The frontal lobes are a toolmaker.

Bob Rafal, Toronto 2000

The title of this book, Principles of Frontal Lobe Function, clearly states our emphasis: the functions of the frontal lobes, and frontal systems. Much of the controversy about executive and frontal lobe functions has been the result of inconsistency of operational definitions and limits of discussion. We hope that this treatise will bring clarity to the field as well as raise key issues for future investigation.

As frequently stated in several chapters, the frontal lobes represent a large proportion of the human brain. Although we have tried to cover the roles of all sections, there is a clear emphasis on what is commonly called prefrontal cortex, that region antecedent to the motor, premotor and supplementary motor areas. Important information on these latter motor-related structures is provided in Chapter 8, by Gemba, and in Chapter 9, by Rafal.

Our intention in organizing the book was to cover the frontal lobes from birth to death, from biochemistry and anatomy to rehabilitation, from theory to function, and from normal to disrupted function. At first we planned to divide it into sections, such as neuroscience bases, theoretical positions, and so on. It eventually became clear that this would be a somewhat arbitrary organization, since so many authors presented material that covered several of these arbitrary distinctions. A second option was to organize the book according to approaches, such as animal research or human research. After some debate, we arranged the chapters more in a logical and conceptual sequence, starting from basic science and ending in more applied work. Although this structure is perhaps still artificial, the attempt was to juxtapose chapters that had some conceptual commonality.

In this introductory chapter, we will present an overview of the different contributions. By highlighting some of the similarities and differences among approaches, we hope to entice the astute reader to consider the diversity of approaches to the same question about the role of the frontal lobes in organized behavior, to advance the field ahead.

We bracketed the book with chapters that introduce and summarize in overarching ways the structure and content of the book. Mesulam, Chapter 2, sets the stage for the rest of the book, and the novice reader of the functions of the frontal lobes should start here. Mesulam’s overview imparts the importance of this field of research. His anatomical and clinical distinctions provide organizational and
memory “hooks” for reading many of the other chapters. Chapter 34, by Knight and Stuss, is the other bookend, providing an overview of much of the content of the book and forecasting what the future will bring.

The discussion of the anatomy of the frontal lobes was charged to Petrides and Pandya (Chapter 3). In their contribution they extend their previous work on architectonic specificity (see, e.g., Petrides & Pandya, 1994) by presenting how the frontal lobes are interconnected with different brain regions through association pathways and how this is reflected in functional observations. We cannot emphasize enough that the study of frontal lobe functions cannot be done solely by pure localization; the study of systems and pathways in relation to function will continue to be one of the important future initiatives. In this regard, development of novel methods to elucidate white matter pathways in the human brain, such as diffusion tensor analysis, is particularly relevant for future research. Petrides and Pandya wisely state in their concluding paragraph: “Proper knowledge of the course of the different fiber pathways is as important as knowledge of their termination in order to interpret properly the functional deficits resulting from damage to particular regions of the cerebral cortex.”

Many other chapters in the book present additional anatomical information related to their particular content. Taken together, these chapters provide a quite astounding amount of information on the anatomy and connectivity of the frontal lobes, and how these relate to different functions. In Chapter 2 Mesulam provides an overview; in Chapter 32 Kolb and Gibb discuss the changes at synaptic levels; in Chapter 29 Diamond discusses maturation at different time points from birth to early adulthood; in Chapter 8 Gennari discusses the role of different subregions in motor control; in Chapter 23 Rolls reviews the anatomy and connections of the orbitofrontal cortex; in Chapter 9 Rafal outlines the cortical and subcortical circuitry for oculomotor control; and in Chapter 26 St. Cyr and colleagues discuss frontal–subcortical circuitry.

If the reader is interested in the neurochemistry of brain functioning, either from a purely scientific view or for the purposes of investigating neuropharmacological treatments of prefrontal cortex function, then Chapter 4 by Arnsten and Robbins will be a godsend. The authors review animal and human research on the mechanisms by which dopamine, norepinephrine, serotonin, and acetylcholine may influence prefrontal cortex cognitive functions. It is clear that the brain (usually anatomy) behavior approach to the study of frontal lobe functions must include to a far greater extent the relation of chemical pathways to function as well. In addition to providing information on anatomical development Diamond describes in Chapter 29 the biochemical changes at several developmental periods. In Chapter 26, St. Cyr and colleagues summarize the neurochemistry of frontal–subcortical circuits as a basis for understanding behavioral consequences and treatment.

The controversial issue of segregation versus integration, or the fractionation or homogeneity of the frontal lobes, is discussed in several chapters, reflecting the salience of this question over the past decade. In Chapter 18, Duncan and Miller, in their theory of adaptive coding, argue less for tight regional specificity and more for joint recruitment of different frontal regions in response to different cognitive demands. They base the idea of adaptive functioning on the observation that the same frontal neurons appear to be configured to solve many different cognitive operations (compare this concept with the one postulated by D’Esposito and Postle in Chapter 11). In Chapter 5, Goldman-Rakic and Leung provide a compelling counterpoint to this view and readers are left to draw their own conclusions.

A large number of chapters come down on the side of heterogeneity of frontal lobe functioning. In Chapter 12, Moscovitch and Winocur suggest a component process model for the strategic role of the frontal lobes in memory. In Chapter 25, Stuss and colleagues provide empirical evidence from neuropsychological tests administered to individuals with discrete focal lesions that different regions of the frontal lobes play different roles. Knight’s electrophysiological research also suggests re-
gional specificity for different aspects of attention and working memory capacity. This specificity is evident in aging, discussed in Chapter 31 by Craik and Grady, and also at some earlier developmental stages, addressed in Chapter 30 by Anderson and colleagues.

Two chapters even have “fractionation” in their titles. In Chapter 16, Baddeley extends his original working memory model to specify in greater detail the role of the third component, the “central executive.” He speculates on what capacities such an executive would need, and uses task performance analysis of patients suffering from early-stage Alzheimer’s disease to test the validity of the separation of the proposed executive functions. This chapter presents an important distinction made earlier: the study of executive functions does not necessarily indicate an analysis of frontal lobe function. In Chapter 17, Shallice presents a higher-order model suggested by Fox and Das (2000) to augment the Norman and Shallice model of the supervisory system. In contrast to Baddeley, however, Shallice’s thesis on the fractionation of the supervisory system does relate to the frontal lobes, since his supporting data derive from functional imaging and lesion research. The constitutive components of the supervisory system, or central executive, that both authors discuss have notable similarities.

In reviewing primarily animal research, Fuster argues in Chapter 6 that prefrontal lobe functions need to be interpreted as an important part of associative neocortical networks which, while distributed, are overlapping and intersecting. His distinction between operations (e.g., monitoring, planning, attention) and representations (executive memory) may be one way of solving the dilemma over the heterogeneity or homogeneity of functions—that is, it may depend on the level of analysis or the quality of description.

There are levels of complexity in the systems approach to frontal lobe functioning. D’Esposito and Postle conclude in Chapter 11 that different regions within the lateral prefrontal cortex are indeed related to different cognitive operations; yet, at the same time, they suggest, as do Duncan and Miller in Chapter 18, that the same region can also be engaged in different cognitive operations. In Chapter 25, Stuss and colleagues show that different changes in context, illustrated in their discussion of task demands, of what appears to be superficially a very similar task, alter which brain regions appear necessary for that task performance. With a simpler task demand, there is evidence of considerable heterogeneity, although it is anatomical systems, not just focal brain regions, that demonstrate this fractionation of function. With different task demands that seem more difficult, there is no evident frontal lobe heterogeneity. In one sense, this latter finding might support Duncan and Miller’s findings; it is less obvious how this relates to Fuster’s concept of representations. Regardless, in the future of frontal lobe research, context will play an ever-increasing role.

In our view, the controversy over the separation and commonality, and the homogeneity and heterogeneity, of frontal lobe function reflects our comment at the beginning of this chapter on the importance of operational definitions. This controversy must also be seen in light of the importance of dynamic, integrated (and perhaps context-dependent) brain systems.

In Chapter 19, Grafman suggests that the frontal lobes store various representational units, which he calls structured event complexes. These elements of memory of higher-level knowledge help guide over time more complex behaviors. Since there is a clear similarity between this proposal and other concepts, Grafman assists the reader by discussing in Chapter 19 the differences and similarities between his approach and similar frameworks. Picton and colleagues, who review human physiological research on frontal lobe functions in Chapter 7, propose a concept that has at least overt similarity to Fuster’s representations. They posit that the prefrontal lobes through representational processing are the “theatre of the mind,” where options are played out, examined, and understood. A key to Picton and colleagues’ model is a return to one of the most important concepts of the 1960s: the Test-Operate-Test-Exit mechanism, to perceive, decode, and respond to informa-
tion (Miller et al., 1960). This model has also been used to explain different levels of awareness (Stuss, 1991; Stuss et al., 2001). The interactivity of different brain regions is again emphasized in these approaches.

Several contributors have focused on a specific function. In Chapter 8, Gemba summarizes the knowledge of motor control, and in Chapter 9, Rafał reviews visuomotor control. While seemingly lower level, these functions are crucial to understanding the action/active role of the frontal lobes in the final common output pathway. The study of motor programming can be seen as the investigation of voluntary behavior. Gemba outlines how different parts of the frontal lobe and other regions (e.g., limbic, premotor, motor, supplementary motor area) combine for voluntary vocalization and hand movements. Rafał uses eye movements as a model system to investigate how midbrain reflex circuits and frontal and parietal systems for eye movement control combine to produce goal-directed behavior. In both chapters the importance of a systems analysis is again confirmed.

Endel Tulving is known for his ability to synthesize important concepts in memorable terms. More importantly, his elaborations of the concepts are lucid and compelling. “Chronesthesia,” as Tulving points out in Chapter 20, has been proposed before—but never in as comprehensive manner as presented here. His idea of mental time travel should be considered by readers in the context of Fuster’s temporal integration, and contrasted with the different temporal domains considered in the workings of memory. There is little doubt that the role of the frontal lobes in the integration of the past and present to look into the future is of major importance. In our opinion, this needs to be investigated in a more comprehensive manner, by looking at different aspects of time and comparing the role of the frontal lobes to the temporal functions of other brain areas, such as the cerebellum or basal ganglia, that have been linked to timing control.

In Chapter 10, Alexander provides a comprehensive view of frontal language functions, moving beyond traditional perspectives. In many regards, he is presenting a model for research of the role of frontal lobe in language, since there are not many studies that have pursued some of the less traditional ideas (discourse, scripts, etc.) with well-documented focal frontal lesions. One might wonder if there is any relationship between the scripts proposed for language and Grafman’s structured event complexes.

Clearly the study of memory in relation to frontal lobe functions has been a major thrust of research, as evidenced by the number of chapters that have the word “memory” in the title and that cover memory within the text. The connection between working memory in particular and the frontal lobes has generated much interest. D’Esposito and Postle again emphasize (in Chapter 11) that one must consider anatomical and functional systems when attempting to disentangle the role of prefrontal areas in memory. They add a new level of complexity to this area of study.

The question remains, however, whether working memory is a function of maintaining information or of attentional selection. In Chapter 14, Passingham and Rowe suggest that holding information in memory and true selection are dissociable processes, and that it is possible that monkeys with lesions in area 46 fail delayed-response tasks, not because of impaired working memory but because of deficient response selection. Our stated goal of highlighting differences in the theoretical positions of different researchers, and indicating why the differences might exist, is wonderfully highlighted in the comparison of the chapters by Passingham and Rowe (Chapter 14) and Goldman-Rakic and Leung (Chapter 5). The idea that the same cell may be capable of performing a different task under different conditions (see Chapters 11 and 18) may provide another answer to this controversy. Holding information and response selection may both be associated with area 46, depending on the exact nature of the task demands. These new distinctions and concepts are clearly exciting avenues of future research.

Two chapters highlight the active, supervisory, strategic, controlling nature of the frontal lobes in memory functions. At first glance, Chapter 13, by Shimamura, and Chapter 12, by Moscovitch and Winocur appear similar in
content. But there are considerable differences in emphases. Moscovitch and Winocur are blatant about how important they feel this role of the frontal lobes is, the medial temporal lobes being viewed as “stupid.” Our apologies in advance to our hippocampal colleagues. They describe the role of the frontal lobes as “working with memory,” and see this use not just for recovering past experiences but also for directing other activities. Shimamura focuses more on an inhibitory model, which he calls the “dynamic filtering theory.” Other processes, such as selecting, maintaining, updating, and rerouting, can be considered in light of this gating function of the frontal lobe.

In Chapter 15, Jonides and colleagues continue the theme of filtering, or selection, but address it independent of memory: they discuss the psychological process of selectively attending to one source of information to the exclusion of others. In a meta-analysis, they review different tasks used to study selective attention, under the construct of conflict resolution, as assessed with functional imaging techniques. Both the anterior cingulate cortex and the dorsolateral prefrontal cortex are involved in some aspect of conflict resolution, which is likely related to different mechanisms. The theme of heterogeneity of function is reflected in these results.

Four chapters provide an excellent overview of the role of orbitofrontal/ventral–medial lobe function in emotional functions and social behavior. In Chapter 21, Watanabe covers the monkey literature related to motivation (orbitofrontal cortex), emotions, and cognition (the latter two being integrated in the lateral prefrontal cortex). The mechanism by which anatomical systems work together is underscored in this chapter: cognition informs motivation and motivation modulates cognition. This chapter again notes the influence of context, this time in the form of the reward expectancy of the monkey.

In Chapter 23, Rolls presents animal and human (lesion and functional imaging) work in his review of the functions of the orbitofrontal cortex. The pivotal point of the reward value of taste and smell demonstrates that there is a very similar base to the behavioral choices made by animals of many species. He proposes the rapid shaping and reversal of reward–punishment contingencies as a key aspect of orbital prefrontal function.

In Chapter 22, Tranel discusses the role of the orbital prefrontal cortex in behavior, with emphasis on the involvement of the ventral–medial prefrontal lobe in emotions and decision making. He demonstrates how use of a “gambling task” has provided the ability to measure decision making and related emotional influences. The somatic marker hypothesis proposed to explain the observed results should be compared with material in all four chapters (21–24) dealing with the emotional changes with frontal lobe damage.

Finally, in Chapter 24, Mayberg takes a common disorder, depression, and shows how limbic–cortical interactions, the play between emotions and cognition, can be so important in depression. This chapter represents the practicality and applied nature of frontal lobe research, and shows the importance of the interrelationships of different approaches. In comparing Chapters 21 with 24, it is clear that Mayberg and Watanabe each approach limbic–cortical relations from quite different perspectives. These studies on the motivational and emotional functions of the frontal lobes announce a return to the early excitement of frontal lobe research—the effect of lesions on personality, emotions, and social behavior. In our view, the story is not yet complete, but rather, unfolding.

Several chapters address how frontal lobe or frontal system damage occurs in specific diseases or disorders. In Chapter 25, Stuss and colleagues summarize the findings of the effects of well-characterized focal frontal lesions, with an emphasis on stroke. In Chapter 28, Levine and colleagues present the effects of traumatic brain injury on frontal lobe functioning. Two practical aspects of this chapter are the critical review of the cognitive and behavioral assessments of traumatic brain injury, and the presentation of a new segmentation approach to assess gray, white, and cerebrospinal fluid compartment volumes. The reader interested in developmental comparisons should read the above two chapters in conjunction with Chapter 30, by Anderson.
and colleagues, who present interesting (and new) data on the effects of focal lesions and traumatic brain injury in children. It is clear from this work that, when one considers the effects of disease on prefrontal function, children cannot be viewed as just small adults.

Chapter 26, by St. Cyr and colleagues, not only is an excellent review of the consequences of neurosurgical treatment of patients with Parkinson’s disease, it epitomizes the value of studying systems and circuitry, particularly the frontal–subcortical circuits. What is new in this chapter is the extension of some of the circuits to include new anatomical regions, and the effect of deep brain stimulation on cognition and motor responses.

In Chapter 27, Braver and colleagues discuss how prefrontal cortex functions change in schizophrenia. This chapter is an example of how a connectionist computational model can be useful in studying psychological constructs.

In our view, the study of frontal lobe functions in different disorders has benefited immensely from new theoretical constructs and advances in anatomy and neurochemistry. This approach needs to be continued and different disorders with supposed frontal system dysfunction also need to be studied in this critical and theoretical manner as well.

There is perhaps no more interesting aspect of frontal lobe function than to see how these functions change developmentally, from birth to old age. Diamond sets the stage for this topic in Chapter 29, by describing how normal development of prefrontal cortex occurs from birth to young adulthood. In this chapter, discussions of anatomy, biochemistry, and function overlap, and the author shows that the functions described and studied in adults unfold in a staged manner in children. If these stages are arrested in some manner, such as by acquired brain damage, what happens? In Chapter 30, Anderson and colleagues contrast the effects of focal lesions and traumatic brain injury as they occur at different developmental stages. In our view, this exciting research is in its infancy—but what a future! Research of frontal lobe functions in adults provides a necessary base for understanding brain–behavior relations; developmental studies have the potential to change education and rehabilitation for long periods of time. These two chapters should be read in relation to Kolb and Gibb’s work in Chapter 32 on frontal brain plasticity.

Currently, there is still evidence for a corresponding staged, peeling away of frontal lobe abilities with aging. Craik and Grady are appropriately cautious in discussing the “frontal lobology” of aging, in Chapter 31. That is what makes their summary of behavioral and imaging changes in memory with aging all the more interesting. Their chapter suggests that memory-performance changes with aging are indeed related to age-related biological changes in the frontal lobes—but not only in the frontal lobes. Brain systems are important at all stages of life, and are perhaps even more important as one adapts to the effects of aging.

In Chapter 27, Braver and colleagues apply their modelling approach to the effects of aging in the context of normal and disordered cognitive control.

The success of rehabilitation of frontal lobe dysfunction is dependent on the correct understanding of the functions of this region. The fact that we are still debating what the systems and functions of the frontal lobes are might be one reason for there being only two chapters on this important topic. In Chapter 32, Kolb and Gibb talk about the change over time in the structure of the frontal lobes, according to results in animal research. How the information will apply to clinical rehabilitation is not yet certain. For example, housing animals in complex environments results in increases in spine density in the frontal lobes, but does not affect dendritic length. In contrast, such experiences do increase dendritic length in motor and sensory areas; the relevance of this to rehabilitation presently remains unclear. Nonetheless, there is a sense that this information will some day provide the ultimate measure of rehabilitation efficacy, perhaps indirectly through functional imaging techniques.

In Chapter 33, Burgess and Robertson approach rehabilitation for frontal lobe dysfunction from a somewhat different perspective. Taking different theories they discuss how each theoretical model leads to different implications for research. The result is a very practical set of six principles that direct how rehabilitation should be done. In our opinion,
this method has the potential to be transformative in the rehabilitation field.

Through this introduction we hope we have whetted the reader’s appetite for an in-depth reading of the individual chapters—not only to gain insight into each chapter’s topic but also to see how the different chapters might inform each other. In the last chapter, we provide a summary of much of the recent work on prefrontal cortex and consider what the field might look like in 2010.

REFERENCES


