

Coordination in Behavior and Cognition

Andreas K. Engel, Karl Friston, J. A. Scott Kelso,
Peter König, Ilona Kovács, Angus MacDonald III,
Earl K. Miller, William A. Phillips, Steven M. Silverstein,
Catherine Tallon-Baudry, Jochen Triesch, and Peter Uhlhaas

Abstract

What is coordination and how is it achieved? This chapter begins with a discussion of the concept and key features of dynamic coordination. Next, its relation to cognitive functions and learning processes are explored, as is the role of neural oscillations in different frequency bands for dynamic coordination. Thereafter, modulation of coordination at the systems level is reviewed, and the relation of the mechanisms discussed to neuropsychiatric disorders is pursued. The purpose of this chapter is not to delineate all properties of coordination or all of its different manifestations. Instead, our intent is to portray the multifaceted problem that stands before us.

Introduction

It is a truism that we know coordination when we see it. At the same time, coordination may be subject to precise measurement and observation. How well we can measure and observe depends on how accessible coordination is and at which level we choose to observe it.

We say that someone like Tiger Woods is coordinated because his golf swing (a) is dynamic, evolving over time in a well-defined sequence directed toward achieving a goal; (b) involves the orchestration of many different sensory, motor, and cognitive processes at many different levels; (c) involves a reduction in dimensionality (i.e., despite the enormous number of degrees of freedom, coordination is coherent and low dimensional); (d) adapts to the perceived environmental conditions as well as the sensed state of the body; (e) is a flexible, creative process that involves decision making and planning; (f) is stable (i.e., resistant to perturbations over the timescale of the behavior); (g) involves

learning and is subject to modification by a number of factors, such as level of attention, stress, or others.

The problem of coordination involves understanding how component parts and processes relate in an orderly fashion to produce a recognizable function. Coordination may thus be defined as a functional ordering among interacting components in space and time. Coming in many guises, coordination represents one of the most striking features of living organisms. Some of the basic phenomena that seem to be of particular relevance to understanding dynamic coordination in the brain and cognition are:

- Patterned states of coordination remain stable in time despite perturbations.
- Component parts and processes (dis)engage in a flexible fashion depending on functional demands and/or changes in environmental conditions.
- Multiple coordination states may exist rendering living things multifunctional, effectively satisfying the same (or different) sets of circumstances.
- Switching from partially to fully coordinated states and vice versa is commonplace.
- Selection of coordination patterns is tailored to suit the current needs of the organism.
- Coordination patterns adapt to changing internal and external contingencies.
- Depending on a balance between competitive and cooperative processes, learning may take the form of abrupt transitions from one coordinated pattern to another.
- The system may remain in the current pattern of coordination even when conditions change, thus exhibiting memory.

We begin by reviewing the concept and key features of dynamic coordination.

How Can Dynamic Coordination Underlying Behavior and Cognitive Processing Be Conceptually and Formally Specified?

Dynamic Coordination as a Result of Self-organization

A key concept for understanding dynamic coordination in complex systems is self-organization. Self-organization refers to the spontaneous formation of patterns and pattern change in systems that are open to exchanges of information with the environment and whose elements adapt to the very patterns of behavior they create. Inevitably, when interacting elements form a coupled system with the environment, coordinated patterns of behavior arise. Naturally occurring environmental conditions or intrinsic, endogenous factors may take

the form of control parameters in a dynamical system. For example, candidate control parameters in neural circuits include neuromodulators and synaptic drive. A circuit may be capable of operating in distinctly different stable modes and switching between them depending on the level of synaptic drive and the degree of neuromodulation (e.g., Briggman and Kristan 2008).

When a control parameter crosses a critical value, instability occurs and leads to the formation of new (or different) patterns. In self-organizing dynamical systems, such as fluids, lasers, and chemical reactions, the enormous compression of degrees of freedom near critical points arises because events occur on different timescales: the faster individual elements in the system become “enslaved” to the slower, “emergent” collective variables which now constitute the relevant information for the system’s dynamic behavior. Collective variables are relational quantities, spanning or enfolding different domains that reflect the coupling among component parts and processes.

Alternatively, and perhaps more in line with how nervous systems are coordinated, one may conceive of a hierarchy of timescales for various processes involved in coordination. On a given level of the hierarchy, dynamic coordination may be subject to constraints (e.g., of the task) that act as boundary conditions on lower-level processes. At the next level down are component processes and events that typically operate on faster timescales. Thus a complete description of coordination on a chosen level of description would seem to require identification of (a) the boundary conditions and control parameters that establish the context for particular coordination phenomena to occur, (b) the relevant collective variables and their dynamics, and (c) the component level and its dynamics including the nonlinear coupling between components.

Self-organized pattern formation in the brain—a subject of much active investigation in the neurosciences—expresses itself in various forms, including brain oscillations (e.g., Basar et al. 2000; Buzsáki 2006), transient phase synchrony among neural populations (e.g., Singer and Gray 1995; Varela et al. 2001; Engel et al. 2001; Bressler and Kelso 2001), multistability, abrupt phase transitions (“switches”) in cortical activity patterns, and so forth. Long ago Katchalsky et al. (1974:58) noted: “The possibility of waves, oscillation, macrostates emerging out of cooperative processes, sudden transitions, pre-patterning, etc., seems made to order to assist in the understanding of integrative processes...particularly in advancing questions of higher order functions that remain unexplained in terms of contemporary neurophysiology.” Here we will discuss numerous studies that explicitly address such manifestations of dynamic coordination in the brain and relate these to cognitive and behavioral functions.

Dimensionality Reduction

The key feature of coordination is that a very large number of heterogeneous elements characterized by mutual interaction “live” in a subspace or manifold

whose dynamics are low dimensional. Near instability, the individual elements must order themselves in new or different ways to accommodate current conditions. The patterns that emerge may be defined as attractor states of the collective variable dynamics; that is, the collective variable may converge in time to a certain limit set or attractor solution. Mathematically, systems composed of many interacting elements are described in terms of a (large) number of time-dependent states that trace out a trajectory in a high-dimensional state-space (so that the current state is represented by a point in state-space). The long-term evolution of many systems can then be characterized in terms of those parts of state-space to which all trajectories are attracted (the attractor manifold). Crucially, in instances of dynamic coordination, this manifold usually has a low dimension and supports wandering (itinerant) trajectories; this means that the states are not fixed but revisit a subset of states in a flexible but reproducible way (e.g., metastability and bistable perception).

The fact that the manifold is low dimensional is key for understanding how order can be synthesized from multiple interacting systems, like neurons or macro columns, and may explain the emergence of percepts with a unitary nature. The mathematical analysis of coupled systems suggests that these manifolds enforce synchronization of the coupled systems (in fact they are referred to as synchronization manifolds). This is the key to understanding the central role of oscillations and synchrony in binding the dynamics of distributed populations in the brain. Furthermore, it speaks to synchronization as a pragmatic measure that can be used to infer the presence of dynamic coordination.

Importantly, the reduction in dimensionality associated with dynamic coordination implies the creation of new knowledge. Let us consider the example of an image that contains a large number of Gabor patches. A full description of the image would require, for each Gabor patch, its location and orientation. However, if those Gabor patches can be integrated in a contour, then the image is fully described by the contour itself: this corresponds to a reduction of the number of state variables necessary to describe the image or, in other words, to the fact that additional knowledge has been created by coordinating the elements into a whole: the contour. This idea of creation of new knowledge is also captured by the axiom “the whole is different from the sum of its parts” and thus dynamic coordination can be viewed as those processes which foster the emergence of the whole from the parts.

The Theory of Coherent Infomax

The concept of dynamic coordination can be specified in informational theoretical terms within the theory of Coherent Infomax (Kay et al. 1998; Phillips et al., this volume). In short, contextual modulation affects the transmission of the information that it modulates, while, in contrast to the signal that it modulates, transmitting little or no conditional mutual information about itself. Alternatively, another way to see what is meant by the phrase “dynamic

coordination” is to think of it as a cover term for at least three fundamental neurocomputational functions: multiplicative gain modulation, dynamic grouping or “binding,” and dynamic routing (cf. Phillips et al., this volume). All three functions can be viewed as involving interactions that affect neural activity but without changing the information transmitted by the cells producing that activity. Tiesinga et al. (2008:106) state that “multiplicative gain modulation is important because it increases or decreases the overall strength of the neuron’s response while preserving the stimulus preference of the neuron.” Multiplicative gain modulation has been closely related to attention, coordinate transformations, the perceptual constancies, and other cases of contextual modulation, which shows the breadth of its range of potential application.

Our discussions, however, also reflected somewhat different views on the degree to which coordinating interactions can change the local “meaning” or representational contents. The Coherent Infomax Theory suggests that coordinating interactions are essentially modulatory in nature and, thus, have only weak effects on the information carried by neural responses, which are considered to result mainly from bottom-up inputs into the respective circuit. However, there may also be cases of coordination where the coordinating interactions are actually constitutive for the meaning (or functional role) of the local neural signals. Recording of a single neuron supplies a high amount of mutual information on the activities of other neurons. Therefore, the information on the activity pattern of one neuron cannot be inferred from the stimulus as such, but only through additional knowledge regarding the activity pattern of other neurons. The interaction of the neurons constitutes a free variable that is not directly affected by the stimulus. Hence, in information theoretic terms, the activity pattern is not determined completely by the evidence (stimulus); the prior (here the conditional probability given that other neurons fire in a specific pattern) has to be taken into account.

Put in neural terms, this latter view implies that the activity of individual neurons, taken on their own, does not carry completely invariant information; it is the context of the neural population (the assembly) that actually determines functional impact and “meaning” for the individual neural responses. Obvious examples can be found at the level of perceptual grouping, where it is known that perception of a complex object is mediated by coordination of massive neural populations; in this case, representational contents are established only at the population level, and coordinating interactions (e.g., synchronization of the respective neural signals) are a necessary condition for generating “meaning” and transmitting information on the “whole” rather than on its “parts.”

Dynamic Pattern Theory

An alternative theoretical approach that also describes the phenomena associated with dynamic coordination is known as Dynamic Pattern Theory. This

approach has been formally defined and studied by Kelso (1995) and others, drawing on Haken's work on synergetics. Important insights into principles of coordination have come from studies of motor coordination, such as that within and between hands, arms, and legs. The mathematical formulations of synergetics and Dynamic Pattern Theory have been more extensively developed than that of Coherent Infomax, but the two approaches seem to have much in common. A number of general conclusions have emerged from studies of motor coordination that are very similar to what has been proposed as applying to "dynamic coordination":

1. Dynamic coordination in sensorimotor control is highly distributed. Swinnen (2002:350), reviewing work on bimanual coordination concludes: "Although the prevailing viewpoint has been to assign bimanual coordination to a single brain locus, more recent evidence points to a distributed network that governs the processes of neural synchronization and desynchronization that underlie the rich variety of coordinated functions."
2. Population coding is common. Most movements are not driven by a single cell but by the combined activity of a population of cells. This has been well illustrated by Georgopoulos (1995), who has shown that the precise direction of movements is more closely related to the activity of cell populations than to that of single cells.
3. The precise timing of neural signals is crucial. In-phase or counter-phase synchronizations between rhythmically contracted homologous muscle groups are particularly common (e.g., in walking, running, and swimming), but other phase relationships can be learned, and constraints on this learning are the subject of much research.
4. The system falls easily into certain preferred patterns of activity (Kelso 1995). Modes of coordination in the motor system are patterns of movement that are easily performed and resistant to perturbation. They are usually well rehearsed and highly automated. They can be thought of as attractors in an energy landscape and are analogous to the idea of attractors in population codes for concepts and memories. An advantage of applying the notion of attractors to the motor system is that the process of attraction can be made concretely visible. This can be done, for example, by making clockwise circling motions with both hands, but with one leading the other by a small proportion of the cycle frequency. As cycle frequency increases there will be a tendency for the two movements to become in phase such that the homologous muscle groups are activated synchronously. As this is a highly stable movement pattern, it attracts similar but unfamiliar movement patterns toward it, thus making the idea of an attractor visible. Specific patterns of interaction occur between command streams at various stages of planning and execution. These can be either mutually interfering or

mutually supportive. This is the basic premise of the “neural crosstalk” approach developed by Swinnen (2002) and others. Well-coordinated actions are therefore those in which mutual support is maximized and mutual interference is minimized.

Understanding Dynamic Coordination

Several key concepts mentioned in the introduction will reemerge throughout the remainder of this chapter. These include dimension reduction (i.e., the notion that dynamic coordination reduces a high number of dimensions or degrees of freedom to a low-dimensional space or manifold); the notion of infomax and the importance of maintaining a high mutual information between the sensorium and its internal representation; and the functional role of dynamic coordination, which can be defined in terms of optimization for both perception and action. It is helpful to see these three constructs as intimately related facets of the same basic process: Put simply, we suppose that the purpose of the brain is to represent the world in a parsimonious and accurate fashion. This entails a mapping from sensory input to an internal representation, so that the representation provides a parsimonious account or explanation of sensory input. This parsimony corresponds to dimension reduction; namely, a collapse of a high-dimensional input space into a low-dimensional representation. The accuracy of this representation means that the sensory inputs can be predicted with minimal error and suggests that dynamic coordination optimizes prediction error. The fact that sensory inputs can be predicted implies a high degree of mutual information between those inputs and their representation. This is the essence of infomax. Coherent infomax addresses the fact that a better representation can be constructed by selectively preserving information that is predictably related across local processors that operate upon different parts of the input data. By so doing it might be possible to discover distal causes in the proximal data. We will return to the theme of optimized mappings between high-dimensional input spaces and low-dimensional representations later, when we consider the relationship between cognitive processes and dynamic coordination.

Is Dynamic Coordination the Basis of Specific Cognitive Functions or Is It a General Optimizer of Cognitive Functioning?

Cases of Dynamic Coordination

Dynamic coordination was originally conceived as a process that was mediated by synchronous interactions among neurons or neuronal populations during perceptual synthesis. It emphasized the contextual disambiguation of cause

and content during the processing of sensory information in neuronal circuits, both local and distributed, and the mergence of unitary representations of the external causes of sensations. Its ubiquitous role in neuronal and biological processes has led to a more inclusive use of the concept to cover the coordination of distributed dynamics, not just among sensory neurons but in the coordination of behavior and, more generally, the coupling of dynamical systems from the electrophysiology level to ethology.

It is useful to seek examples of the various forms of dynamic coordination at different levels of analysis from local circuits to behavior. Examples of contextual gain modulation at the level of single cells, or local groups of cells, include much evidence for the modulatory effects of attention and concurrent stimulus inputs from beyond the classical receptive field, as reviewed, for example, by Reynolds and Desimone (1999).

Examples at the level of cognition and behavior include endless demonstrations of contextual disambiguation, both within and between modalities. Rigorous examples from perception range from the effects of task irrelevant collinear or non-collinear surrounds on contrast detection, as studied in humans by Polat and Sagi (1994) and in awake-behaving monkeys by Kapadia et al. (1995), to effects on speech, face and scene perception. Many other examples are given by Edelman (2008a) and include paintings by Magritte designed to increase our awareness of the way in which context modulates interpretation of the local data.

Examples of dynamic grouping at the behavioral level include the contour integration task (reviewed by Kovács and Julesz 1993; Field et al. 1993; Hess et al. 2003). This task is designed so that explanations in terms of prespecified feature detectors are unlikely. It has also been used to test dynamic grouping in awake-behaving monkeys by Kreiter and Singer (1996) as well as in experiments combining behavioral and physiological measures (e.g., Müller et al. 1997).

Taking the example of visual perception, there is an obvious need for back-and-forth interaction among several levels of processing. Let us consider the perception of moving bodies: the nonrigid movements of the different body parts require an efficient and coupled coding of visual shape and motion information. For the efficient transfer of this coupled information, a representation (or code) is needed that optimizes space-time resolution (e.g., preserving a sufficient amount of spatial information in the presence of good temporal resolution). The point-light displays used by Johansson (1973) and the motion capture techniques more recently employed in studies of biological motion perception (Troje 2002) exemplify the effectiveness of dimensionality reduction that bring about “meaning” in the course of dynamic coordination.

Cognitive Processes and Coordination

One of the challenges encountered in our discussions of the relation between coordination and cognition was that the concept of “dynamic coordination” seems to relate to an enormous variety of neural and cognitive functions. In the extreme, “dynamic coordination” could even become a synonym for “cognition.” One way to address the problem of over-inclusiveness is to assume a heuristic rather than formal approach. This can be accomplished by conceptualizing the framework along two axes (Figure 18.1): the number of elements to be coordinated during the process and the degree of flexibility associated with the process under study. For clarity, only a few neural and cognitive processes are shown in this diagram, highlighting typical examples used during our discussions.

In Figure 18.1, the horizontal axis (“number of coordinated elements”) represents intuitions about the extent to which a task is complex, as defined by the combination of the number of elements required. As we shall see below, this dimension seems to covary with the extent to which synchronous oscillatory activity is evoked, the number of neurons or neural modules involved, as well as the extent to which intra- or inter-regional feedback is required. The vertical axis (“flexibility”) refers to the number of choices in the given task and represents intuitions about the extent to which a task involves selecting an interpretation (from an ambiguous input) or action (when performing a task) from an increasingly broad range of options. In addition, this dimension maps

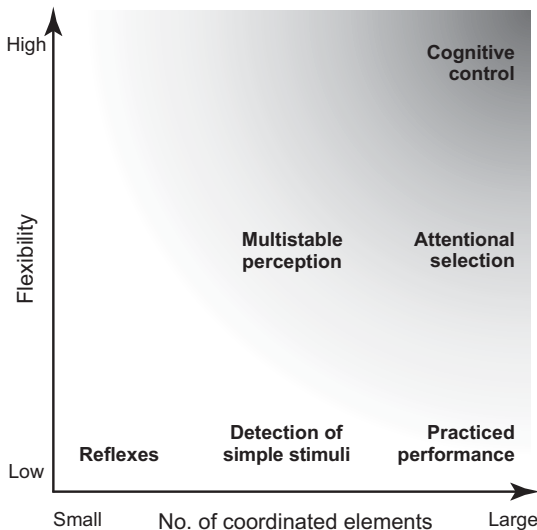


Figure 18.1 Two dimensions of dynamic coordination. The horizontal axis represents the number of coordinated elements; the vertical axis depicts “flexibility.” Gray shading indicates degree of dynamic coordination.

the extent to which a task is more novel or requires more control. Accordingly, a high degree of dynamic coordination would be associated with both coordination of large numbers of elements and high flexibility, as indicated by the gray shading of the figure background. The key question is whether the same parameter ranges are typically required for cognitive processes. In our discussions, consideration of numerous examples suggests that this may generally be the case, although exceptions seem possible.

Clearly, the relation between both dimensions is not symmetric. Relevant examples suggest that increasing the demands on flexibility (e.g., by allowing for selection between a wide range of choices) imposes a necessity for coordinating increasingly large numbers of elements in the system. Suitable examples include, at an intermediate level of both parameters, multistable perception or, at a very high level in both axes, the process of cognitive control. We note, however, that the converse is not true; coordination of large numbers of elements can take place without large flexibility on the task. For example, skilled performance in an overlearned motor task may represent a high level of coordination even when the flexibility is highly constrained. Thus, a proficient piano player touching a specific key at a specific time with a specific force clearly requires a high level of coordination even when no other outputs are under consideration. Importantly, for the current purposes, dynamic coordination is less evident, or absent, in a number of familiar functions (e.g., simple perceptions, reflexes, and prepotent responses). These processes share the property of being capable of being accomplished with first order statistics.

Silverstein (this volume) has detailed the nature of perceptual organization and how it places demands on dynamic coordination. The example of attentional gain control is also illustrative in this instance. One well-studied aspect of this process is the selection of one of a number of sensory stimuli for further processing from an array of different sensory stimuli. Here, the selection of one object in a visual scene for detailed processing by higher visual cortical areas requires the harmonious coordination of a number of lower and higher visual-processing areas. Such a selection process can be seen as a special case of the more general notion of dynamically coordinating the flow of information through the brain. Consider the example of driving a car while engaging in a conversation. Visual information about the location of the car, with respect to the road and the current traffic situation, is processed and ultimately routed to the muscles controlling our hands on the steering wheel and our feet on the accelerator or brake pedal. At the same time, acoustic information associated with the words of our conversation partner will be processed and ultimately routed to our own vocal apparatus as we respond. However, this pattern of information flow can be quickly and flexibly altered if, for example, our conversation partner asks us to stop the car—an acoustic stimulus prompting us to step on the brake.

Dynamic coordination, by definition, is required when the output of a given level of processors cannot be specified in advance on the basis of the input.

That is, multiple outputs are possible, and the output is determined in part by contextual factors. In this way, dynamic coordination can be seen as a basis of any process that requires such coordination; as noted above, this includes a wide range of perceptual and cognitive functions. What differentiates cognitive functions is, of course, the nature of the representations that must be created and transformed: visual vs. auditory input, codes for muscle movement, memory representations, sensorimotor integration, semantic information, etc. Moreover, the nature of the coordinating process appears to depend on a number of factors, including the speed at which coordination is needed (which can affect whether the primary coordinating mechanism is an initial neural spike vs. a slower or faster rhythm) and the number of processes that must be carried out simultaneously. In the latter case, multiple frequency bands will be “opened” and oscillatory activity in each will subserve a different process, although these may interact (Tallon-Baudry, this volume).

Dynamic Coordination as Optimization

It may be useful to understand some essential characteristics of dynamic coordination in terms of optimization. This rests on reducing the function of the brain to the optimization of specific quantities and thinking about what this entails for neuronal dynamics.

For nearly every aspect of brain function, from elementary perceptual categorization to optimal decision making under uncertainty, one can frame the problem (objective) faced by the brain in terms of an objective function. For perception, this objective function is the evidence for an internal (generative) model of how its sensory inputs were caused. Under some simplifying assumptions, this reduces to the amount of prediction error—the mismatch between sensory inputs and the predicted inputs under an optimized model. Perception, therefore, reduces to the suppression or explanation of (bottom-up) prediction error by (top-down) predictions; this is known as predictive coding and is a special case of more general Bayesian formulations in terms of free energy (Friston and Stephan 2007).

In action and motor control, several objective functions have been proposed, most in the service of finessing forward models of motor control. Recent formulations suggest that the same sort of prediction error minimized by predictive coding is minimized in optimal motor control (i.e., sensory prediction errors on proprioceptive channels reflect the mismatch between sensed and anticipated, or desired, consequences of movement). In procedural and reinforcement learning, the role of (reward) prediction error is again central to many formulations, such as temporal difference models and simpler versions in psychology (e.g., the Rescorla-Wagner model). In game theory and optimal decision theory, the objective function comprises expected loss under uncertainty or (in behavioral economics) its complement: expected utility or value. In fact, the value or expected reward can be linked to the surprise or amount of

prediction error minimized by action and perception. The basic idea here is that we can think of brain function as optimizing something (usually minimizing prediction error). So what does this entail for the optimization process?

Biophysical optimization schemes generally use some type of stochastic search (e.g., natural selection) or gradient descent. Gradient descent is inherently a dynamic process, most often formulated in terms of differential or difference equations. This means that any optimization in the brain (that uses gradient descent) must be a dynamic process (if it involves distributed neuronal states) and must involve dynamic coordination. The signature of gradient descent is that the dynamics move current states of the brain towards an attractor that represents the (fixed-point) optimal solution; where the objective function is brought to an extreme. For example, in perception, this would be the maximum a posteriori estimate of the causes of sensory input, at which point the prediction error is usually minimized. This means that dynamic coordination must attract brain states to an invariant set (the desired or optimal solution). Happily, this is the hallmark of dynamic coordination: the organization of the degrees of freedom in large numbers of distributed neuronal systems, so that they are contained in a low-dimensional space.

Can we be more precise about the sorts of dynamic coordination this might evoke? To do so, we need to consider dynamic coordination at different scales. A fair amount of evidence suggests that the reciprocal message passing between different levels or cortical areas in visual cortex is a key determinant of coordinated dynamics and, counterintuitively, may be faster than local lateral interactions within an area. This recursive and self-organized message passing is mandated by biological formulations of (predictive coding) perceptual inference and calls on dynamic coordination at a timescale of tens to hundred of milliseconds over a spatial scale of millimeters to centimeters. Most importantly, it must be self-limiting because its function is to suppress or explain away prediction errors (cf. the self-limiting transients observed electrophysiologically). This means there must be some variant of a feedback loop that ensures convergence to the optimal state. Thus, we might expect (functionally) suppressive effects of top-down extrinsic (between area) connections.

Synchrony and Dynamic Coordination

How does the preceding discussion relate to synchronous interactions between neurons or neuronal populations? A large number of studies carried out over the past two decades suggests that temporal correlations in neural activity play a key role for dynamic coordination in various sensory modalities (von der Malsburg and Schneider 1986; Singer and Gray 1995; Singer 1999; Tallon-Baudry and Bertrand 1999; Engel et al. 1992, 2001; Herrmann, Munk et al. 2004; Fries 2005). As shown by numerous studies in both animals and humans,

synchronized oscillatory activity, in particular at gamma-band frequencies (> 30 Hz), is related to a large variety of cognitive and sensorimotor functions.

Fast synchronization may play many essential roles. They all rely on a key mechanistic aspect of fast (e.g., gamma) synchronization that enhances the effective coupling between neurons—synchronous gain—in a flexible and context-dependent fashion. The majority of the available studies were conducted in the visual modality, relating gamma-band coherence of neural assemblies to processes such as feature integration over short and long distances (Engel, König, and Singer 1991; Engel, König, Kreiter et al. 1991; Tallon-Baudry et al. 1996), surface segregation (Gray et al. 1989; Castelo-Branco et al. 2000), perceptual stimulus selection (Fries et al. 1997; Siegel et al. 2007), and attention (Müller et al. 2000; Fries, Reynolds et al. 2001; Siegel et al. 2008).

Beyond the visual modality, gamma-band synchrony has also been observed in the auditory (Brosch et al. 2002; Debener et al. 2003), somatosensory (Bauer et al. 2006), and olfactory (Wehr and Laurent 1996) systems. Moreover, gamma-band synchrony has been implicated in processes such as sensorimotor integration (Roelfsema et al. 1997; Womelsdorf et al. 2006), movement preparation (Sanes and Donoghue 1993; Farmer 1998), and memory formation (Fell et al. 2001; Csicsvari et al. 2003; Gruber and Müller 2005; Herrmann, Lenz et al. 2004). Collectively, these data provide strong support for the hypothesis that synchronization of neural signals is a key mechanism for integrating and selecting information in distributed networks (Singer and Gray 1995; Singer 1999; Engel et al. 2001). What they suggest is that coherence of neural signals allows for the establishment of highly specific patterns of effective neuronal coupling, thus enabling flexible and context-dependent binding, the selection of relevant information, and the efficient routing of signals through processing pathways (Salinas and Sejnowski 2001a; Fries 2005; Womelsdorf et al. 2007).

Consideration of numerous examples for processes requiring dynamic coordination shows that these are generally associated with task- or context-specific changes in oscillatory activity and/or coherence. Supportive evidence for this includes studies on Gestalt perception, attention, long-term memory encoding and retrieval, working memory, choice and cognitive sequencing, multimodal integration, language comprehension, and even awareness. Table 18.1 presents an overview of key examples for such studies. As the table shows, oscillatory processes covary with cognitive functions in multiple frequency bands (discussed further below).

In summary, dynamic coordination at a timescale of tens to hundreds of milliseconds may be essential for optimization of distributed representations in the brain. The dynamic nature of this optimization is shaped by the underlying connectivity, which is subject to plasticity on a slower timescale. Emerging from anatomical connectivity, patterns of synchronous interactions may be coordinated dynamically on a faster timescale. Processes occurring at these two timescales can mutually constrain each other through mechanisms

Table 18.1 Cognitive processes and oscillatory neural activity.

Cognitive process	Evidence for oscillations	Evidence for coherence	Frequency band(s)	Species	Brain region	Method	Reference
Grouping	+	-	Gamma	Human	Posterior cortex	EEG	Tallon-Baudry et al. (1996)
Grouping	-	+	Alpha	Human	Posterior cortex	EEG	Mima et al. (2001)
Spatial attention	+	-	Alpha	Human	Posterior cortex	EEG	Thut et al. (2006)
Spatial attention	+	+	Gamma	Human	FEF, IPS, MT+	MEG	Siegel et al. (2008)
Attention (gain)	+	+	Gamma	Monkey	V4, LIP, PFC	Microelectrode recording	Fries, Reynolds et al. (2001); Buschman and Miller (2007)
Attention (timing)	+	-	Beta	Monkey	FEF	Microelectrode recording	Buschman and Miller (2009)
Working memory	+	+	Beta	Human	Posterior cortex	intracranial EEG	Tallon-Baudry et al. (2001)
Working memory	-	+	Beta	Monkey	IT	ECoG	Tallon-Baudry et al. (2004)
Working memory	+	-	Beta, gamma	Monkey	PFC	Microelectrode recording	Siegel et al. (2009)
Long-term memory encoding	-	+	Gamma	Human	Hippocampus	Intracranial EEG	Fell et al. (2001)
Long-term memory retrieval	+	-	Gamma	Human	Posterior cortex	EEG	Herrmann, Lenz et al. (2004)

Cognitive process	Evidence for oscillations	Evidence for coherence	Frequency band(s)	Species	Brain region	Method	Reference
Awareness	+	-	Gamma	Human	Sensory areas	MEG	Wyart and Tallon-Baudry (2008)
Awareness	+	-	Alpha, beta	Human	Sensory areas	MEG	Linkenkaer et al. (2004)
Multisensory integration	+	-	Gamma	Human	Temporal cortex	EEG	Schneider et al. (2008)
Multisensory integration	+	+	Alpha, beta	Monkey	Auditory cortex, temporal cortex	Microelectrode recording	Kayser and Logothetis (2009)
Visuomotor integration	+	-	Alpha, beta, gamma	Human	Sensorimotor cortex	MEG	Chen et al. (2003)
Language comprehension	+	-	Theta, alpha, beta	Human	Temporal cortex	EEG	Bastiaansen et al. (2005)
Social coordination	+	-	"Phi" (alpha range)	Human	Centroparietal cortex	EEG	Tognoli et al. (2007)

FEF: frontal eye fields PFC: prefrontal cortex

IPS: intraparietal sulcus IT: inferotemporal cortex

MT+: middle temporal region EcoG: electrocorticography

LIP: lateral intraparietal

of time-dependent plasticity and experience-dependent consolidation of architectures selected by synchronization of the sort indexed by gamma oscillations.

Is Dynamic Coordination Learned and Does Dynamic Coordination Modify Learning?

Relation between Dynamic Coordination and Learning

Dynamic coordination and learning are likely to have a profound influence on each other, but understanding this relationship is far from trivial. On one hand, dynamic coordination may be the result of learning processes and/or subject to developmental change. On the other, dynamic coordination may shape learning by selecting flexibly created relationships between internal representations that should be laid down in synaptic weight patterns.

Essentially all behaviors or complex competencies associated with dynamic coordination discussed above improve during ontogenetic development. This could mean that the competencies and neural structures being coordinated are improving, but it also suggests that coordination may be improving through learning. What may be the underlying mechanisms?

Learning processes are associated with a range of synaptic (and other) plasticity mechanisms. Dynamic coordination may also be realized through a number of mechanisms among which the synchronization of neuronal responses and oscillations in the gamma frequency band are prominent candidates. The question then is: How do the known plasticity mechanisms shape the (putative) mechanisms for coordination? For example, are there learning processes that will tend to improve neuronal synchronization? Or should the ability to synchronize be viewed instead as a generic circuit property, which learning processes may exploit for, say, the dynamic routing of information? To what extent do learning mechanisms shape dynamic coordination in a task-dependent manner that is influenced by reward signals to improve behavioral performance? Do learning processes ultimately transfer dynamically coordinated states into efficient but inflexible special purpose circuits?

Importantly, dynamic coordination may also affect learning. In particular, it may select from a multitude of possible association patterns those that are meaningful and should be remembered. As a specific example, consider the situation where dynamic coordination takes the form of synchronizing the firing of a population of neurons at the level of a few milliseconds. Interestingly, work on spike-timing-dependent plasticity (STDP) shows that whether a synapse between two neurons is strengthened or weakened can depend on the millisecond-scale precise timing of their action potentials (Markram et al. 1997). If the presynaptic neuron fires shortly before the postsynaptic neuron, the connection is strengthened. If, however, the presynaptic neuron fires shortly after the postsynaptic neuron, the synapse is depressed. Thus, dynamic coordination

processes that control the spike timing of groups of neurons (e.g., by synchronizing them) will have a huge impact on what synapses are strengthened or weakened. Dynamic coordination processes, together with the action of neuromodulators, may in fact be controlling the expression of plasticity.

Neural Synchrony during Human Ontogeny

The development and maturation of cortical networks critically depends on neuronal activity, whereby synchronized oscillatory activity plays an important role in the stabilization and pruning of connections. In STDP, pre- and postsynaptic spiking within a critical window of tens of milliseconds has profound functional implications (Markram et al. 1997). Stimulation at the depolarizing peak of the theta cycle in the hippocampus favors long-term potentiation (LTP), whereas stimulation in the trough causes depotentiation (LTD) (Huerta and Lisman 1993). The same relationship holds for oscillations in the beta and gamma frequency range (Wespatat et al. 2004).

Furthermore, synchronization of oscillatory activity is an important index of the maturity and efficiency of cortical networks. Neural oscillations are energy-efficient mechanisms for the coordination of distributed neural activity that are dependent upon anatomical and physiological parameters (Buzsáki and Draguhn 2004) which undergo significant changes during development. Thus, synchronization of oscillatory activity in the beta and gamma frequency range is dependent upon corticocortical connections that reciprocally link cells situated in the same cortical area, across different areas or even across the two hemispheres (Engel, König, and Singer 1991; Engel, König, Kreiter et al. 1991). Furthermore, GABAergic interneurons play a pivotal role in establishing neural synchrony in local circuits as indicated by research that shows that a single GABAergic neuron may be sufficient to synchronize the firing of a large population of pyramidal neurons (Cobb et al. 1995) and the duration of the inhibitory postsynaptic potential (IPSP) can determine the dominant frequency of oscillations within a network (Wang and Buzsáki 1996). As brain maturation involves changes in both GABAergic neurotransmission (Hashimoto et al. 2009; Doischer et al. 2008) and the myelination of long axonal tracts (Ashtari et al. 2007; Perrin et al. 2009), changes can be expected in the frequency and amplitude of oscillations as well as in the precision with which rhythmic activity can be synchronized over longer distances at different developmental stages.

During development of resting state activity, there is a reduction in the amplitude of slow-wave (delta, theta, alpha activity) rhythms, while fast (beta- and gamma-band) rhythms increase during childhood and adolescence. This is accompanied by increases in the coherence of oscillatory activity (for a review, see Niedermeyer and Silva 2005). Development of task-related activity in the gamma band coincides with the emergence of cognitive functions during early childhood (Csibra et al. 2000), suggesting that the maturation of high frequency activity could be related to cognitive development. Following

infancy, continued development of neural synchrony is observed whereby oscillations shift to higher frequencies and synchronization becomes more precise. Specifically, this is not complete until early adulthood; neural synchrony continues to mature throughout the adolescent period, which represents a critical phase of brain maturation (Uhlhaas et al. 2009).

Coordination in Perceptual and Motor Development

The human development of perceptual organization as measured behaviorally (Kovács 2000) seems to follow a similar maturational course, as suggested above, with respect to neural synchrony, continuing into adolescence and early adulthood. Perceptual integration can be taken as an example. Sensitivity to contour closure—a Gestalt property, definitely requiring dynamic perceptual organization—has been shown to be a measurable skill in adult human observers, enhancing the segmentation of noisy images (Kovács and Julesz 1993). Closure sensitivity is missing in three-month-old human infants (Gerhardtstein et al. 2004), and the underlying ability to integrate spatial information across the visual field develops until the end of adolescence in humans (Kovács et al. 1999). The normal course of development in perceptual organization is affected by the nature of input to the visual system. Abnormal visual input in, for example, amblyopia leads to a severe deficit in perceptual organization related to the amblyopic eye (Kovács et al. 2000). The contour integration stimuli used in the amblyopic study have been designed mainly to involve primary visual cortex processing, and a neuropsychological study confirmed the sufficiency of the primary visual cortex in this task (Giersch et al. 2000). It has been shown in the cat that amblyopia is associated with altered intracortical processing in V1 (Schmidt et al. 2004), and reduced synchronization of population responses has been suggested as a neurophysiological correlate of strabismic amblyopia (König et al. 1993; Roelfsema et al. 1994). It remains to be seen, however, whether synchronization in V1 underlies both intact contour integration in humans and deficient processing in human amblyopes.

Is reduced perceptual performance in children—either in terms of precision or timing—due to less efficient or slower synchrony, or to the fact that basic visual skills can become overlearned and automated over the course of development, leading to more efficient/faster processing? Alternatively, can all dynamically coordinated activities be trained to an “automatic” level? Wonderful examples in both perceptual (e.g., Karni and Sagi 1993) and motor learning (Karni et al. 1998) demonstrate that performance is improved over time, both in terms of precision and in terms of the time taken in individual trials. In both cases, there seems to be an initial phase of learning that involves the activity of a number of cortical areas; later on, plastic changes will be specific to the primary sensory or motor cortices. It might be argued that dynamic coordination is only involved in the first phase of learning, while during the second

stage a more inflexible structure carries out the task. Perceptual and motor learning might be excellent grounds for testing the idea of reduced dynamic coordination following practice as both seem to show a very high level of specificity in terms of learning. This specificity is graded, however, and the amount of transfer varies across tasks. Transfer properties of different skill learning cases might tell us about the involved cortical structures and the flexibility of coordination.

Another important aspect of basic skill learning in the perceptual and motor domains is that learning is sleep-dependent. It seems that sleep actively contributes to performance improvements in procedural learning (Stickgold et al. 2000; Walker et al. 2002, 2003). In addition, it contributes to learning in the contour integration task—a task designed to rely heavily on dynamic integration (Gervan and Kovács 2010).

Learning and Dynamic Coordination

One of the roles of dynamic coordination is to encode new relationships. However, if those relationships turn out to be stable ones, encountered repeatedly, then it is probably worth creating a neural route dedicated to those items that are bound by stable links. This new route would result from the modification of synaptic efficiency in repeated jointly activated assemblies. It seems reasonable to assume that this new route is fast and recruits a smaller number of neurons. Thus it does not necessarily require flexible, dynamic coordination any longer: the new route would correspond to a prespecified spatiotemporal pattern of neural activity.

Recent data in humans are compatible with this schema. Subjects performed a typical visual search task in which they had to detect a target at different locations and report its orientation. Two types of images were interspersed: in predictive images, the layout of the distractors predicted accurately the location of the target, while in nonpredictive images, the target could appear anywhere. Subjects learned these regularities: after five or six presentations, they were faster at reporting the orientation of the target in predictive images than in nonpredictive ones. During the learning phase, before any behavioral advantage to predictive images occurred, oscillations in the low-gamma range appeared specifically in response to predictive images, suggesting that the brain was detecting the stability of the relationship between distractors and target (Chaumon, Hasboun et al. 2009). As soon as those relations were learned and the behavioral advantage to predictive images appeared, those low frequency gamma oscillations stopped. Predictive images were processed now in a very different way, with evoked responses specific to predictive images in the temporal lobe and orbitofrontal cortex occurring before 100 ms (Chaumon et al. 2008; Chaumon, Schwartz et al. 2009). The result of learning thus seems to

be a modification of the early volley of feedforward processing in response to predictive images.

What Is the Role of Different Frequency Bands for Dynamic Coordination?

Oscillations in Different Frequency Bands

Ongoing intrinsic and event-related oscillations are usually categorized into five frequency bands: delta (0.5–3.5 Hz), theta (4–7 Hz), alpha (8–12 Hz), beta (13–30 Hz), and gamma (> 30 Hz). A large body of evidence suggests that oscillatory activity in these frequency bands is linked to a broad variety of perceptual, sensorimotor, and cognitive operations (Engel et al. 1992, 2001; Singer and Gray 1995; Basar et al. 2000; Klimesch et al. 2006; Palva and Palva 2007; see also Table 18.1). Oscillatory activity in the delta band has been related to motivational processes, the brain reward system, and is the predominant frequency during deep sleep phases (Basar et al. 2000; Knyazev 2007). Activity in the theta band has been linked to working memory functions, emotional arousal, and fear conditioning (Knyazev 2007; Jensen and Lisman 2005). The prominent alpha-band responses, discovered in the human EEG by Hans Berger in the late 1920s, have been suggested to reflect cortical operations during the awake-resting state in the absence of sensory inputs. More recent theories have proposed that alpha-band oscillations may also relate to disengagement of task-irrelevant brain areas (Klimesch et al. 2006), as well as working memory function and short-term memory retention (Palva and Palva 2007). Neuronal responses in the beta band have been frequently linked to sensorimotor processing (e.g., Roelfsema et al. 1997; Brovelli et al. 2004) as well as many other functions including working memory and multi-sensory integration (see Table 18.1). As discussed above, the putative functions of synchronization in the gamma band seem to be particularly diverse, ranging from feature integration, stimulus selection, attention, and awareness to sensorimotor integration, movement preparation, and memory formation. This striking diversity indicates that it may be difficult to associate cognitive functions or even classes of functions in any unique and direct way with oscillatory dynamic coupling in specific frequency bands. The examples discussed below yield a rather complex picture. While they provide clear cases of task- or context-related modulation of frequencies or even switching between different frequency ranges, they do not yet suggest generalizable conclusions.

Currently, another unresolved issue concerns the interaction of multiple frequency bands. Phase synchrony and phase modulation of oscillations across different frequency bands has recently been suggested to play a key role for the organization of networks engaged in speech processing (Schroeder et al. 2008) and memory encoding (Palva and Palva 2007; Jensen and Lisman 2005). This

clearly adds to the complexity of the picture already presented by the findings on individual frequency bands. The possibility of multifrequency coupling has also been addressed in the framework of Dynamical Systems Theory (Kelso 1995). As mentioned earlier, the effective degrees of freedom of complex, dynamical systems are often reduced to the space of coupled nonlinear oscillators where a rich variety of behaviors is possible. In particular, a system's ability to generate multifrequency behavior is governed by the differential stability of mode-lockings as seen through so-called "Arnold Tongues" (named after the Russian mathematician Vladimir Arnold). In this dynamic scenario, pattern complexity is related to a hierarchy of frequency ratios.

Role of Different Frequency Bands in Sensory Processing

Recording in primary visual cortex of alert cats, Siegel and König (2003) demonstrated that neuronal activity, as characterized by the local field potential, is optimally orientation-tuned when the gamma band in the frequency range between 40–100 Hz is considered. Synchronization in a lower frequency band with different properties suggested distinct functional roles of low and high frequency synchronization. Subsequently, it has been shown that natural visual stimuli induce robust responses in the gamma frequency band (Kayser et al. 2003). A second frequency band, located at the classical alpha and low beta bands (8–23 Hz), showed reliable tuning to stimulus features (Kayser and König 2004). In marked contrast, tight locking to temporal properties of the stimulus was found in the remaining frequency bands. This locking is independent of the spatial structure of the stimulus. Together these four frequency bands cover the whole frequency range investigated. These studies demonstrate that the entire frequency range of the local field potential can be assigned a role in visual processing, but presumably these roles differ profoundly.

Another study investigated interareal interactions during processing of expected and novel stimuli in the cat visual system (von Stein et al. 2000). Processing of expected stimuli was characterized by high alpha-band activity, and phase relationships and laminar distribution suggested an influence of higher onto lower areas. In contrast, new and surprising stimuli induced high gamma-band activity. These data could be accounted for in a detailed simulation assigning gamma activity to an iterative bottom-up directed processing mode and alpha activity to a top-down directed processing mode. These data offer a new perspective to the classical view that alpha activity is an idling rhythm (i.e., expressing properties of the visual system at rest), whereas gamma activity is thought to be involved in Gestalt perception and figure-ground segmentation (see above). The alpha rhythm might be better described as reflecting visual processing guided by expectations, whereas gamma activity may arise as new stimulus configurations are freshly interpreted in light of previous experience.

Recent evidence suggests that multisensory integration may also relate to neuronal interactions in different frequency bands. Schall et al. (2009) investigated audiovisual binding by presenting continuously changing, temporally congruent and incongruent stimuli. Spectrotemporal analysis of EEG signals revealed locking to visual stimulus dynamics in both a broad alpha band and the lower beta band. This matches results on the role of different frequency bands during processing of natural visual stimuli observed in alert cats (Kayser and König 2004).

Role of Different Frequency Bands in Attention and Awareness

Some evidence for different roles of frequency bands comes from recent observations that different forms of visual attention result in increased coherence in different frequency bands (Buschman and Miller 2007, 2009). When monkeys shifted attention in a bottom-up fashion to a salient “pop-out” stimulus, there was a greater increase in coherence between the frontal and parietal cortices in an upper frequency band (35–55 Hz). By contrast, when attention was shifted in a top-down fashion (to a target that matched one held in short-term memory), there was a greater increase in a lower frequency band (22–34 Hz). Higher frequency oscillations may result from superficial pyramidal cells, which form feedforward connections. They show stronger gamma frequencies than the deep pyramidal cells that originate feedback connections. This also fits well with more recent observations that lower frequency coherence may play a role in controlling the timing of the shifts of attention in the top-down attention condition. Buschman and Miller (2009) found that monkeys shifted the location of their attention every 40 ms as they searched for the visual target. This was reflected in frontal eye fields (FEF) spiking activity and was correlated with the lower frequency band oscillations, suggesting that the lower frequency oscillations can provide a “clocking” signal that helps coordinate when different brain areas contribute to a shift of attention.

Indeed, one role for oscillations may be to coordinate complex, multistep computations. An oscillating wave of inhibition would allow computations to be temporally constrained and information to be released in a “packet” at a time when a downstream area is ready to receive it. This would cause a “discretizing” of events and explain psychophysical observations of a periodic allotment of attention (VanRullen et al. 2007). Attention appears to be allocated in discrete chunks of time and not as a continuous function that smoothly shifts from location to location.

This predicts that oscillation frequencies would vary with the nature of the computation. Highly localized computations may be able to oscillate at higher frequencies while more complex, integrative, or inherently slower computations may result in slower oscillations. For example, consider covert versus overt attention. A purely covert search task without eye movements (as in Buschman and Miller 2007, 2009) allows faster shifts of attention and thus locking to

relatively higher (beta) frequency oscillations. By contrast, in overt attention there is a slower time constant because of the increased “overhead” of moving the eyes with each attentional shift. Under these conditions, there are stronger theta oscillations that are time-locked to the eye movements (Desimone, pers. comm.). Computations that have even less temporal overhead and that occur within more local networks might lock to even higher frequencies. For example, gamma-band oscillations have been associated with working memory, surface segregation, perceptual stimulus selection, and focused attention not requiring serial shifts of attention (see above). Computations might use the closest inherent “eigenfrequency” or resonance of the cortical network given the constraints of the computation and the demands of the task at hand.

Evidence from human studies suggests that different subranges in the gamma frequency band can relate to distinct cognitive functions (Tallon-Baudry, this volume). In one experiment (Wyart and Tallon-Baudry 2008, 2009), subjects were cued to attend to the left or right hemifield, and were then presented with a faint oriented grating, either on the attended or unattended side. At each trial, subjects were asked whether they had experienced the stimulus consciously. Each stimulus can therefore be classified as (a) attended or unattended and (b) consciously perceived or not. These two cognitive functions were expressed separately in distinct subfrequency ranges within the gamma range. Gamma-band oscillations related to awareness originated in lateral occipital cortex and were centered around 60 Hz. They were not influenced by spatial attention. Attention-related gamma oscillations were observed at more parietal locations and around 80 Hz, without any influence of whether the subject had consciously perceived the stimulus or not. This could suggest that whenever two distinct cognitive processes have to remain segregated, gamma-band oscillations appear in a narrower frequency band, dedicated to that process, leaving other “slots” available for other concomitant processes to be implemented.

Role of Different Frequency Bands in Motor Circuits

Neurophysiological evidence on the complementary role of oscillations in different frequency bands also comes from recordings in human subcortical structures that are carried out during stereotactic operations for the treatment of movement disorders, such as Parkinson’s disease (Brown and Marsden 1998; Brown 2003; Engel et al. 2005). This surgical approach opens up the possibility of recording both unit and field potential signals from the target structures and testing the presence of oscillatory activity and its coherence with EEG and EMG signals during motor tasks in the patients. In a series of studies, Brown and coworkers investigated task- and dopamine-dependent changes of neural coherence between cortex and basal ganglia structures (Brown et al. 2001; Marsden et al. 2001; Cassidy et al. 2002). They investigated shifts in the frequency range of coherence when the patient was under different states of medication or in different behavioral states. Measurements without medication

showed that in the akinetic “OFF” state, coherence between the basal ganglia and cortex is dominated by tremor frequencies and frequencies in the beta band. Interestingly, treatment with the dopamine precursor levo-dopa reduced low frequency activity and resulted in a new coherence peak at 70 Hz in the gamma band (Brown et al. 2001). Importantly, electrical stimulation at those sites where beta-band coherence was highest with the EEG and the contralateral EMG yielded the best amelioration of Parkinsonian symptoms (Marsden et al. 2001). In another study, the functional significance of high frequency activity was investigated by testing the modulation of coherence before and during voluntary movement. In the OFF state, beta activity was suppressed during movement preparation and execution, whereas in the ON state (i.e., after levo-dopa treatment), gamma coherence was enhanced in relation to the movement (Cassidy et al. 2002). These findings are compatible with a model in which interactions between the basal ganglia, thalamus, and cortex in different frequency bands modulate basal ganglia functions in a task- and state-dependent way (Brown 2003; Brown and Marsden 1998). Slow oscillations at tremor frequencies or in the beta band, resulting from dopamine depletion, seem to disrupt normal motor function. By contrast, gamma-band rhythms seem to be important for the organization of normal voluntary movement, as indicated by the emergence of these fast oscillations in the ON state, and by the prokinetic effects of deep brain stimulation at these frequencies or higher harmonics (Limousin et al. 1995).

Which Processes Modulate Dynamic Coordination at the Systems Level?

The importance of the emergence of dynamic coordination as a concept in cognitive neuroscience is that, among other things, it provides a balance to strictly localizationalist views of cognitive function. Based on data, computational models, the sociohistorical context of this intellectual development, and the position of this construct within the matrix of ideas in neuroscience, the focus of much research in this area has been on within-region coordination, with an emphasis on self-organization based on processing within regions. When discussed within the broader field of brain function, we can ask whether large-scale coordination operates according to similar mechanisms as more local or intra-regional coordination. Another important, but relatively unexplored issue, is to what extent the speed and strength of dynamic coordination is affected by more global modulatory influences in the brain. As noted above, data on development and learning indicate that there is plasticity in dynamic coordination. In addition, the well-known effects of psychopathology (e.g., schizophrenia; see Silverstein, this volume) and NMDA antagonists (e.g., ketamine, phencyclidine; Phillips and Silverstein 2003) on dynamic coordination indicate that these processes can operate within a wide range of efficiency.

However, relatively little attention has been paid to factors such as emotion, arousal, or fatigue.

There is both positive and negative evidence regarding the effects of emotion on coordination. For example, it has been demonstrated that the emotional content of pictures had little effect on early event-related potentials reflecting perceptual organization (Bradley et al. 2007). A more complex picture was revealed in a study by Colzato et al. (2007) in which the affective valence of pictures did not affect binding of visual features, but strongly affected binding of visual and response codes. Because it has been shown that sensory encoding in the visual cortex can be facilitated by affective cue-driven “natural selective attention” (Schupp et al. 2003), this suggests that affect modulates signals at a level beyond intra-sensory coordination, although it affects higher-level sensorimotor coordination. To date little is known about the effects of arousal or fatigue on dynamic coordination. However, the well-known effects of these factors on cognition, in general (e.g., Yerkes–Dodson law), suggest that it is worth exploring whether arousal effects occur at the level of coordinating interactions, and whether any such effects overlap completely with those of attention and occur at later stages.

We turn now to two closely related questions of particular interest: Are certain brain regions of particular importance for modulating dynamic coordination? To what extent is dynamic coordination constrained by top-down influences?

Prefrontal Cortex Modulates Dynamic Coordination

The ability to conceptualize and describe dynamic coordination in terms of formal models, in combination with the known similarity of local circuitry throughout the cortex (Phillips and Singer 1997), suggests that coordinating processes can occur within any brain region and, for coordination within a single sensory domain, no guidance from outside that region is necessary. The extent to which this is true needs further exploration. For example, while contour integration is typically seen as involving interactions only between neurons within the visual cortex, a recent study indicated that patients with traumatic brain injury to the frontal cortex were deficient in binding sparsely arranged, but still orientation-correlated, Gabor patches (Ciaramelli et al. 2007). This is consistent with evidence from a recent study of schizophrenia, in which reduced contour integration was associated with less frontal activity compared to healthy controls (Silverstein et al. 2009). In the latter case, while the largest and most consistent differences between groups were in visual cortex areas known to involve integration and to subserve perceptual grouping (e.g., V2, V3, V4), data on differences in frontal activation suggest that a larger network may be involved in normal dynamic coordination in vision than previously believed.

Given that the frontal lobe, and especially the prefrontal cortex (PFC), has been traditionally construed as a “central executive,” it is important to clarify

the extent to which activity in this region affects coordination in other areas, the conditions under which it occurs, and the specific types of coordination that it affects and provides. As we hope is evident in this chapter, dynamic coordination occurs throughout the brain at many levels of processing. Dynamic coordination is also required at a higher, meta level. Complex, goal-directed behavior would be impossible without brain systems and mechanisms that coordinate other systems to organize their processing and keep them on task and directed toward goals. Without it, thought and action would be determined solely by whatever sensory inputs happen to be most salient and the well-learned or reflexive responses associated with them. This ability is called cognitive control. It no doubt involves neural circuitry that extends over much of the brain, but it is commonly held that the PFC is particularly important.

The PFC occupies a far greater proportion of the human cerebral cortex than in other animals, suggesting that it might contribute to distinctively human cognitive capacities. Humans and monkeys with PFC damage seem to lack cognitive control: they become “stimulus-bound,” their behavior dominated by reflexive reactions to the environment. Miller and Cohen (2001) proposed a guided activation model in which this cognitive control stems from the PFC’s active maintenance of patterns of activity that represent goals and the means to achieve them (i.e., rules). This is thought to provide bias signals to other brain structures whose net effect is to guide the flow of activity along neural pathways that establish the proper mappings between inputs, internal states, and outputs needed to perform a given task, dynamically coordinating cortical processing to meet the demands of the task at hand.

Much of the evidence for this is, at the moment, indirect. One line holds that the PFC has complex multimodal properties that encode the type of information needed for goal direction: after training, many of its neurons reflect task rules (Miller 2000; Miller and Cohen 2001). Another line maintains that the PFC is anatomically well suited to coordinate cortical processing. It is interconnected with virtually the entire cerebral cortex, with the exception of primary sensory and motor areas. It is also interconnected with other major brain systems, including the basal ganglia, hippocampus, and anterior cingulate. Thus, it is well situated to integrate information about the external world and the animal’s internal state and to send back signals that modulate processing in widespread brain areas.

More direct evidence for a role of the PFC in top-down modulation of posterior cortex has been mounting. Naya et al. (1996) showed that the PFC is needed for the recall of visual information in the inferior temporal cortex. By cutting the corpus callosum and the anterior commissure in two stages, they showed that activity in the inferior temporal cortex (reflecting the recall of an object from long-term memory) depended on top-down signals from the PFC. Moore and colleagues showed that microstimulation of the FEF causes attention-like modulations of neural responses in the visual cortex (Moore and Armstrong 2003). They electrically stimulated sites within the FEF and

measured its effect on the activity of neurons in area V4. V4 neuron responses to a visual stimulus were enhanced after brief stimulation of retinotopically corresponding sites within the FEF below that needed to evoke saccades. Further, stimulation of noncorresponding FEF representations suppressed V4 responses. Buschman and Miller (2007) also found direct evidence that top-down attention signals arise from the frontal cortex and act on the posterior cortex. When monkeys shifted attention in a bottom-up fashion (to a salient, pop-out, stimulus), neurons in the parietal cortex reflected the shift of attention to the target before neurons in the PFC and FEF. By contrast, when attention was shifted in a top-down fashion (to a target that matched one held in short-term memory), the opposite was true: neurons in the frontal cortex showed a shorter latency to reflect the attention shift than those in the parietal cortex. This suggested that top-down and bottom-up attention signals arise from frontal and sensory cortex, respectively. Taken together, these considerations suggest that PFC is one of the dominant sources of modulatory signals that have an impact on dynamic coordination within and across other brain regions.

In addition to the frontal cortex, it has also been proposed that the cerebellum exerts a strong influence on cognitive coordination and that coordination impairments such as those occurring in schizophrenia can be attributed to cerebellar abnormalities (e.g., Andreasen and Pierson 2008). To date, however, data linking cerebellar function to a primary role in coordination of cognitive activity at the cortical level are lacking. However, it is still possible that the cerebellum contributes timing signals which serve a general coordinating function.

Top-down Processing and Neural Coherence

Most of the models considering the functional importance of top-down mechanisms make use of the *anatomical* notion of top-down processing: they assume that predictions or hypotheses about the features of environmental stimuli are expressed by signals travelling along feedback connections from “higher” to “lower” areas in a processing hierarchy. One of the earliest examples of such a model is the Adaptive Resonance Theory (Grossberg 1980). The theory assumes complementarity between ascending and descending pathways among sensory areas, the former allowing adaptive filtering of the input signals and the latter carrying predictive signals (templates of expected patterns that need to be matched by the current input). Related models that also postulate a key role of feedback influences in pattern recognition have been suggested by Mumford (1992) and Ullman (1995). These models also suggest that the comparison of sensory input with existing knowledge is essential for perception. Current top-down models of attentional selection and cognitive control (Frith and Dolan 1997; Fuster 1989; Miller 2000) assume that top-down influences originate in prefrontal and parietal cortical areas. As discussed above, a crucial idea is that assemblies of neurons that represent action goals in the PFC provide modulatory “bias signals” (Miller 2000) to sensorimotor circuits that

have to carry out response selection. Thus, prefrontal signals are assumed to exert top-down control over the routing of information flow through specific sensorimotor loops.

A different idea of how top-down influences might be implemented neurally may lead to what could be called a dynamicist view (Engel et al. 2001). This view is motivated by the evidence that synchrony can be intrinsically generated (not imposed on the system by external stimuli) and modulated by intrinsic signals that reflect experience, contextual influences, and action goals (reviewed by Singer 1999; Engel et al. 2001). In this context, the search for the mechanisms of top-down control becomes equivalent to the investigation of the influence of ongoing patterns of activity on the processing of sensory signals and, in particular, on their selection and grouping through oscillatory patterning and synchronization. In contrast to the top-down models discussed above, the patterns relevant to the dynamic selection of input signals would be generated not only by assemblies in association cortices that carry more abstract, invariant representations, but as the result of continuous large-scale interactions between higher- and lower-order cortical areas. The patterns of coherent activity emanating from such large-scale interactions could bias the synchronization of input signals, leading to a selective enhancement of temporal correlations in subsets of the activated populations. This would result in enhanced saliency and a competitive advantage for the selected populations of neurons.

Evidence for top-down control by changes in the dynamics of intrinsically active networks has been obtained in a recent study of spatial attention shifts in humans (Siegel et al. 2008). In this study, MEG was combined in a spatially cued motion discrimination task with source-reconstruction techniques to characterize attentional effects on neuronal synchronization across key stages of the human dorsal visual pathway. The results demonstrate that visuospatial attention modulates oscillatory synchronization between visual, parietal cortex, and PFC in a spatially selective fashion. In particular, analysis of phase coherence in source space showed that during attentive processing of a visual stimulus, gamma-band coherence increases between regions corresponding to FEF, intraparietal sulcus, and middle temporal region. This suggests that attentional selection is mediated by frequency-specific synchronization between prefrontal, parietal, and visual cortex and that the intrinsic dynamics of frontoparietal networks is important for controlling attentional shifts (Engel et al. 2001; Corbetta and Shulman 2002). An interesting finding in this context is that this selection network did not involve prefrontal, but premotor regions, supporting what has been called the “premotor theory of attention” (Rizzolatti et al. 1987). Recently, similar observations have been made in studies on large-scale interactions accompanying shifts of attention in the monkey brain, showing that attention is associated with enhanced coherence between FEF and visual cortical areas (Gregoriou et al. 2009).

How Is Dynamic Coordination Related to Brain Disorders?

Disturbance of Dynamic Coordination in Schizophrenia

Research into psychiatric disorders may not only lead to insights into the mechanisms underlying abnormal mental functioning but may also be an ideal testing ground for examining the validity of current theories of healthy brain functioning. Schizophrenia is of particular relevance for testing the concept of dynamic coordination, and much of our discussion on the pathophysiological alteration of coordination mechanisms centered on this clinical condition.

From its earliest beginnings, the pathophysiology of schizophrenia has been described as a disorder involving a deficit in the integration and coordination of neural activity that leads to dysfunctions in cognition. Symptoms can involve false perceptual inference (e.g., hallucinations; failure to integrate subtle or distracting cues during perceptual grouping), false conceptual inference and contextual disambiguation (e.g., delusions and passivity phenomena), and a secondary failure of learning (psychomotor poverty). Bleuler (1911) chose the word “schizophrenia” to highlight the fragmentation of mental functions. Indeed, current theories of schizophrenia (Friston 1999; Phillips and Silverstein 2003) converge on the notion that core aspects of the pathophysiology are due to deficits in the coordination of distributed neural processes that involve multiple cortical areas. This perspective, which considers schizophrenia as a functional dysconnection syndrome, contrasts earlier views which emphasized a regionally specific pathophysiological process as the underlying cause for the signs and symptoms of schizophrenia. This view, which considers the symptoms experienced by the patient as a product of ensuing dysfunctional dynamic coordination, places abnormal synaptic function at the heart of the etiology. It emphasizes the primary role of synaptic plasticity and, in particular, its modulation by neuronal dynamics and neurotransmitter systems.

Support for the notion that dynamic coordination may be central to the pathophysiology of schizophrenia stems from the cognitive deficits central to the condition. These involve functions that are paradigmatic examples of dynamic coordination, such as working memory, attention, and perceptual organization (for a review, see Phillips and Silverstein 2003). In addition, if dynamic coordination is impaired in schizophrenia, one of the physiological manifestations should be impaired synchronous oscillatory activity. Evidence suggests that this is so. A substantial body of EEG/MEG studies support the hypothesis that cognitive deficits are related to impaired neural synchrony. Examination of auditory and visual steady-state responses to repetitive stimulation in patients with schizophrenia has revealed a specific reduction in the power of the stimulus-locked response in the beta and gamma frequency range, but not in the lower frequencies (Krishnan et al. 2005; Kwon et al. 1999). Reductions in evoked oscillatory activity have been reported for tasks involving visual binding (Spencer et al. 2003, 2004), for backward masking (Wynn et al. 2005), in

auditory oddball paradigms (Gallinat et al. 2004), and during TMS-evoked activity over frontal regions (Ferrarelli et al. 2008). These results suggest selective deficiencies in the ability of cortical networks or cortico-thalamo-cortical loops to engage in precisely synchronized high frequency oscillations.

In addition to analyses of spectral power, several studies have also examined phase synchrony between distributed neuronal populations while patients performed cognitive tasks (Slewa-Younan et al. 2004; Spencer et al. 2003; Uhlhaas, Linden et al. 2006). Overall, these studies conclude that patients with schizophrenia are characterized by reduced phase locking of oscillations in the beta- and lower gamma-band range; this underscores that, in addition to abnormalities in local circuits, large-scale integration of neural activity is impaired. It is currently unclear, however, to what extent impairments in local circuits contribute to long-range synchronization impairments or whether these represent two independent phenomena.

Significant correlations, found in multiple studies across different laboratories, between reduced perceptual organization and reduced conceptual organization (i.e., the presence of formal thought disorder) (Uhlhaas and Silverstein 2005), and covariation of changes in both with treatment (Uhlhaas, Linden et al. 2006) provide evidence that different forms of dynamic coordination may be supported by a single mechanism. Correlations between cognitive dysfunctions and alterations in neural synchrony are furthermore suggested by relationships between the positive symptoms of schizophrenia and changes in the amplitude of beta- and gamma-band oscillations. Thus, patients with auditory hallucinations show an increase in oscillatory activity in temporal regions compared to patients without hallucinations (Lee et al. 2006; Spencer et al. 2008).

Further evidence for the role of neural synchrony in the pathophysiology of schizophrenia is the coincidence of symptom expression during the transition from adolescence to adulthood and developmental changes in power and synchronization of oscillations in the theta, beta, and gamma frequency range during normal brain development. Recently, Uhlhaas et al. (2009) showed that these parameters undergo profound changes during late adolescence, reflecting an increase in the temporal precision of cortical networks. This suggests the possibility that abnormal brain development in schizophrenia during the late adolescent period is unable to support precise temporal coding, which then leads to the decompensation of the network and the accompanying emergence of psychotic symptoms.

Impaired dynamic coordination in schizophrenia is consistent with deficits at the anatomical and physiological level in schizophrenia. One prominent candidate mechanism for the changes in neural synchrony is a dysfunction in GABAergic interneurons (for a review, see Lewis et al. 2005). For example, there is consistent evidence for reduced GABA synthesis in the parvalbumin-containing subpopulation of inhibitory GABA neurons in schizophrenia, which are critically involved in the generation of cortical and hippocampal oscillatory

activity. Furthermore, impairments in long-range synchronization in schizophrenia can be related to changes in white matter volume and organization, as long distance synchronization of oscillatory responses is mediated by reciprocal corticocortical connections (Löwel and Singer 1992; König et al. 1993). This possibility is supported by *in vivo* anatomical examinations with diffusion tensor imaging that have revealed white matter anomalies throughout cortical and subcortical structures (for a review, see Kubicki et al. 2007).

These data suggest that dynamic coordination is a useful construct to understand the pathophysiology of schizophrenia. Yet, several questions remain open that are crucial for progress in this field of research. One intriguing phenomenon is the fact that cognitive and physiological dysfunctions are present throughout the cortex in schizophrenia. This raises the problem of which mechanisms can account for such a distributed impairment. One possible implication of this finding could be that core deficits in schizophrenia arise out of the altered global dynamics, which then lead to widespread impairments in local circuits. Accordingly, one strategy is to identify global coordination dynamics failures in schizophrenia. Furthermore, alterations in neural synchrony have been identified in several brain disorders and thus raise the question of diagnostic specificity. One possible assumption is that different syndromes are related to distinct but overlapping pathologies in the coordination of distributed neuronal activity patterns that are revealed by the systematic investigation of the temporal and spatial organization of neural synchrony across different frequency bands. This is undoubtedly a challenging task, but such a research program would ultimately result in better diagnostic tools for early diagnosis and intervention.

What Can Be Learned from This with Respect to Normal Brain Function?

Schizophrenia can be seen as a paradigmatic example of impaired dynamic coordination (Silverstein and Schenkel 1997; Phillips and Silverstein 2003) because there are several impairments which *prima facie* indicate reduced organization of elements into coherent wholes (e.g., in visual and auditory perception, working memory, selective attention, language, theory of mind, and binding of self-representation with action representation during ongoing behavior). Moreover, unlike much classic neuropsychological research, evidence of reduced dynamic coordination in schizophrenia is sometimes revealed by superior task performance (e.g., in terms of faster processing of single elements due to reduced contextual sensitivity), and these findings cannot be accounted for by medication effects.

To the extent that schizophrenia is seen as a model of relatively context-deficient cortical computation, the functions that are preserved in schizophrenia inform us about those functions that possibly do not require a high degree of dynamic coordination. Such functions include:

- understanding the meaning of individual words (as opposed to the reduced contextual constraint of words on later words in sentences),
- basic color perception (as opposed to color constancy or assimilation which rely on contextual cues),
- visual acuity,
- overlearned social behaviors (as opposed to being able to function in novel social contexts),
- basic motor functions,
- procedural memory, and
- understanding of basic cause-effect relationships (outside of interpretation of phenomena and events that affect self-esteem or sense of vulnerability).

Also, data on schizophrenia demonstrate the importance not only of NMDA receptor function for dynamic coordination, but also of GABA-mediated inhibitory interneuron function. However, schizophrenia is not the only disorder where impairments in dynamic coordination are evident. A comparison across disorders could assist our understanding of both the causes of dynamic coordination impairments and the bases of normal dynamic coordination (Silverstein, this volume).

Comparing schizophrenia with other developmental disorders, are there types of coordination impairments that generalize across disorders? For example, reductions in visual perceptual organization and theory of mind have been noted in developmental (autism spectrum) disorders (e.g., Silverstein and Palumbo 1995), and there is genetic and symptom overlap between schizophrenia and these disorders (Silverstein, this volume). Another interesting case is provided by Williams syndrome, a genetic condition in which a relatively consistent neurobehavioral phenotype is produced by a small deletion on chromosome 7 (e.g., Bellugi et al. 2000). One of the intriguing aspects of this syndrome is a characteristic abnormality of neural connectivity in a single cortical area, the primary visual cortex (Reiss et al. 2000; Galaburda and Bellugi 2000). Presumably due to these structural abnormalities in the primary visual cortex, patients with Williams syndrome present with a specific disruption of visual spatial integration (Kovács 2004). The example of Williams syndrome is particularly interesting because a well-defined structural abnormality is behind a perceptual deficit that is usually attributed to dynamic coordination. Strabismic amblyopia represents another interesting developmental abnormality, where a clear relation between structural changes in the cortical network, impairments of dynamic coordination, and disturbed perceptual and behavioral function has been established. As shown in studies in cat visual cortex, the impaired feature integration observed in amblyopic animals can be related to diminished intra- and interareal synchrony (König et al. 1993; Roelfsema et al. 1994; Schmidt et al. 2004).

These studies provide evidence for a common mechanism underlying contextual modulation in multiple functions, and evidence that neurodevelopmental changes can produce specific and profound changes in more than one of these domains. Identifiable neurobiological factors, such as the extent of white matter reduction, the number of cortical regions affected by suppression of sensory input during development, and the developmental onset of coordination failures, can account for variance in the cognitive and clinical manifestations in different disease states (Silverstein, this volume). The links established by those studies between behavioral evidence for impaired dynamic coordination (e.g., visual binding) and abnormal oscillatory activity (e.g., in gamma and beta bands) strongly support the notion that there is functional significance of coordinated neural activity, that multiple forms of cognitive functioning rely on dynamic coordination, and that coherence of neural oscillations in multiple frequency bands may indeed constitute one of the key mechanisms underlying dynamic coordination in the nervous system.

Acknowledgments

We thank Maurizio Corbetta, Shimon Edelman, Pascal Fries, Wolf Singer, and Matthew Wilson for contributing to our group discussions.