5

Evolution of Dynamic Coordination

Evan Balaban, Shimon Edelman, Sten Grillner,
Uri Grodzinski, Erich D. Jarvis, Jon H. Kaas,
Gilles Laurent, and Gordon Pipa

Introduction

What insights does comparative biology provide for furthering scientific understanding of the evolution of dynamic coordination? Our discussions covered three major themes: (a) the fundamental unity in functional aspects of neurons, neural circuits, and neural computations across the animal kingdom; (b) brain organization–behavior relationships across animal taxa; and (c) the need for broadly comparative studies of the relationship of neural structures, neural functions, and behavioral coordination. Below we present an overview of neural machinery and computations that are shared by all nervous systems across the animal kingdom, and the related fact that there really are no "simple" relationships in coordination between nervous systems and the behavior they produce. The simplest relationships seen in living organisms are already fairly complex by computational standards. These realizations led us to think about ways that brain similarities and differences could be used to produce new insights into complex brain–behavior phenomena (including a critical appraisal of the roles of cortical and noncortical structures in mammalian behavior), and to think briefly about how future studies could best exploit comparative methods to elucidate better general principles underlying the neural mechanisms associated with behavioral coordination. In our view, it is unlikely that the intricacies interrelating neural and behavioral coordination are due to one particular manifestation (such as neural oscillation or the possession of a six-layered cortex). Instead of considering the human cortex to be the standard against which all things are measured (and thus something to crow about), both broad and focused comparative studies on behavioral similarities and differences will be necessary to elucidate the fundamental principles underlying dynamic coordination.

Comparative Approaches to Brain Structure and Function: Is Cortex Something to Crow About?

Conversations combining evolution and coordinative phenomena in behavior and the nervous system are intellectually bewildering, because they might progress along a diverse number of lines. For example, a common approach for evolutionary biologists is to attempt to pinpoint the ultimate reasons underlying selection for behavioral coordinating mechanisms. In contrast, neuroscientists often prefer to think about more mechanistic aspects of brain structure and function without the need for explicit specification of the evolutionary force(s) selecting for particular classes of functionality. For example, this volume is filled with attempts to elucidate meaningful connections between coordinative phenomena in the brain and behavioral/cognitive abilities. In many instances, the mammalian cerebral cortex is assumed to subserve many of the computations underlying complex behaviors, and it is also assumed that such computations are not possible with other neural organizations. In the following discussion, we emphasize an evolutionary perspective and the unique and powerful insights that can be achieved from a broadly comparative approach to the mechanistic neurobehavioral questions at hand.

A comparative approach can elucidate mechanisms that mediate behavioral and neural coordination by revealing broad classes of constraints that separate organisms. For example, a particular organism could simply have neural machinery that is incompatible with instantiating particular cellular or circuit functions, or that is unable to flexibly organize circuits into fleeting, larger-scale assemblies that are necessary to perform particular kinds of computations. We first consider whether there are any fundamental "phase transitions" seen across groups of organisms in the basic components that build neural circuits, and in the kind of computations that these can perform. Similarly, we consider whether there are any major transitions in kind in the types of basic neural building blocks that behaviors are assembled from, for example the often-heard distinction between "hardwired" and "flexible" behaviors.

The Fundamental Unity of the Functional Aspects of Neurons, Neural Circuits, and Neural Computations across the Animal Kingdom

It is a useful exercise to examine whether different animal groups, which people subjectively associate with different levels of behavioral complexity (e.g., roundworms, as compared to honeybees, as compared to sparrows, as compared to humans), have nervous systems that function in fundamentally different ways. Do there appear to be any major phylogenetic transitions in the basic building blocks of nervous systems that might limit the kinds of cell assemblies which can be realized, or the kinds of basic computations that can

be accomplished? Such building blocks include the structural and functional components of cells, their molecular constituents, the types of substances they use to communicate, and the kinds of interactions they have. A quick way of obtaining an answer is to survey that part of the animal kingdom without backbones—the invertebrates—to see whether human brains contain some basic structural or functional feature that the brain of an insect or a mollusc lacks.

The few invertebrate species that have been studied to date do not do justice to the diversity of invertebrates, because there are a few dozen invertebrate phyla (e.g., molluscs, arthropods, flatworms, roundworms) compared to only one vertebrate phylum (chordates). Some of the invertebrate phyla have enormous numbers of species: there are about one million known (and between 5–10 million estimated) species of insects, thought to represent 90% of the differing life forms on Earth, compared to close to 60,000 species of vertebrates (The World Conservation Union's 2007 IUCN Red List of Threatened Species, based on summary statistics from 1996–2007). When discussing invertebrates, therefore, we talk about a tiny known sample in a pool with enormous diversity.

To perform evolutionary analyses, one needs to consider the phylogenetic relationships of the organisms under study. Based on current molecular and anatomical evidence, there are three major groups of metazoa (Figure 5.1): the deuterostomia (to which vertebrates belong), the lophorochrozoa (to which annelids, and molluscs, such as the octopus and squid, belong), and ecdysozoa (to which the nematodes, insects, and other arthropods belong) (Mitchell et al. 1988). Several representative subgroups from each of these major groups have been intensively studied in neuroscience, such as rodents and birds among vertebrates, annelid worms among lophotrochozoa, and fruitflies and roundworms among ecdysozoa. With this wealth of information it is now becoming possible to ask whether there are basic principles underlying nervous systems functions across phyla.

To facilitate this exercise, we have defined seven broad areas in which to compare invertebrate and vertebrate nervous systems, and we have examined how invertebrate nervous systems rate in each of these areas: molecular building blocks (e.g., structural, cell-signaling molecules, ion channels), neuronal geometry, nervous system size/scale, mapping/connectivity relations between neurons, local circuit motifs, local computation, and global emergent properties.

Molecular Building Blocks

The explosion of molecular data made available by gene-sequencing studies performed on vertebrates and invertebrates has clearly indicated that there are no known broad classes of molecules involved in mammalian or other vertebrate brains that are absent in invertebrate brains. This is true for ligand-gated channels, voltage-gated channels, gap junctions, the neurotransmitters, neuromodulators and their receptors used for intercellular communication, as well as for the second-messenger pathways used intracellularly to plastically change
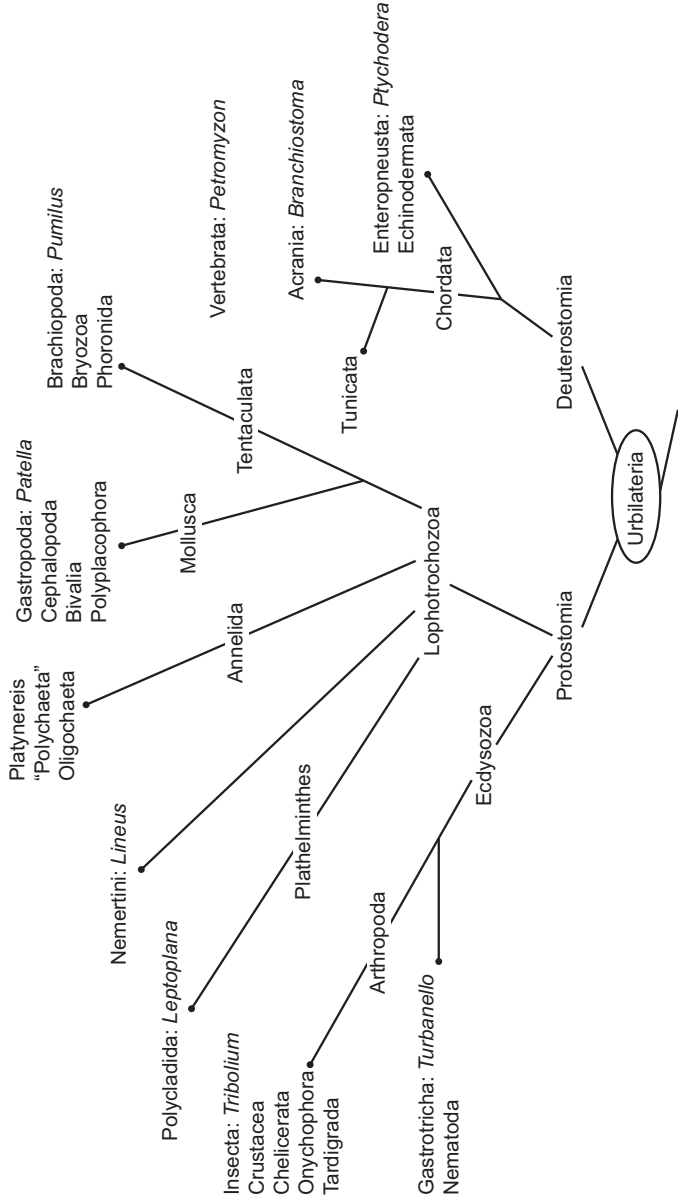
Figure 5.1 The phylogenetic tree of all organisms (after Tessmar-Raible and Arendt 2003).

operational characteristics of cells (some of these same molecules are also found in plants). For example, invertebrates have NMDA channels, inward rectifier current channels, and Ca-activated K channels (Bargmann 1998). Consequently, these neurons exhibit all of the complex phenomena shown by mammalian neurons, including dendritic nonlinearities and intrinsic resonance. Some neuromodulator systems involved in learning or "mood" regulation in vertebrates, such as dopamine and serotonin, are present in invertebrates and appear to be used in behavioral circuits in similar ways (Fiala 2007).

Some similarities are functional rather than sequence-based. Odorant receptors, for example, show cross-phylum similarities in the diversity of the three-dimensional structure of the sites on receptor cells that bind odorant molecules, even if vertebrates and invertebrates may not employ similar sequences in the parts of the proteins that define these binding regions (Benton 2006). In such cases, the functional similarity in vertebrate and invertebrate odorant-binding mechanisms may be the result of selection for similar functions in vertebrate and invertebrate olfactory receptors (convergent evolution), rather than shared ancestry. Vertebrates and insects also use different mechanisms to transduce molecular binding of specific odorants into neural impulses (secondary messenger systems vs. direct channel gating) (Wicher et al. 2008; Nakagawa and Vosshall 2009).

There are also other differences in the deployment of particular mechanisms that both vertebrates and invertebrates possess. For example, photoreceptor conductances are hyperpolarizing in insects but depolarizing in vertebrates. In vertebrates, glutamate is the main excitatory neurotransmitter in the CNS, while acetylcholine is the transmitter at the neuromuscular junction. In insects, this relationship is reversed. In both vertebrates and invertebrates, there are considerable species differences in the elaboration and functional specialization of classes of nervous system molecules. For example, the number of variant forms of particular neurotransmitter receptors may differ in the two groups. The NMDA receptor has two major forms found in both vertebrates and invertebrates, but vertebrates have a component of the receptor (the NR2B subunit) that is not found in insects (Ryan et al. 2008; Emes et al. 2008; Ryan and Grant 2009).

So, the basic molecular components of vertebrate and invertebrate neurons appear to be shared and, when this is not the case, similar functions appear to have evolved convergently. There are also examples of divergences from this general pattern in all groups to meet special circumstances. However, the places in the nervous system where common molecular components get deployed are not necessarily consistent across phyla.

Neuronal Geometry

Santiago Ramon y Cajal (1911) was of the opinion that insect brains are to vertebrate brains what fine watches are to grandfather clocks: "the quality of the psychic machine does not increase with the zoological hierarchy. It is as if

we are attempting to equate the qualities of a great wall clock with those of a miniature watch." However, there exists as wide a diversity of dendritic/axonal geometries and shapes (linear, planar, three-dimensional, sparse to dense) among insect neurons as among vertebrate ones. Some invertebrate neurons are very strictly polarized with clearly separated input and output fields, linked via a neurite with a spike initiation zone. Others have intermingled pre- and postsynaptic sites forming local dendro-dendritic circuits. Some neurons, involved in motor coordination between different segments in arthropods can have multiple spike initiation zones (typically one per segment), a feature never described, to our knowledge, in vertebrates.

A feature characteristic (though not universal) of most vertebrate neurons—a soma interposed between dendritic and axonal segments—is absent in most invertebrate neurons, in which somata are often devoid of synapses. Invertebrate neuropil is thus typically devoid of cell bodies, and the spike initiation zone is located on a neuritic segment. Whether the incorporation of cell bodies within the neuropil seen in vertebrate brains is a requirement for their increased growth and/or lamination (or conversely, a constraint that precludes large size increases of invertebrate brains) is not known, but the correlation is suggestive.

Molecular fingerprinting studies within vertebrates (mammals, birds, reptiles, amphibians, and fish) and invertebrates (insects, nematodes, and annelids) have revealed that the centralized nervous systems in both groups are developmentally controlled by many of the same genes that are expressed in specific cell types of developing mammalian cortex, basal ganglia, and spinal cord. For example, the layer V cortex-specific transcription factor ER81 is also found in the forebrain projection neurons in the arcopallium of birds, and in the anterior part of the nervous systems of annelids (Laudet et al. 1999). Annelids have differentiating neurogenic zones that express the same molecules that have been used as cortical and basal ganglia markers in vertebrates. The Hox genes, which are involved in the control of body segmentation, divide the nervous systems of vertebrates and invertebrates into similar segments (Pearson et al. 2005). In spite of some differences in cellular structure between vertebrates and invertebrates, the same global structural and molecular principles appear to produce comparable cell types across the animal kingdom.

Brain Size and Scale

Some invertebrates are minute, such as the parasitic mites of insects, whereas others are gigantic, such as the giant squid (up to 14 meters in length). A sense of scale can be derived from the following numbers. The brain of Drosophila contains about 250,000 neurons, whereas that of a large insect contains about 1 million. The mushroom body of a cockroach—a structure containing odorant-processing cells and interneurons and which may be analogous to parts of the vertebrate forebrain—contains 300,000 Kenyon cells (greater than the number

of pyramidal cells in a rat's hippocampus). A large arthropod, such as a ten-year-old horseshoe crab, has tens of millions of neurons in its brain, mostly in its mushroom body (Laurent 2002). Cephalopod brains are even larger; the brain size of a giant squid is thought to be the largest invertebrate brain currently on the planet, but is essentially unknown.

Synapse numbers are not very well characterized, though this is likely to change in the near future. Known ranges of convergence on single neurons in one species (locust) are between a few (order 10) in some early visual neurons, and many hundreds onto Kenyon cell dendrites (Jortner et al. 2007; Turner et al. 2008). Divergent synapses are even less well characterized, but known examples are between ~1 in the synapse between the lobular giant movement detector and the the descending contralateral movement detector of the locust (Rind 1984), and ~20,000 in locust antennal lobe projection neuron–Kenyon cell populations (Jortner et al. 2007).

Conduction velocity is one feature in which vertebrates were thought to have come up with an evolutionary novelty: the myelin sheaths that enclose axons. Whereas invertebrate groups do not appear to have a myelin basic protein—a building block often used in vertebrate preparations to detect the presence of myelin—crustaceans, shrimps, annelids, and copepods do have sheaths that enclose axons in similar ways and which function physiologically in the same way as myelin (Hartline and Colman 2007).

Mapping Relations between Neurons

Topographic neural maps exist in insects that are comparable to ones found in mammals. Some examples are the somatotopic map of the wind-sensitive cercal sensory system in crickets and cockroaches (Jacobs and Theunissen 1996), functionally similar to the dermatotopic somatosensory maps in the S1/layer IV of rodent somatosensory cortex; the tonotopic map in the auditory system of bush crickets (Imaizumi and Pollack 1999), which is similar to the tonotopic auditory maps of mammalian auditory pathways; and the nontopographic projections from the antennal lobe neurons to the mushroom bodies of the locust's "generalist" olfactory system, similar to the ones seen in the nonpheromonal portion of the olfactory system of mammals (Jortner et al. 2007). Finally, one finds regions in which there is clear connectional structure (e.g., the olfactory receptor cell projections to insect antennal lobes or to vertebrate olfactory bulbs) but in which the underlying rules of the mapping are equally unknown.

While it is often thought that the connectivity of invertebrate brains is rigidly specified genetically, earlier studies on genetically identical waterfleas and grasshoppers indicate that this was not always the case (Macagno et al. 1973; Goodman 1978). More recent data indicate that genetically identifiable Drosophila Kenyon cells cannot be identified on the basis of their tuning to odors, whereas the neurons presynaptic to them can (Murthy et al. 2008). Similarly, using genetic and developmental manipulations, it has been shown

that the number of morphological local interneuron types in the antennal lobes of several thousands of individual flies exceeds the number of local interneuron types in any one antennal lobe (Liqun Luo, pers. comm.). These pieces of evidence suggest that interindividual variations of internal connectivity, similar in kind to those seen in vertebrate brains, also exist in the brains of insects. Experience-dependent modulation of the strength of local connections is well-known across a wide variety of invertebrate systems (Roberts and Glanzmann 2003; Cassenaer and Laurent 2007), so vertebrate and insect brains appear to share similar basic principles for establishing and changing connectivity.

However, there are three connectional features known in vertebrates that have not so far been found in invertebrates: (a) sensory and motor maps that are registered with each other in an interconnected way, such as those seen in the mammalian or avian superior colliculus; (b) massive feedback loops such as those seen between the primary cortices and thalamus in mammalian brains; and (c) nesting of sequences of modular local circuits, such as those seen in mammalian hippocampal circuits.

Local Circuit Motifs

There are no apparent differences between invertebrate and vertebrate circuits in local circuit motifs. Both vertebrate and invertebrate circuits can include: local or global–local inhibition, reciprocal inhibition, feedforward inhibition, lateral inhibition, lateral excitation, focal convergence (olfactory glomeruli), wide divergence (50%), and all-to-all negative feedback (Laurent 1999).

Local Computation or Operations

There are no major differences between vertebrate and invertebrate nervous systems, of which we are aware, for local computations and operations. Insect brain systems exhibit shunting inhibition, dendritic multiplication, infra- and supra-linear summation, plastic changes mediated via synaptic Hebbian rules, Elementary Motion Detection and directional selectivity, and gating by efference copies (Poulet and Hedwig 2002, 2006; Gabbiani et al. 2005; Cassenaer and Laurent 2007).

Global Emergent Properties

Invertebrate nervous systems exhibit the functional reconfiguration of network output (frequency and phase) in response to neuromodulators (e.g., crustacean stomatogastric system; Marder and Bucher 2007), the adaptive regularization of synchronized oscillatory output by synaptic, timing-dependent plasticity (e.g., locust olfactory system; Cassenaer and Laurent 2007), and various forms of oscillatory synchronization at frequencies from < 1 Hz (Limax) to 20–30 Hz (Schistocerca) (Laurent and Davidowitz 1994; Gelperin and Tank 1990).

The frequency range of oscillations discovered thus far is narrower than in vertebrates, and high frequency bouts nested within lower frequency ones have not yet been described.

The overall conclusion of these considerations is that there is a common mechanistic toolkit at multiple levels, from the molecules that participate in neural structure and function, to properties of single cells, to properties of cell assemblies, shared by all animals with nervous systems. While species differences can exist at many of these levels, the overwhelming impression is that the mechanisms underlying neural computations and the nature of those computations do not undergo dramatic phylogenetic shifts.

The reasons for such conservation of neural computational functions across phyla and ecological niches may be found in boundary constraints that apply to the evolution of neural computation. As noted by Herbert Simon (1973): "…nature is organized in levels, and the pattern at each level is most clearly discerned by abstracting from the detail of the levels far below.…nature is organized in levels because hierarchical structures—systems of Chinese boxes— provide the most viable form for any system of even moderate complexity" (cf. the discussion of hierarchical abstraction in Edelman 2008a:30–31).

The implication of Simon's insight for understanding neural systems is that homogeneously interconnected (i.e., unstructured) networks of basic units would not scale up well for all but the simplest tasks, placing them at a disadvantage relative to networks that embody hierarchical abstraction through the existence of multiple levels of organization and multiple functional units at each level (Edelman 2003). This computational constraint should be kept in mind as we attempt to understand the neural basis of complex coordinated behaviors that exhibit serial order (Lashley 1951). Indeed, computational considerations suggest that the most complex types of these behaviors (including language), which require dynamic coordination across many levels of abstraction, timescales, and individuals, would be unlearnable and unsustainable in the absence of a properly structured and presumably dynamically coordinated computational substrate (neural or artificial).

Computational considerations also offer a solution to the usual puzzle of explaining, without resorting to conceptual "skyhooks" (Dennett 1995), how complex functions, and the correspondingly complex neural architectures that support them, can evolve without disrupting the existing mechanisms. The solution arises from the concept of *subsumption architecture*: an approach to incremental and nondisruptive augmentation of function proposed by Brooks (1991) and developed by him and others in the context of evolutionary robotics (see Sloman and Chrisley 2005). In a subsumption architecture, modifications to an existing circuit are initially introduced as modulatory add-ons that do not disrupt its functioning; subsequent evolution may cause the original circuit to be eventually completely replaced by the novel components acting in concert, or its encapsulation and persistence as a fall-back mechanism that continues to provide basic functionality (e.g., the decorticate cat, which will be

discussed later). Clearly, smooth functioning of subsumption-based neural systems requires dynamic coordination among their components at all levels. In this process, evolutionarily newer organizational entities may exert disproportionate amounts of control over preexisting entities; an example of the kind of downward causation (Thompson and Varela 2001; Edelman 2008b) that may arise in such cases has been aptly described by Shakespeare near the end of Hamlet's famous soliloquy:

> Thus conscience does make cowards of us all,
> And thus the native hue of resolution
> Is sicklied o'er with the pale cast of thought,
> And enterprise of great pitch and moment
> With this regard their currents turn awry
> And lose the name of action.

Brain Similarities and Differences Can Be Used to Gain Novel and Fundamental Insights into Complex Brain–Behavior Relationships

All Levels of Coordination between the Nervous System and Behavior Are "Complex" though Some May Be More "Complex" than Others

The idea of a common mechanistic and computational neuronal toolkit that is applicable across animal species is fundamentally antagonistic to notions that there is some kind of *scala naturae*, according to which species with "simpler" nervous systems exhibit "simple" forms of behavior, while it is only species that share particular brain features with humans (such as the possession of large swaths of six-layered cortex in their forebrains) that are capable of showing "complex" behavior.

   With few exceptions, every perceptual/cognitive/motor act in which an organism engages involves problems of coordination and control which must be adapted to the immediate conditions and circumstances that exist when the act is performed. To do this, both vertebrates and invertebrates appear to have organized local circuits that are wired together at relatively early stages of development (typically in the embryo) called central pattern generators (CPGs). These circuits were originally discovered in the context of neural work relating the organization of circuits in the vertebrate spinal cord to locomotion, and such locomotory circuits have broad similarities in organization and function in species ranging from lampreys to mammals (Grillner 2003, 2006). Such circuits exist in both the motor and sensory domains, and may exist in more abstract domains of function not easily characterized as either sensory or motor. A good example of a fairly complex, nonspinal implementation of these circuits and the fundamental role that comparative work can play in elucidating

them was shown by experiments using developmental manipulations of the species identity of brain cells in avian embryos.

Balaban and collaborators used early transplants of neural tube tissue between quail and chicken embryos to examine species differences in neural circuits associated with "crowing," a vocalization that male chickens and quails use in the context of mate attraction as well as agonistic interactions (the chicken form is the well-known rooster "cock-a-doodle-doo" vocalization). Unlike the functionally similar "song" vocalizations of songbirds, which will be discussed below, "crowing" is a vocal motor sequence that does not depend on imitative learning. A songbird (or a human) who is deaf from an early age will later sing a song (or produce speech) that is not generally recognizable, while a congenitally deaf chicken will sing a song that may have subtle deficiencies but is nevertheless unmistakably recognizable. By transplanting both large and small sets of adjacent cells along the entire brain primordium between chickens and quails at a time in development when brain regions have already been determined, but neurons have not yet started to differentiate, Balaban et al. (1988) found a midbrain region that transferred the acoustic characteristics of the vocalization between species but left the head movements used to deliver it unaltered. Balaban (1997) then found a brainstem region that transferred the head movements used to deliver the vocalization between species but not the acoustic characteristics of the sound. The latter transplants also revealed a rostrocaudal organization in the circuits mediating the sequence of head movements delivered with the crowing vocalization. Transplants that differed in their rostrocaudal extent reliably transferred different temporal portions of the head movement sequence of the donor species. These transplants had no effect on the kinematic characteristics of other head movements that chickens and quail perform identically (such as yawning), and transplanted animals showed perfect integration between head movement and vocal aspects of the behavior. In operations conducted between two chickens, animals with similar transplants showed normal chicken behavior.

Although the concept of a CPG may seem to belong exclusively in the motor domain, it does have a close counterpart in perception: the classical receptive field (RF). Computationally, the RF is simply a template: a filter that responds with a certain degree of selectivity to stimuli that appear within a region of the input space. In mammalian vision, for instance, the RFs of neurons in the lateral geniculate nucleus of the thalamus have a circular center-surround organization in the visual field whose response profile is well approximated by a difference of Gaussians, which is to say that they respond well to spots of light against a dark background or vice versa (depending on the neuron). Feedforward "recognizers" for progressively more complex shapes can be constructed from RF-like building blocks (Edelman 1999); these, however, need to be coordinated in some fashion if more sophisticated function, such as compositional treatment of shapes and scenes, is required (Edelman and Intrator 2003).

The existence of CPG-like circuits involved in perception was shown by Long et al. (2001), who found a region at the junction between the midbrain and thalamus that transferred preferential response to parental warning calls between the two species. Under normal circumstances, chicken and quail chicks have the ability to walk and feed themselves within a short time after hatching; in the presence of danger, there is an acoustically distinctive vocalization that parent birds give to call the young. This vocalization is acoustically different in chickens and quail, and young animals hatched in the absence of prior exposure to these calls, and given equal experience with them in a choice situation, show a statistically significant preference for approaching the calls of their own species (Park and Balaban 1991). Animals with the effective transplant produced individuals who had significant statistical preferences for approaching the call of the donor species, and the strength of their preference was significantly stronger than that of unoperated donor individuals (the quail donor species develops at a faster rate than the host chicken species). The vocalizations of transplanted animals were not affected by the transplants, precluding an indirect effect of changes to the individual's own vocalizations as an explanation for the effect on auditory-mediated approach preferences.

While many of the early scientists who discovered CPGs emphasized their stereotypy, CPGs must be modulated to adapt flexibly to the changing circumstances that are part of the everyday lives of all organisms. For example, in the case of chickens, young animals appear to learn the auditory characteristics of the danger calls of their particular parents rapidly (Kent 1987, 1989). If they suddenly find themselves in the care of new parents, they have the capability to "relearn" their responses to the calls of the new set of parents. In the case of locomotory circuits, they must flexibly regulate their parameters with feedback from the environment to compensate for path obstructions, changes in angle of the ground surface, and other behavioral acts that an organism may be engaging in during locomotion.

This interplay between circuit elements that attain their functional characteristics early in development (like CPGs) and other circuit elements that recruit them flexibly into higher-order sequences of behavior and mediate plastic changes within them is a feature shared by *all* behaviors in all organisms. There is no behavior that is truly "hardwired," and no behavior that is completely flexible. Locomotion in insects and fish, the detection of particular objects in visual scenes by cats and primates, and people's participation in conversations all utilize a complex interplay between CPGs and other circuits that are flexibly mediated. The neural difference between the singing behavior of a bird that learns its song by imitation (like a cardinal) and one that does not (like a chicken) resides in differences in the interaction of neural circuits that are recruited during these tasks (Jarvis 2004). These species differences depend on differences in connectivity patterns laid down during embryonic development. The net result is that songbird brains during the learning period bring together information about a desired song form, together with information on

the vocalization that they have just produced, whereas chicken brains do not. Both species flexibly use a combination of sensory, motor, and other CPGs together with other circuits to perform their respective behaviors.

Learning General Principles from Different Brain Organizations That Solve Similar Problems

A major advantage of comparative studies using species differences is to analyze how different brain organizations solve similar problems. With regard to problems of behavioral coordination, social communication is perhaps the quintessential example of a widely spread complex, coordinated activity. Two major vertebrate taxa—birds and mammals—have achieved considerable sophistication in their use of vocal communication, and in the means by which vocal behavior is acquired.

Oscine song birds, like humans, need exposure to their species vocalizations during development to produce normal vocal social signals in adulthood (Doupe and Kuhl 1999). Both oscine songs and human speech are vocal examples of imitation, a complex type of learning which is considered important for human social cognitive abilities. Although vocal imitation ability is rare, evidence for nonvocal imitation is starting to accumulate in many taxa (reviewed in Huber et al. 2009; Zentall 2004). For a behavior to be considered an imitation, an organism needs to perform a motor output corresponding to the sensory input of another organism's behavior that it has observed prior to producing the behavior. This is known as "the correspondence problem"(reviewed in Heyes 2009). The discovery of so-called "mirror" neurons, which are active when an action is perceived as well as when it is performed (Ferrari et al. 2009; Gallese et al. 1996) or in songbirds when a song is heard versus sung (Prather et al. 2008), suggests a mechanism by which the brain solves this problem (Ferrari et al. 2009). However, the existence of such neurons in the adult brain does not explain how the "right connections" came to be made in the first place. For example, connections between the visual input of a grasping movement and the motor output of grasping require an ontogenetic explanation. Such connections can either be specified during brain development and preexist prior to their use, as in the CPG examples described above, or could be built during ontogeny by the co-occurrence of the corresponding output and input when the individual itself performs a behavior. In this latter case, the formation of the "right" connections between these two systems would depend on mechanisms of neural plasticity that would need to be deployed properly in these pathways to make such learning possible (the hypothesis of associated sequence learning, and the evidence for it, are reviewed in Catmur et al. 2009; Heyes 2001).

As we have discussed, the computational problem of correspondence needs to be solved to imitate. However, it is also important to distinguish between imitation and other types of social learning which do not require overcoming

the correspondence problem. In many cases, the probability of performing a certain behavior, or the speed of learning a new behavior, is increased by observing another individual (a "demonstrator") perform the behavior. Instead of imitation, however, this can be attributed to observation increasing the probability that the subject will engage in similar behavior that it already has in its repertoire ("social facilitation," e.g., Fiorito and Scotto 1992), or will act to achieve *the same goal* achieved by the demonstrator ("emulation"). Note we are not at all dismissing the complexity of these other forms of social learning, but are simply pointing out the fact that they pose different computational challenges and that they need to be distinguished before anything can be said about what it is that the animal's nervous system needs to compute.

Mammals and Birds: Similar Levels of Behavioral Complexity Despite Major Differences in Brain Organization

Comparing Avian and Mammalian Brain Organization

One of the better understood comparative analyses involves brain comparisons between birds and mammals. This analysis has challenged and forced a revision to the classical view of brain evolution and the supremacy of the mammalian cortex (Reiner et al. 2004; Jarvis et al. 2005). The classical view is that the avian cerebrum, along with that of other vertebrates, evolved in progressive dorsal-to-ventral stages from so-called primitive to advanced species (Edinger 1908). The current view holds that the avian cerebrum, and those of other vertebrates, was inherited as a package consisting of pallial, striatal, and pallidal domains, which together function in perceiving and producing complex behaviors (Jarvis et al. 2005; see also Figure 5.2). This current view is associated with a new brain terminology for birds developed by an international consortium of neuroscientists.

According to the classical view, evolution was unilinear and progressive, from fish to amphibians, to reptiles, to birds and mammals, to primates, and finally to humans, ascending from "lower" to "higher" intelligence in a chronological series. Proponents of this view believed that the brains of extant vertebrates retained ancestral structures, and thus the origin of specific human brain subdivisions could be traced back in time by examining the brains of extant nonhuman vertebrates. They also believed that evolution occurred in progressive stages of increasing complexity and size, and culminated with the human cerebrum. Thus Edinger (1908) argued that there was first the old brain—the paleoencephalon (also called the basal ganglia or subpallium), which controlled instinctive behaviors—followed by the addition of a new brain—the neoencephalon (also called the pallium or mantle at the top), which controlled learned and intelligent behaviors. To support this view, he and his students named the telencephalic subdivisions with the prefixes "paleo" (oldest), "archi" (archaic), and "neo" (new) to designate the presumed relative order of

evolutionary appearance of that subdivision. To these prefixes, the root word "striatum" was added for the presumed paleoencephalic subdivisions and "pallium" (meaning mantle), or "cortex," for the presumed neoencephalic subdivisions. Fish were thought to have only "paleostriatum" (old striatum) and paleocortex was said to be the antecedent of the human globus pallidus. Amphibians were said then to evolve an archistriatum (i.e., amygdala) above the paleostriatum and an archicortex, the antecedant of the human hippocampus. Reptiles were said to evolve a neostriatum, which they passed onto birds, who then evolved a hyperstriatum. Birds and reptiles were not thought to "advance" the paleocortex and archicortex. Instead, mammals were thought to have evolved from the paleocortex and/or archicortex, a "neocortex." The archicortex and paleocortex with their 2–3 cell layers were assumed to be primitive; the neocortex with its six layers was assumed to be more recently evolved and a substrate for more sophisticated behavior. The avian cerebrum was thought to consist primarily of basal ganglia territories, and these were thought to control mostly primitive behaviors. This classical view was codified in the major comparative neuroanatomy text by Ariëns-Kappers, Huber, and Crosby (1936) and became pervasive throughout neuroscience. However, this view is now known to be incorrect.

Based on molecular, cellular, anatomical, electrophysiological, developmental, lesion, and behavioral evidence, an international consortium of specialists in avian, mammalian, reptilian, and fish neurobiology published a new nomenclature that represents the current understanding of avian telencephalic organization and homologies with mammals and other vertebrates (Jarvis et al. 2005; Reiner et al. 2004). They concluded that the telencephalon is organized into three main, developmentally distinct domains that are homologous in fish, amphibians, reptiles, birds, and mammals: pallial, striatal, and pallidal domains. It is hypothesized that the telencephalon of early fishes possessed all three domains, which were then inherited as a package by later vertebrates, including birds, and independently modified by them. The consortium eliminated all phylogeny-based prefixes (paleo-, archi-, and neo-) that erroneously implied the relative age of each subdivision.

They also concluded that the organization of the true basal ganglia among vertebrates (i.e., distinct nuclear striatal and pallidal domains) is quite conserved. Some key similarities between vertebrates, best studied in birds and mammals, include a high enrichment of dopaminergic axon terminals in the striatum that originate from a homologous substantia nigra pars compacta and ventral tegmental area neurons of the midbrain. Both avian and mammalian striatum contain two major classes of spiny neuron types: those with the neuropeptide substance P (SP) and those with the neuropeptide enkephalin (ENK), which project to two different neuron populations in the pallidum. In both birds and mammals, the SP neurons seem to be involved in promoting planned movement, while the ENK neurons seem to be involved in inhibiting unwanted movements. Both the avian and mammalian striatum participate not only in

instinctive behavior and movement, but also in motor learning. Developmental studies indicate that the avian and mammalian subpallium consists of two separate histogenetic zones that express different sets of transcription factors: a dorsal zone that corresponds to the lateral ganglionic eminence and that selectively expresses the transcription factors Dlx1 and Dlx2 but not Nkx2.1, and a ventral zone that corresponds to the medial ganglionic eminence and selectively expresses all three transcription factors. The lateral ganglionic eminence gives rise to the striatum; the medial ganglionic eminence gives rise to the pallidum. Similar striatal and pallidal territories have been found in reptiles.

In contrast, the organization of vertebrate pallial domains differs to a greater degree. Like the striatum, the avian and reptilian pallium has a nuclear type of organization. The avian hyperpallium, however, possesses a unique organization so far found only in birds; its dorsal surface consists of semilayered subdivisions and might have evolved more recently than the mammalian six-layered cortex, since birds evolved well after mammals (by ~50–100 million years) (Jarvis et al. 2005). The six-layered cortex is a pallial organization unique to mammals. As all major groups of living mammals (monotremes, marsupials, and placentals) have a six-layered cortex, it was presumably inherited from their common therapsid ancestor over 200 million years ago. As all nonmammalian therapsids are now extinct, it is difficult to trace the evolutionary history of mammalian telencephalic organization from stem amniotes to mammals: layered, nuclear, or otherwise. Thus, the reptilian nuclear pallial organization cannot be assumed to represent the ancestral condition for mammals, as it is for birds.

Comparing Avian and Mammalian Cognitive Behaviors

Based on the modern view, the adult avian pallium, as in mammals, comprises ~75% of the telencephalic volume. This realization of a relatively large and well-developed avian pallium that processes information in a similar manner to mammalian sensory and motor cortices may help to explain some of the cognitive abilities of birds. Recent studies show that some bird species may have behavioral complexity on a par with nonhuman primates. Some of the best examples come from studies of physical cognition, where the classical trap-tube test has been used both with primates and birds (reviewed in Martin-Ordas et al. 2008; see also Grodzinski and Clayton, this volume). Many primate and other species have been trained to use a tool to push a piece of food placed in a transparent tube away from a trap, but subsequently failed to show an understanding of the properties of the trap as they continued to do so when the tube was inverted; the trap became ineffective (Martin-Ordas et al. 2008). In fact, the first nonhuman species to demonstrate such an understanding in modified versions of the trap-tube design are two species of birds: rooks (Seed et al. 2006) and New Caledonian crows (Taylor et al. 2009), recently joined by chimpanzees (Seed, Emery et al. 2009; see also Grodzinski and Clayton,

this volume). The striking abilities of tool-using New Caledonian crows (Weir et al. 2002) and nontool-using rooks (Bird and Emery 2009) to manufacture, manipulate, and use tools in novel ways suggests some understanding of the physical properties of the tasks at hand, the likes of which are yet to be shown in other nonhumans. In another field of comparative cognition research, social cognition, food-caching corvids have attracted recent attention. When these birds try to steal each others' caches, as well as when they apply a number of cache-protection strategies to avoid being pilfered, they are most sensitive to their competitors' location and previous knowledge (Bugnyar and Heinrich 2005; Emery and Clayton 2001). This suggests a sort of "theory of mind" comparable to that previously suggested in chimpanzees (Hare et al. 2001). The recent developments in the field of comparative cognition also include studies showing bird episodic-like memory (reviewed in Grodzinski and Clayton, this volume) and transitive inference (Vasconcelos 2008). Other work has also shown that pigeons can memorize up to 725 different visual patterns, learn to discriminate categorically objects as "human-made" versus "natural," discriminate cubistic and impressionistic styles of painting, communicate using visual symbols, rank patterns using transitive inferential logic, and occasionally "lie" (reviewed in Jarvis et al. 2005). Together, all of these studies point out that the behavioral complexity of some bird species is comparable with that of the most behaviorally advanced nonhuman primates.

Some bird species even possess traits found in humans and not in nonhuman primates. The most notable is the rare skill of vocal imitation, or more broadly vocal learning. Not only do oscine songbirds have this trait, but parrots and hummingbirds do as well. This trait is a critical substrate in humans for spoken language and with the exceptions of cetaceans, bats, elephants, and possibly sea lions, it has not been found in any other mammal (Jarvis 2004; Janik and Slater 2000). Parrots, in addition, can learn human words and use them to communicate reciprocally with humans. African gray parrots, in particular, can use human words in numerical and relational concepts, abilities once thought unique to humans (Pepperberg 2006).

In general, these cognitive functions include important contributions from the telencephalon, including the six-layered cortex in mammals and the nuclear pallial areas in birds. The mammalian six-layered cortical architecture does not appear, therefore, to be the only neuroarchitectural solution for the generation of complex cognitive behaviors. Pallial-cortical folding is also not required. Birds' brains do not exhibit the complex pattern of gyral and sulcal folds in their pallia that mammals do; among mammals, such folding is more related to absolute brain size than it is to behavioral complexity.

The best-studied comparative circuit example is the vocal learning/speech brain pathways in birds and humans (reviewed in Jarvis 2004). The major groups of vocal-learning birds are distantly related to each other and seem to have evolved similar solutions, although not identical solutions, as humans for the generation of imitative vocal learning behavior. Vocal learning and vocal

nonlearning birds and mammals (i.e., nonhuman primates and chickens) have very similar auditory pathways to the telencephalon, used for complex auditory processing and auditory learning. Thus, this is not a rare trait. However, only vocal learners (songbirds, parrots, hummingbirds, and humans) have brain regions in their cerebrums (pallium and striatum with pallidal cells) that control the acoustic structure and syntax of their vocalizations. These systems in birds consist of seven comparable vocal brain nuclei segregated into two pathways: a posterior vocal motor pathway responsible for production of learned song and calls (determined only in songbirds and parrots) and anterior nuclei (connectivity examined only in songbirds and parrots), which are part of an anterior vocal pathway responsible for vocal imitation and modification (Figure 5.2).

(a) Songbird brain
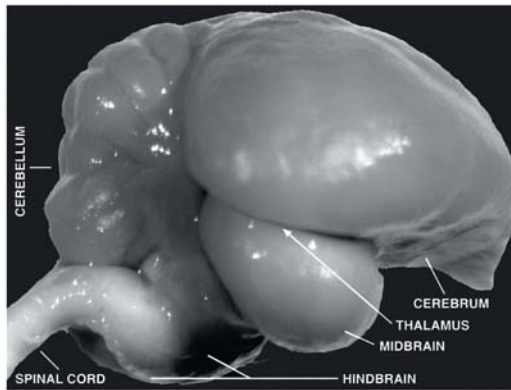
(c) Songbird brain subdivisions
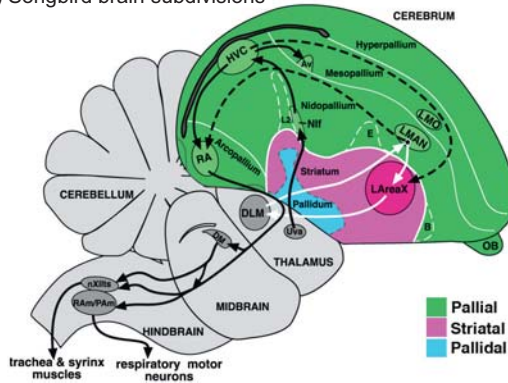
Figure 5.2 Avian and mammalian brain relationships. (a) Side view of a songbird (zebra finch) and (b) human brain to represent avian and mammalian species. The songbird cerebrum covers the thalamus, whereas the human cerebrum covers the thalamus and midbrain. Inset (left) next to the human brain is the zebra finch brain drawn to the same scale. Sagittal view of brain subdivisions according to the modern understanding of (c) avian and (d) mammalian brain relationships (Reiner et al. 2004; Jarvis et al. 2005). Solid white lines are lamina, which are cell-sparse zones separating brain

This motor pathway is similar to descending motor pathways in mammals, and the anterior pathway is similar to cortical-basal-ganglia-thalamic loops. These two pathways have nuclei that are functionally analogous to human cortical, striatal, and thalamic regions required for speech acquistion and production (Jarvis 2004).
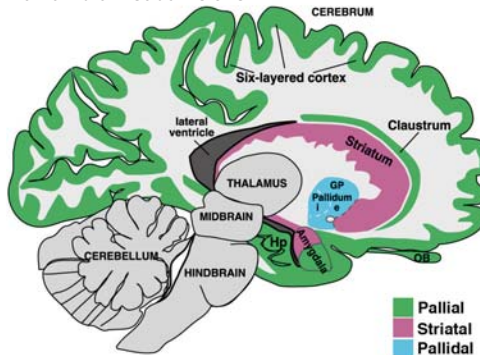
Evolution of Brain Pathways for Complex Traits

How might a complex trait like vocal learning have independently evolved a similar circuit diagram in birds and mammals? Recent studies have suggested

(b) Human brain
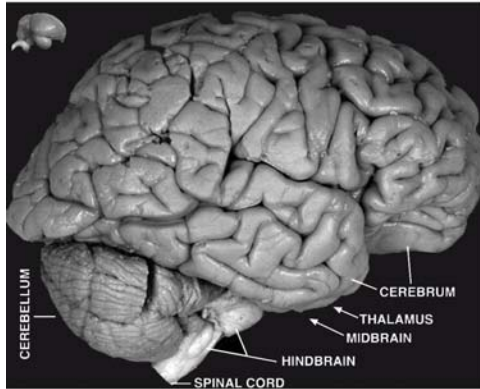
(d) Human brain subdivisions

subdivisions. Large white areas in the human cerebrum are axon pathways called white matter. Dashed white lines separate primary sensory neuron populations from adjacent regions. The avian pallium consists of large nuclear regions, whereas the human is layered. Both are involved in vocal learning. The song learning system for the songbird brain is shown. Black arrows, the posterior vocal pathway; white arrows, the anterior vocal pathway; dashed arrows, connectivity between the two pathways. Figure based on (Jarvis et al. 2005; Reiner et al. 2004).

that the telencephalic vocal nuclei of vocal learning birds are embedded within a larger brain system that is active during the production of limb and body movements (Feenders et al. 2008). Likewise, in humans, the unique "spoken language" brain areas not found in nonhuman primates are either embedded within, or adjacent to, motor-learning brain areas found in nonhuman primates (reviewed in Jarvis et al. 2005; Feenders et al. 2008). These and related findings have led to a "motor" theory for the origin of vocal learning. The basic idea is that a preexisting motor system in a vocal nonlearner ancestor is organized as two sub-pathways: an anterior premotor pathway that forms a pallial-basal-ganglia-thalamic-pallial loop and a posterior motor pathway that sends descending projections to brainstem and spinal cord premotor and α-motor neurons. Subsequently, a mutational event or events caused projections of descending pallial-spinal/cortico-spinal neurons, which normally synapse onto nonvocal motor neurons, to synapse instead onto vocal motor neurons in vocal learners. Thereafter, cerebral vocal brain regions developed out of adjacent motor brain regions using the preexisting connectivity and genes. Such a mutational event would be expected to occur in genes that regulate synaptic connectivity.

According to this hypothesis, the vocal learning pathways in birds are analogous to those in humans, in that they are newly evolved neural systems performing complex computations for learned vocal communication. They are, however, homologous in that they share a deep homology with premotor and motor neural circuits that may have existed before the split of birds and mammals over 300 million years ago. This type of brain pathway evolution with shared mechanisms of a deep past is not only restricted to vocal learning, but can apply across multiple traits that require dynamic coordination.

Reconsidering How Different Forebrain Regions Apportion Their Labors

The six-layered mammalian neocortex is often assumed to control practically all aspects of behavior, from the simplest joint movement to the most complex aspects of cognition. Classic lesion studies from several decades ago teach us, however, that subcortical forebrain structures are able to handle many aspects of complex, goal-directed behaviors. For instance, Bjunsten et al. (1976) studied cats whose cortex was removed some weeks after birth (leaving all other parts of the brain intact), and who were able to move around in an exploratory way, become hungry, search for food, and eat. They could solve tasks in a T-maze and find their way out of a complex maze (Sten Grillner and Ulf Norrsell, per. comm.). They reacted emotionally, could successfully attack and drive normal cats away, and went through periods of sleep as well as displaying other aspects of relatively normal circadian rhythms. They were thus able to perform most, if not all, aspects of the standard goal-directed motor repertoire that cats typically show in a constrained laboratory environment, and their movements were well adapted to this environment. This clearly suggests

that the subcortical infrastructure of the mammalian brain is capable of subserving a higher level of behavioral function than is generally assumed. These old observations were unfortunately not accompanied by precise quantitative studies of the "cognitive deficits" which inevitably will occur in animals without a cortex. We believe that specifying the unique contributions of cortex to behavior is an extremely important line of research using modern techniques for the quantitative study of behavior, as well as histochemical and imaging analyses to study the progression of the structural and biochemical effects of the lesions over time and their correlations with behavioral effects.

Subcortical forebrain structures, in particular the basal ganglia, are critical for maintaining the goal-directed aspect of motor behavior after the neocortical lesions. How could this come about? The striatum, the input level of the basal ganglia, receives a prominent topographic input from nearly all of cortex (making up about 55% of its inputs); it receives the other 45% of its inputs from the thalamus (Doig et al. 2009; J. P. Bolam, pers. comm.). Part of the thalamic input is sent to both cortex and striatum. Devoid of the cortical input to the striatum (after lesions), it will have to rely entirely on the direct input it receives from the thalamus. Although a fairly detailed knowledge is available on cell types, synaptic interaction, synaptic markers, dopamine innervation, and membrane properties, we do not yet understand the detailed mode of operation of the striatal microcircuitry that most likely plays a prominent role in determining which motor or cognitive programs are selected at any given instant. The striatum becomes severely incapacitated after dopamine denervation as in Parkinson's disease, which affects all aspects of action, motor and cognitive coordination. The output side of the basal ganglia is more well defined, and it contains subpopulations of spontaneously active GABAergic neurons which, at rest, are thought to keep the different brainstem motor centers under tonic inhibition (in addition to the thalamocortical projections). There are different subpopulations that control not only saccadic eye movements but also a variety of other motor centers (e.g., those that control locomotion, posture, chewing). The subcortical forebrain structures are required for the goal-directed aspect, whereas brainstem animals can be made to coordinate the different motor acts (e.g., walking, chewing, eye movements, or pecking), but not in the context of goal-directed adaptive behavior.

In summary, although a lot more work needs to done, the comparative work emphasized in this discussion shows that the opportunity to study analogous behavioral systems, which vary considerably in their complexity across taxa, is of great theoretical and practical importance. Such studies cannot only suggest which neural mechanisms and computations covary with behavioral complexity, but will also give us a better quantitative grounding for relating circuit complexity, computational complexity and behavior.

Functions That Appear to Be Solved in Similar
Ways: Comparisons across Diverse Taxa

Although the emphasis in this section has been laid on comparative work examining differences, we thought it was important to point out the future promise of work examining how similar structures can be put to a variety of uses. One example could be provided by the glomerulus, a neural structure that is common to both invertebrate and vertebrate olfaction, and which also has a very high degree of correspondence in the first-order computations it carries out despite evidence that it convergently evolved in these separate taxa. We believe that much can be learned in the future from studies that elucidate the diversity of mechanisms and computations of functionally equivalent structures at a very fine scale of resolution

Need for a Broad Comparative Model System to Study
the Relationship of Neural Structures, Neural Functions,
and Behavioral Coordination, and for Universal Metrics
for Quantifying the Complexity of Behavioral Tasks

There is a need to develop broad comparative neural and behavioral "model systems" to study analogous neural systems across diverse taxa. A promising area for such studies would be a behavior that is widely distributed among a variety of vertebrate and invertebrate species and which is organized into sequences. Grooming behavior is one ideal candidate, as it is widely distributed (Sachs 1988). Next, it would be important to identify instantiations in particular species that differ in complexity, with examples of several different species at each level of complexity studied, and to compare their neural correlates. This would have the joint advantages of providing people interested in dynamic coordination with an independent set of tools to bring to bear on questions relating neural oscillations, synchrony, and behavioral coordination, as well as providing scientists with an empirical method for sifting out the neural mechanisms that vary with particular aspects of behavioral complexity, which can then be targeted for more expensive and time-consuming mechanistic explorations.

Such studies could also bolster the adoption and improvement of common methodologies for quantifying behavioral complexity, a field that has great promise thanks to the introduction of new and powerful computational techniques. Traditionally, the description of coordinated behaviors, such as rodent grooming (Aldridge and Berridge 1998) or spoon-feeding a baby (Duncan 1997), have been primarily heuristic. A variety of computational tools are now available for conducting formal quantitative analysis of the complexity of animal behaviors. It is tempting to divide those a priori into continuous and discrete, but we stress that in many borderline cases, this decision itself should be left to a quantitative analysis with a clearly defined set of criteria.

For example, does the pre-shaping of the hand prior to grasping an object consist of a series of discrete steps? In the general case, the record of an instance of a behavior consists of a trajectory in the space defined by the measurement variables. A bundle of such trajectories can be processed to determine whether they are amenable to a low-dimensional description (i.e., in a manifold whose dimensionality is lower than the nominal dimensionality of the measurement space) or whether a discrete, sequentially modular representation in terms of "dynamical symbols" is in order (Dale and Spivey 2005; Edelman 2008b).

More complex behaviors exhibited by animals are likely to be sequentially modular and hierarchically structured, for reasons of computational tractability, and better fit to the structure of the environment. For such behaviors, a natural formal tool for representation and complexity analysis is grammar. For instance, if a behavior is described in terms of a finite set of states and the transitions among them, it can be represented concisely in the form of a so-called regular grammar. If the transitions are probabilistic, the grammar would have a corresponding annotation. Other classes of formal grammars, such as context-free or context-sensitive, as defined in computer science (Bod et al. 2003; Hopcroft and Ullman 1979) can be used to describe progressively more complex behaviors, including language. The computational methods of inferring a grammar from behavioral data and for using it for complexity analysis, which are akin to the problems of language acquisition and of parsing, may be highly nontrivial, but they are certainly worth the trouble. Behavioral science, and with it the neuroscience of behavior, cannot be considered sound unless it rests on a reasonable quantitative measurement methodology.

Finally, more comparative studies are needed which identify commonalities and differences in neuron structure, cell types, and the ways that brain regions are specified and connectivity develops across taxa. We believe that a more extensive across-taxa neural-comparative toolkit will enable better-informed conclusions about the neural architectures that support dynamic coordination and all other types of computational tasks accomplished by neural systems.

Conclusions

Broad comparative data are necessary to make stronger inferences about the relationship between structure and function. Vertebrates and invertebrates have a common basic neural toolkit that evolutionary processes build upon to generate diverse, but shared forms and principles. The tool kit consists of common genes, cell types, connections, and computations.

Within vertebrates, inroads have been made in understanding the relationships between birds and mammals. However, more of this type of work must be conducted with reptiles, amphibians, and fish.

There is, to date, no general understanding of the functional significance of having a layered (mammal) versus clustered (bird) pallium, since similar

behavioral capabilities appear to be attained by both types of organization. Similarly, there is no rigorous evidence-based understanding of the division of labor between pallial (cortex) and nonpallial (basal ganglia) forebrain structures in mammals, despite widespread beliefs about this issue. Both the six-layered mammalian cortex and the nuclear pallial divisions of the avian brain are able to support vocal imitation and other complex cognitive behaviors once thought unique to humans.

Given that coordination occurs at the levels of neurons, circuits, and behavior within and among organisms across the whole animal kingdom, it is unlikely that coordination or oscillation as such is limited to particular neural architectures, such as a six-layered cortex. A cortex may turn out to be something to crow about for some as-yet-unidentified behavioral or computational traits, but it certainly does not work to work in isolation. Both broad and focused comparative studies on behavioral similarities and differences will be necessary to elucidate first principles underlying such phenomena.