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Animal Foraging and the Evolution of Goal-Directed Cognition

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Abstract

Foraging- and feeding-related behaviors across eumetazoans share similar molecular mechanisms, suggesting the early evolution of an optimal foraging behavior called area-restricted search (ARS), involving mechanisms of dopamine and glutamate in the modulation of behavioral focus. Similar mechanisms in the vertebrate basal ganglia control motor behavior and cognition and reveal an evolutionary progression toward increasing internal connections between prefrontal cortex and striatum in moving from amphibian to primate. The basal ganglia in higher vertebrates show the ability to transfer dopaminergic activity from unconditioned stimuli to conditioned stimuli. The evolutionary role of dopamine in the modulation of goal-directed behavior and cognition is further supported by pathologies of human goal-directed cognition, which have motor and cognitive dysfunction and organize themselves, with respect to dopaminergic activity, along the gradient described by ARS, from perseverative to unfocused. The evidence strongly supports the evolution of goal-directed cognition out of mechanisms initially in control of spatial foraging but, through increasing cortical connections, eventually used to forage for information.

Keywords: Genetic algorithm; Striatum; Basal ganglia; Dopamine; Area-restricted search; Evolution; Animal foraging; Goal-directed behavior; Attention; ADHD; Schizophrenia; OCD; Cognitive flexibility; Priming

1. Introduction

Stanislaw Ulam, the Russian mathematician, once observed that the mind is like a pack of dogs (Ulam, 1991). When the mind seeks a solution, it lets loose the dogs, which sniff around in the multidimensional cognitive space of our cortex, searching for the answer. Until very recently, metaphors of cognitive exploration as a kind of foraging behavior have existed strictly at the level of analogy. This analogy is not new to psychology. William James (1890, p. 654)

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used it in the following way: "We make search in our memory for a forgotten idea, just as we rummage our house for a lost object. In both cases we visit what seems to us the probable neighborhood of that which we miss."

Recent evidence gathered in a number of fields suggests that this relation is not just one of analogy, but of evolutionary homology. That is, molecular machinery that initially evolved for the control of foraging and goal-directed behavior was co-opted over evolutionary time to modulate the control of goal-directed cognition. What was once foraging in a physical space for tangible resources became, over evolutionary time, foraging in cognitive space for information related to those resources.

Although many pathways are involved in the control of behavior, there is ample evidence to suggest a dominant role for dopamine in the control of goal-directed behaviors (Floresco, Seamans, & Phillips, 1996; J. Salamone, Correa, Mingote, & Weber, 2005; Seamans, Floresco, & Phillips, 1998; Wang, Vijayraghavan, & Goldman-Rakic, 2004; Watanabe, Kodama, & Hikosaka, 1997). Dopamine's role in these behaviors appears to be as modulator between two behavioral extremes. When dopaminergic activity is high, behavior is focused, and in extremes, stereotypic. When dopaminergic activity is low, behavior is unfocused and fails to persist. This systematic relation between dopaminergic activity and behavioral abnormalities is seen in a wide variety of animals and under an equally wide variety of conditions (see Section 3). Similar dopaminergic relations are found in human pathologies of goal-directed cognition (reviewed in Nieoullon, 2002, and Section 4).

To date, although these dopaminergic relations have been observed in various contexts, the evidence has not been integrated with respect to a particular evolutionary precursor of goal-directed cognition. Dopamine is commonly identified as a reward or novelty detector, but the evolutionary details of that reward are cloudy. Is there a most recent common reward in the evolutionary history of dopamine? Unless dopamine simultaneously arose in multiple neurons transducing multiple kinds of reward stimuli, the answer is probably yes. If so, are the dopaminergic aspects of goal-directed cognition modulated in similar ways to those downstream behaviors associated with the original reward?

This work addresses these questions by first observing that dopamine and glutamate are key components in what appears to be a very old, but presently ubiquitous, optimal foraging behavior called area-restricted search (ARS; see Sections 2 and 3). ARS is found in all major eumetazoan clades (insects, vertebrates, mollusks, and nematodes). The conserved role for dopamine with respect to ARS across eumetazoan clades suggests this behavior evolved early in the history of eumetazoans. Although dopamine is a key component in foraging behaviors in invertebrates (Section 3.1) and vertebrates (Section 3.2), in vertebrates dopamine is also associated with goal-directed cognition. The evolutionary relation between foraging and cognition is supported by the fact that vertebrate neuroanatomical features related to spatial cognition and their evolution are conserved across vertebrates, ranging from fish to mammals (Salas, Broglio, & Rodriquez, 2003) and primarily involve the basal ganglia in the control of movement (Houk, Davis, & Beiser, 1995; Reiner, Medina, & Veenman, 1998). As detailed in Section 3.3, the evolution of the vertebrate basal ganglia is marked primarily by an increasing number of cortical inputs to the striatum. The modulatory relations of these inputs with respect to glutamate and dopamine appear unchanged from those found in control of goal-directed movement in primitive vertebrate clades (Reiner et al., 1998; Salas et al., 2003). Furthermore,

similar relations between dopamine and glutamate are observed controlling nearly identical ARS-like behaviors in *Caenorhabditis elegans* (Hills, Brockie, & Maricq, 2004), and there is strong evidence for similar relations in invertebrates (see Section 3.1).

Evidence from molecular mechanisms in the prefrontal cortex and the striatum suggests that cognitive goals are maintained via dopaminergic activity (Schultz et al., 1995), which operates to create persistent attention to rewards, novel or unexpected stimuli, or aversive stimuli, much like dopamine increases spatial focus in ARS. Addictive behaviors operate via similar mechanisms (Berke & Hyman, 2000). As stated previously and discussed further in Section 4, inappropriate levels of dopaminergic activity lead to predictable over- or underfocused behavior in human cognitive pathologies. This dopaminergic focus is required for specific forms of associative learning, which allows for information about resources (conditioned stimuli) to become targets of goal-directed cognition and behavior (see Section 5).

A descriptive model is presented that elaborates on the goal-directed process of cognition by showing how dopaminergic activity identifies and integrates information about environmental predictors around "best expectations" until those expectations fail to appropriately predict successful solutions, either internally or externally verified. This method is effective in searching for both external and cognitive resources. In this respect, information that can be used to acquire tangible resources such as food and mates is not distantly removed from the resources themselves and is available to cognitive representations as appropriately defined associative networks. Although the molecular mechanisms and certain aspects of the phenomenology are similar, one must be warned away from assuming that spatial foraging observed in two dimensions—for example, when a squirrel hunts for acorns on the ground—is similar to what is observed in the cortex, where the space is multidimensional, and many searches may take place in parallel (discussed in Section 5).

The theory presented here is based on evidence from multiple disciplines, from behavioral ecology to molecular genetics, and touches on many branches of cognitive science. This evidence focuses primarily on dopaminergic pathways because these are most well understood at many levels, both molecularly and behaviorally, within eumetazoans, and therefore provide solid ground for an evolutionary investigation. However, it should not be assumed that other mechanisms are not involved, nor should it be assumed that they will support the evolutionary theory presented here (see Section 6). What is described here is not a new theory of how cognition works, but rather a plausible evolutionary origin for goal-directed cognition, as we currently understand it.

2. The foraging behavior: ARS

ARS is characterized by a concentration of searching effort around areas where rewards in the form of specific resources have been found in the past. When resources are encountered less frequently, behavior changes such that the search becomes less sensitive, but covers more space. In an ecological context, animals using ARS will turn more frequently following an encounter with food, restricting their search around the area where food was last encountered. As the period of time since the last food encounter increases, animals turn less frequently and be-

gin to move away, following a more linear path. Fig. 1 allows you to experience ARS in a visual search task (read the directions please).

ARS is observed in a wide variety of animals, including house flies (J. White, Tobin, & Bell, 1984), leeches (O'Gara, Chae, Latham, & Friesen, 1991), moths (Vickers, 2000), ladybug beetles (Kareiva & Odell, 1987), rodents (Benedix, 1993), nematodes (Hills et al., 2004), humans (Hills & Stroup, 2004), and many other animals (see Bell, 1991). The behavior is incredibly common and easily observed in house pets, children, or even students and professors looking for classrooms (personal observation).

Why do so many animals do an ARS? One kind of answer is that ARS is an optimal search strategy under a common set of environmental conditions. Mathematical models from the optimal foraging literature suggest that ARS is the best strategy when resources are clumpy and when information is limited with regard to the direction of nearby resources (Grunbaum, 2000; Kareiva & Odell, 1987; Walsh, 1996). Barring other kinds of information, the best place to look for resources is near where they have been found in the past. Basically, an animal should prove to itself that it has done a reasonable job of harvesting nearby resources before it is willing to travel any distance in search of another patch. However, once it has made the appropriate nearby search, it should move on rapidly in search of the next patch, which will more likely than not be easier to find than any last remnants of the previous patch.

Biological environments are prone to clumpy resource distributions because living organisms grow, reproduce, and disperse in spatially autocorrelated ways. This is true to such an extent that ecologists commonly use the term *patch* to refer to local resource environments. So one answer to the why question is that conditions that support life tend to generate clumpy resource distributions, which in turn lead to selection for an appropriate general foraging strategy to find those resources, for which ARS is quite adequate.

To further test the evolutionary robustness of this behavior, I developed a genetic algorithm (Hills, 2004), using NetLogo (Wilensky, 1999) that allows agents to search for food in a

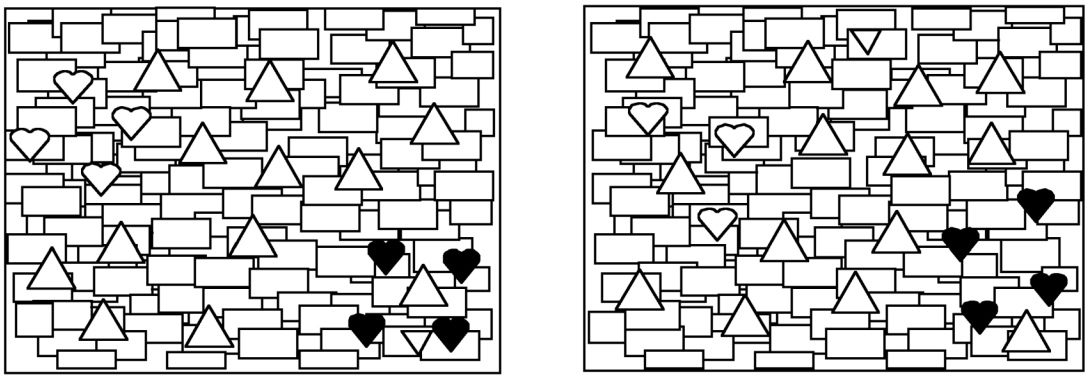

Fig. 1. Paying attention to where your eyes look, begin in the left figure and look for the upside down triangle (there is only one). Then, move to the figure on the right. Go ahead and do that now. If your eyes looked first near the black hearts in the right figure, then more likely than not you performed an ARS by focusing attention around the area where you thought the upside down triangle might be (based on your experience with the left figure) and then performing a rapid visual scan of the rest of the image (for descriptions of visual search reminiscent of that described here for foraging, see Tipper, Weaver, Jerreat, & Burak, 1994).

two-dimensional space. The goal of the genetic algorithm is twofold: to understand the conditions where ARS is likely to evolve and also to understand a minimal set of mechanistic parameters required for the behavior's evolution. In this simulation, the agents have three genes that control turning angle per time step when they are "on food," turning angle per time step when they are "off food," and a memory depth that describes the number of time steps it takes for the animals to progress from the on-food to the off-food turning angle once they have left food (the inverse of memory depth is the slope of change in turning angle per time step). The initial population is generated with a random 24-bit genome per individual (8 bits per gene). The genes assign the foraging rules each generation. Animals then compete in a two-dimensional foraging arena. After an appropriate life span, individuals mate and recombine—disproportionately according to how well they foraged—and a new generation is created, subject to a small mutation rate.

The results of the algorithm show that when resources are spatially patchy, the evolution of ARS is an inevitable consequence (Fig. 2). Agents evolve toward high on-food turning angles and low off-food turning angles. Although memory depth is always greater than zero, it appears to be more sensitive to the random initial distribution of resource clumps, as clumps may be more or less close to one another, and the rate at which an agent "gives up" is likely to influence the rate at which it encounters nearby clumps. Nonetheless, ARS—high-angled on-food turning, low-angled off-food turning, and appropriate transition between the two—is the outcome in a wide variety of resource distributions and is not dependent on specific turning distributions or slope formulations for memory depth (data not shown, but the algorithm and software are freely available; see Hills, 2004).

Under this basic model, the only exception to the evolution of ARS is when resources are spatially uncorrelated. In uncorrelated resource environments (where finding one red pixel provides no information about the nearness of the next; patches are a single pixel in size), the behavior fails to converge. Under these conditions, there is no evolutionary benefit to looking near other resources, because resources are independently arranged. Recent work on random search suggests that in an *uncorrelated* two-dimensional environment, the best search solutions are static and not constructed of temporally correlated reductions in turning, but should be randomly chosen from an inverse power law distribution of run lengths (Vishwanathan et al., 1999).

With respect to foraging, learning represents the creation of associative relations between behavior and the presence or absence of resources. In this situation, learning is not required to evolve ARS, but it still may be involved in its production. The existence of ARS in eumetazoans with limited learning abilities (e.g., *C. elegans*) suggests that to the extent that learning is involved, it is working with machinery predisposed to produce ARSs of varying degrees. It is extremely unlikely that learning would abolish ARS because, by its very nature, ARS is a mechanism for giving up when the environment no longer meets expectations. In this respect, it may be very closely related to basic neural mechanisms such as habituation and sensitization. Successful learning about foraging is characterized by the ability to *give up* on unsuccessful foraging decisions. Although the depth of this relation is unclear, it is very likely to involve understanding the evolutionary relations between these two mechanisms; the problem is clearly an open one.

Still, many animals do not perform an ARS when they have sufficiently high levels of information. For example, many animals are capable of determining their position in space using

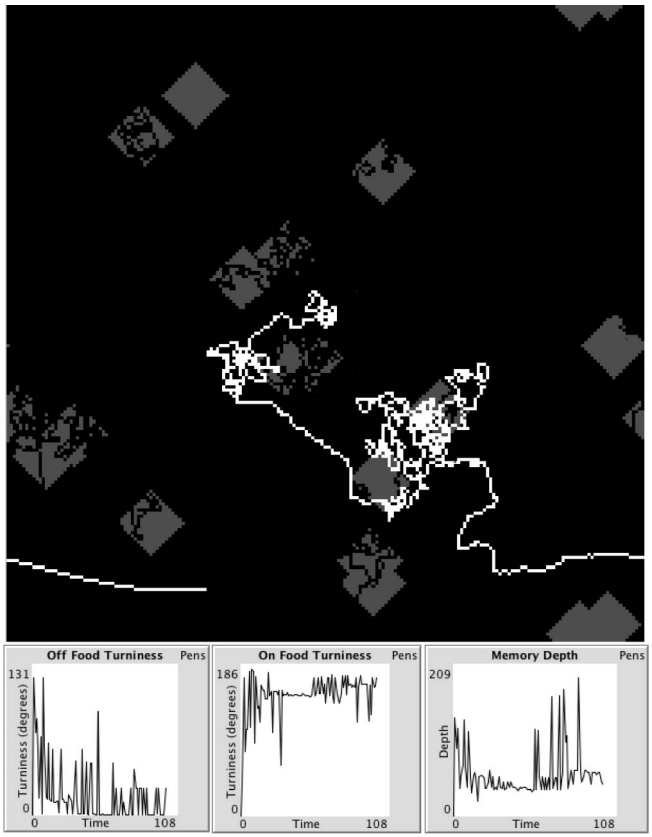

Fig. 2. Typical results from the foraging genetic algorithm. The top image shows the path of the agent with the most successful genome in the previous generation (a clone). The environment is on the surface of a torus (i.e., agents pass from one side of the screen to the other). Food is represented by diamonds, of which the agent "eats" individual pixels. The path is shown for one individual in the 100th generation (the paths of other individuals are not shown, but can be partially seen as traces in the food). Cumulative data is shown in the graphs below. "off-food turniness" represents the average turning angle when the animal is off food and has no memory of food. "on-food turniness" is the average turning angle when the animal is on food. The turning angle moves from the on-food to the off-food value linearly per pixel step, with a slope equal to the inverse of the "memory depth." For example, it would take 40 pixel steps to move from the average on-food turniness to the average off-food turniness if the memory depth were 40.

path integration based on information they acquire along the path (Dyer, 1998; Labhart & Meyer, 2002). For example, the desert ant *Cataglyphis* sp. can take a very meandering path as it searches outward from its home, yet on return, it sets a homeward course that is very direct, and it appears to do this without using landmarks (reviewed in Dyer, 1998). However, like many animals that use alternate methods to orient in space, when the homing direction is imperfect (as it often is), the animal resorts to an ARS-like behavior around the expected location of its home (Wehner & Srinivasan, 1981). There are various other forms of animal orientation involving response to specific stimuli, such as chemotaxis, geotaxis, phototaxis, and movement away from and toward specific temperatures (Labhart & Meyer, 2002; Martin & Gordon, 2001; Schone, 1984; Tobin & Bargmann, 2004; Wittenburg & Baumeister, 1999). There are

also associated optimal foraging strategies (reviewed in Stephens & Krebs, 1986). Still, as described for *Escherichia coli,* when the stimulus disappears or when expectations associated with the stimulus are not met, animals engage in ARS-like behavior as a way of giving up on "bad" situations (for examples, see Bell, 1991).

The main goal of the genetic algorithm was to act as an independent control on the mathematical theory. It provides us with evidence that the behavior will readily evolve under common resource distributions and that roughly three parameters are sufficient for its production. These three parameters correspond to specific physiological prerequisites required for the development of ARS. In practice, these must perform the following functions. If the resource being searched for becomes locally scarce, organisms need (a) a way to detect this and to determine when to start looking elsewhere (i.e., a physiological clock that keeps track of time elapsed since their last encounter with food). This could be gut fullness (Kareiva & Odell, 1987), or it could be a decay of activity in a neural circuit in association with dephosphorylation times or decay of specific proteins (reviewed in Hills, 2003). When the organism starts looking elsewhere, it needs (b) a way to modulate its search behavior appropriately such that more area is covered in less time. And finally, when the organism encounters clumped resources again, it needs (c) a way to modulate its search behavior to stay near its present location.

Why so many animals do an ARS appears to be answered by the fact that the behavior is readily evolved under essentially all common resource distributions and that the behavior itself is not mechanistically complicated to produce. This creates a relatively firm theoretical foundation for the conjecture that this behavior evolved early in the history of foraging organisms. If this is true, then we should expect to find empirical evidence for the control of foraging behaviors by similar or nearly identical molecular mechanisms across a wide range of eumetazoans (i.e., insects, mollusks, and vertebrates). Furthermore, we may expect to see that this molecular functionality is conserved and used (i.e., exapted) to control behaviors *related* to foraging in more recent evolutionary productions and perhaps cognition.

3. The evolution of goal-directed cognition

3.1. Invertebrate foraging and feeding behavior

Here, I describe what is known about the molecular control of feeding- and foraging-related behaviors in invertebrates, specifically focusing on comparative molecular and behavioral evidence that is informative with respect to the evolution of ARS. Although many of these animals do an ARS, much of the molecular work has focused more generally on foraging- and feeding-related behaviors, with no effort to situate these behaviors with respect to the ecological literature. Nonetheless, the molecular similarities reveal strong evidence that the neural machinery controlling foraging-related behaviors is of similar evolutionary origin.

Although the evidence is lacking to point to a specific evolutionary origin for the molecular machinery, there are molecular precursors in protozoa that reveal the first inklings of timekeepers in control of ARS. The most primitive example of the temporal modulation of turning behavior in response to resources (i.e., foraging) is found in coliform bacteria such as *E. coli*

and *Salmonella typhimurium.* These bacteria use the direction of flagellar motors to control "run and tumble" movement. Runs provide forward motion, whereas tumbles create random turns. Receptor proteins in the membrane bind to external stimuli and then signal, using a phosphorylation cascade, to proteins in the flagellar motor, which by reversing the motor's direction is able to switch between run and tumble behavior (Stock & Surette, 1996). Binding changes the shape of the proteins and influences their ability to interact with other proteins, which at the far end of the chain of reactions leads to changes in the motor's direction. This allows bacteria to move up chemical gradients by using runs and to avoid moving toward repellents or low resource environments by using tumbles.

Bacteria use temporal information to detect gradients (Macnab & Koshland, 1972). In part, this comes as a consequence of dephosphorylation rates, which allow proteins to move to an inactive state after a short period of activation. When gradients are rapidly shifted, *E. coli* will continue their run for a few seconds before they turn. This first turn after removal from food is at least the beginning of an ARS, an attempt to return to a better local resource environment. Due to this short memory of *E. coli,* bounded by a dephosphorylation rate, they rapidly shift to a global search strategy described previously, the optimal inverse power law search (Korobkova, Emonet, Vilar, Shimizu, & Cluzel, 2004; Vishwanathan et al., 1999).

The most basal eumetazoan for which we have molecular details about ARS is the nematode *C. elegans* (Fig. 3). *C. elegans* performs an ARS on removal from food, showing initially a high frequency of turns that, over a period of 30 min, is modulated to a lower frequency. Recent work has exposed some of the molecular and neural mechanisms underlying this behavior (Hills et al., 2004; Sawin, Ranganathan, & Horvitz, 2000). The neural circuit consists of eight sensory neurons presynaptic to eight interneurons. The interneurons coordinate forward and backward movement (Chalfie et al., 1985; Zheng, Brockie, Mellem, Madsen, & Maricq, 1999). Similar to *E. coli, C. elegans* changes directions most dramatically by brief intervals of backward movement (i.e., reversals), which are followed by a head-to-tail turn called a *pirouette.*

C. elegans sensory neurons appear to alter reversal frequency by releasing dopamine on glutamatergic interneurons, modulating glutamate receptor function. For example, exogenous applications of dopamine increase turning frequency, whereas applications of dopamine antagonists reduce turning and eliminate ARS. As well, knocking out genetic function of specific glutamate receptors eliminates the neuromodulatory effect of exogenous dopamine (Hills et al., 2004). A model consistent with these and other observations suggests that some time immediately before or after *C. elegans* is removed from food the sensory neurons release dopamine, which leads to increased switching behavior, via the action of glutamate, in the

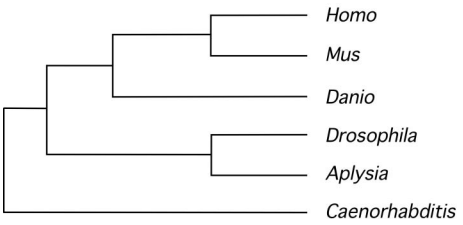

Fig. 3. A phylogenetic tree of eumetazoans. The tree is reconstructed from Raible and Arendt (2004) and Blair et al. (2002).

interneurons and more turns. When off food, dopaminergic activity is reduced, and the interneurons reduce their switching frequency, leading to fewer turns. Perhaps our best guess of the molecular mechanisms for this temporal neural switching is like the phosphorylation decay mechanisms found in *E. coli,* modulated by other dopamine–glutamate interaction proteins such as those found in similar neural relations in vertebrates (see Greengard, 2001; also see the information that follows).

C. elegans is the only organism for which there exists a detailed neuromolecular analysis of ARS. However, for the other major clades in Fig. 3 the evidence is strongly suggestive of a conserved relation between dopaminergic neuromodulation of glutamatergic synapses. The co-occurrence of dopamine and glutamate in modulatory relations is a common feature across eumetazoan clades (Acerbo, Gargiulo, Krug, & Delius, 2002; Cleland & Selverston, 1997; Fienberg et al., 1998; Hills et al., 2004). For example, glutamate is the major excitatory neurotransmitter at insect motor neurons and has both inhibitory and excitatory roles in interneurons (see Nassel, 1996). Dopaminergic neurons in the abdominal ganglion of insects are typically sparsely distributed but show large branching patterns, indicative of neuromodulatory effects (Nassel, 1996). Specific examples of these effects have been documented for flight control in *Manduca sexta* (Claassen & Kammer, 1986) and escape response in the cockroach, *Leucophaea maderae* (Casagrand & Ritzmann, 1992).

Other neuromodulators are present in these animals, such as serotonin, histamine, and octopamine, and research may go on to show that these, too, are conserved in their relations with glutamate and foraging-like behaviors, but at present the bulk of the research with regard to goal-directed behavior rests with dopamine. This is not an argument that dopamine and glutamate are the only evolutionary precursors of goal-directed cognition, or that they are even the most important precursors, only that they are at present most informative with respect to the evolutionary relation between foraging and cognition.

A great deal more is known about dopamine in the fruit fly, *Drosophila melanogaster,* than in most other insects. Much of this information comes from studies of the fly as a model organism for human drug addiction. Flies show behavioral, neurochemical, and molecular similarities to mammals in terms of their responses to cocaine and ethanol (Bainton et al., 2000; Rothenfluh & Heberlein, 2002). For example, the effect of low levels of cocaine on wild-type flies leads to highly perseverative turning, where flies turn around in circles for up to 5 min (Bainton et al., 2000). However, when given a competitive antagonist to tyrosine hydroxylase (required for the synthesis of dopamine), flies show 10-fold reductions in global dopamine levels and fail to begin perseverative turning following treatment with cocaine. Treatment with L-dopa restores normal sensitivity. High dopamine levels therefore increase turning, and low dopamine levels reduce it. Other drugs have similar effects on movement and are also shown to be in part mediated by dopamine. The effects of these, too, are altered by the presence of food. For example, flies show increased levels of hyperactivity following low doses of ethanol, which is reduced and increased through the actions of an antagonist for tyrosine hydroxylase and L-dopa, respectively (Bainton et al., 2000). Further reinforcing the relation between food and dopamine is the observation that the effects of the dopamine antagonists can be partially reversed by placing the animals on food, which is presumed to increase dopamine release (Neckameyer, 1996).

For both *C. elegans* and *D. melanogaster,* dopamine appears to modulate turning behavior in response to a perceived "reward," either in the form of food or drugs. This is in part evidenced

by the fact that dopamine mimics the effects of food on behavior and is consistent with models of human drug addiction where the drug is proposed to circumnavigate natural reward circuits by acting directly on dopaminergic pathways (Berke & Hyman, 2000). Conversely, the inhibition of dopaminergic function creates an inability to perform behaviors normally associated with staying near the source of the recent reward.

This dopaminergic modulation of behavior in response to external rewards is ubiquitous across invertebrates. In mollusks and crustaceans, dopamine modulates the control of pattern-generating interneurons associated with movement (Harris-Warrick, Coniglio, Barazangi, Guckenheimer, & Gueron, 1995), and in the lobster stomatogastric ganglion this is known to be directly mediated through glutamate (Cleland & Selverston, 1997; Johnson & Harris-Warrick, 1997). Dopamine also modulates various aspects of feeding in *Aplysia* (Due, Jing, & Klaudiusz, 2004; Kabotyanski, Baxter, Cushman, & Byrne, 2000) and the gastropod mollusks *Helisoma, Lymnaea,* and *Limax maximus* (Elliott & Vehovszky, 2000; Trimble & Barker, 1984; Wieland & Gelperin, 1983). Dopamine induces the salivary response of the cockroach, *Periplaneta americana* (Baumann, Dames, Kühnel, & Walz, 2002), and other insects (see Nassel, 1996). In the honeybee, *Apis mellifera,* dopamine is found in its highest concentration in the insect's brain when the animal becomes a forager (Wagener-Hulme, Kuehn, Schulz, & Robinson, 1999). A number of these and other invertebrates have been used as models for human drug addiction, because they reveal similar relations between dopaminergic circuitry and perseverative behavior (Betz, Mihalic, Pinto, & Raffa, 2000; reviewed in Wolf & Heberlein, 2003).

In summary, there is strong evidence for an evolutionary relation between dopamine and foraging- or feeding-related behaviors in invertebrates. In many animals there is direct evidence that this is ARS-like in nature, with specific locomotory- or feeding-related behaviors modulated along a dimension from highly repetitive to infrequent. Furthermore, dopamine is central to the modulation of these behaviors and consistently produces perseverative behavior in high concentrations. It is not expected that dopaminergic mechanism and function will be identical across invertebrates. Given widely different evolutionary histories, it is instead expected that if dopamine modulated primitive foraging behaviors in the common ancestors of invertebrates, dopamine would preserve aspects of its earlier functionality in extant behaviors. Dopamine's perseverating qualities related to foraging and feeding across very divergent invertebrate clades is strong evidence that dopamine modulated behaviors in a similar way in very primitive invertebrates and perhaps did so before the divergence of vertebrates.

3.2. Vertebrates: Motor control and goal-directed behavior

To further investigate the evolutionary origins of dopaminergic perseveration in relation to foraging, we now turn to evidence for its involvement in foraging behaviors in vertebrates. First, however, it is important to make clear that this phylogenetic evidence (Fig. 3) supports a most recent common ancestor for vertebrates and insects either after or near the divergence of nematodes. There is no decisive evidence that any two of these clades are more closely related to each other than they are to the third. This is important because it should not be assumed that the molecular mechanisms and behavior found in *C. elegans* gave rise to insects and then vertebrates. Instead, it appears that nematodes may have diverged first, then insects and vertebrates

diverged from each other at about the same time very soon thereafter (Blair, Ikeo, Gojobori, & Hedges, 2002; Raible & Arendt, 2004).

Given these phylogenetic relations, it is not a priori clear what to expect from vertebrates with respect to their foraging and dopaminergic functionality. If dopamine functioned in the role of foraging or feeding or both (i.e., in response to rewards) in the most recent common ancestor to all of these clades, then we may expect to find it operating in a similar capacity in vertebrates. However, if in this most recent common ancestor dopamine modulated other aspects of behavior or development (e.g., gut elimination in response to food arrival or neuron growth), then we should expect evidence for this in extant vertebrates, from which we could reasonably presume that the perseverative role of dopamine in the foraging behavior of protostomes (e.g., insects and mollusks) evolved after the divergence of vertebrates. The evidence does not support this latter claim. Instead, it reveals a strong relation between perseverative foraging and dopaminergic mechanisms in all major eumetazoan clades, including vertebrates.

Relations between dopamine, feeding, and movement are reported in many vertebrates. Once again, in many instances hyperdopaminergic activity leads directly to perseverative feeding behaviors. For example, dopaminergic antagonists induce stereotypic biting in the tortoise (Anderson, Braestrup, & Randrup, 1975). In pigeons, dopamine initiates stereotypic pecking and vocalization behavior (Acerbo et al., 2002; Goodman, Zacny, Osman, Azzaro, & Donovan, 1983; Nistico & Stephenson, 1979; Reiner, Brauth, & Karten, 1984). In mice, the genetic knockout of a protein involved in dopamine production (tyrosine hydroxylase) leads to hypophagic behavior, in which the animals fail to eat or seek food normally (Szczypka et al., 1999). As with the flies described previously, when exogenous dopamine is given to mice, they are again able to attend to foraging. When genes responsible for *removing dopamine from the synapse* are knocked out, mice engage in repetitive motor patterns, or perseveration (Ralph, Paulus, Fumagalli, Caron, & Geyer, 2001), similar to that described previously for high dopamine levels in *C. elegans* and *D. melanogaster.* Rats show similar defects in feeding and finding behaviors when suffering from dopaminergic insults. After learning the location of a platform target in the Morris water maze, rats are unable to find that target if their nigrostriatal dopaminergic neurons have been selectively killed (Mura & Feldon, 2003). Similarly, pharmacological agonists and antagonists of dopamine block performance in the water maze (Whishaw & Dunnett, 1985). As well, dopamine initiates stereotypic sniffing, licking, and gnawing (Blackburn, Pfaust, & Phillips, 1992; McCulloch, Savaki, & Sokoloff, 1982).

This relation is preserved among animals with more developed cognitive structures in the vertebrate lineage. For example, in nonhuman primates, amphetamines, which cause the release of dopamine, increase food-seeking behavior (Foltin, 2001). *Rhesus macaques* given unrestricted food access show reduced drug-seeking behavior compared with the same monkeys with restricted food access (Macenski & Meisch, 1999), again, not unlike the experiment described previously for *D. melanogaster.*

However, in vertebrates behaviors modified by dopamine begin to involve a broader class of motion, not necessarily related to moving toward food. For example, frogs and toads both maintain dopaminergic control of visuomotor focus on prey times (Buxbaum-Conradi & Ewert, 1999; Patton & Grobstein, 1998). Similar dopaminergic involvement in visuomotor focus is seen in rats and humans (Barrett, Bell, Watson, & King, 2004; Dursun, Wright, & Reveley, 1999; Evenden, Turpin, Oliver, & Jennings, 1993). This is not insignificant, as visual

search shows a clear relation with ARS in what has been called *inhibition of return,* in which the viewer shows significant latencies or inhibitions in revisiting objects or regions of images that have already been investigated, as well as highly perseverative saccadic eye movements around areas of greatest interest (Tipper, Driver, & Weaver, 1991; Tipper et al., 1994).

Overall, there is ample evidence that vertebrates, such as other major clades of eumetazoans, use dopaminergic mechanisms to modulate foraging and feeding behaviors in similar ARS-like ways. This is not isolated to gross organismal movements—such as that shown for stomatogastric ganglion in lobster—numerous studies have shown a direct relation between dopamine and spinal locomotor movements in vertebrates (Grillner & Zanger, 1979; Guertin, 2004; Svennson, Woolley, Wikstrom, & Grillner, 2003; Viala & Buser, 1971). More evidence of these similarities will be provided in what follows. Principally, when one views the vertebrate lineage's relation with dopamine from an evolutionary perspective, it becomes clear, especially in humans and nonhuman primates, that a substantial role for dopamine is in what has been termed *goal-directed cognition.* Understanding what exactly this goal-directed cognition is and how it is like or not like that described previously for foraging- or goal-directed behavior requires that we look more closely at the vertebrate neuroanatomy associated with goal-directed cognition with an eye toward the evolutionary history of these neural structures.

3.3. The striatum and vertebrate goal-directed cognition

The most outstanding neural architecture in the contemporary neuroscience literature associated with goal-directed behavior is that of the basal ganglia and, specifically, the striatum. The basal ganglia have long been associated with the control of limb movement and movement-related disorders (DeLong, 1990; Reiner, 1994), and more recent evidence suggests this is in part mediated through motor areas in the frontal lobe (reviewed in Dum & Strick, 1991). The role of the basal ganglia is still a focus of considerable research, but its function can be summarized somewhat as a guide to motor behavior based on information it integrates from multiple areas of the nervous system, involving aspects of procedural learning, habit formation, and the control of voluntary movement (Houk, Davis, et al., 1995; Reiner et al., 1998). With respect to the control of these behaviors, a substantial majority of inputs to the basal ganglia are from the cerebral cortex and the substantia nigra (Alexander, DeLong, & Strick, 1986).

Information is received in the basal ganglia at the striatum, which consists primarily of spiny neurons, receiving input from up to 10,000 different afferent input fibers at numerous dendritic spines on each neuron (Houk, 1995). A massive number of these inputs are dopaminergic (Reiner et al., 1998), and recent evidence suggests that these inputs are used to coordinate activity in the striatum with respect to external reinforcement possibilities (Schultz et al., 1995; Wickens, 1990). These dopaminergic inputs are atypical in their anatomy, often associated with spine necks, not tips, and with numerous small synapses as opposed to the larger synapses often observed for other neurotransmitters (reviewed in Groves et al., 1995).

Outlining the evolutionary evidence for the basal ganglia is beyond the scope of this article and not particularly informative with respect to the article's thesis because much of the neural connectivity and cellular localizations of neurotransmitters in the basal ganglia are conserved across modern mammals, birds, and reptiles (amniotes; reviewed in Reiner et al., 1998; Salas

et al., 2003). It appears that the major dramatic change from anamniotes (fish and amphibians) to amniotes is the rapid proliferation of dopaminergic neurons inputting to the striatum (Reiner et al., 1998). Which is to say, the striatum does not appear to alter its circuitry in this evolutionary progression—merely to impressively expand its inputs from interneurons in the cortex. This presumably increased the power of the striatum to integrate numerous inputs from multiple sources and, given the role of the striatum, is likely to facilitate increasingly complex associative relations. Otherwise, there is no mention of striatal or basal ganglia-like structures in the literature with respect to organisms outside the vertebrate lineage. Presumably these structures have some evolutionary precursor, but present research has not identified them above the level of the circuit, which was described previously.

The interaction between dopamine and glutamate in the striatum is key to proper striatal function (Dani & Zhou, 2004; Smith, Raju, Pare, & Sidibe, 2004). The imbalance of these two neurotransmitters is suspected in a number of goal-directed pathologies, including Parkinson's disease, schizophrenia, and addiction (see Section 6). In the striatum, dopaminergic neurons at the neck of dendritic spines are believed to modulate glutamatergic inputs to the tip of the spine in what may be called striatal microcircuits. These circuits appear to filter out less active inputs and reinforce others (Bamford et al., 2004). These microcircuits are dramatically similar to the circuitry proposed to modulate ARS in *C. elegans* (Hills et al., 2004). In fact, the main difference in the associated neural circuitry is the presence of the protrusion in the membrane, or the spine (Fig. 4). Postsynaptic neurons for *C. elegans* also receive numerous inputs, although for spiny neurons the number is several orders of magnitude higher and comes primarily from connections to cortical neurons (White, Southgate, Thomson, & Brenner, 1986). Otherwise, at the level of the microcircuit, we appear to be observing similar neural architecture in the nematode

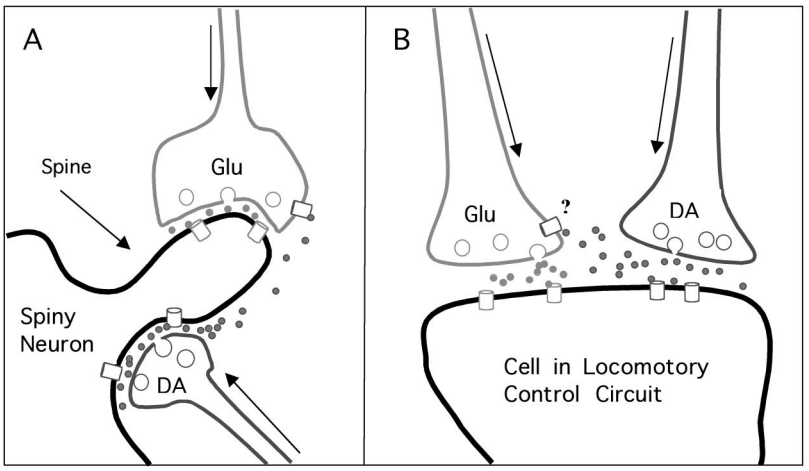

Fig. 4. Two representations of dopaminergic–glutamatergic interactions at interneurons in the mammalian striatum (A) and the locomotory control circuit in *C. elegans* (B). "Glu" and "DA" represent glutamatergic and dopaminergic presynaptic neurons, respectively. In both cases, there is evidence that release of dopamine from the dopaminergic neuron alters the postsynaptic neurons' response to glutamate. In *C. elegans* it is not known whether this is a presynaptic response of glutamatergic neurons (indicated by "?") and/or a postsynaptic response of the locomotory control interneurons. A is redrawn from Dani and Zhou, 2004. B is redrawn from Hills et al., 2004.

and all amniote vertebrates, with nearly identical activity characterized by the dopaminergic neuromodulation of glutamatergic synapses.

Although other differences exist at the level of the protein—DARPP-32 arrives in the transition from anamniotes to amniotes and provides substantial computational power at this level (Fienberg et al., 1998; Greengard, 2001; Reiner et al., 1998)—the major difference appears to be in terms of what the incoming neural signals represent. That is, in *C. elegans* or *Drosophila,* the afferent neural signal can reliably be said to represent the presence of food, whereas in higher vertebrates, the signal may represent the expectation of a reward (Schultz et al., 1995). The critical transition appears to be from a concrete reward to its neural representation. Where once we would expect the animal to perseverate in the presence of the reward, we may now expect the animal to perseverate on the expectation (stimulated by external or internal cues) or "idea" of the reward.

Still, the exact role of dopamine in the ancestor is unknown. It is well argued that its role in extant species is associated with novelty or reward detection. However, this cannot be a complete definition with respect to evolution, because evolution cannot act on a detector that is not associated with some subsequent behavioral or physiological modulation. The complete answer must consider not only what dopamine release was responding to, but also how it led to a response in the animal. A reasonable answer given the evidence described previously is that dopamine detected some kind of reward (probably food) and then initiated a perseverative behavioral response associated with that reward, either feeding or turning. The evolutionary theory described here is therefore completely consistent with the reward theory of dopamine, but adds the evolutionary hypothesis that the initial rewards represented by the release of dopamine were food. Only later was this system co-opted to represent the expectation of a reward, which allows for goal-directed cognition.

A region of the striatum notably related to goal-directed behavior is that of the nucleus accumbens (NAcc). Another major region of the striatum is the putamen, and research has shown it to have similar anticipatory effects (Houk, Adams, & Barto, 1995). The NAcc has been implicated in goal-directed behaviors (Cardinal, Pennicott, Sugathapala, Robbins, & Everitt, 2001; Carelli, 2004; Di Chiara et al., 2004; Miyazaki, Miyazaki, & Matsumoto, 2004; Yun, Nicola, & Fields, 2004) and locomotion and foraging behaviors (Floresco, Braaksma, & Phillips, 1999; Floresco, Seamans, & Phillips, 1996; Seamans & Phillips, 1994). As reported previously for the striatum as a whole, one of the key neurotransmitters involved in the modulation of these behaviors in the NAcc is dopamine (Floresco et al., 1996; J. Salamone et al., 2005).

The precise role of the NAcc is a matter of debate, but it is the site most typically associated with the reward hypothesis for dopamine (Robbins & Everitt, 1996; J. Salamone et al., 2005; J. D. Salamone, Cousins, & Snyder, 1997) and plays a major role in behaviors associated with drugs of abuse (Di Chiara et al., 2004; Nestler, 2004). The reward hypothesis, however, appears to be an oversimplified view of the NAcc, as considerable evidence points to NAcc involvement in mediating responses to negative and novel stimuli (reviewed in Salamone et al. 1997; Weissenborn & Winn, 1992). For this reason, J. D. Salamone et al. (1997, p. 352) suggested the role of the NAcc is in the "activational aspects of motivation, response allocation, and responsiveness to conditioned stimuli." It is important to note that conditioned stimuli represent information about resources, not the resources themselves, and very likely represent the

first evolutionary move in foraging from a search for resources to a search for information about those resources.

To further detail the evidence described previously for the microcircuit, a key shared feature of the NAcc and the *C. elegans* microcircuitry is that both modulate responses to multiple stimuli (Carelli, 2004; Chalfie et al., 1985; Hills et al., 2004; J. D. Salamone et al., 1997). This operates via multiple afferent inputs to these subsets of neurons, which signal the impending nature of relevant stimuli. For example, in *C. elegans,* the locomotory command interneurons are the final source of modulation between appetitive and aversive stimuli, such that the animal can attend to one or the other based on their relative importance at a given moment in time (Chalfie et al., 1985; Tobin & Bargmann, 2004). Similarly, the ability to choose, as well as to not make impulsive decisions, appears to lie in part with the NAcc (Cardinal et al., 2001; King, Tenney, Rossi, Colamussi, & Burdick, 2003). Similar to behaviors seen with high dopamine levels in invertebrates, damage to the NAcc leads to perseveration and reduced behavior switching in rats (Taghzouti, Simon, Louilot, Herman, & Le Moal, 1985).

The NAcc receives afferent connections from the prefrontal cortex, the amygdala, the hippocampus, and the ventral tegmental area (O'Donnell & Grace, 1995). As a mediator of these connections, the NAcc appears to coordinate behavior by allowing activation of NAcc cells when it receives matching inputs from different areas of the brain, but inhibiting the many other excitatory inputs that are not "related" to this context defined by the hippocampus (Wagar & Thagard, 2004). Dopaminergic inputs to spiny neurons are good candidates for establishing this context (this is explored further in Section 5).

Outside the basal ganglia, a region strongly implicated in goal-directed behavior, is the prefrontal cortex (PFC). Although clearly the PFC is a late arriver on the evolutionary scene, it is nonetheless deeply connected with goal-directed behavior, with direct connections to the striatum (O'Donnell & Grace, 1995). The PFC is also implicated in the general features of working memory, such as remembering or encoding information about place or strategy (reviewed in Eichenbaum and Cohen, 2001; Fuster, 2001) and disabilities in visual search (Mort & Kennard, 2003). Similar to the striatum, cells in the PFC show sustained activation in brief memory tasks (Cohen et al., 1997; Courtney, Ungerleider, Keil, & Haxby, 1997; Goldman-Rakic, 1995; Orlov, Kurzina, & Shutov, 1988), and dopamine is a major factor involved in this sustained activation (Seamans et al., 1998; Wang et al., 2004; Watanabe et al., 1997), again, with the involvement of glutamate (Durstewitz, Kelc, & Gunturkun, 1999; Seamans, Durstewitz, Christie, Stevens, & Sejnowski, 2001).

Because the PFC is multifunctional, highly interconnected with other areas of the brain, including the basal ganglia, and involved in the production of behaviors associated with both concrete objects in the environment and abstract rules (Cools, Clark, & Robbins, 2004; Eichenbaum & Cohen, 2001; Fuster, 2001), this has led to a number of models of the PFC, which use dopamine to modulate the access of its afferent connections (Durstewitz et al., 1999; Miller and Cohen, 2001). Here dopamine is hypothesized to hold objects in attention long enough for appropriate behaviors to be activated and successful cognitive associations reinforced (Braver & Cohen, 2000).

Consistent with the theory of area-restricted cognition is evidence that existing solutions mediated by the PFC are most typically tried as initial solutions when problem solving in novel situations (see Dehaene & Changeux, 1992; Eichenbaum & Cohen, 2001). In this way, cogni-

tion tends to wander down well-worn paths in our day-to-day behavior (presumably represented by specific network activation patterns), which may range in complexity from motor habits to verbal rants. The PFC's role appears to be in an executive mediation of these possible behavioral sequences (see Miller & Cohen, 2001). When the PFC is damaged, mediation fails, and the consequences are consistently either perseveration or the failure of ideas to persist (see Eichenbaum & Cohen, 2001; Miller & Cohen, 2001). Again we see that in the same way that animals modulate their location in space, the PFC appears to modulate the location of attention, most likely through its relation with the basal ganglion.

The context of goal-directed behavior must be composed of both internal and external stimuli, both by the control of attention and the appropriate alignment of the incoming stimuli with previous expectations. This is likely to be in part controlled by the PFC efferents to the NAcc or the striatum in general, which modulate attention, eye movement, and the maintenance of working memory (Bertolucci-D'Angio, Serrano, & Scatton, 1990; Floresco et al., 1999; Schultz, 2004; Schultz et al., 1995; see also Section 5). Novel stimuli lead to correlated increases in dopamine concentrations in both the NAcc and the prefrontal cortex (Berns, McClure, Pagnoni, & Montague, 2001; Rebec, Grabner, Johnson, Pierce, & Bard, 1996). Altering the activity of neurons in the PFC, either through induced cell death or pharmacological interventions, alters the responsiveness of dopaminergic neurons in the NAcc (Louilot, Le Moal, & Simon, 1989; Thompson & Moss, 1995). As described previously, this in turn leads to deficits in goal-directed behavior.

In the evolutionary history of vertebrates, it is therefore possible to witness a development from the dopaminergic striatal control of visuomotor focus in frogs and toads (Buxbaum-Conradi & Ewert, 1999; Patton & Grobstein, 1998) to the similarly controlled maintenance of ideas in working memory (Schultz et al., 1995). What lies in the transition from early chordates to vertebrates is not so well understood. Dopamine is present in animals such as amphioxus, *Branchiostoma lanceolatum,* and the sea pansy, *Renilla koellikeri* (Anctil et al., 2002; Moret et al., 2004), but what behaviors are being mediated and by what circuitry remain areas of future study. It is reasonable to predict that the neural relations between dopamine and glutamate will be preserved in these organisms and that the likely behaviors will involve maintenance of a specific behavior in response to found resources. It is more likely that behavior in response to the expectation of resources is an evolutionary consequence of increased inputs to the striatum, which through their coincident circuitry are able to establish relations between conditioned and unconditioned stimuli (see Section 5).

Numerous gene duplication events have been associated with the evolution of the dopamine receptor in vertebrates (Callier et al., 2003). As well, the dopamine–glutamate circuitry in vertebrates at the level of the whole brain is far from the near-linear relation observed between presynaptic sensory neurons and postsynaptic interneurons in *C. elegans.* For example, cerebral cortex efferent neurons target the striatum, which in turn targets the pallidum (and others), which targets the thalamus, which targets both the striatum and frontal cortex (Houk, 1995). These brain regions involve dopamine, glutamate, and a host of other neurotransmitters (Greif, Lin, Liu, & Freedman, 1995; Kretschmer, 1999; Mansvelder & McGehee, 2000; Scott et al., 2002). As well, the hippocampus is clearly active in the formation of memory, both spatial and episodic (Fletcher, Fritch, & Rugg, 1997; Hills, 2003; Mizumori, LaVoie, & Kalyani, 1996), but it often operates antagonistically with the striatum (Dagher, Owen, Boecker, & Brooks,

2001), and its evolutionary history is less well understood. There is no effort here to simplify the vertebrate nervous system to match that of prevertebrates. There is still a great deal of active research on the relation between many other neurotransmitters and goal-directed cognition. For example, a close relative of dopamine, norepinephrine, also modulates cognitive flexibility in abstract problem solving in humans (Beversdorf, Hughes, Steinberg, Lewis, & Heilman, 1999). There is no doubt that these other mechanisms hold stories of their own with respect to the evolution of goal-directed cognition. At present, however, dopamine offers us the strongest evolutionary evidence.

In humans, general strategies also appear to be conserved across spatial foraging and more abstract or cognitive search. Normal individuals prone to perseverate in spatial foraging tasks also show tendencies to perseverate in cognitive problem-solving tasks, whereas those who explore globally in one task are likely to do so in another (Hills & Stroup, 2004). This relation is explored further in the following section with respect to pathologies of goal-directed cognition.

4. The evidence from pathologies of goal-directed behavior

This evolutionary progression outlined previously suggests a number of predictions. Foremost, we should find evidence of a wide variety of human cognitive pathologies that show characteristic similarities with foraging behavior and specifically ARS. Principally, this prediction should manifest itself in the following ways: (a) that the behaviors exhibit deviations from appropriate control of attention, involving either a bias toward abnormally long or abnormally short attentional focus, analogous to perseverative turning in space or overly short giving-up times (e.g., the inability to focus); (b) that these behaviors involve dopaminergic modulation consistent with that seen in foraging animals (e.g., more dopamine initiates more focus and vice versa); and (c) that the pathological control is not strictly cognitive, but also involves motor control, consistent with the evolutionary argument for development of goal-directed cognition from preexisting motor control mechanisms.

The evidence from cognitive pathologies of goal-directed behavior is highly consistent with the above predictions and remarkably suggestive of a link with the evolutionary history of foraging, as described in the previous section. Most pathologies of attention fall into two broad categories, typical of the pathological extremes observed for high and low dopamine levels seen in foraging behavior (reviewed in Nieoullon, 2002). These consist of those pathologies involving perseverative or stereotypic behaviors that endure past what might be considered the normal temporal duration and, on the other extreme, those behaviors that fail to persist for the necessary duration (Fig. 5). Metaphorically, these are akin to modulating the duration of the high-turning component of ARS (in the genetic algorithm this corresponds to the "memory depth" parameter). Furthermore, the molecular mechanisms involved in the control of these pathological forms of attention are consistent with high and low levels of dopamine observed for foraging, respectively, as in, for example, *C. elegans, D. melanogaster,* and the mouse (Hills et al., 2004; Ralph et al., 2001; Szczypka et al., 1999). And finally, these ARS-like pathologies are not merely pathologies of cognition, but range from motor pathologies, to ritualized behavior, through the persistence of ideas.

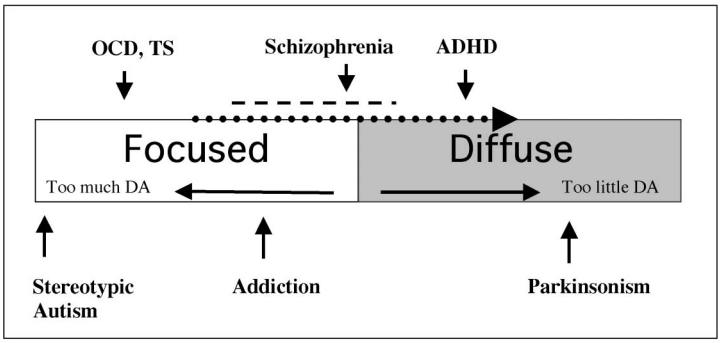

Fig. 5. A visual characterization of goal-directed pathologies along a continuum of dopaminergic activity. The dotted line at the top represents the normal temporal progression of dopaminergic activity in ARS, from high to low, modulating behavior from focused to diffuse search (i.e., from local to global). The placement of the pathologies is not prescriptive, but based on general descriptions and prevailing theories of the underlying mechanisms, which themselves are based on the fact that all of these behavioral phenotypes are treated with dopamine (if too "diffuse") or its antagonists (if too "focused"). Though dopamine is clearly a control factor in all of these pathologies, other mechanisms *are* involved. Schizophrenia is an obvious case where mechanisms are not well understood, and I represent its enigmatic position with a dashed line. OCD is obsessive–compulsive disorder and TS is Tourette syndrome.

The two broad classes of goal-directed pathologies range, therefore, from stereotypic (including schizophrenia, some types of autism, drug addiction, and obsessive–compulsive disorder [OCD]) through failure to persist (including attention deficit hyperactivity disorder [ADHD] and Parkinson's disease). The claim is *not* that these behaviors are controlled solely by dopamine, but that the ARS-like features of these pathologies can either be attributed to dopaminergic defects or treated with dopaminergic drugs. The following disorders of attention were chosen because they are highly represented in the literature on goal-directed pathologies, and the information regarding their symptoms and treatment is reasonably well developed (although far from being completely understood).

4.1. Perseverative disorders

Schizophrenia is characterized by stereotypies at multiple levels of neural control. These range from tics or motor spasms to highly ritualized behavior and idea persistence. The persistence of ideas in schizophrenia has been called a "poverty of ideas" because the repetition of language patterns, from individual words to phrases, is confined to a specific content suggesting a highly constrained ideational attention (reviewed in Ridley, 1994).

Failure to perform smooth visual pursuit in saccadic eye movements is also characteristic of patients with schizophrenia (Dursun et al., 1999; Hong, Avila, Adami, Elliot, & Thaker, 2003) and may be evidence of visual perseveration. This characteristic of visual attention in patients with schizophrenia is both an early warning sign of schizophrenia and a hereditary marker, as similar visual abnormalities are observed in first-degree relatives (Hong et al., 2003). This evidence is consistent with observations of hypofrontality (frontal metabolic and blood flow deficiencies) in those with schizophrenia (Davidson & Heinrichs, 2003), as eye movement is in

part controlled by frontal lobe centers that maintain attention to specific objects (LaBerge, 1998).

Despite schizophrenia's multidimensional characterization (see Crow, 1980; K. L. Davis, Kahn, Ko, & Davidson, 1991), the most successful (although insufficient) hypothesis for the biological basis of schizophrenia is called the *dopamine hypothesis.* This was originally based on the efficacy of antidopaminergic drugs used to treat schizophrenia's positive symptoms (e.g., hallucinations and delusions), as well as the schizophrenia-like effects of dopaminergic drugs (Snyder, Banerjee, Yamamura, & Greenberg, 1974). More recent evidence from a variety of sources suggest that deficits are associated with both dopaminergic and glutamatergic dysfunction (reviewed in Laruelle, Kegeles, Abi-Dargham, 2003). Schizophrenia is consistent with all three predictions for goal-directed cognitive pathologies; it shows pathological behavior consistent with high levels of dopamine, consisting of both motor and cognitive deficits.

One of the behavioral symptoms commonly associated with certain subtypes of autism is perseverative or stereotypic behavior, consisting of repeated motor patterns, often involving objects (Kaplan, Sacock, & Grebb, 1994). Frith (1989) cited evidence that this stereotypic behavior is pervasive to the point of operating prior to the level of integrating perceptual features, what she called "weak central coherence." That is, patients with autism fail to solve the "binding problem" and instead appear to show abnormally focused attention on specific object features (Happe, 1999). In this case, the focus of attention appears to be so acute that the individual is unable to see the whole object—obviously, a very extreme form of cognitive perseveration.

Whether or not autism is a disorder of dopaminergic function remains a subject of debate. However, in practice, antidopaminergic treatments (e.g., haloperidol) help some patients with autism to overcome stereotypic behavior and to integrate perceptual features (reviewed in Posey and McDougle, 2000). Autism appears to lie at the very extreme end of perseverative cognition, and levels of the dopaminergic metabolite, homovanillic acid, are significantly higher in individuals with stereotypic autism than they are in other individuals with autism or in those without autism (reviewed in Tsai, 1999).

Drug addiction is characterized by an apparently involuntary search for and consumption of drugs. Of principal interest with regard to the theory of cognitive foraging are its distinctly cognitive features in which individuals perseverate on the idea of the drug, even in its absence. Many accounts of this are available in the popular literature (Burroughs, 1977; M. Davis and Troupe, 1990) and exhibit a kind of cognitive turning that finds itself forever unable to leave the vicinity of the idea of the drug, such that it seems to motivate all actions. The prevailing evidence regarding drug addiction suggests that drugs are addictive because they circumnavigate natural reward mechanisms and eventually modify dopaminergic pathways in the brain (Berke & Hyman, 2000; Ritz, Lamb, Goldberg, & Kuhar, 1987; Volkow, Fowler, Wang, & Swanson, 2004). This may happen as a long-term developmental result of manipulating dopamine concentrations at the synapse (Berke & Hyman, 2000). Imaging studies further suggest that this acts to reduce frontal lobe response to non-drug-related stimuli, but enhances the response (and reduces disinhibition) to drug-related stimuli (Volkow et al., 2004). Again, other mechanisms have been implicated (Rocha et al., 1998), but the overall phenomenology is highly consistent with a dopamine-induced persistence of ideas.

Finally, there are two more cases worthy of discussion, both of which exemplify the predictions of cognitive ARS and also nicely contrast the difficulty of separating cognitive function from motor function. The first, OCD, involves components of both ideational perseveration and compulsive behaviors, which are usually performed to alleviate emotional factors associated with the obsessive idea (Kaplan et al., 1994; Rapaport, 1990). Motor tics are often associated with OCD and again reveal a correlation between perseverative behavior and perseverative thoughts (Ridley, 1994). Nearly half of OCD patients treated with serotonin uptake inhibitors fail to show positive clinical outcomes, but in cases involving tics the addition of dopamine antagonists shows significant improvement (McDougle, Goodman, & Price, 1994). The second, Tourette syndrome (TS), involves motor perseveration, such as sniffing or blinking, and the inability to inhibit specific behaviors, such as jumping, obscene language, or mannerisms, sometimes called vocal tics (Graybiel & Canales, 2001). Pimozide, an antidopaminergic drug, is often successful in treatment (Sallee, Nesbitt, Jackson, Sine, & Sethuraman, 1997).

4.2. Inattentional disorders

On the other side of the dopaminergic spectrum, we have cognitive disorders represented by too little dopamine that, like the description for foraging animals, reveal an inability to stay in one place, or their cognitive parallel, the inability to focus attention for an appropriate duration to guide effective behavior. I discuss two prominent pathologies here.

ADHD shares symptoms that are largely the inverse of obsessive–compulsive and addictive behaviors, although like many syndromes it has multiple subtypes. Although ADHD is very likely a polygenetic trait (Schinka, Letsch, & Crawford, 2002), behavior associated with ADHD has been correlated with specific polymorphisms in dopaminergic proteins (Lowe et al., 2004; Muglai, Jain, Macciardi, & Kennedy, 2000; Swanson et al., 2000). Individuals diagnosed with ADHD also show elevated levels of the dopamine transporter, responsible for moving dopamine out of the synaptic cleft (Krause, Dresel, Krause, la Fougere, & Ackenheil, 2003). The implications are that ADHD is a result of too little dopamine in the synapse, and this results in the inability to focus as well as behaviors that appear to be related to novelty-seeking (Schinka et al., 2002)

For over 60 years the treatment of ADHD has involved sympathomimetics, which stimulate the release of dopamine (Kaplan et al., 1994; Markowitz, Straughn, & Patrick, 2003). One of the hypotheses associated with the efficacy of dopaminergic drugs in the treatment of ADHD is that dopamine increases the executive control of cognitive and behavioral inhibition (Kaplan et al., 1994). That is, dopamine improves attentional focus by inhibiting other possible sources of internal or external distraction. Consistent with this hypothesis, recent work by Potter and Newhouse (2004) suggested that the high prevalence of smoking among individuals with ADHD may be a result of individuals self-medicating with nicotine, which increases the release of dopamine to the synapse, thereby increasing cognitive focus (Mansvelder, Keath, & McGehee, 2002).

The etiology of Parkinson's disease is known to involve the degeneration of dopaminergic neurons in substantia nigra pars compacta (Parent & Cossette, 2001), but the description of the symptoms has proved very challenging. The disease can be characterized as the failure to vol-

untarily initiate action, but several studies suggest the pathology involves pervasive cognitive deficits as well. These include deficits in attention, the ability to plan, and difficulty in concept formation. These all appear to be related to dysfunctional communication between the prefrontal lobe and the basal ganglia (reviewed in Kulisevsky, 2000). Nonetheless, Parkinson's disease is often treated effectively, during the early stages of the disease, with L-dopa, which increases the supply of dopamine to the brain (Rascol, Ferreira, Thalamas, Galitsky, & Montastruc, 2001). Recent approaches to treatment also take into consideration the glutamatergic pathways in the basal ganglia as possible targets for pharmaceuticals (Marino et al., 2003).

4.3. Conclusions from pathologies of goal-directed behavior

All of the pathologies listed previously meet the criteria of the three predictions described at the beginning of this section. They show behavioral characteristics consistent with bias toward too much or too little focus. With respect to dopamine, the behavioral characteristics are modulated in nearly identical ways with that described previously for foraging animals. The behaviors also demonstrate a range of cognitive depth, from simple motor tics to the ability to plan and form conceptual ideas. There is far more to all of these behaviors than dopamine—the treatment of OCD and schizophrenia being particularly obvious examples. Yet, taken as a whole, these disorders are remarkably consistent with a theory of area-restricted cognition, involving dopamine balancing attention and subsequent downstream behavior between too much and too little attentional focus. Like dysfunctional foragers in the genetic algorithm, individuals with these pathologies appear to forage both spatially and cognitively as if they existed in worlds where, for example, resources were hard to find but always nearby (as in perseverative disorders) or easy to find but nowhere close (as in inattentive disorders).

5. Area-restricted cognition: Multidimensional foraging for information

The principle observation made with respect to dopaminergic afferent neurons arriving in the striatum is that they indicate unexpected stimuli with potential relevance to future success in the environment (Schultz et al., 1995). This is indicated by a number of studies that show activity in these neurons in response to unexpected stimuli, rewards, or potentially aversive stimuli (e.g., Fiorillo, Tobler, & Schultz, 2003; for reviews see Carelli, 2004; J. Salamone et al., 2005; J. D. Salamone et al., 1997). Studies also show the activity of dopaminergic neurons can be transferred to predictive (i.e., conditioned) stimuli when these stimuli signal future rewards (Houk, Adams, et al., 1995; Ljungberg, Apicella, & Schultz, 1992), and this creates a very strong implication in support of the evolution of goal-directed cognition.

This use for dopaminergic neurons is consistent with that observed in spatial foraging, the main difference being that in a cognitive context the resource can now be conditioned stimuli, or information. Specifically, this is information that is predictive of future resources (whether those resources be food, mates, territory, the absence of aversive stimuli, or even other information). Focused attention to specific reward-related details in the environment leads to an acquisition of that information in the form of learning.

As with foraging, an encounter with a reward-related event creates a perseverative behavior that focuses the animal on the event. This observation has given rise to the behavior systems view (Timberlake, 1997), which extends the behaviorist paradigm in important ways by observing that animals respond differently to stimuli depending on the perceived resource context of the stimulus. For example, animals are more likely to engage a non-food-related item when that item is presented out of context with food (Silva & Timberlake, 1998). In alternate contexts, Bell (1991) described a situation for houseflies, where the insect, on encountering a drop of sugar, now begins to turn frequently in what is apparently a search for other droplets nearby. Benedix (1993) described a similar situation for rodents. For rats, this turning in response to resources is directly related to dopaminergic signaling, which apparently leads to preferential activation of specific neurons associated with the reward and subsequent behaviors associated with its acquisition (Mura & Feldon, 2003). In cognition, the analog of turning becomes a prolonged dopaminergic activation of local cell assemblies associated with the reward. Simultaneously, the dopaminergic neurons facilitate learning about the rewards and thereby restructure the network itself (Kulisevsky, 2000; Nieoullon, 2002; Schultz et al., 1995; Wickens, 1990).

An explanation for the associated learning is that striatal neurons, due to numerous dendritic spines—as many as 10,000 per neuron—are able to correlate additional co-occurring stimuli with the occurrence of the reward. The striatum, via this coincident network, learns what in the environment is related to the reward. If attention focuses on an event or object while a reward-related stimuli arrives simultaneously, dopaminergic neurons act to integrate the reward with its predictor. However, if a reward does not arrive, the absence of dopaminergic inputs leads to a decrement in the relative strength of the relation (similar to the reward-prediction-error hypothesis, see Hollerman & Schultz, 1998). Therefore, active dopaminergic networks create relevancy frameworks for assessing situations or guiding actions with respect to some reward, and by focusing the animal's attention on these items, it further facilitates the search for relevant information about appropriate reward predictors.

The examples provided previously are based on the acquisition of an external reward, but the same neural mechanisms may be at work in efforts to solve an internal cognitive representation problem. For example, suppose a participant is attempting to remember a name associated with a particular face. Those dopaminergic neurons related to intention activate the "face" representation, which is held in working memory in the prefrontal cortex (see Miller & Cohen, 2001), whereas other neural assemblies are tested against the face representation in search of an appropriate neural "fit." If the distance of this target representation is represented by numerous indirect associations, the path to that network representation may require cognitive flexibility associated with a more global search or spreading activation pattern. Perseverative attempts to match the face will likely lead to failed searches. But where network relations are more direct or less perseverative, the path to the solution may appear linear, as the name appears almost simultaneously with the face.

This is not a linear spatial search of the cortex. By reducing the local dopaminergic "hold" on possible matches, the ARS-like mechanisms in the striatum allow a simultaneous global search of a larger portion of the cortical space. So it is not as if one representation is seeking a match and sorting through possibilities one at a time, but one idea seeks a match by looking at gross features of many possible matches simultaneously and then moving to more detailed rep-

resentations as it narrows the search to a most likely candidate. This is analogous with simulated annealing algorithms that rely on a variable, such as temperature, that modulates between global and local levels of similarity matching (originally described by Kirkpatrick, Gelatt, & Vecchi, 1983). This is also similar to spreading activation theory described to explain results of indirect semantic priming (see Section 6; Collins & Loftus, 1975; Neely, 1977).

An example of this is seen in cortical activity levels following learning of mathematics in college students. Using functional MRI, Qin et al. (2003) were able to show that during initial learning of novel mathematical symbol manipulations, students exhibited far more neural activity across a much more diffuse region of the cortex than they did 5 days later. This is consistent with the role of the dopaminergic activity in the striatum described previously, but also suggests that in problems with many unknowns the attentional mechanisms are not sure which novel stimuli are related to the solution, but must discover them through a global activation pattern. This is very likely to be a global dopaminergic elevation in the striatum that is not initially associated with any clear competitive winners. This global activation may also explain the somewhat counterintuitive observation that higher levels of dopamine release are associated with increased, not decreased, cognitive flexibility (see Ashby, Isen, & Turken, 1999). There appear to be very important differences among local, global, and relative dopaminergic release patterns.

Situations where the target problem is least well understood should therefore show the largest patterns of cortical activation, as the network exhibits relatively weak stable solutions in what has been appropriately termed *network frustration* (Strogatz, 2001). As the network representations feed back on themselves (via the pathway outlined in Section 3) and begin to identify appropriate predictors through more strongly competitive dopaminergic activity, less global activation is seen. As a consistent approach to the solution is achieved, the global search becomes less necessary, and global dopaminergic activity in the striatum is narrowed to local activation patterns (as observed by Schultz et al., 1995).

The search in the global cognitive space is very likely to be initially guided by modulating the number of striatal connections with specific areas of the cortex, which feed back in closed loops through the striatum (see Houk, 1995). This would appear to be precisely the mechanism by which an area-restricted cognition could localize or globalize attention to modulate focus in response to the success of specific cognitive suspicions. If the striatal network has access to a wide field of cortical representations, then the active striatal network is able to compare problems with numerous potential solutions, based on previous experiences and expectations. Overly perseverative striatal activation patterns fail to search the cognitive space and maintain convictions beyond an appropriate giving-up time, whereas striatal networks that fail to persist are unable to maintain potential solutions or goals. An appropriately modulated striatal activation pattern must form and then slowly modify the target (e.g., problem representation), based on feedback, so as to search the global space in a heuristic fashion. Dopaminergic activity maintains the striatal network pattern, but must also be flexible enough in the face of new information, either external or internal, to update the target.

In environmental problem situations, poorly defined problems should lead to initially desynchronized or global activity patterns, as dopaminergic inputs weakly test the predictive roles of environmental stimuli, searching for appropriate reward predictors. In recordings of local populations of neurons in rats solving the T-maze paradigm, there are global and consis-

tent changes in firing patterns that are well correlated with the animal's performance in the maze. Jog, Kubota, Connolly, Hillegaart, and Graybiel (1999) showed that over the course of learning, there is more striatal activity when the animal is unfamiliar with the appropriate predictors. However, as the animal begins to learn the appropriate predictors of resources, activity decreases. Furthermore, the global response patterns from all local fields recorded in the striatum show an increase in temporally correlated firing, revealing a pattern from desynchronized firing early in learning to more synchronized firing after learning has taken place.

Using functional MRI, Sakai et al. (1998) observed similar learning-related activity in the frontal lobe. During early stages of learning the correct ordering of two button presses, the dorsolateral PFC was most active, compared to later stages of learning when this area was less active. Sakai et al. (1998) suggested the initial activity of the PFC is due to a working-memory process (see also, Goldman-Rakic, 1987; McCarthy et al., 1994). The reduction in activity they saw is similar to that observed by others (Jenkins, Brooks, Nixon, Frackowiak, & Passingham, 1994; Shadmehr & Holcomb, 1997). The reduction in PFC activity is met with an increase of activity in the parietal cortex, which is also connected with the striatum. The parietal cortex is related to retrieval from long-term memory, more associated with "intention" than "perception" (Goodale & Milner, 1992; Mazzoni, Bracewell, Barash, & Andersen, 1996; L. H. Snyder et al., 1997).

The previously mentioned evidence for an area-restricted cognition would suggest that when individuals are simultaneously confused and seeking to solve a problem, specific cells in the nervous system are used to maintain the goal representation at a top hierarchical level, whereas other cells transition from local synchronized activation to global desynchronized activation, as the "problem" reveals itself. As the desynchronized network activates internally consistent information relative to the target, or locates external information with similar corroborative characteristics, the network may then settle on more stable activation patterns. The search is hardly linear, as in the case of spatial foraging in two dimensions. But rather, cognitive foraging happens in a multidimensional space where resources are represented by the architecture and stability of specific activity patterns in the network, which themselves represent learned associations between external stimuli or cognitive representations.

6. Discussion and future directions

The evidence described previously lays out a theory for the evolution of goal-directed cognition. This aspect of cognition is born out of mechanisms initially evolved in the service of foraging- and feeding-related behaviors. Although it is dubious whether our most primitive eumetazoan ancestors had brains, they most assuredly had mouths, and by all existing evidence, they involved dopaminergic mechanisms in their control. The evidence further suggests a secondary argument that requires more research to fully corroborate, which is that a very specific foraging behavior, ARS, is a precursor to goal-directed cognition. ARS is an optimal foraging behavior for a wide variety of circumstances and especially where information about resources is limited. Empirically, ARS is found in all major eumetazoan clades. The molecular machinery controlling ARS is also very similar across eumetazoan clades, and this is true for

both the foraging behavior, that is, goal-directed behavior, and many aspects of goal-directed cognition. Together, this is consistent with an evolutionary origin of ARS early in the lineage of multicellular organisms. Furthermore, there is considerable evidence of adaptive consequences on the evolution of goal-directed behavior and subsequently goal-directed cognition, as it relates to the evolution of the basal ganglia, the prefrontal cortex, and associated pathologies of goal-directed cognition.

Dopamine's predominant involvement as a reward or novelty detector only supports this relation. The argument made here is that the reason dopamine is seen to respond to reward or novelty is that these represent information about resources, which the evolution of coincident networks in the basal ganglia identifies in classic associative relations as conditioned stimuli (the information) that predict the unconditioned stimuli (the resource). Indirectly, this makes the information the resource. This theory extends the dopamine as novelty or reward-detector literature by offering an evolutionary precursor for the reward, involving a specific downstream behavior (foraging), and addressing how the reward may have evolved from the resources themselves to the expectation of those resources in the form of information. Evidence suggests this happens via the process of reassociating dopaminergic activity with conditioned stimuli and modulating and updating the organization of information through cortical loops between the basal ganglia and other cortical structures.

The evidence provided here is unified by the theory. Nonetheless, the theory is sufficiently constrained to be wrong. ARS and goal-directed cognition may have evolved independently from the same initial machinery. This, however, is not supported by an integrated striatum that controls both goal-directed behavior and goal-directed cognition in vertebrates. Nor are these functions separable in other eumetazoans. Still, it is possible that primitive ARS structures were lost in the development of the striatum. The striatum must have therefore usurped control of movement from structures previously in control of movement. This seems unlikely, but more work must be done to identify the evolutionary source of the striatum and what structures might be alternatives for behavioral control centers in early vertebrates. If the early vertebrate striatum modulated ARS and then gave rise to goal-directed cognition, then one of the major claims of the theory is supported. Our understanding of this evolutionary relation would benefit from more comparative work in invertebrate brain anatomy, which may point to specific neuroanatomical structures with a direct evolutionary link to goal-directed centers in humans. Because many eumetazoans are currently popular as model organisms for various human diseases, understanding the nature of this neural relation beyond the standard genetic argument from sequence homology, and especially understanding places where the structures are divergent, would be especially informative with respect to what we may harvest from this large body of cognitive research in other organisms.

It must also be understood that there are a host of other molecular mechanisms involved in goal-directed behavior and cognition as well as evolutionary histories associated with other neuroanatomical regions. There is no guarantee that they will support the evolutionary argument set forth here. To my knowledge, none are at present well understood enough to present a cogent evolutionary counterargument. The hippocampus is an unlikely candidate, playing a large role in both spatial and temporal memory formation, but a less significant role in goal-directed recall (see Hills, 2003). It also appears to function separately and possibly antagonistically to the striatum (reviewed in Dagher et al., 2001; N. M. White, 1997). Of equal con-

cern is the issue of dopamine receptor subtypes and their evolutionary history and function in goal-directed cognition. Future evidence gathered on these neural components may provide alternate hypotheses about the origins of goal-directed cognition. The evidence, such as that presented here, will require comparative molecular and behavioral support from a sufficiently wide base of organisms, such that a plausible precursor for goal-directed cognition is evident.

Although the exact details of the evolutionary lineage of goal-directed cognition are out of our temporal reach, the major observations associated with the behavioral theory are nonetheless ripe for further investigation. There are a host of observations in the cognitive science literature that may become more well defined by understanding their relation with area-restricted cognition, be it corroborative of the evolutionary theory or not. For example, modeling the computational roles of dopaminergic circuits is revealing numerous insights into cognition and behavior (see Montague, Hyman, & Cohen, 2004), and simulation modeling using the microcircuits described in Section 4 would help explain how scaling up and layering neural assemblies of this type can create and navigate abstract cognitive representations.

Studies on the neural correlates of associative priming provide support for concrete vestiges of ARS in cognitive search spaces. Associative priming involves exposing a subject to a stimulus that influences the meaning or reaction time of a future stimulus (e.g., Faust, 1998). For example, patients with amnesia are unable to consciously remember seeing particular faces in the recent past; however, when asked to determine if two faces are the same or different, they respond more quickly when they have had recent experience with the face (Paller et al., 1992). When individuals are asked to identify specific Arabic numerals, they do so more quickly when they have had recent experience with names associated with that number (e.g., *747* and *Boeing;* see Alameda, Cuetos, & Brysbaert, 2003). Similarly, music has been shown to prime for word recognition when the musical excerpts are related in "subjective" meaning to the target word (e.g., *staircase* and ascending pitch steps; see Koelsch et al., 2004). Priming research reveals a kind of conceptual nearness, in which concepts live in local neighborhoods; some conceptual representations are closer than others. This does not translate to anatomical nearness, but it does hint at a cognitive geography in which concepts are located in distributed representations in such a way that some representations are "close," whereas others are "far."

Priming's relation with area-restricted cognition suggests that differences in dopaminergic control influence the apparent shape of the cognitive landscape, by modulating the rate of local to global activation. Work on direct and indirect semantic priming supports this architecture for semantic networks in a spreading activation theory (Collins & Loftus, 1975; Neely, 1977). Here, words are represented by specific activation patterns, and closely associated words share direct links (e.g., *light* and *dark*). Direct links imply direct priming, whereas indirect priming requires intermediate associations (e.g., *summer* and *snow* are mediated by *winter*). If cognition is similar to ARS, then high levels of dopamine released by individual cells should reduce spreading activation and therefore slow reaction times in indirect priming experiments. In an experiment where participants were asked to determine if a word was a common word or a nonsense word, after being primed for 200 msec with the priming word, participants took significantly longer to identify indirect priming relations if they had just ingested L-dopa (Kischka et al. 1996). High levels of local dopamine release may therefore inhibit spreading activation patterns that lead to indirect relations.

Studies of memory chunking (see Ericcson, Chase, & Falloon, 1980; Shettleworth, 1998) may also reveal dopaminergic tendencies consistent with those seen for area-restricted foraging. Varying levels of dopamine may create isolated memories or be prerequisites for certain kinds of creative association. Furthermore, the theory of area-restricted cognition would suggest that certain kinds of thinking are associated with certain kinds of multidimensional foraging strategies. Evidence supporting skilled memory theory shows that professionals are more likely to remember items configured according to the rules of their domain, as in chess (Chase & Simon, 1973) and figure skating choreography (Deakin & Allard, 1991). Some domains may be inherently more flexible than others, which may call for more or less flexible navigation (e.g., jazz vs. classical musicians).

As observed for animals living in heterogeneous versus homogeneous resource environments, search strategies are likely to be different for different cognitive domains, and furthermore, some headway can be made in quantifying these differences as they relate to the parameters described by the basic algorithm for ARS (Section 2). How much time is spent with a best guess? How much time is spent with least likely solutions? How long does it take the individual to make the transition from one to the other? Or, more succinctly, what is the shape of the recall curve, with time spent on the solution on one axis and a successive number of the solution on the other? To my knowledge, this kind of work on the natural diversity of cognitive landscapes and navigation strategies has not been done before, but it is critical to understanding how we solve problems and how both environmental and pharmacological perturbations alter the shape of learning and decision making.

A great deal of work remains to be done in understanding what information looks like in a cognitive space and how specific features of, among others, the PFC and striatum are used to navigate and construct that space. In many of the cases listed previously, evidence suggests working-memory operations in the PFC, both in the mediation of voluntary and involuntary priming (Gabrieli, Poldrack, & Desmond, 1998; LaBerge, 1998), the organization of information into chunks (Bor, Duncan, Wiseman, & Owen, 2003), the maintenance of goals (Miller & Cohen, 2001), and the voluntary movement of animals in space (Seamans et al., 1998). The model of area-restricted cognition presented here suggests that information is what cognitive foraging is all about and that finding that information is, even in a high-dimensional space, dramatically similar both in behavior and mechanism with that described for animals foraging in two dimensions.

Due to the many thousands of synapses, even on a single spiny neuron, the cognitive space is of very high dimension, and therefore a two-dimensional foraging analogy fails if literal space is taken as the medium of the homology. That is not what is intended here. One should not confuse the previously mentioned model as requiring something such as somatosensory maps of the conceptual world. Multidimensional surfaces do not map well onto low-dimensional surfaces without losing information about specific relations. Foraging in cognitive space requires manipulating relational pathways, and the evidence suggests that cognition at the level of the striatum is more akin to parallel foraging in multiple dimensions where the map can be adjusted on the fly (as described in Section 5). This is curiously like the inverse of what is taking place in the hippocampus with location-coding cells, which maps two-dimensional space onto a three-dimensional neural representation and uses individual cells to refer to multiple locations (e.g., Mizumori et al., 1996). What works in literal space for spatial foragers is taking place in many locations simultaneously in a network space for cognitive foraging.

Fig. 6 is a possible representation of a cognitive foraging event one might experience if on arriving home after a conference one realized one's keys were missing. Initially, the problem of the missing keys is fixed in working memory, via dopaminergic mechanisms operating in the PFC. These then activate coincident networks in the striatum, which work to reconstruct the historical context of the missing keys out of co-occurring events or memories. The first question might be, "Where did I see them last?" If it was the hotel room, one would initially perform the cognitive search (not spatial) around areas highly associated with the hotel. The exhaustion of the cognitive hotel space at some point may come into competition with the airport space, and dopaminergic mechanisms are likely to be involved in the depth of search at a given location and therefore with the cognitive switch from one to another. Notice, the search moves between neighborhoods, not necessarily through the temporal sequence. As well, to move to different locations in the hotel, one does not need to take the elevator or the stairs, but cognitive

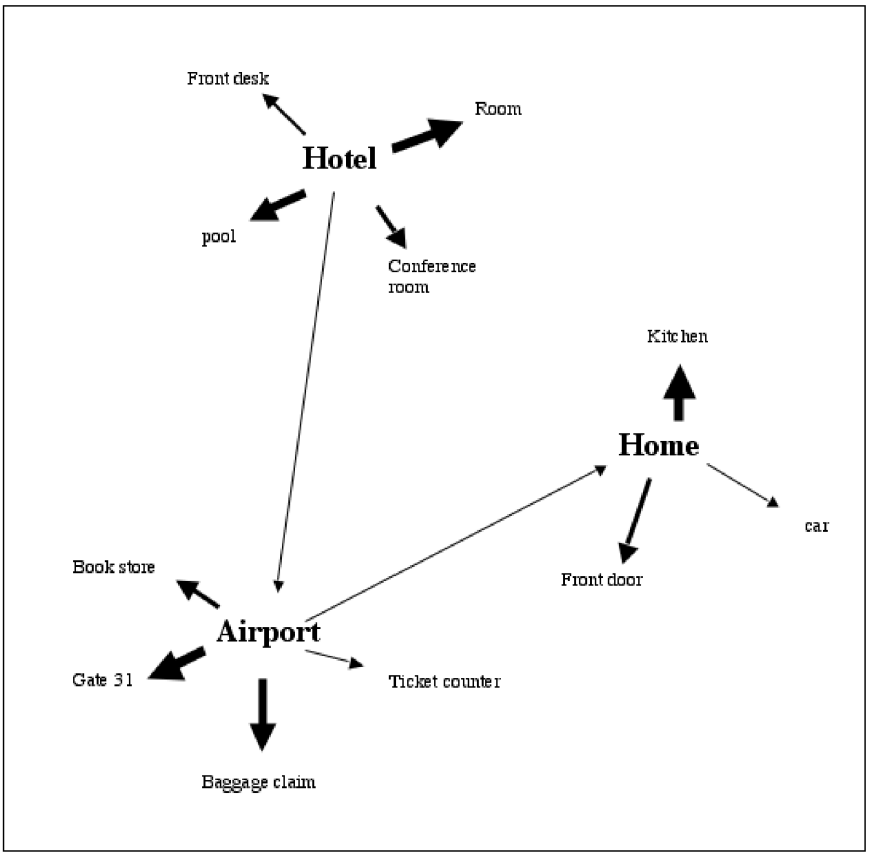

Fig. 6. Representation of a cognitive ARS, which begins when one realizes one has lost track of one's keys at some point during a recent conference. Holding the goal of "keys" in one's attention, one then moves through a cognitive representation of the past visit to the place where the keys were seen last: "the hotel room." From here, details are searched at each node, and the progression is always from highest expectation (largest arrows) to lowest expectation (narrowest arrows). The path also moves from hubs, or local neighborhoods, represented by the "hotel," "airport," and "home," with dopaminergic activity modulating the giving-up time at each location.

jumps are made by moving to places as ordered by their associative coincidence with the keys and possibly their weight in historical (episodic) memory. The weight may consist of time or noteworthy events, such as a memory of dropping your keys at the baggage claim or of a particularly delirious afternoon spent with old friends by the pool. In the figure, the density of the arrows represents the most strongly associated nodes, called into short-term memory by their coincident activation with respect to the cognitive foraging target (i.e., where are the keys?).

Attentional mechanisms operate by spending time attending to nodes (and details downstream) in proportion to their expectation. The expectation is represented by dopaminergically modified weights, representing information about the expected success in finding the "key" resource, which, when found, provides very direct survival-related resources such as food and shelter. In this way, the key itself is seen as a kind of information about how to find other resources—specifically, it is the required information to get through a locked door. In our common sense this language is unfamiliar, but in an evolutionary sense the ultimate goals are principally survival and reproduction, and anything shy of those goals is likely to represent a tool in their acquisition. The tool may be a key or it may be a secret password. It may, in fact, be very sharp teeth.

It is difficult to imagine how such neighborhoods could come into being if not for the means to navigate between them. Yet, once the navigational machinery is present, the evolutionary emergence of new brain structures may have immediate survival value. This is especially true if these structures can be given contemporary relevance through learning, as described previously.

Furthermore, we may also expect natural selection to act on attentional mechanisms along the gradient of perseveration described for ARS. Organisms with an evolutionary or ecological history of heterogeneous and novel environments should show more global search strategies when looking for solutions. Organisms that experience rapidly changing environments where old solutions are less likely to work should show evidence of selection toward less perseverative solution seeking. The *E. coli* mechanism described in Section 3.1 is an example. Another source of evidence for such selection is found in humans, where positive selection has been identified in a dopamine receptor protein (DRD4) associated with ADHD (Ding et al., 2002). The positive selection appears to correlate strongly with the survivors of early human migrations, or those most capable of dealing with environmental novelty (Chen, Burton, Greenberger, & Dmitrieva, 1999; Ding et al., 2002; Harpending & Cochran, 2002). These individuals are least likely to perseverate on old solutions. To the extent that the navigational machinery also teaches the network, we should also see learned ADHD or perseverative disorders in response to overly heterogeneous or homogeneous environments.

The implications of the evolution of cognition out of foraging behavior are multifold, and the relation inspires a host of questions. What does it mean to forget something? Perhaps that you cannot get there from here, or the memory is so unstable that it is hidden by nearby memories and cannot therefore be an object of conscious attention. Can we learn optimal thinking strategies that are adapted for particular kinds of information? Can one construct waypoints in the space of ideas, as some kind of plan or argument? If such waypoints were used frequently, creating a well-worn path, how would this play itself out in our attention? Could such well-worn paths represent our sense of conscious continuity, becoming the stories we tell ourselves about the world we live in? Are the stories we construct in our minds—for example, when we are dreaming or trying to make sense of the behavior of others—composed of mean-

dering paths through near multidimensional neighborhoods, guided by a specific logic of emotion or reason? How do different drugs or emotional states lead to different kinds of paths? Are there specific developmental states associated with higher rates of spreading activation? What does it mean to be confused or to have conflicting ideas? Do these ideas represent energetically unstable forks in the road, posing different trajectories from the same starting point? Are there emotional consequences associated with neural paths that are inconsistent yet somehow of nearly equal stability in terms of cognitive representation? If it is possible to arrive at an old idea from a new place, does arriving at such a place after leaving competing ideas account for the emotional feeling of insight?

These questions and others, although highly speculative, are a consequence of thinking of the mind as a forager for information, foraging for coherent (i.e., stable) relations between representations that are themselves predictive of other resources. Once cognition is able to create indirect relations between information and tangible resources, it can then begin to assess relations between information in pursuit of patterns of information—information that taken together reveals new information. At this point, the goals of the foraging mind expand dramatically, even to the point of including abstract representations of mind itself.

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