

Subcortical loops through the basal ganglia

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Parallel, largely segregated, closed-loop projections are an important component of cortical–basal ganglia–cortical connective architecture. Here, we present the hypothesis that such loops involving the neocortex are neither novel nor the first evolutionary example of closed-loop architecture involving the basal ganglia. Specifically, we propose that a phylogenetically older, closed-loop series of subcortical connections exists between the basal ganglia and brainstem sensorimotor structures, a good example of which is the midbrain superior colliculus. Insofar as this organization represents a general feature of brain architecture, cortical and subcortical inputs to the basal ganglia might act independently, co-operatively or competitively to influence the mechanisms of action selection.

Introduction

Basal ganglia dysfunctions have long been associated with a range of debilitating clinical conditions whose most obvious manifestations are disturbances in movement. It is increasingly recognized, however, that many of these disorders, including Parkinson's disease, Huntington's chorea, schizophrenia, attention deficit disorder, Tourette's syndrome and various addictive behaviours, have associated cognitive and affective components. This new multidimensional view is consistent with anatomical findings that the basal ganglia are connected to functionally disparate regions of the cerebral cortex. An important component of this general architecture is characterized by parallel, mainly segregated, closed-loop projections [1–3] that originate from, and return to, the same neocortical domains. Indeed, it has been proposed that the functional organization of the basal ganglia is conditioned largely by their connections with the cerebral cortex [1].

Although there is an implicit assumption that this re-entrant cortical–basal ganglia architecture is unique, there is good reason to modify this perspective to one that generalizes the closed-loop concept to include connections between the basal ganglia and many subcortical structures. In this paper, we highlight one subcortical structure, the midbrain superior colliculus, as an example to advance this case [4]. Having established that re-entrant loops could be one of the common means by

which both cortical and subcortical structures interact with the basal ganglia, we proceed to consider some of the computational properties of looped architectures in the general context of selection mechanisms. Specifically, we propose that cortical and subcortical looped connections with the basal ganglia provide an elegant solution to the problem of conflict between multiple distributed parallel-processing sensory, cognitive and affective systems, which simultaneously seek access to limited attentional and motor resources. The fact that this mechanism evaluates competing priorities between functional systems represented at cortical and subcortical levels has widespread and profound implications for our understanding of the general issue of behavioural choice.

Basal ganglia: connective architecture

The basal ganglia have two primary input ports: the striatum and the subthalamic nucleus. These nuclei receive direct afferents from the cerebral cortex, limbic structures [5–7] and the thalamus (principally the midline and intralaminar nuclei) [8,9], in addition to modulatory inputs from the midbrain substantia nigra pars compacta (releasing dopamine [5]) and the dorsal raphe (releasing 5-hydroxytryptamine [10]). These two basal ganglia input structures then relay signals, via direct and indirect routes [5,11], to the principal output nuclei, namely, the internal globus pallidus (entopeduncular nucleus in rodents) and the substantia nigra pars reticulata. The output nuclei project directly to the thalamus, midbrain and medulla, and indirectly, via the thalamus, to target cortical and limbic regions from which the basal ganglia input originated [1–3]. Alexander *et al.* [1] were the first to appreciate the basic closed-loop component of neocortical connections with the basal ganglia and related thalamic nuclei. Their seminal review highlights five anatomically and functionally separated loops, all originating from, and returning to, different regions of the cerebral cortex. The projections of these loops, as they pass sequentially through the basal ganglia nuclei, are parallel and largely segregated, although there is evidence for interactions between the main projection lines both within the basal ganglia and between external structures [7,12,13]. Thus, a wide range of experimental evidence supports the concept that cortical–basal ganglia–thalamic–cortical channels have a significant closed component [1–3], which has

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been incorporated into contemporary models of basal ganglia function [14–17].

Subcortical loops

Anatomical evidence from various species suggests that many subcortical structures with the capacity to guide movement also have connections with the basal ganglia that are best conceived of as a series of parallel, at least partially closed, loops. In contrast to the cortical–basal ganglia loops, however, subcortical loops have a thalamic relay on the input, rather than on the return, link of the circuit (Figure 1a,b). Midbrain and hindbrain structures with the potential to provide input to the basal ganglia via a relay in the midline intralaminar complex of the thalamus include the superior and inferior colliculi [18,19], periaqueductal grey [20], pedunculopontine nucleus [21], cuneiform area and parabrachial complex [22], and various pontine and medullary reticular nuclei [19]. Correspondingly, a direct return link to each of these midbrain and hindbrain structures from either one or both of the main basal ganglia output nuclei has been reported [23–29]. The characteristics of individual components of the proposed closed loops between subcortical regions and the basal ganglia have been documented, but the full extent to which they actually represent functionally segregated parallel closed loops remains to be determined. However, for one midbrain structure, the superior colliculus, anatomical evidence for May and Hall's original concept of closed-loop connectivity with the basal ganglia [4] is robust, and this can serve as an exemplar against which the loop hypothesis can be evaluated for other subcortical structures.

Superior colliculus: looped connections with the basal ganglia

The superior colliculus, the mammalian homologue of the optic tectum, is, from a phylogenetic perspective, an ancient structure. It is composed of a variable number of alternating cell-rich and fibre-rich layers [30,31] and is responsible for the sensorimotor transformations required

to direct gaze shifts towards or away from unexpected, biologically salient events [32–35]. In most instances, a functional distinction is drawn [36] between the superficial layers, which receive unisensory visual input from the retina (and visual cortex in mammals), and the deep layers, which receive visual, auditory, somatosensory (tactile and noxious) and non-sensory modulatory inputs from widespread cortical and subcortical regions [35,37]. Descending outputs from the deep layers make direct contact with hindbrain premotor nuclei responsible for directing the animal towards or away from salient cues [32–35]. Deep-layer neurons are responsive to unisensory and multisensory stimuli [35] and exhibit bursts of activity tightly coupled to stimulus onset, to the initiation of a motor response, or to both [38]. In addition to its sensorimotor connections, the superior colliculus is one of the principal targets of both major output nuclei of the basal ganglia [23,25,26,39]. Traditionally, these connections are considered to be the principal routes whereby information processing within the basal ganglia influences brainstem motor mechanisms, particularly in the context of oculomotor control [40].

In addition to their descending projections to the pons and the medulla, both the superficial and the deep layers of the superior colliculus also have ascending connections to targets in the thalamus, including the lateral posterior nucleus [41–44] and the midline intralaminar nuclear complex [18,45]. In the present context, it is significant that ascending projections from the superior colliculus specifically target regions of the thalamus that provide the major thalamic input to the two principal input structures of the basal ganglia [9,46,47]. This arrangement suggests that the superior colliculus is an important afferent source of both sensory and motor information, in addition to a principal recipient of basal ganglia output. In this particular case, the input–output relationships are best characterized as several possibly independent, but overlapping, closed-looped systems.

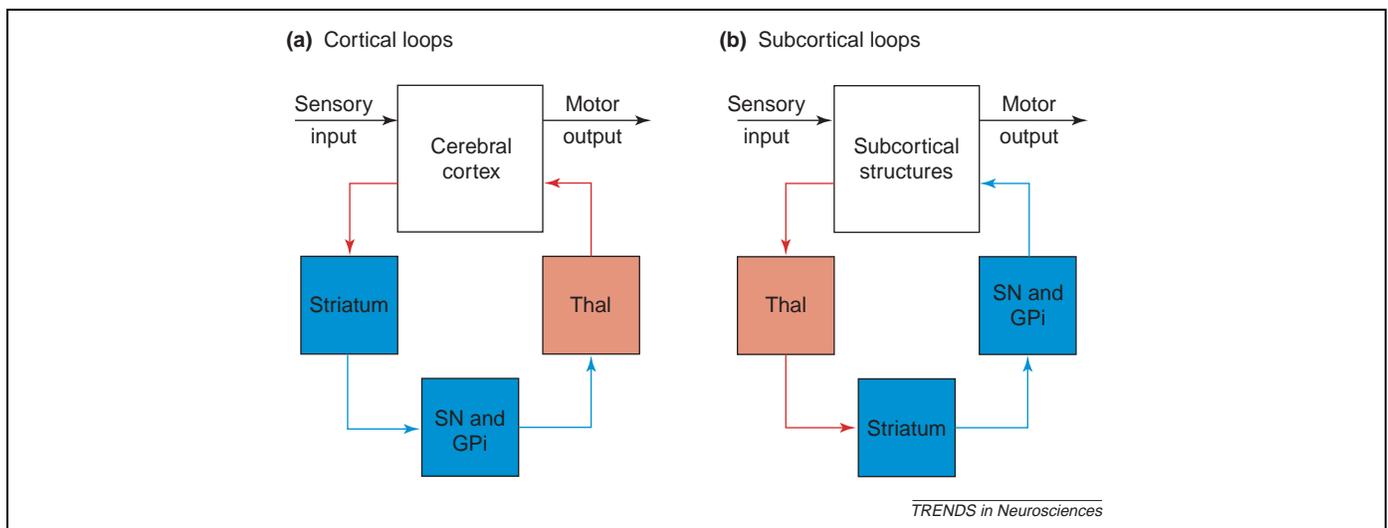


Figure 1. Cortical and subcortical sensorimotor loops through the basal ganglia. (a) For cortical loops with the basal ganglia, the position of the thalamic relay is on the return arm of the loop. (b) In the case of all subcortical loops, the thalamic relay is on the input side of the loop. Predominantly excitatory regions and connections are in red; inhibitory regions and connections are in blue. Abbreviations: GPi, internal globus pallidus; SN, substantia nigra; Thal, thalamus.

Superior colliculus: multiple loops

Close examination of ascending projections from the superior colliculus to the thalamus suggests that there are at least three functionally segregated systems, one originating from the superficial layers and two from the deep layers. The loops can be distinguished primarily according to their thalamic targets, and then according to how these thalamic regions subsequently connect with the striatum.

The superficial layer–extrageniculate visual thalamic loop (Figure 2a)

The major ascending output of the exclusively visual superficial layers is directed to the extrageniculate visual thalamus (the lateral posterior nucleus and pulvinar) [41–44]. In addition to its connections with extrastriate visual cortex [48,49], this thalamic region also projects extensively to lateral aspects of the body and tail of the caudate and dorsolateral putamen [43,44,46,50] (Figure 2a). The relay in the lateral posterior thalamus provides a route by which subcortical visual input can be made directly available to the striatum [43,44,46,50]. In the next link of the loop, the ‘direct’ striatonigral projection topography ensures that visual information associated with input from the lateral posterior thalamus would be directed preferentially to lateral aspects of the substantia nigra pars reticulata and to the substantia nigra pars lateralis [5]. It is within these nigral regions that signals related to visual orienting are most frequently encountered [51], and from which the final return link of the visual loop back to the superficial layers (and possibly to the deeper collicular layers) originates [52,53].

The deep layer–intralaminar thalamic loops (Figure 2b,c)

Ascending projections from the deep layers of the superior colliculus also terminate mainly in regions of the thalamus that give rise to significant afferent projections to the basal ganglia input nuclei. These are the caudal intralaminar complex (centromedian and parafascicular nuclei) (Figure 2b) and the rostral intralaminar thalamic group (central lateral, paracentral and central medial nuclei) (Figure 2c and Figure 3) [18,45]. Given that both the caudal and rostral intralaminar thalamic nuclei provide topographically ordered projections to all functional territories within the striatum [8,9], the colliculo–thalamo–basal ganglia–collicular projections involving these subregions of the intralaminar thalamus could represent components of functionally independent parallel loops (Figure 2b,c). Two differences in the type of contact made by fibres from the caudal and rostral intralaminar nuclei with striatal medium spiny neurons support this view. (i) Individual fibres from the caudal intralaminar nuclei tend to form clusters of terminals that make multiple contacts with individual medium spiny neurons [54,55]. By contrast, sparsely arborizing axons from the rostral intralaminar group (e.g. centrolateral nucleus) make relatively few contacts with many medium spiny neurons [56]. (ii) Synaptic contacts from the caudal intralaminar nuclei appear mainly on the dendritic shafts of medium spiny neurons [57], whereas synaptic input from the rostral intralaminar group (e.g. centrolateral

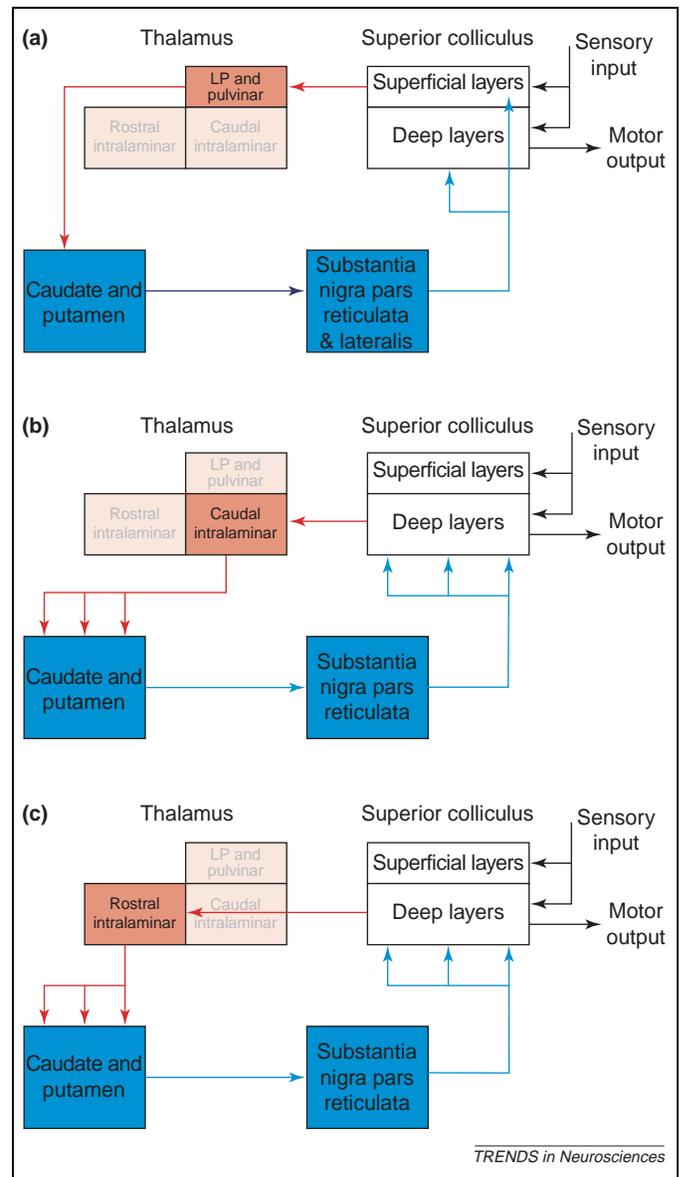
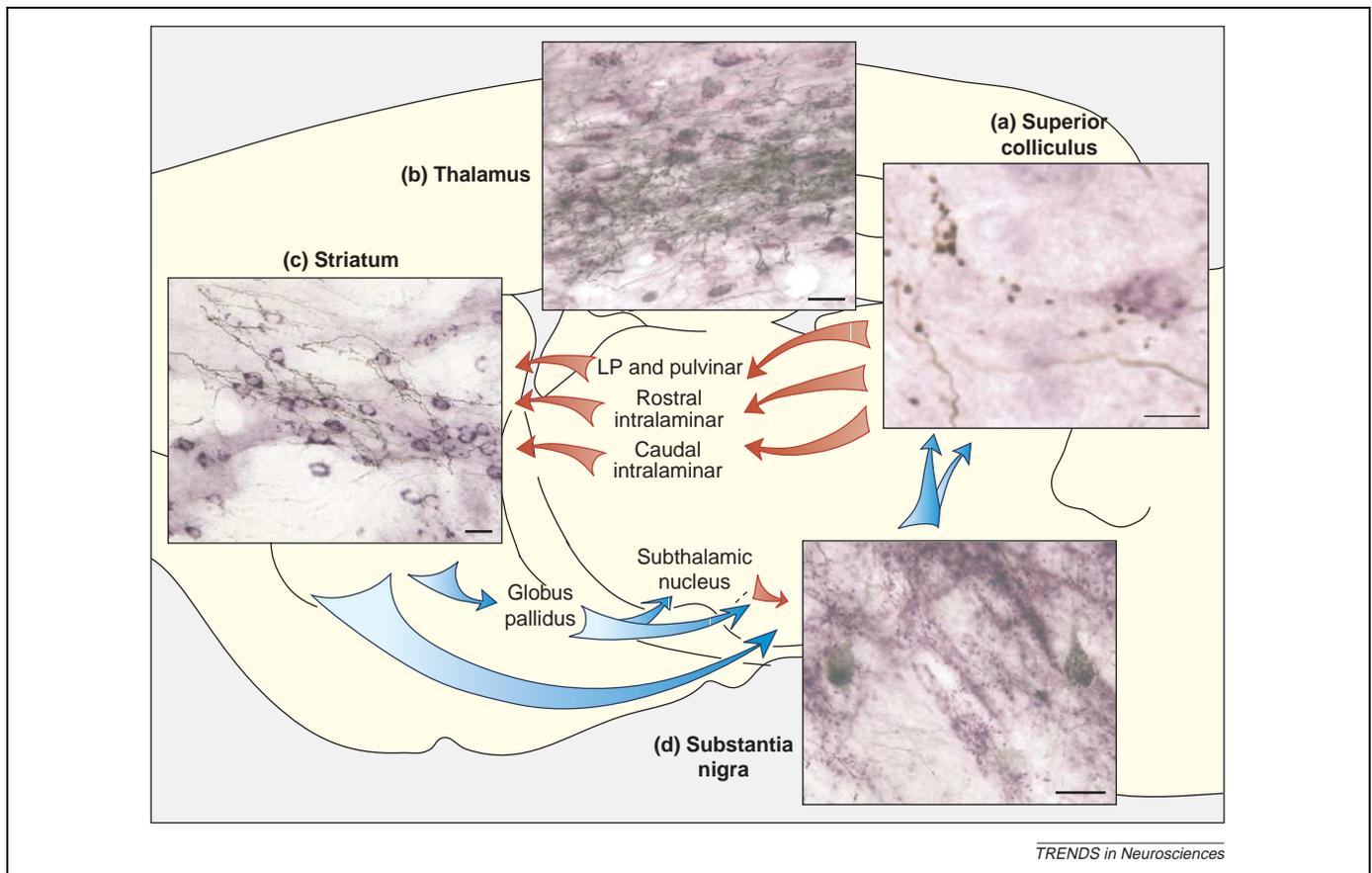


Figure 2. Multiple loops through the basal ganglia originating in the superior colliculus. (a) The superficial layer–extrageniculate visual thalamic loop. Ascending projections from the superficial layers relay in the visual thalamus [the lateral posterior nucleus (LP) and pulvinar], which in turn projects to the dorsolateral putamen. (b) The deep layer–caudal intralaminar loop. Projections from the deep collicular layers terminate in caudal intralaminar thalamic nuclei, which in turn project to all functional territories of the striatum. (c) The deep layer–rostral intralaminar loop. Projections from the deep collicular layers continue forward to contact the rostral intralaminar thalamic nuclei, which also project to all functional territories of the striatum. Return connections from the basal ganglia output nuclei (substantia nigra pars reticulata and/or pars lateralis) to the superior colliculus potentially close each of the three loops. Predominantly excitatory regions and connections are in red; inhibitory regions and connections are in blue.

nucleus) appears to predominate on dendritic spines [56]. It should also be noted that terminals from the caudal intralaminar complex are directed preferentially to substance-P-positive medium spiny neurons and make significant contact with the large aspiny cholinergic interneurons [57].

The remaining components of loops originating from the collicular deep layers have been well characterized [5] (Figure 2b,c and Figure 3). Hence, the intrinsic projection topography from all parts of the striatum to the basal ganglia output nuclei, and the projections from both



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Figure 3. Potentially closed connectivity in the colliculo–thalamo–basal ganglia–collicular loops. **(a)** In the superior colliculus, tectothalamic cells (purple) retrogradely labelled using cholera toxin subunit b (CTb) are in close association with nigroretectal terminals (black) anterogradely labelled using biotinylated dextran (BDA). **(b)** In the thalamus, thalamostriatal neurons (purple) retrogradely labelled using CTb are in close association with tectothalamic terminals (black) anterogradely labelled using BDA. **(c)** In the striatum, striatonigral neurons (purple) retrogradely labelled using CTb are in close association with thalamostriatal terminals (black) anterogradely labelled using BDA. **(d)** In the substantia nigra, nigroretectal neurons (black) retrogradely labelled using BDA are in close association with striatonigral terminals (purple) anterogradely labelled using CTb. Predominantly excitatory connections are in red; inhibitory connections are in blue. Scale bars: 10 μm (superior colliculus) and 20 μm (thalamus, striatum and substantia nigra).

output nuclei back to the deep layers of the superior colliculus [23,25,26,52,53,58], where the majority of colliculothalamic neurons reside (Figure 3), have been described in detail.

Thus, in summary, there appear to be at least two, and possibly three, presumably closed subcortical looped systems through the basal ganglia arising from, and returning to, the superior colliculus (Figure 3). These systems cover largely overlapping territories within the basal ganglia, but can be distinguished on the basis of different input relay nuclei in the thalamus. Many questions concerning functions of these anatomically segregated inputs remain. Perhaps they convey separate outputs from collicular circuits that are differentially sensitive to threats or appetitive stimuli [34]. Alternatively, they could relay different functional characteristics of collicular sensorimotor signals (e.g. position, salience or timing of motor commands) [35]. How these apparently separate inputs from the thalamus are processed within the basal ganglia to generate the specific disinhibitory output signals projected back to the superior colliculus also needs investigation. Given the canonical microcircuitry of intrinsic basal ganglia nuclei [2,5], resolution of such issues will help to clarify the computational functions performed by anatomically

defined channels through the basal ganglia – an issue that we will now address.

Why looped architectures?

A general statement of the current proposal is that mainly closed-loop connections are a fundamental feature of architecture linking the basal ganglia not only with cortical domains but also with subcortical systems. An immediate question is what unique feature of looped architectures through the basal ganglia caused them to appear early in evolution and to be retained in a highly conserved form in most vertebrate species [59]. One suggestion [15], for which there is growing empirical support, is that by prioritizing simultaneous potentially incompatible inputs and then returning the solution to the sites from which the inputs originated (i.e. via closed loops), the intrinsic circuitry of the basal ganglia could provide an elegant solution to the ‘selection problem’. This fundamental computational issue arises when multiple distributed parallel-processing sensory, cognitive and affective systems, each with the potential to influence movement, have to share a limited set of motor resources. Given the maladaptive consequences of having two incompatible systems (e.g. ‘approach’ and ‘avoid’) trying to influence the same set of muscles simultaneously, a

solution must be present in any effective multifunctional system to ensure orderly access to shared motor resources.

One way of solving this 'selection problem', which was devised independently for artificial control systems [60], is to have competing functional systems separately submit phasic excitatory 'bids' (or inputs) to a central selection mechanism, which in turn exerts tonic inhibitory control over all competitors via individual return inhibitory links (the outputs). Based on the relative salience of the input bids, the central selector, through a process of selective disinhibition [60], withdraws inhibition from the 'winning' competitor, thereby allowing it sole access to relevant components of the motor plant (i.e. effectors and their local control circuitry). This system relies on a largely segregated looped architecture comprising excitatory inputs to, and inhibitory outputs from, a central selection mechanism. It is on this basis that the basal ganglia were proposed as a mechanism to arbitrate between distributed, parallel processing functional systems within the brain [15]. Uniquely, this proposal has been supported by the use of biologically constrained models of basal ganglia architecture, both in simulation [16,17] and in the control of action selection in a mobile robot [61]. It also was noted that the intrinsic architecture of the basal ganglia, which is more-or-less common to all functional territories, could equally well be used to select between inputs representing overall competing behavioural goals (limbic inputs), competing actions to achieve a selected goal (associative inputs) and competing movements to achieve a selected action (sensorimotor inputs) [15]. In the context of orienting gaze shifts, subcortical loops through the basal ganglia associated with the superior colliculus could serve to interrupt ongoing behaviour and enable the guidance of oculomotor and related motor plant to be switched to the initiating sensory event. With this and other functional systems, the current hypothesis – that some of the inputs representing behavioural goals, actions and movements could derive from subcortical sources – has profound implications for understanding the neural substrates underlying behavioural choice.

Implications of cortical and subcortical loops

The immediate consequence of having cortical and subcortical command systems 'bidding' to control a shared motor resource is that such bids can be submitted jointly (cooperatively) or independently (in competition with each other). Again, we draw on the superior colliculus and cortical oculomotor systems as examples to illustrate these possibilities. Anatomical connections between the superior colliculus, the cortical frontal eye fields and the basal ganglia would enable cooperative or competitive control of eye movements. For example, cortical and striatal targets of individual midline and intralaminar thalamic nuclei tend to be connected via topographically organized corticostriatal connections [62]. Potentially, this arrangement could enable the salience of a 'bid' to the striatum from the superior colliculus to be supported or boosted by simultaneously activated input from the frontal cortex. Similarly, direct connections from the frontal eye fields to the superior colliculus [63,64] could

also be used to recruit support (via colliculo-thalamo-striatal projections) for a 'bid' originating in the cortex. Alternatively, given that the sensory mechanisms of the superior colliculus seem particularly tuned to signal unpredicted visual change (e.g. appearance, disappearance or movement [32,33,35]), with the cortical oculomotor systems perhaps more crucial for generating saccades on the basis of more complex stimulus-response contingencies (e.g. to remembered goals, requiring following of abstract rules or modelling of the distant future [65–67]), the potential for conflict between cortical and subcortical systems to direct eye movements to different locations in space is obvious. At this juncture, it is interesting to note that some features of the thalamostriatal input to the basal ganglia described here could give subcortical systems the edge in any straight competition with the cortex. For example, projections from caudal intralaminar regions have dense terminals on striatal neurons that make direct connections with the basal ganglia output nuclei [54,55,57] involved in movement selection [14–17], whereas corticostriatal input is more diffusely distributed to multiple neurons of the direct and indirect pathways [5]. This arrangement would require a comparatively large synchronized population response within the cortex to produce a comparable effect on striatal output. Similarly, thalamic afferents, but apparently not corticostriatal inputs [57], target the large tonically active cholinergic neurons that can also influence striatal activity profoundly. Perhaps these differences can explain why unexpected, physically weak sensory events, conveyed by input from subcortical loops, can find it comparatively easy to interrupt ongoing activity and elicit orientating responses.

Finally, we should like to suggest that, in its most general form, the current proposal of cortical and subcortical control systems interacting with a central selection mechanism has implications far beyond the redirection of gaze [68]. Could the competitive advantage of subcortical systems in certain circumstances provide an explanation for seemingly ill-conceived or irrational choices [69]? Consider, for example, drug addiction, where intellectual (presumably cortical) considerations can be in direct conflict with lower-level (possibly subcortical) motivations: addicts can often articulate many reasons why they should abstain from drug use, yet at certain times (especially when faced with sensory stimuli associated with prior drug taking) feel uncontrollable urges to indulge. Within an even wider context, perhaps it is the looped arrangement of competing inputs from cortical and subcortical systems to a central selection mechanism that underlies the enduring conflict between 'head' and 'heart' in human art and literature ...and life.

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References

- 1 Alexander, G.E. *et al.* (1986) Parallel organization of functionally segregated circuits linking basal ganglia and cortex. *Annu. Rev. Neurosci.* 9, 357–381
- 2 Parent, A. and Hazrati, L.N. (1995) Functional anatomy of the basal ganglia. I. The cortico–basal ganglia–thalamo–cortical loop. *Brain Res. Rev.* 20, 91–127
- 3 Middleton, F.A. and Strick, P.L. (2000) Basal ganglia and cerebellar loops: motor and cognitive circuits. *Brain Res. Rev.* 31, 236–250
- 4 May, P.J. and Hall, W.C. (1984) Relationships between the nigrotectal pathway and the cells of origin of the predorsal bundle. *J. Comp. Neurol.* 226, 357–376
- 5 Gerfen, C.R. and Wilson, C.J. (1996) The basal ganglia. In *Handbook of Chemical Neuroanatomy* (Vol 12) *Integrated Systems of the CNS, Part III* (Swanson, L.W. *et al.*, eds), pp. 371–468, Elsevier
- 6 Kolomiets, B.P. *et al.* (2003) Basal ganglia and processing of cortical information: functional interactions between trans-striatal and trans-subthalamic circuits in the substantia nigra pars reticulata. *Neuroscience* 117, 931–938
- 7 Groenewegen, H.J. *et al.* (1999) Integration and segregation of limbic cortico–striatal loops at the thalamic level: an experimental tracing study in rats. *J. Chem. Neuroanat.* 16, 167–185
- 8 Mengual, E. *et al.* (1999) Thalamic interaction between the input and the output systems of the basal ganglia. *J. Chem. Neuroanat.* 16, 187–200
- 9 Van der Werf, Y.D. *et al.* (2002) The intralaminar and midline nuclei of the thalamus. Anatomical and functional evidence for participation in processes of arousal and awareness. *Brain Res. Rev.* 39, 107–140
- 10 Steinbusch, H.W. (1981) Distribution of serotonin-immunoreactivity in the central nervous system of the rat – cell bodies and terminals. *Neuroscience* 6, 557–618
- 11 Smith, Y. *et al.* (1998) Microcircuitry of the direct and indirect pathways of the basal ganglia. *Neuroscience* 86, 353–387
- 12 Joel, D. and Weiner, I. (1994) The organization of the basal ganglia–thalamocortical circuits: open interconnected rather than closed segregated. *Neuroscience* 63, 363–379
- 13 Haber, S.N. (2003) The primate basal ganglia: parallel and integrative networks. *J. Chem. Neuroanat.* 26, 317–330
- 14 Mink, J.W. (1996) The basal ganglia: focused selection and inhibition of competing motor programs. *Prog. Neurobiol.* 50, 381–425
- 15 Redgrave, P. *et al.* (1999) The basal ganglia: a vertebrate solution to the selection problem? *Neuroscience* 89, 1009–1023
- 16 Gurney, K. *et al.* (2001) A computational model of action selection in the basal ganglia. I. A new functional anatomy. *Biol. Cybern.* 84, 401–410
- 17 Gurney, K. *et al.* (2001) A computational model of action selection in the basal ganglia. II. Analysis and simulation of behaviour. *Biol. Cybern.* 84, 411–423
- 18 Krout, K.E. *et al.* (2001) Superior colliculus projections to midline and intralaminar thalamic nuclei of the rat. *J. Comp. Neurol.* 431, 198–216
- 19 Krout, K.E. *et al.* (2002) Brainstem projections to midline and intralaminar thalamic nuclei of the rat. *J. Comp. Neurol.* 448, 53–101
- 20 Krout, K.E. and Loewy, A.D. (2000) Periaqueductal gray matter projections to midline and intralaminar thalamic nuclei of the rat. *J. Comp. Neurol.* 424, 111–141
- 21 Erro, E. *et al.* (1999) Relationships between thalamostriatal neurons and pedunculo-pontine projections to the thalamus: a neuroanatomical tract-tracing study in the rat. *Exp. Brain Res.* 127, 162–170
- 22 Krout, K.E. and Loewy, A.D. (2000) Parabrachial nucleus projections to midline and intralaminar thalamic nuclei of the rat. *J. Comp. Neurol.* 428, 475–494
- 23 Takada, M. *et al.* (1994) Direct projections from the entopeduncular nucleus to the lower brainstem in the rat. *J. Comp. Neurol.* 342, 409–429
- 24 Kirouac, G.J. *et al.* (2004) GABAergic projection from the ventral tegmental area and substantia nigra to the periaqueductal gray region and the dorsal raphe nucleus. *J. Comp. Neurol.* 469, 170–184
- 25 Deniau, J.M. and Chevalier, G. (1992) The lamellar organization of the rat substantia nigra pars reticulata – distribution of projection neurons. *Neuroscience* 46, 361–377
- 26 Redgrave, P. *et al.* (1992) Topographical organization of the nigrotectal projection in rat: evidence for segregated channels. *Neuroscience* 50, 571–595
- 27 Yasui, Y. *et al.* (1991) Non-dopaminergic projections from the substantia-nigra pars lateralis to the inferior colliculus in the rat. *Brain Res.* 559, 139–144
- 28 Schneider, J.S. (1986) Interactions between the basal ganglia, the pontine parabrachial region, and the trigeminal system in cat. *Neuroscience* 19, 411–425
- 29 Takakusaki, K. *et al.* (2004) Role of basal ganglia–brainstem pathways in the control of motor behaviors. *Neurosci. Res.* 50, 137–151
- 30 Kanaseki, T. and Sprague, J.M. (1974) Anatomical organization of pretectal and tectal laminae in the cat. *J. Comp. Neurol.* 158, 319–337
- 31 Reiner, A. (1994) Laminar distribution of the cells of origin of ascending and descending tectofugal pathways in turtles: implications for the evolution of tectal lamination. *Brain Behav. Evol.* 43, 254–292
- 32 Wurtz, R.H. and Albano, J.E. (1980) Visual–motor function of the primate superior colliculus. *Annu. Rev. Neurosci.* 3, 189–226
- 33 Sparks, D.L. (1986) Translation of sensory signals into commands for control of saccadic eye movements: role of the primate superior colliculus. *Physiol. Rev.* 66, 118–171
- 34 Dean, P. *et al.* (1989) Event or emergency? Two response systems in the mammalian superior colliculus. *Trends Neurosci.* 12, 137–147
- 35 Stein, B.E. and Meredith, M.A. (1993) *The Merging of the Senses*, MIT Press
- 36 Casagrande, V.A. *et al.* (1972) Superior colliculus of the tree shrew: a structural and functional subdivision into superficial and deep layers. *Science* 177, 444–447
- 37 Sefton, A.J. and Dreher, B. (1995) Visual system. In *The Rat Nervous System* (Paxinos, G., ed.), pp. 833–898, Academic Press
- 38 Jay, M.F. and Sparks, D.L. (1987) Sensorimotor integration in the primate superior colliculus. I Motor convergence. *J. Neurophysiol.* 57, 22–34
- 39 Jiang, H. *et al.* (2003) Opposing basal ganglia processes shape midbrain visuomotor activity bilaterally. *Nature* 423, 982–986
- 40 Hikosaka, O. *et al.* (2000) Role of the basal ganglia in the control of purposive saccadic eye movements. *Physiol. Rev.* 80, 953–978
- 41 Abramson, B.P. and Chalupa, L.M. (1988) Multiple pathways from the superior colliculus to the extrageniculate visual thalamus of the cat. *J. Comp. Neurol.* 271, 397–418
- 42 Berson, D.M. and Graybiel, A.M. (1991) Tectorecipient zone of cat lateral posterior nucleus – evidence that collicular afferents contain acetylcholinesterase. *Exp. Brain Res.* 84, 478–486
- 43 Harting, J.K. *et al.* (2001) The visual–oculomotor striatum of the cat: functional relationship to the superior colliculus. *Exp. Brain Res.* 136, 138–142
- 44 Lin, C.S. *et al.* (1984) Nonintralaminar thalamostriatal projections in the gray squirrel (*Sciurus carolinensis*) and tree shrew (*Tupaia glis*). *J. Comp. Neurol.* 230, 33–46
- 45 Chevalier, G. and Deniau, J.M. (1984) Spatio–temporal organization of a branched tecto–spinal/tecto–diencephalic neuronal system. *Neuroscience* 12, 427–439
- 46 Takada, M. *et al.* (1985) Topographical projections from the posterior thalamic regions to the striatum in the cat, with reference to possible tecto–thalamo–striatal connections. *Exp. Brain Res.* 60, 385–396
- 47 Feger, J. *et al.* (1994) The projections from the parafascicular thalamic nucleus to the subthalamic nucleus and the striatum arise from separate neuronal populations – a comparison with the corticostriatal and corticosubthalamic efferents in a retrograde fluorescent double-labelling study. *Neuroscience* 60, 125–132
- 48 Updyke, B.V. (1981) Projections from visual areas of the middle suprasylvian sulcus onto the lateral posterior complex and adjacent thalamic nuclei in cat. *J. Comp. Neurol.* 201, 477–506
- 49 Raczkowski, D. and Rosenquist, A.C. (1983) Connections of the multiple visual cortical areas with the lateral posterior-pulvinar complex and adjacent thalamic nuclei in the cat. *J. Neurosci.* 3, 1912–1942
- 50 Harting, J.K. *et al.* (2001) Striatal projections from the cat visual thalamus. *Eur. J. Neurosci.* 14, 893–896
- 51 Hikosaka, O. and Wurtz, R.H. (1983) Visual and oculomotor function of monkey substantia nigra pars reticulata. I. Relation of visual and auditory responses to saccades. *J. Neurophysiol.* 49, 1230–1253
- 52 Redgrave, P. *et al.* (1992) Anticonvulsant role of nigrotectal projection in the maximal electroshock model of epilepsy – II. Pathways from substantia nigra pars lateralis and adjacent peripeduncular area to the dorsal midbrain. *Neuroscience* 46, 391–406

- 53 Harting, J.K. *et al.* (1988) Neuroanatomical studies of the nigrotectal projection in the cat. *J. Comp. Neurol.* 278, 615–631
- 54 Deschenes, M. *et al.* (1995) Two different types of thalamic fibers innervate the rat striatum. *Brain Res.* 701, 288–292
- 55 Parent, M. and Parent, A. (2005) Single-axon tracing and three-dimensional reconstruction of centre median-parafascicular thalamic neurons in primates. *J. Comp. Neurol.* 481, 127–144
- 56 Ichinohe, N. *et al.* (2001) Intrastratial targets of projection fibers from the central lateral nucleus of the rat thalamus. *Neurosci. Lett.* 302, 105–108
- 57 Smith, Y. *et al.* (2004) The thalamostriatal system: a highly specific network of the basal ganglia circuitry. *Trends Neurosci.* 27, 520–527
- 58 Graybiel, A.M. (1978) Organisation of the nigrotectal connection: an experimental tracer study in the cat. *Brain Res.* 143, 339–348
- 59 Reiner, A. *et al.* (1998) Structural and functional evolution of the basal ganglia in vertebrates. *Brain Res. Rev.* 28, 235–285
- 60 Snaith, S. and Holland, O. (1990) An investigation of two mediation strategies suitable for behavioural control in animals and animats. In *From Animals to Animats: Proceedings of the First International Conference on the Simulation of Adaptive Behaviour* (Meyer, J.-A. and Wilson, S., eds), pp. 255–262, MIT Press
- 61 Prescott, T.J. *et al.* (2002) The robot basal ganglia: action selection by an embedded model of the basal ganglia. In *Basal Ganglia VII* (Nicholson, L. and Faull, R., eds), pp. 349–356, Plenum Press
- 62 Groenewegen, H.J. and Berendse, H.W. (1994) The specificity of the nonspecific midline and intralaminar thalamic nuclei. *Trends Neurosci.* 17, 52–57
- 63 Leichnetz, G.R. *et al.* (1981) The prefrontal corticotectal projection in the monkey; an anterograde and retrograde horseradish peroxidase study. *Neuroscience* 6, 1023–1041
- 64 Hartwich-Young, R. and Weber, J.T. (1986) The projection of frontal cortical oculomotor areas to the superior colliculus in the domestic cat. *J. Comp. Neurol.* 253, 342–357
- 65 Gold, J.I. and Shadlen, M.N. (2001) Neural computations that underlie decisions about sensory stimuli. *Trends Cogn. Sci.* 5, 10–16
- 66 Schall, J.D. (2002) The neural selection and control of saccades by the frontal eye field. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 357, 1073–1082
- 67 Glimcher, P.W. (2003) The neurobiology of visual-saccadic decision making. *Annu. Rev. Neurosci.* 26, 133–179
- 68 Prescott, T.J. *et al.* (1999) Layered control architectures in robots and vertebrates. *Adaptive Behav.* 7, 99–127
- 69 Berridge, K.C. (2002) Irrational pursuit: Hyper-incentive from a visceral brain. In *The Psychology of Economic Decisions* (Vol. 1) (Brocas, I. and Carrillo, J.D., eds), pp. 17–40, Oxford University Press

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