

The Striatopallidal System and Intentional Perception

Daniel Pouzner

daniel@pouzner.name

Abstract

The neostriatum and associated organs are a widely distributed and densely interconnected subcortical system. Anatomically, through a variety of stages and pathways, the striatopallidal system (SPS) is a complex mosaic of segregation, convergence, and divergence. Computationally, it is characterized by competitive selection and reinforcement-driven learning. Although the SPS is canonically a system of motor control and performance, more recent research has established that it is integral to cognition and other non-motor functions. Selection (decision) is its essential function, and selection is as integral to cognition, memory, attention, and perception, as to motor performance. It is the role of the SPS in perception that has received the least attention, but this role is a natural aspect of its role in selection, and is well-attested by recent experiments.

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1 Introduction

In 1925, British neurologist Kinnear Wilson described the basal ganglia as the “dark basement of the brain” (Wilson, 1925). The twentieth century would see striking progress in the functional parcellation of the cerebral cortex, spinal and peripheral nervous system, brain stem, and diencephalon. But alas, the striatopallidal system¹ would remain largely in the dark.

A revolution in thinking on the SPS can be traced to the parallel segregated loop model described by Alexander et al. (1986), and to the striosome-matrisome finding described by Graybiel and Ragsdale (1978). With these advances, internal structural organization was appreciated where none had been before.

It is no coincidence that the cortical and diencephalic regions that have proved least amenable to functional parcellation – notably, prefrontal cortex (PFC) and intralaminar thalamic nuclei – are also the regions that are most intimate with the SPS. Nonetheless, enough thought and evidence has accumulated on the question

¹ The “striatopallidal system” (SPS) is circumscribed to include the neostriatum, both segments of the pallidum, their respective ventral extensions, the substantia nigra (SN, all parts), the ventral tegmental area (VTA), the subthalamic nucleus (STN), and the nucleus basalis (NB). For a similar circumscription and terminology, see Marín et al. (1998a). The traditional appellation “basal ganglia” has various shortcomings, as does a related neologism, “striatal complex”. The basal ganglia frequently, but inconsistently, are held to include the amygdala (itself a controversial designation (e.g. Swanson and Petrovich, 1998)) and claustrum even though neither is hodologically integral to or cytologically consistent with the system. The VTA is seldom included, even though it is continuous with the SNc and occupies a closely related position in basal ganglia circuitry. But perhaps the decisive complaint about “basal ganglia” is that the basal ganglia are not ganglia at all, but a widely distributed set of nuclei. In comparison, the only problem with the neologism “striatal complex” is that its abbreviation leads to confusion with the abbreviation for the superior colliculus. But this is a serious problem, because the SC is intimate with the SPS.

of SPS function to shed some real light on it. Elucidating its perceptual functions is probably a particularly effective avenue whereby to bring it into the community of organs understood to be integral and indispensable to all domains of mentation.

I argue in this paper that the SPS is extensively involved in *purposeful perception* – in which one (to be glib) sees the world the way one wants to see it, or indeed sees the world one wants to see. Attention and mental imagery are the most recognized examples of this, and comprise the bulk of the evidence recapitulated below.

But there is a broader sense in which perception can be purposeful, and it is suggested by the capacity for mental imagery. *Intentional perception* is perception as a sort of engine, in which the nature (the intrinsic intent) of perceived objects is modelled. Sensation serves to maintain registration of the models with the outside world. This sort of perception is evidently contingent on internally directed, rule-pursuant actions, and it would be surprising were the SPS not intimately involved in this phenomenon.

2 What does the striatopallidal system do?

The SPS is a labyrinth (Appendix A is an overview of its circuitry and chemistry), but after the SPS revolution noted above, many investigators have described relatively simple unified functional models. Two themes recur: reinforcement learning, particularly the actor-critic architecture (in which the evaluator is separate from, and trains, the orchestrator), and selection, particularly with a competitive winner-

take-all dynamic.

Any autonomous system that must take effective and flexible actions in a complex and underconstraining environment must have a highly integrative engine of adaptive action selection. In one conception (Redgrave et al., 1999), the SPS is an instantiation of this class of engine, peculiar to the vertebrate phylogeny (see also Marín et al., 1998b).

Another prominent conception (Graybiel, 1998) emphasizes the propensity of the SPS to orchestrate complex, multi-step responses to context, and to amass collections of such responses in a gradual and continuing learning process. The SPS is thus viewed as a pattern generator guiding cognition and behavior. The neocortex supplies most of the context, which is informationally compressed in the SPS to drive pattern selection; thalamic and tectal targets receive the patterns.

The most generic descriptions of SPS function distill its operation down to the mathematical abstraction of reduction of dimension (of degrees of freedom) according to rules engendered by a history of reinforcement signals (Bar-Gad et al., 2003). These models are motivated in large part by the anatomical imperatives of the SPS – its vast input is funneled from the neocortex in successive stages to a relatively (three to four orders of magnitude) smaller population of neurons that output to the thalamus. The dimensionality reduction paradigm is evidently compatible with and suggestive of the selection and pattern generation paradigms.

Reduction of dimension is a generally applicable computation, useful in perception,

cognition, and the orchestration of motor output. While the latter has often featured in functional accounts of the SPS, wider function (including perception and mental imagery) has in fact long been recognized (Brown et al., 1997).

To lay the foundation for a review of current thinking on the role of the SPS in perceptual cognition, I will first briefly review the relation of the SPS to other brain organs, particularly the neocortex and thalamus. I emphasize the reinforcement driven dimensionality reduction (RDDR) paradigm, and suggest the relevance of it to perception.

The pallidal output of the SPS targets thalamic and midbrain loci that are intimate with neocortical regions characterized by a large intrinsic number of degrees of freedom (i.e., thalamocortical subsystems whose states are not tightly constrained by their extrinsic inputs). The thalamocortical subsystems that are in straightforward topographic registration with sensory organs are not direct targets of pallidal output, because their states are well-determined by their inputs. Indeed, primary sensory areas are arranged for highly parallel processing (topographically arranged projection neurons with small receptive fields subject to highly localized lateral inhibition), and an arbitrating supervisor would tend to disrupt this deleteriously.

With increasing distance from these primary subsystems, degrees of freedom and pallidal influence grow. As processing progresses toward motor output, projection neurons have larger receptive fields in terms of sensory input topography, so that there is less potential for parallelism. Arbitration is progressively more applicable.

To reconcile excessive freedom with ever more contentious cognitive resources, the SPS contributes constraints, allowing moment-to-moment solutions in the underdetermined systems under its influence. This influence can be viewed as strategic selection.

Reward is usually the goal underlying the strategy. For example, the SPS can select direction of gaze on this basis (Hikosaka et al., 2006). More specifically, the SPS appears to make selections that tend to minimize conflicts (Redgrave et al., 1999; Stafford and Gurney, 2005) and the effort and expense (Burns et al., 1997) of goal pursuit. Conflict is essentially inherent in an individual's repertoire of goals, which have complicated internal relations of predication and antagonism. The SPS has a selection role in this overdetermined system, as much as to underdetermined systems.

It is particularly easy to relate this conception (RDDR, disambiguation, and conflict resolution) to thalamocortical motor subsystems. There, the output has an enormous number of degrees of freedom, there is only one body to command (a relative paucity of parallelism), action carries an immediate and substantial metabolic cost, and the control system must contend with a complicated set of constraints associated with goals, the body's dynamical envelope, and the objects and obstacles of the environment. This arrangement explains, in large part, why pallidally innervated motor subsystems are much closer to primary motor subsystems, than are pallidally innervated sensory subsystems to the primary sensory subsystems that precede them. But that the pallidum does indeed innervate sensory subsystems, as

detailed below, underscores the generality of the SPS's role as arbiter in underdetermined subsystems.

The winner-take-all dynamic mentioned above as a dynamical characteristic of the SPS, has a generalized parallel induced by inhibitory interneurons throughout the neuraxis, but notably in sensory channels (Guyonneau et al., 2004). These local inhibitions cause that population of neurons that reaches threshold first to tend to be the only population that reaches threshold for the moment. The effect of pallidal disinhibition, then, is to bias which cells will tend to reach threshold first, and hence drive downstream cognitive infrastructure.

This is not just a mechanism for mediating attention, but also for determining which pathways will participate in the expression of plasticity, which itself is highly dependent on timing (Markram et al., 1997). The pallidum thus drives the thalamo-cortical system to gain expertise associated with percepts that are, in the judgement of the SPS, important. Because the SPS is largely driven by neocortical afferents, the effect is that the neocortex and SPS train each other. What the SPS adds to the rapid, local k-winners-take-all dynamic of the perceptual neocortex, is a broader, slower winner-take-all dynamic. The reticular nucleus of the thalamus likely serves a similar and related role.

While modulation of spike primacy bias may predominate as a mechanism of perceptual attention, clearly it is the modulation of sustained spike density that predominates in late motor channels, in which effortful and sustained action must be

induced directly.

Alexander et al. (1986) describe five closed circuits from neocortex through the SPS to the thalamus, and back to neocortex, each identified by the implicated neocortical region. While their model is not complete, it is nonetheless instructive that the neocortical regions implicated in their “dorsolateral prefrontal”, “lateral orbitofrontal”, and “anterior cingulate” circuits account (in humans) for the better part of neocortical surface area addressed in their model. It has been appreciated, at least since the time of Phineas Gage’s 1848 encounter with a tamping iron (Macmillan and Macmillan, 1999), that these three cortical areas are implicated not in motor performance but in more abstract mental functions, collectively designated “personality”.

In models of PFC and anterior cingulate cortex (ACC) function, there is extensive overlap with the SPS functions described above. Miller and Cohen (2001) describe the PFC as a supervisor that orchestrates goal-relevant perception, cognition, and action. Set shifting (dynamic, context-driven alteration of stimulus-response relations, with a prominent top-down attentional component) is a related function of the PFC (Ravizza and Ciranni, 2002). And the putative role of the ACC in orchestrating resolution of conflicts in a highly integrative fashion (Paus, 2001; Botvinick et al., 2001; Wang et al., 2005; Davis et al., 2005) is consistent with the conflict minimization role posited for the SPS.

Plausibly, the central mechanism whereby the PFC inhibits goal-irrelevant neural activity is through its projections through the SPS to the thalamus. On this basis

alone, the PFC and SPS may constitute a single indivisible system. The effects of neostriatal lesions in humans (particularly of the head of the caudate nucleus) are marked impairments of intention, attention, working memory, and other top-down control and reconciliation mechanisms (Benke et al., 2003). Thus, neostriatal lesions and PFC/ACC lesions result in strikingly similar deficits.

The thalamic targets of the SPS project back upon the PFC, tightening the integration and positioning the SPS to act as arbiter of the supremely underdetermined PFC. In a continuing succession of instants, the SPS can thus select which among the immense repertoire of goals represented in PFC is actively driving cognition and behavior, and can organize cognition and behavior around these goals. This intimacy of the PFC with the SPS will become significant below as I scrutinize the role of the SPS in perception.

The A10 cluster of nuclei in the midbrain, collectively termed the ventral tegmental area (VTA), is at the center of the SPS's reward mechanism, with influence spanning the neuraxis (Geisler and Zahm, 2005). The SPS's reward mechanism, in turn, is at the center of the brain's neuroeconomical engine – the biological computer that maximizes reward and minimizes effort (Glimcher and Rustichini, 2004). Among isocortical regions, VTA innervates the ACC most intensely. ACC is central to the recruitment of the machinery of supervisory arbitration (chiefly PFC and the SPS) upon detection of cognitive conflict and contention (Paus, 2001). Thus VTA's projection to ACC carries messages of frustration, and over time the ACC learns to preempt the behaviors that lead to these messages (Magno et al., 2006).

VTA also projects directly to sensory cortices of all modalities (Oades and Halliday, 1987), a significant relation in a consideration of the perceptual roles of the SPS. Parsimony, the sort of representation approached by a neuroeconomical engine, is crucial in forming the cognitive models that constitute perception.

The final stop in this abbreviated tour of the SPS is the nucleus basalis of Meynert, magnocellular part (NBM), the major source of cholinergic innervation for the neocortex and hippocampus, among other targets (Mufson et al., 2003). The NBM receives projections from the neostriatum and paleostriatum (c.f. Appendix A). Stimulation of NBM's projections is a putative mechanism whereby attention can be directed and heightened in response to subjective behavioral relevance and valence (Wenk, 1997). Significantly, NBM stimulation coincident with sensory stimulation can induce large scale reorganization in sensory neocortex (Kilgard and Merzenich, 1998). In short, through NBM the SPS exerts a profound influence throughout the cerebral cortex, and of particular relevance here, over sensory cortical regions.

An important feature of the SPS is tonic activity. The dopaminergic projectors (chiefly, VTA and SNc) are tonically active, so that dopamine can be either reduced (relaying deterrence, signifying disappointment or aversive stimuli) or increased (relaying reinforcement, signifying expectation of or surprise at reward) relative to the resting baseline (Schultz, 2006). While the projection neurons of the CPu are tonically quiescent, the CPu contains tonically active interneurons that are a putative substrate for the learning of associations between sensory-cognitive circumstance and patterns of excitation that induce utilitarian CPu output (Aosaki et al.,

1994). The projection neurons in the GP and SNr are tonically active, so that at rest the GPi and SNr moderately inhibit their thalamic targets (and the GPe moderately inhibits the STN).

The system of the thalamus and cerebral cortex, with its exhaustive and highly specific complement of mutual projections – the vehicle of the thalamocortical dialogue (Llinás and Ribary, 2001) – is the principal source of input for the SPS, and is the principal target upon which the SPS acts. The thalamocortical and corticothalamic projections are both glutamatergic, so that without adequate damping the system tends to oscillate synchronously and globally. The thalamocortical system has intrinsic damping mechanisms (*e.g.* the reticular and intralaminar nuclei of the thalamus and various GABAergic interneurons in cortex – curiously, somatic corticofugal fibers that collateralize in the striatum or reticular nucleus do not collateralize in both (Lévesque et al., 1996)). But the inhibitory action of the SPS on the thalamus can be so strong that it arrests thalamocortical motor activity, as it does pathologically in parkinsonism (etiologically, loss of midbrain dopamine neurons, with the loss most pronounced in the SNc). Alternatively, when SPS output is pathologically absent, the resulting thalamic and tectal disinhibition is such that sensory stimuli induce involuntary stereotyped motor responses. (These pathologies are reviewed briefly in Redgrave et al. (1999).)

In a view gaining currency, the thalamocortical system is viewed as a host for controlled chaos (Djurfeldt et al., 2001; Cossart et al., 2003), and for sustained cascades of structured activity. A cultivated tonic balance of excitation and inhibition

(Mariño et al., 2005; Liu, 2004) produces a sensitivity to perturbations that can result in chaos. Within this burble of fluctuations the SPS detects meaningful patterns (contexts), chooses putatively advantageous responses, and expresses the responses by imposing sparse patterns of spatially distributed phasic disinhibition. This instantiates transient thalamocortical ensembles, which can be viewed as context-relevant ephemeral agents – agents of the sort imagined by Minsky (1986), but possessing persistency only by dint of reconstitutability. Since the agents themselves become part of the context driving the SPS, they are chained together in a cascade. These putative agents usually have a significant perceptual dimension. In general, the exquisite sensitivity to perturbations engendered by excitatory-inhibitory balance has a special significance for perception, where it allows for detection of very small changes in sensory input.

3 Bridging the motor-perception divide

Before plunging into a consideration of the SPS's direct involvement in perception, it is worth taking a few moments to consider the accumulating evidence for extensive motoric influence on perception. Because the SPS has an established role in motor performance, this evidence leads one to deduce a role for the SPS in perception.

Gandevia et al. (2006) show that proprioceptive awareness of limb position is maintained even in the effective absence of the limb. That is, the mind perceives a limb

that reacts to applied effort, even when the possible pathways from applied effort to perception all run entirely within the CNS. This phenomenon may be explained by some form of efferent copy, by some form of top-down control (probably implicating the SPS), or by both. The SPS's influence over late stages of motor processing is well appreciated, but a component of the corticostriatal projection is collaterals of late stage motor output (Lévesque et al., 1996), i.e. efferent copy. The SPS is thus similarly arranged for closed-loop observation of actions.

While the phenomenon reported by Gandevia et al. directly implicates superior frontal and parietal cortex, the prefrontal cortex – with its superlative versatility and its supervisory function – is the most fruitful region of interest in a search for motoric influence on perception. The role of the PFC as arbiter of conflicts, for example, certainly extends to perception. In an experiment investigating the bistable vision condition, subjects with well-localized PFC lesions were significantly impaired in their capacity to willfully switch between the candidate percepts (Windmann et al., 2006). The role of the SPS itself in this type of attentional task is discussed below, as an example of the general machinery of set shifting.

Deliberate (premeditated) attention is an example of intentional perception. By biasing the saliency of percepts, it can exclude irrelevant stimuli from awareness, and greatly improve awareness of desired stimuli (Pessoa et al., 2003). Attention is quite precise. For example, attention to a potential visual stimulus shows fine retinotopy in precise registration with the activity induced by the actual stimulus. The perceptual significance of selective attention can hardly be overstated. Poten-

tial percepts that are not attended are largely absent from awareness, and often have little or no bearing on cognition and behavior.

Marisa Carrasco and colleagues have made a multifarious case that covert gaze alters the contents of perception. Studying the visual domain, they have found that attention by itself increases apparent contrast (Carrasco et al., 2004), spatial resolution (Yeshurun and Carrasco, 1998), and the rate of perceptual processing (Carrasco and McElree, 2001). They find that basic attributes of visual stimuli – e.g., spatial frequency and gap size – are subjectively altered by covert attention (Gobell and Carrasco, 2005).

Marc Sommer reports (Sommer, 2006) that individual neurons in V1 display ephemeral receptive fields in anticipation of saccades. In the moment before execution of a saccade, a single neuron briefly responds to a stimulus positioned in the visual field such that it will be in the static RF of that neuron after completion of the saccade. This is, evidently, clear evidence of closed loop motor modulation of sensory response. Both the direction and the magnitude of the saccade are precisely relayed from the saccade planning centers (chiefly, frontal and supplementary eye fields and SC) to visual cortex, inducing superposition of a spatially shifted map of receptive fields. (The physiological mechanism of this superposition is not yet known.)

Mental imagery – in which a stimulus is perceived that originates (often deliberately) within the mind – is perhaps the ultimate form of intentional perception. Imagery may be nothing more than an extension of attention, which – as noted

above – is very precise. Attention is likely realized through increases in excitatory inputs (chiefly arising in the neocortex and in/via the thalamus), and decreases in inhibitory inputs (chiefly mediated by the SPS), to loci involved in perception of the attended subject. In attention, these effects induce few depolarizations. But if the effect is simply intensified quantitatively, thresholds are exceeded (and propagated associatively and retrogradely through sensory processing pipelines), and intrinsically generated percepts – mental imagery – result. This progression is a phenomenon readily familiar to the layman: a prolonged and intensive search is often accompanied by false alarms and fleeting phantom percepts.

4 The SPS in Perception

Given the foregoing, the reader will evidently be unsurprised by a catalog of physiological and functional intimacies between the SPS and the uncontroverted correlates of sensation and perception. I begin by noting several findings relating to visual cognition.

That the SPS has disynaptic projections to inferotemporal (Middleton and Strick, 1996) and anterior inferior parietal (Clower et al., 2005) cortex, just as it does to the classic five areas of the Alexander model, suggests that the role of the SPS in mental imagery is neither incidental nor peripheral. That these regions of cortex are integral to visual imagery has been established for some time (Mellet et al., 1996).

In an experiment probing the physiological correlates of a visual categorization task

contingent on mental rotation (Alivisatos and Petrides, 1997), striatal activation (measured with PET) was similar in significance to activation in parietal cortex.

The visual system at the mesencephalic level (the superior colliculus) is a target of SPS (SNr) output (e.g. Jiang et al., 2003). While the SC is implicated in shift and tracking of gaze, it is also involved in attention *per se*, and stimulation of the SC can drive covert gaze (Müller et al., 2005). The frontal and supplementary eye fields (FEF/SEF) are under SPS influence (the oculomotor circuit of Alexander et al. (1986) involves them), but activity in them can direct attention without directing oculomotor output (Schall, 2004). Moreover, as noted above, the NBM and VTA project directly to visual sensory areas. Clearly, then, the SPS can drive visual attention through a variety of pathways and mechanisms.

Auditory imagery also involves the SPS. In a PET study in which subjects internally recapitulated a familiar tune from memory upon presentation of an auditory cue of the first few notes (Halpern and Zatorre, 1999), the putamen was significantly activated during cueing and imagery relative to a control task (passive listening to a tune), but not for uncued imagery relative to control. This evidently suggests the SPS recruits the auditory program appropriate for the presented cue. (*n.b.* the authors did not address this activation in the text of the article.) In a study of classification-intensive auditory perception (listening to speech) (Meyer et al., 2004), significant neostriatal activation accompanied listening to speech degraded so that only fundamental frequency was preserved, suggesting SPS engagement when the usual perceptual strategies prove ineffective. Evidently this is the sort of

scenario classically associated with intervention and supervision by PFC, and so serves as a reminder of the extensive functional overlap and integration of PFC and the SPS.

A recent finding shows just how direct and fundamental is the effect of the SPS on perception. Shuler and Bear (2006) report that neurons in rodent V1 show elevated activity contingent on the expectation of reward associated with visual stimuli that implicate those neurons. This is clearly something separate from, if clearly related to, SPS-mediated reward contingency in the oculomotor command stream (Hikosaka et al., 2006), the sort of role consistent with the traditional circumscription of SPS domain. In one promising model (Zink et al., 2006) it is saliency – be it novelty or reward – that provokes the SPS to judiciously recruit cognitive resources associated with the salient stimulus. Clearly, anticipatory recruitment of sensory infrastructure is a natural component of this SPS function.

The sense of time passage and the estimation of time intervals implicate the SPS in a domain of perception at a very basic level. In fact, sensation of time is the only physical phenomenon sensation that inheres in mentation, rather than reaching it through a pipeline of intermediaries. The judgements that are predicated on the integration of time sense have an economic character to them, reminding us of the role of the SPS as a neuroeconomic engine.

The physiology directly implicated in time sense, and in the integration of percepts over time intervals, includes most of the anatomy implicated in cognitive control

(Buhusi and Meck, 2005). The dorsal neostriatum, PFC, supplementary motor area (SMA), and posterior parietal cortex (PPC), all show activity that is significantly parametrically correlated with timing-related demands of task. The SPS dopaminergic centers demonstrate a particularly clear involvement in timing, a finding reinforced with respect to sensation by Shuler and Bear (2006), discussed above. Parkinsonism is accompanied by deterioration in interval judgement. In rat, an interesting timing deficit accompanies NBM lesioning: timing of a single stimulus is essentially normal, whereas timing performance on concurrent independent stimuli is significantly impaired. This reinforces the hypothesis that the NBM mediates attentional allocation and control, mentioned briefly above.

Buhusi and Meck propose that a general mechanism of timing, and of awareness of position along the time continuum, is the recognition by the neostriatum of patterns in the afferents from cortex, emanating from regularly but independently oscillating local cortical ensembles, such that particular instantaneous phase relationships among these afferents can be detected as a sort of intrinsic tick. Importantly, Buhusi and Meck venture that the mechanism of interval timing, of which neostriatal pattern recognition is a key component, is in fact more general, underlying judgements of quantity and numerosity. These, evidently, are also matters of perception, and furthermore, are similarly prominent in neuroeconomics.

The PFC and the SPS are both integral to set shifting (Ravizza and Ciranni, 2002; Aron et al., 2003). The perceptual aspects of set shifting can be seen as context-driven top-down biasing of inter-percept competition (e.g. Desimone, 1998). At-

tention is the overarching phenomenon here. In English, we have a saying, “pay attention”, and there’s a lesson in this: attention is something we invest, and we invest it in the way we expect to pay off most (Glimcher and Rustichini, 2004). The need for attention arises because, as noted above, cognitive infrastructure is a limited and contentious commodity for which thoughts (here, the propagative processing of percepts) compete (Desimone and Duncan, 1995).

5 Hallucination and Delusion: A Window on SPS Functionality

Middleton and Strick (1996) discuss the possibility that dysfunction of the SPS loop through area TE (inferotemporal visual cortex) may underlie the visual hallucinations characteristic of positive symptom schizophrenia. This dovetails with a consideration of schizophrenia as a collapse of the intentional component of perception, as proposed by Edmund Husserl (Fuchs, 2005). In any case, etiological theories of schizophrenia have long implicated dysfunction of dopamine systems, which evidently are components of or intimate with the SPS. And most neuroleptics used to treat the symptoms of schizophrenia exert their effects on dopamine systems.

There is significant correlation between the morphology of the head of the caudate nucleus and incidence of schizotypal personality disorder (Levitt et al., 2004). Among these patients, there is moreover a significant correlation between degree of morphological distortion of the caudate head, and severity of deficits on tasks

contingent on visuospatial, auditory, and visual working memory.

Obsessive-Compulsive Disorder (OCD) is posited to be a dysfunction of neocortical-SPS circuits (Graybiel and Rauch, 2000). OCD might be usefully viewed as a dysfunction of perception: the normal sensitivity of the SPS to changes in context is not expressed, thus the SPS does not induce the appropriate set shift in the thalamocortical system. The SPS thus continues to promote a perception-action ensemble (an agent) which is superfluous, and the thalamocortical system perseveres with the inappropriate perception and the actions that follow from that inappropriate perception.

The potential for SPS dysfunction to induce delusory states of mind is underscored by the finding that stimulation of the STN can induce laughter associated with actual subjective humor appreciation and “mirth” (Krack et al., 2001).

6 Closing Thoughts

Physical objects and ensembles thereof – the subjects of normal perception – are governed by physical rules. These rules constitute a sort of intentionality intrinsic to those objects. Knowledge of the behavioral rules that govern a physical system can be combined with superficial observations of the system to construct theories of the system’s deep state. These theories are constructed in a continuous process of integration and reconciliation of multiple, usually prominently probabilistic, streams of constraints. To the degree that knowledge or observations are paltry, the constraints

are also frequently conflicting.

When the PFC/ACC/SPS involves itself in perception, the resulting interior dynamical system is a suitable substrate for this process of integration and reconciliation, culminating in continuous adaptive modelling of exterior dynamical phenomena. When I speak of intentional perception, I speak primarily of this mechanism, in which the intentionality of the environment is mentally modelled. The PFC/ACC/SPS works to assure that the rules that govern the environment also govern the mental model. These mental models are therefore intended perception, representing far more of the environment than either the physical rules, or the observational perceptions, represent in themselves.

When perception represents and reflects the intentional structure of the perceived phenomena, prediction is greatly facilitated. Prediction allows for negative reaction times, with evident dividends. But that prediction is one of the central goods obtained by PFC/ACC/SPS involvement in perception, squares with models of reinforcement learning (e.g. Schultz, 2006) that posit a sensitivity and reactivity to prediction errors within this same anatomy.

In humans, the mechanism of intentional perception becomes so powerful that articulate theories of mind are enabled. These, in turn, are part of the foundation upon which rests the syntactic language facility. Intentional perception is thus central to what makes humans human.

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A What is the striatopallidal system?

In the terminology of human neuroanatomy, the SPS is composed of the caudate nucleus and putamen (CPu), the segments of the globus pallidus (internal, GPi, and external, GPe), their respective ventral extensions (ventral striatum, VS, including the accumbens complex, NAc, and the ventral pallidum, VP), the substantia nigra reticulata (SNr), the subthalamic nucleus (STN), two mesencephalic dopaminergic centers (substantia nigra compacta A9, SNc, and ventral tegmental area A10, VTA), and the nucleus basalis (NB). The CPu, VS, and NB are telencephalic derivatives, and the GP, VP, and STN are diencephalic. Grouped by cytoarchitecture and hodology, the CPu and VS together constitute the neostriatum (or “striatum”), and the GP, VP, and SNr together constitute the paleostriatum (or “pallidum”).

Synaptic release of the SPS’s main output projections is modulatory (dopamine or gamma-aminobutyric acid, GABA), and its extrinsic inputs are mostly excitatory (glutamate, Glu). Its excitatory input is derived mostly from the cerebral cortex (including the atypical cortex of the medial temporal lobe and rhinencephalon), with the remainder arising from motor and intralaminar nuclei of the thalamus, from the cerebellum by way of the thalamus (Hoshi et al., 2005), and from the affective organs of the basal forebrain (chiefly, the amygdala and hypothalamus). The serotonergic and noradrenergic modulatory centers of the brainstem, which diffusely innervate the cerebral cortex and the thalamus, also similarly innervate the SPS. The GABAergic output of the SPS targets associative motor nuclei of the thalamus, particularly the large mediodorsal (MD) and ventral anterior/ventral lateral (VA/VL) nuclear

masses. The dopaminergic output arising in the ventral tegmental area targets PFC and anterior cingulate cortex (ACC).

Physiological segregation of functional domain in the SPS, mentioned above in the introduction, has an organ-level granularity, and within organs, well-defined finer patterns of topographic specificity. Projections of the extended amygdala and atypical cortex to the SPS are largely confined to the VS. Corticostriatal projections arising in that part of neocortex which is posterior to the PFC/ACC is largely confined to the CPu. The PFC/ACC projects extensively to both VS and CPu (also, PFC/ACC is physiologically intimate with both the extended amygdala and atypical cortex, and with the isocortex posterior to it). PFC/ACC is distinguished with respect to the SPS in other ways: it is the isocortical region most profusely innervated dopaminergically by the SPS, it is the origin of the only direct corticosubthalamic projection, and it is the principal reentrant (feedback) recipient of the output of the SPS (by way of the thalamus), though as will be explored below, it is not the only one.

The internal connectivity and chemistry of the SPS is complicated enough to frustrate easy description. The neostriatum constitutes the canonical input stage, receiving the glutamatergic projections described above. The paleostriatum constitutes the canonical output stage, giving rise to the GABAergic projections described above. In computational models, the SPS is often viewed as a hidden layer, with an internal architecture that is opaque to organs outside the SPS. However, this oversimplifies in important ways. Immediately above are examples of this – STN receives a glutamatergic projection from PFC/ACC, and VTA gives rise to dopaminergic and GABAergic projections to PFC/ACC.

In the direct pathway, Glu inputs to the CPu and VS give rise to GABA inputs to GPi and SNr, which give rise to GABA inputs to thalamic targets. In the indirect pathway, the CPu and VS give rise to GABA inputs to the GPe, which gives rise to GABA inputs to the STN, which give rise to Glu inputs to GPi and SNr (GPe also projects directly, but relatively sparsely, to GPi and SN). Thus, in the direct pathway, excitatory input to the SPS yields disinhibition at its output, whereas in the indirect pathway, excitatory input yields inhibitory output.

Moreover, through intraneostriatal collaterals, the direct pathway projection conveys substance P (SP) whereas the indirect pathway conveys enkephalins (Enk) (Lee et al., 1997) (though in primates, SNr-bound fibers convey either Enk or SP, in similar numbers (Inagaki and Parent, 1984)). These neuropeptides are associated throughout the neuraxis with aversive stimuli and analgesia (respectively), and are mutually antagonistic (Mudge et al., 1979). Through their action in the neostriatum, aversion tends to induce thalamic disinhibition (facilitating responsive perception, cognition, and action) whereas analgesia enhances thalamic inhibition.

The input stage pathway is also divided, into matrisomal and striosomal trajectories (Graybiel and Ragsdale, 1978). The striosomes are neostriatal compartments (patches) many of whose neurons contain neuropeptides such as enkephalins (Enk) and substance P (SP), which are comparatively lacking in the neurons of the matrisome (matrix) that separates them. The processes of a given neostriatal neuron are conspicuously segregated to a single compartment. The matrisomal trajectory, arising in more superficial layers of cortex (III-Va), gives rise to the direct and indirect pathways introduced above. The striosomal trajectory, arising in deeper layers of

cortex (Vb-VI), projects GABAergically to the SNc (unresolved citation, 9999). In the ventral striatum, the matrisome-striosome compartmentation is confused, but a shell-core arrangement is prominent in the NAc (unresolved citation, 9999). The SNc then gives rise to dopaminergic projections to matrisomal neostriatum. Dopamine has a facilitatory effect on target cells when the postsynaptic receptors are type D1, as they are for striatal cells in the direct pathway, and an inhibitory effect when the receptors are type D2, as they are for striatal cells in the indirect pathway. Thus increased SNc dopamine output tends to decrease the inhibitory output of the SPS, and decreased dopamine tends to increase inhibitory output. This arrangement is most clear in the dorsal SPS.

The Glu output of the STN to the GPi induces inhibition at the SPS's thalamic targets. However, the STN also projects glutamatergically back to the GPe, and this arrangement constitutes a putative substrate for an SPS-intrinsic oscillatory dynamic (Berns and Sejnowski, 1998). As noted above, PFC projects glutamatergically to STN, and through this path PFC can directly effect excitation of the SPS's output stage, hence inhibition of the SPS's thalamic targets. This has been interpreted as a pathway for a "stop" signal (unresolved citation, 9999), but it is also a mechanism whereby PFC can induce broad inhibition while PFC and other cortical regions simultaneously induce focal disinhibition through the direct pathway (unresolved citation, 9999).

The projections linking the CPu, VS, GP, SNr, and STN, have extensive topographic specificity (in somathetic/skeletomotor regions, fractured somatotopy), some of which has already been described in the literature, but much of which has yet to be elucidated. Representational maps in the SPS are arrayed in three dimensions, as in

the thalamus, and unlike the cortex of either the cerebrum or the cerebellum.

The efferent pathways of the VTA are various and diverse, and give it an extensive intimacy with the PFC/ACC and the rest of the SPS (Oades and Halliday, 1987). It projects directly and extensively to PFC (dorsolateral and orbital) and ACC, and to the neostriatum, and also projects to thalamic nuclei (anterodorsal, mediodorsal, central medial, and reuniens) that are intimate with PFC, ACC, and the neostriatum, and to most of the structures of the medial temporal lobe. In carnivores and primates, there is additional significant VTA innervation in insular and visual cortex, and some innervation of auditory and somatosensory cortex. In rhesus monkey (and probably other primates), anterior temporal cortex is innervated, and in cat (and possibly also primates) ventral temporal and retrosplenial cortices are strongly innervated. The afferents of VTA arise chiefly in the PFC, in the ventral striatum and pallidum, and in several basal forebrain structures including particularly the hypothalamus (Geisler and Zahm, 2005). The chemistry of VTA efferents is chiefly dopaminergic and GABAergic, and its afferents are chiefly glutamatergic (or aspartatergic) and GABAergic.

The nucleus basalis is considered part of the basal ganglia. Indeed, Theodor Her-

mann Meynert (its discoverer) called it the *ganglion basale* (Meynert, 1872). Because of its hodological and thematic relationships with the neostriatum, paleostriatum, and neocortex, it is natural to consider it an integral component of the SPS. Like several other nuclei of the SPS, it is cytologically distinct, but like those other nuclei, it is functionally integral.

The nucleus basalis magnocellularis (NBM) and the adjoining portion of the VP include a large population of cholinergic neurons that are the principal extrinsic source of cholinergic innervation for the entire cerebral cortex. Non-SPS afferents to the NBM are like those of the ventral striatum (Mesulam and Mufson, 1984; Zaborszky et al., 1997), and the cholinergic neurons of the NBM are innervated directly by the GPe (Grove et al., 1986). The CPu also contains a population of projection neurons, distinguished cytologically from the projection neurons implicated in the direct and indirect pathways, that send neuropeptide-bearing fibers to the nucleus basalis (Furuta et al., 2000). Thus the NBM is under the direct regulatory influence of both the neostriatum and the paleostriatum.

In fact, the above gives only the barest outlines of the chemistry and labyrinthine microcircuitry of the SPS. For detailed reviews, see *e.g.* Holt et al. (1997) and Parent et al. (1995).