that evolutionary span, cortical and thalamic motor circuits have changed dramatically. As a consequence, while the dorsal striatum receives input from nearly the entire neocortex, estimated to be ~20 million projection neurons in rats [17], the primary output projections reveal a remarkable bottleneck. For example, the SNr has been estimated to contain only ~25,000 projection neurons [18]. This reduction in neuron number of roughly three orders of magnitude implies a low-dimensional representation of motor command signals. The extensive interconnectivity of output projection neurons [19,20] leads to correlated output activity [21] and therefore a further reduction in the information capacity of this output pathway. In the context of the central control of movement, this anatomical organization suggests that the basal ganglia receive descending motor cortical commands and then feed back to the motor cortex via thalamus as well as projecting feed-forward onto downstream premotor targets (Figure 1).

We propose that this functional organization — parallel processing of motor cortical commands to produce a low dimensional output — is consistent with a model in which the overt kinematics of movement are the consequence of combining the output commands from motor cortex with ‘implicit motivational signals’ from basal ganglia. More broadly, we argue that this reflects the fact that the basal ganglia have evolved from having a direct role in the control of movement in early vertebrates to a more indirect and specific role in controlling movement vigor. This view of basal ganglia function makes some predictions about the role of the basal ganglia in the central control of movement. First, basal ganglia activity should represent ongoing movement kinematics and be predictive of movement vigor. Second, basal ganglia activity should be sufficient to produce changes in movement kinematics, specifically during movement execution. Finally, both direct command and indirect motivational functions should be apparent in some vertebrates reflecting the evolving function of the basal ganglia.

⁴ Note that the projection to pontine nuclei arise from the subthalamic nucleus.

Figure 1



Functional architecture of the dorsal basal ganglia circuit in mammals. A schematic representation of the cortico-basal ganglia-thalamic circuit is shown; further anatomical details can be found elsewhere [6]. A number of features of the organization are mentioned in the main text and highlighted here. First, we note that corticofugal projection neurons from motor areas of cortex project both to brainstem and spinal cord targets (pathway *i*). These same neurons elaborate extensive collaterals in the dorsal striatum. The dorsal basal ganglia is composed of a primary input structure, striatum, which contains two opponent populations of projection neurons (schematized in blue and red) that together provide an opponent projection onto the major output nuclei, SNr and GPi (purple). In addition, the dramatic reduction in projection neuron number from cortex to striatum to SNr is indicated by the decreasing size of the schematic representations. Finally, SNr output both projects feed-forward onto premotor neurons in the pontine nuclei and superior colliculus schematized by pathway *ii* as well as projecting recurrently to anterior thalamic nuclei (i.e. ventrolateral, ventromedial) that project back to cortex and striatum. We postulate that overt movement kinematics (*iii*) result from the combination of motor command signals (*i*) and vigor control signals (*ii*).

Do the basal ganglia generate motor commands?

Since the pioneering work by Buchwald and colleagues in the 1970s it has been suggested that the basal ganglia may play a more prominent role in the initiation or selection of actions rather than controlling the execution of movements *per se* [22,23]. While this was primarily thought to be a role in preparing central circuits for movement⁵ it became a stronger claim that basal ganglia activity provided a trigger for movement initiation or selection. There have long been issues, however, with the notion that the basal ganglia trigger movement directly. Notably,

⁵ “Our working hypothesis in this regard is that the basal ganglia are not as importantly involved in producing movements, *per se* as in their preparation.” [22].

perturbation of basal ganglia output and movement can be ‘uncoupled’⁶ in time [24]. Recently, cell-type specific stimulation using optogenetic strategies has similarly shown that stimulation can be uncoupled from movement initiation [25].

Our proposal that the basal ganglia are critical for controlling the vigor of motor skill needs to be related to and disambiguated from a direct role in motor execution. While there may be subsets of movements in which vigor as a kinematic command could be envisaged, for example in a saccade or fast reach, the vigor of an action and its execution likely become more uncoupled as skills become more complex and play out over longer time windows. For example, walking to catch a bus versus running to avoid missing it, represents the combination of a difference in vigor and the difference in how walking and running are executed. Shooting a basketball or pressing a lever are complex movements that coordinate across the body and unfold over time using feedback [26,27]. Moreover, the effect of altering vigor commands depends upon the phase of the movement at which they are generated and thus should require real-time estimates of kinematics [28] much like when pushing one’s child on a swing the phase of the swing at which a push is added determines its effect on amplitude and velocity. Controlling the vigor of skilled movement requires continuous monitoring of kinematics without disrupting execution-related commands that presumably come from elsewhere.

Several lines of evidence do support a direct role for the basal ganglia in the control of movement execution. For example, lesion studies in a variety of mammals from rodents to cats reveal that a substantial fraction of motor behavior can recover after massive lesions of motor regions of neocortex [29]. This result demonstrates that subcortical circuits are sufficient for the control of movement. Nonetheless, it is important to distinguish recovery after a lesion via alternative compensatory actions from cases where the same actions are implemented with the same movement kinematics. A recent study in rats demonstrated the latter. Kawai *et al.* [30^{*}] showed that highly trained movements could be executed with nearly indistinguishable kinematics before and after massive lesions of motor cortex. While the role of the basal ganglia remains to be demonstrated definitively, a very likely interpretation of these results is that the basal ganglia are

⁶ “...the long latency of movement onset produced by intranigral injection of muscimol does not reasonably match the latency of collicular disinhibition resulting from this drug application. Another set of data obtained in alert monkeys does not support the ‘trigger hypothesis’. When the animal had to make a delayed saccade to a remembered target, the nigrocollicular cells were inactivated long before the saccade was triggered (Fig. 4). Since the nigrocollicular silencing and the saccade release can be uncoupled, we have evidence that disinhibition of the basal ganglia is not alone sufficient to trigger a coordinated movement.” [24].

a critical component of the subcortical circuit that is sufficient to generate commands at least for simple, over-trained movements [29].

In a classic series of papers, Horak and Anderson [31^{**},32,33] combined electrophysiological recordings, microstimulation, and perturbations of activity in the GPi of monkeys trained to perform forelimb movements. Their results demonstrated that most of the change in activity in the GPi occurred during movement execution, that the primary effect of perturbations on activity was to change movement kinematics as opposed to movement initiation, and finally that stimulation late in movement planning, at the early stages of execution, had the largest effects on kinematics. A more recent study extended these results using a task in which monkeys learned to reach to each of 4 targets either in a specific sequence or in random order. Turner and Desmurget [34^{*}] found that the primary effect of GPi inactivation was to slow reaching movements with no effect on the initiation of movement or the proper selection of movements in a sequence.

While it has been clear in primates for some time that most modulation of activity in the basal ganglia circuit occurs during movement execution [31^{**}], this has been less clear in rodents. For example, rats trained to run a T-maze will generally show ‘task-bracketing’ activity that emerges with sustained training [35]. For more discrete actions, such as bouts of cyclical arm movements during grooming [36] or repetitive pressing of a lever [37], the majority of activity appears biased to the start or stop of movement bouts. These results suggest that the basal ganglia could be primarily involved in selection and raise the question of whether basal ganglia activity is consistent with a role in controlling movement execution in rodents. However, sustained activity of individual neurons in the basal ganglia during execution is commonly observed. For example, an influential early study of sequence specific activity during grooming noted that the modulation of activity actually occurred after onset of movement⁷ [38]. Nonetheless, it remains unclear from these studies whether basal ganglia activity during movement is related to movement execution itself.

Rueda-Orozco & Robbe [39^{**}] used a task in which rats were trained to outrun an opposing treadmill motion to receive rewards. After extended training, rats developed stereotyped sequences of acceleration, elevated velocity and deceleration. The authors found that single units recorded in the dorsal striatum contained information about kinematics during the execution of running sequences and that pharmacological inhibition produced

⁷ “Close inspection of the timing indicates that SNpr [sic] firing bursts may be a consequence or efferent copy marker for the behavioural initiation of sequences, rather than a preceding cause of initiation. The strongest activation began after the first forward limb movement had already started...” [38].

highly variable kinematics, specifically running speed. Importantly, using hand-guided trials to produce kinematically matched control trials in untrained animals, Rueda-Orozco & Robbe demonstrated that learning produced a preponderance of neurons highly correlated to movement kinematics. This suggests that striatal activity is a critical determinant of the vigor with which the motor skill was executed. These observations are also consistent with recordings of activity in the striatum and SNr of mice that demonstrate representations of movement kinematics during execution of appetitive head movements towards a reward [40,41]. Recently, the circuit basis for the control of the vigor of locomotion by dorsal striatum has been described and opens up exciting possibilities for understanding computational details about how vigor signals are integrated with command signals for locomotion [42].

A recent study also examined the role of striatum in mediating changes in the control of a trained forelimb movement following depletion of midbrain dopamine neurons. Chronic depletion of dopamine neurons in Parkinsonian patients, particularly neurons projecting to dorsal striatum, leads not only to reductions in voluntary behavior, but also a profound slowing of movement or bradykinesia. Panigrahi *et al.* [43**] showed that bradykinesia was a prominent feature of both locomotor and reaching movements in a murine model of Parkinson's disease [44] with a number of similarities to deficits in human patients [1**,45**]. Alterations in the striatal representation of movement kinematics specifically during execution were correlated with the emergence of bradykinesia and its cessation following acute repletion of dopamine. Importantly, both the Rueda-Orozco & Robbe and Panigrahi *et al.* observed that striatal activity could represent movement kinematics both prospectively and retrospectively during execution. In the latter case, the data in Panigrahi *et al.* suggested that these two roles might be present in distinct neuron populations with differential sensitivity to dopamine depletion [43**]. Importantly, acute optogenetic suppression of striatal neurons during movement execution produced bradykinetic movements in mice [43**]. This observation suggests that basal ganglia activity may be the normal determinant of movement vigor during purposive actions in mice as it is in primates [32].

Finally, while these studies demonstrate that activity in dorsal basal ganglia circuits appear to be necessary for the control of movement vigor, they leave open the question of whether plastic changes localized to the basal ganglia are sufficient for learned changes in vigor. Recently, Yttri & Dudman delivered closed-loop optogenetic stimulation of striatal projection neurons while mice moved a joystick past a fixed threshold in exchange for a water reward [46**]. Photostimulation during the execution of movements that were relatively fast or relatively slow was sufficient to produce learned changes in movement

velocity without generalized changes in other kinematic parameters or apparent changes in the explicit motivation. Model fitting and recording of striatal activity during closed-loop stimulation indicated that a change in the gain at corticostriatal inputs was sufficient to account for learned changes in movement vigor.

The data reviewed above demonstrate that in mice and rats, as in primates, the extent of direct basal ganglia involvement in movement execution varies across experiments and species but activity consistently both tracks and predicts the kinematic parameters of movement execution. Moreover, perturbations of normal basal ganglia activity indicate that striatum regulates movement vigor and stimulation experiments demonstrate changes in striatal activity are sufficient to produce learned changes in movement vigor. These data are thus consistent with the expectations of a circuit that controls the flexible parameterization, specifically vigor, of skilled movement.

The basal ganglia and the control of vigor

Human subjects show changes in movement vigor that depend upon expected outcomes in a wide variety of movements [47]. A recent study has also built upon previous evidence for implicit motivation in the control of saccadic eye movements [48] to argue persuasively that the same system that assigns values to choices also controls the vigor of saccades [49*]. This implicates the basal ganglia in the control of movement vigor. Deficits in basal ganglia function in Parkinson's disease patients produce movements of reduced vigor both when the subject is free to choose movement speed [45**] and when task performance depends upon moving at an instructed velocity [1**]. These deficits in movement vigor can also be partially ameliorated by deep brain stimulation [45**]. Thus, several lines of evidence argue for a critical role of the basal ganglia in implicit motivation operating through the control of vigor in human subjects.

It should be stressed that just because the basal ganglia can influence vigor this does not imply the converse: that vigor parameters are always under the obligate control of the basal ganglia. For example, the hind-legs of a spinalized cat can walk at multiple speeds without basal ganglia input. Rather we argue that movement vigor is that aspect of movement kinematics subject to control by implicit motivational states. Motivation, whether implicit or explicit, is tied to value. Thus, goal-directed movements are subject to motivation effects that are expressed through vigor [50,51,52]. It could be conjectured that reflexive or automatic movements, not being goal-directed, have kinematics insensitive to changes in implicit motivation; such habitual movements are often characterized by their stereotypy. We suggest that stereotypy is, in fact, habitual kinematics.

The notion that the basal ganglia control vigor parameters appears to be contradicted by those studies that have shown that activity in the basal ganglia can track movement kinematics in some contexts, but not in other contexts even when the actions appear to be indistinguishable phenotypically. This uncoupling between the basal ganglia and movement kinematics is most apparent for sequences [35–38]. One possibility is that each of the action elements in overlearned, automatized sequences is no longer individually controlled, unlike early in learning. It has recently been shown that early on in sequence learning, each element is subject to motivational effects. Specifically, knowledge of parts of a sequence of actions can produce a generalized speeding up of the execution of all sequence elements, even for novel elements of the sequence [53**]. This generalized speeding of execution is equivalent to a motivational effect associated with knowledge of an element's position in a sequence rather than experience with sequence elements or transitions. Wong *et al.* [53**] further suggested that motivational effects are responsible for sequence-specific performance differences rather than the amount of practice with a particular sequence. An open question is whether all tasks described as sequential actions engage similar circuit mechanisms. For example, in rats trained on a sequential action task with variable order (i.e. more similar to [53**]) striatal activity was associated with each action rather than sequence boundaries [54]. We suggest that the movement vigor of chunked, overlearned sequences can become, as for stereotypical habitual actions, independent of dorsal basal ganglia control of implicit motivation. A similar hierarchical control has also been proposed for explicit motivational control of sequential habitual actions by ventral basal ganglia circuits [55*].

One prominent argument for a role of the basal ganglia specifically in the production of sequential actions has been the observation of deficits in Parkinsonian patients [56]. Deficits in movement vigor in Parkinsonian patients are also one of the primary arguments for a role of the basal ganglia in implicit motivation [1**]. While deficits in movement vigor tend to correlate with the severity of Parkinsonian symptoms [1**,45**], sequencing deficits such as latency to switch between elements, errors, or movement corrections can be independent of disease severity⁸ [57,58]. Moreover, basal ganglia activation fails to correlate with sequence complexity [59], whereas it generally correlates with movement vigor [39**,43**,52,60,61]. It has been proposed that apparent deficits in the performance of sequential actions may be secondary to a deficit in movement vigor in Parkinsonian

⁸ “The results showed that while the more advanced PD group was slower in execution and made more errors (possibly due to the slowness) ($P < 0.05$), the pattern of motor programming deficits as inferred by sequence length and delay interval effects was similar for both groups.” [57].

patients [1**]. The Wong *et al.* [53**] data further suggests that a primary deficit in implicit motivation could manifest as a deficit in performance of sequential actions. Whether differences in implicit motivation are indeed sufficient to account for the diverse measurements of sequencing impairments will require further attention. An alternative, or complementary, possibility is that agents are particularly prone to solving sequential tasks by learning stereotyped or chunked movements that are relatively insensitive to implicit motivation.

Our hypothesis implies that a dual role for the basal ganglia may be present in some vertebrates. We have argued that recent lesion experiments, electrophysiology data, and acute perturbations point to a critical role for basal ganglia in the execution of motor skill in rodents. This raises the question of whether implicit motivation processes are present in rodents. While depletion of dopamine in the ventral basal ganglia has long been known to produce dramatic reductions in the motivated performance of a motor skill [5], it was unclear whether the dorsal basal ganglia was critical for controlling the vigor with which motor skills are executed (implicit motivation) analogous to its role in primates. Panigrahi *et al.* used a murine model of Parkinsons disease to show that as midbrain dopamine neurons were progressively lost, the vigor of both uninstructed (locomotion) and skilled movements (joystick movements) declined concomitantly [43**]. In mice, like in human patients, the reduction of movement vigor is not a consequence of altered coordination or a lack of sensitivity to feed back about outcomes, but is a persistent bias towards making enervated movements. Thus taken together, the data reviewed here indicate that, at least in the rodent, the basal ganglia both control vigor as in primates and, under some circumstances, are likely sufficient to directly command movement execution as in lower vertebrates.

Summary and outlook

Here we propose that the basal ganglia have evolved from a role in commanding relatively simple movements to a role in controlling the vigor of more complex movements during vertebrate evolution. The basal ganglia have also been implicated in the initiation and selection of action as well as the chunking of action sequences. In principle, it is possible that the basal ganglia possess multiple functions, however, the data reviewed here highlights the possibility that a circumscribed description of dorsal basal ganglia function, namely implicit motivation expressed through movement vigor, might be sufficient to account for multiple observed consequences of disrupted basal ganglia function.

We have referred to the control of movement vigor in purposive actions as implicit motivation that controls *how* an agent executes an action to distinguish it from the explicit forms of motivation that govern *what* action to

perform. However, we have also consciously invoked the term motivation to draw out parallels between these processes [3^{*},4,5]. Implicit motivation and value are also closely related in the sense that those actions that tend to elicit greater reward are generally (although we stress not *necessarily*) pursued with movements of greater vigor. It does not seem a mere coincidence that representation of movement vigor and expected value reference? are both prominent in dorsal basal ganglia activity. While it has been proposed that movement vigor might be a consequence of expected value [51], the evolution of basal ganglia function we have proposed suggests a provocative alternative: value signals, at least in the dorsal basal ganglia, may be derived from the representation of implicit motivation.

The parallels between implicit and explicit motivation may extend to more mechanistic details as well. For example, we have proposed that stereotyped movements are movements of a specific vigor represented as a discrete action. Basal ganglia activity could then select from a set of possible stereotyped actions and thereby specify both the action and the parameterization of the underlying movements. This might be thought of as ‘cached vigor’ by analogy to the role of cached values in model-free reinforcement learning [62]. It is implausible that the control of purposive action can be exclusively controlled by cached vigor. Rather, the multiple roles of basal ganglia could stand in hierarchical relation — once an action in its entirety is cached it is released as a stereotypy without the need to control the vigor of its individual elements [55^{*}]. As we suggest above, some tasks such as those requiring extensively trained, sequential movements are those efficiently performed using stereotyped movements of specified and inflexible vigor.

Our suggestion that implicit motivation is the critical function of the dorsal basal ganglia in mammals underlines the importance of making careful, quantitative measurements of movement kinematics in the study of motor skill or instrumental learning. For example, movement vigor tends to correlate with the expected value of the outcome of an action [50,51] and neural activity in basal ganglia correlates with vigor [39^{**},40,43^{**},52,60]. Thus, to disambiguate activity related to the expected value of an action from activity related to the implicit motivational state requires relating activity to movement kinematics. Similarly, if a given sequential action is represented with cached vigor, this implies that activity specific to the action should be independent of variation in the kinematics of specific executed instantiations of the sequence. Variance in movement vigor would reflect ‘noise’ derived from an extra-basal ganglia source. To date, studies that have argued for a specific role of the basal ganglia in the selection or initiation of action sequences have generally not measured quantitative relationships between variation in movement kinematics

and recorded neural activity [35–38]. A recent exception is the study by Rueda-Orozco & Robbe, which found that the representation of movement kinematics in striatum increased, rather than decreased, with extended training [39^{**}].

We have argued that controlling movement vigor, at least in complex and sustained actions, requires continuous monitoring of kinematics in order to inject vigor commands at appropriate phases of movement. This implies both a representation of ongoing kinematics as well as activity that predicts future kinematics- putative vigor commands. Consistent with this implication, two recent studies in the rodent have shown that activity in the striatum that is correlated with kinematics both leads and lags the movement [39^{**},43^{**}]. Specifically, Panigrahi *et al.* observed that distinct striatal neurons appeared to lead and lag movement kinematics and that dopamine depletion, which impaired implicit motivation, was associated with a preferential loss of neurons that led (predicted) movement kinematics [43^{**}]. Although currently untested, the notion of cached vigor implies **that** for stereotyped, habitual movements, activity **may** become less correlated with kinematics. **Conversely**, however, for complex, sequential movements that can be executed independent of motor cortex [30^{*}] vigor commands could be sufficient to control execution **and therefore a continued correlation would be seen.**

Conclusion

In humans, loss of motor cortex due to a stroke can have devastating consequences for the control of limb movement. By contrast, in many mammalian species near complete recovery of function following large cortical lesions is commonplace. Loss of basal ganglia function either due to intervention, stroke, or disease has the unique distinction of producing both profound and yet subtle dysfunction in all mammalian species. We propose that over the course of vertebrate evolution the basal ganglia have transitioned from a circuit sufficient to generate purposive movements to a circuit that plays a role primarily in controlling the vigor of movements that are generated elsewhere. We propose that rodents are, in a sense, atavistic; their basal ganglia maintain some command properties but also mediate the specific invigoration of purposive movement in close analogy to their function in humans. Finally, we used our previously defined term implicit motivation to describe the function of the basal ganglia in part to acknowledge that the invigoration of movement is simply a convenient and observable aspect of a more general motivational principle. The striatum receives input from nearly all regions of the neocortex including dense innervation from frontal and associative cortices. It is likely that there are other aspects of cognition that are analogous to implicit motivation. [63^{*}].

Conflict of interest statement

The authors declare no conflicts of interest.

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Papers of particular interest, published within the period of review, have been highlighted as:

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Although not the focus of this review, ventral basal ganglia circuits play a critical role in the control of explicit motivation and response vigor. This article presents an important summary and synthesis of ideas. A complementary and important review of the behavioral pharmacology of ventral basal ganglia manipulations is presented in [5].

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 27. Wolpert DM, Ghahramani Z: **Computational principles of movement neuroscience.** *Nat Neurosci* 2000, **3(Suppl.)**:1212-1217.
 28. Novak KE, Miller LE, Houk JC: **The use of overlapping submovements in the control of rapid hand movements.** *Exp Brain Res* 2002, **144(3)**:351-364.
 29. Grillner S: **Action: the role of motor cortex challenged.** *Curr Biol* 2015, **25(12)**:R508-R511.
 30. Kawai R *et al.*: **Motor cortex is required for learning but not for executing a motor skill.** *Neuron* 2015, **86(3)**:800-812.
- Although there has long been evidence that decorticate animals could exhibit much of their normal behavioral repertoire, it was less clear whether these reflected compensatory strategies or simply reflected subcortical control of movement. The authors demonstrated that the fine kinematic details of an overtrained instrumental task spontaneously recovered following extensive motor cortical lesions.
31. Anderson ME, Horak FB: **Influence of the globus pallidus on arm movements in monkeys. III. Timing of movement-related information.** *J Neurophysiol* 1985, **54(2)**:433-448.
- These three classic papers from Horak and Anderson combined perturbation experiments, both pharmacological inactivation and microstimulation, combined with electrophysiological recordings in what remains one of the most thorough studies of globus pallidus function during skilled forelimb movements in primates.
32. Horak FB, Anderson ME: **Influence of globus pallidus on arm movements in monkeys. II. Effects of stimulation.** *J Neurophysiol* 1984, **52(2)**:305-322.
 33. Horak FB, Anderson ME: **Influence of globus pallidus on arm movements in monkeys. I. Effects of kainic acid-induced lesions.** *J Neurophysiol* 1984, **52(2)**:290-304.
 34. Desmurget M, Turner RS: **Motor sequences and the basal ganglia: kinematics, not habits.** *J Neurosci* 2010, **30(22)**:7685-7690.

An open question in the Horak and Anderson studies was whether selection of a specific forelimb movement in addition to kinematics was affected by pharmacological inactivation of the globus pallidus. Using an elegant design the authors showed that the selection of actions, both in random and trained sequences, were unaltered by inactivation while confirming similar kinematic deficits to those observed in Horak and Anderson.

35. Barnes TD *et al.*: **Activity of striatal neurons reflects dynamic encoding and recoding of procedural memories.** *Nature* 2005, **437(7062)**:1158-1161.

36. Aldridge JW, Berridge KC: **Coding of serial order by neostriatal neurons: a “natural action” approach to movement sequence.** *J Neurosci* 1998, **18(7)**:2777-2787.

37. Jin X, Costa RM: **Start/stop signals emerge in nigrostriatal circuits during sequence learning.** *Nature* 2010, **466(7305)**:457-462.

38. Meyer-Luehmann M *et al.*: **Substantia nigra pars reticulata neurons code initiation of a serial pattern: implications for natural action sequences and sequential disorders.** *Eur J Neurosci* 2002, **16(8)**:1599-1608.

39. Rueda-Orozco PE, Robbe D: **The striatum multiplexes ●● contextual and kinematic information to constrain motor habits execution.** *Nat Neurosci* 2015, **18(3)**:453-460.

The authors design an elegant task in which rats were required to run against the movement of a powered treadmill to get reward available at specific intervals. Rats developed highly stereotyped kinematics with substantial training on the task. The authors were able to show clear representations of movement kinematics in striatal activity and using a clever hand-guided control to show that the accurate representation of movement kinematics in striatum was a product of training.

40. Kim N *et al.*: **Striatal firing rate reflects head movement velocity.** *Eur J Neurosci* 2014, **40(10)**:3481-3490.

41. Barter JW *et al.*: **Basal ganglia outputs map instantaneous position coordinates during behavior.** *J Neurosci* 2015, **35(6)**:2703-2716.

42. Roseberry TK *et al.*: **Cell-type-specific control of brainstem locomotor circuits by Basal Ganglia.** *Cell* 2016, **164(3)**:526-537.

43. Panigrahi B *et al.*: **Dopamine is required for the neural ●● representation and control of movement vigor.** *Cell* 2015, **162(6)**:1418-1430.

Loss of dopamine in Parkinson's disease produces deficits in the initiation, speed, and fluidity of voluntary movement. This study showed that these deficits are very accurately recapitulated in a genetic mouse model of progressive dopamine depletion. Physiological recordings from striatum in wild-type mice revealed a representation of movement in the striatum that predicted the future vigor of movement. This representation was dramatically reduced by dopamine depletion and partially restored by acute repletion. The enervation of purposive forelimb movements could be mimicked by acute optogenetic inhibition of striatal activity during movement execution providing evidence that basal ganglia activity during can control movement vigor.

44. Ekstrand MI, Galter D: **The MitoPark Mouse – an animal model of Parkinson's disease with impaired respiratory chain function in dopamine neurons.** *Parkinsonism Relat Disord* 2009, **15(Suppl. 3)**:S185-S188.

45. Baraduc P *et al.*: **A common optimization principle for motor ●● execution in healthy subjects and parkinsonian patients.** *J Neurosci* 2013, **33(2)**:665-677.

In Mazzoni *et al.* subjects were instructed to move at specific velocities. This left open the question of whether given free choice of movement speed Parkinsonian patients would move slower or adopt distinct control strategies. Baraduc *et al.* used an elegant modeling approach to infer that a number of differences in kinematics of movement in Parkinsonian patients could be explained by a reduced range of movement vigor used by patients. Importantly, they also demonstrated that these differences were partially normalized by deep brain stimulation of the subthalamic nucleus.

46. Yttri EA, Dudman JT: **Neural correlates of bidirectional kinetic ●● control and reinforcement in the basal ganglia; Talk 654.04; Society for Neuroscience Annual Meeting 2015.**

Demonstrates the sufficiency of striatal activity for learned, persistent changes in implicit motivation. Using their stimulation approach, the authors were also able to demonstrate that basal ganglia pathways

are sufficient for opponent and bidirectional changes in movement vigor – a key feature for a circuit that determines the flexible parameterization of movement kinematics.

47. Turner RS, Desmurget M: **Basal ganglia contributions to motor control: a vigorous tutor.** *Curr Opin Neurobiol* 2010, **20(6)**:704-716.

48. Xu-Wilson M, Zee DS, Shadmehr R: **The intrinsic value of visual information affects saccade velocities.** *Exp Brain Res* 2009, **196(4)**:475-481.

49. Reppert TR *et al.*: **Modulation of saccade vigor during value-based decision making.** *J Neurosci* 2015, **35(46)**:15369-15378. Previous work from this group had indicated that the vigor of saccadic eye movements to a target are sensitive expected outcomes and had implicated the basal ganglia in that process. This study expanded upon that by arguing that the same circuitry was responsible for determining expected values and movement vigor providing even stronger evidence that the basal ganglia are critical for implicit motivation.

50. Haith AM, Reppert TR, Shadmehr R: **Evidence for hyperbolic temporal discounting of reward in control of movements.** *J Neurosci* 2012, **32(34)**:11727-11736.

51. Shadmehr R *et al.*: **Temporal discounting of reward and the cost of time in motor control.** *J Neurosci* 2010, **30(31)**:10507-10516.

52. Tachibana Y, Hikosaka O: **The primate ventral pallidum encodes expected reward value and regulates motor action.** *Neuron* 2012, **76(4)**:826-837.

53. Wong AL *et al.*: **Explicit knowledge enhances motor vigor and ●● performance: motivation versus practice in sequence tasks.** *J Neurophysiol* 2015, **114(1)**:219-232.

In tasks requiring sequential actions training reduces the time required to perform the sequential actions, often through reducing transition times between elements. This is thought to occur through a learned representation of task structure. However, the authors showed generalized effects on novel sequence elements or randomly ordered sequences suggesting that motivational effects can confound the interpretation of performance improvements in execution of sequential tasks.

54. Ma L *et al.*: **Tracking progress toward a goal in corticostriatal ensembles.** *J Neurosci* 2014, **34(6)**:2244-2253.

55. Collins AL *et al.*: **Dynamic mesolimbic dopamine signaling ●● during action sequence learning and expectation violation.** *Sci Rep* 2016, **6**:20231.

This paper tracks dopamine release in the nucleus accumbens as rats are trained and overtrained on a sequential action task. The authors propose a hierarchical motivational control in which explicit motivation comes to control only to the complete, ‘chunked’ sequence of actions. This tracking of changes in dopamine release over the course of training is an important complement to studies that focus on only a specific point in training.

56. Marsden CD: **Which motor disorder in Parkinson's disease indicates the true motor function of the basal ganglia?** *Ciba Found Symp* 1984, **107**:225-241.

57. Harrington DL, Haaland KY: **Sequencing in Parkinson's disease. Abnormalities in programming and controlling movement.** *Brain* 1991, **114(Pt 1A)**:99-115.

58. Desmurget M *et al.*: **On-line motor control in patients with Parkinson's disease.** *Brain* 2004, **127(Pt 8)**:1755-1773.

59. Harrington DL *et al.*: **Specialized neural systems underlying representations of sequential movements.** *J Cogn Neurosci* 2000, **12(1)**:56-77.

60. Turner RS *et al.*: **Motor subcircuits mediating the control of movement extent and speed.** *J Neurophysiol* 2003, **90(6)**:3958-3966.

61. Kawagoe R, Takikawa Y, Hikosaka O: **Expectation of reward modulates cognitive signals in the basal ganglia.** *Nat Neurosci* 1998:411-416.

62. Daw ND, Niv Y, Dayan P: **Uncertainty-based competition between prefrontal and dorsolateral striatal systems for behavioral control.** *Nat Neurosci* 2005, **8(12)**:1704-1711.

63. Manohar SG *et al.*: **Reward pays the cost of noise reduction in motor and cognitive control.** *Curr Biol* 2015, **25(13)**:1707-1716.
This paper derives the prediction that both speed and accuracy can be enhanced from the normative assumption that controlling variability is

subject to a cost. Behavioral data in normal subjects validate this prediction. Additionally, they show that Parkinsonian patients act as though the cost of control is elevated similar to the cost of vigorous movement in [1].