CHAPTER 10

Conceptualizing Developmental Language Disorders: A Theoretical Framework Including the Role of the Cerebellum in Language-Related Functioning

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INTRODUCTION

Previous chapters have reviewed the role of the cerebellum in aspects of language processing. The functions covered in these chapters make it clear that language is not a monolithic entity; it is not "one thing." Language is a categorical term comprising a group of processes that *can* either be considered independently or as that which operates as a system. Therefore, in aggregate, these functions combine to generate the deceptively simple and misleading impression that language is a unitary construct. Instead, when language processes coordinate, they perform seamlessly. When an element of the language system breaks down, it generates a symptom, or even a constellation of symptoms, dependent upon the brain regions involved and/or the extent of brain pathology.

This chapter specifically focuses on the Declarative-Procedural model of language to serve as a base for conceptualizing developmental language disorders. This linguistic paradigm emerges as a product from the evolution of the vertebrate brain. We begin by summarizing the characteristics of diagnostic systems for the classification of language disturbances. We review the fractionation inherent in the study of the science of language. This is followed by introducing the concept of large–scale brain systems. Next, we debunk the verbal–nonverbal dichotomy as a fundamental principle of hemispheric brain organization and we replace it with a dynamic principle that is universally consistent across phylogeny and with our knowledge of brain networks. This allows for a deeper understanding of

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the Declarative–Procedural language model that is characterized by neural network interactions. The evidence we offer establishes an anchor point for understanding how language is organized within the brain. In our view, it is impossible to approach "development" without knowing its goal, or end point, which is equivalent to taking a journey without knowledge about where one is intending to go. Therefore, although development proceeds from "bottom-up," or from proximal to distal brain regions, we are essentially starting this presentation at the "top," with the "completed project" to understand the linguistic system. However, the paradigm we offer calls into question the fundamental nature and organization of all constructs, *including language*, because they are based upon artificial distinctions; these arbitrary constructs are not defined by the manner in which they appear to be organized within the vertebrate brain. That said, we are finally in a position to explore how the cerebellum might fundamentally support the development of language processes, and the ongoing role it plays in language-related functioning.

WHY BOTHER TO INCLUDE THE CEREBELLUM?

"It is well known that the cerebellum has traditionally been considered a co-processor of movement." This type of quotation, found in countless introductions to manuscripts, is a fine example of literary and/or ideational perseveration. Implicitly, the reader may gain the cynical impression that neuroscience is defending itself instead of explaining the role of the cerebellum in nonmotor functions. Schmahmann (1997) is arguably the first clinical investigator who gathered a group of experts, with wide-ranging perspectives, to systematically discuss the functions of the cerebellum. This groundbreaking manuscript, consisting of seven sections and 30 chapters authored by 58 contributors, presents persuasive evidence supporting the role of the cerebellum in cognition. Nevertheless, this cerebellum motor-nonmotor functional debate continues among professional circles, and in our view, this is just as archaic as a model of left-right hemispheric brain organization dependent upon the principle of the verbal-nonverbal dichotomy of human brain functioning. Today's questions should ask *how* the cerebellum supports a wide range of cognitive processes, moving forward and beyond the putative assumption. We propose that the cerebellum is a coprocessor of the cerebral cortex and the basal ganglia (which, of course, reside deep within the cortex). Unfortunately, because of our level of understanding of the language "system," and the inherent nature of an *ensemble,* it is

impossible to completely isolate the cerebellum from the corticocerebellar "composite unit," certainly with respect to cognitive development.

THE VERTEBRATE BRAIN: NEOCORTEX, BASAL GANGLIA, AND CEREBELLUM

Not only is the vertebrate brain remarkably predictable in its organization but the phylogenetic development of *corticobasal ganglia* and *cerebrocerebellar* circuitry systems have been well-established (Buckner & Krienen, 2013). This leads to the conclusion that *functional development occurs within these networks*, which generates the biologic expectation of commonalities in functional processes between language and nonlanguage systems. The applied consequences of these systemic modifications must be considered to fully appreciate linguistic capabilities (Benitez-Burraco & Boeckx, 2014). The cerebral cortex, basal ganglia, and the cerebellum are all topographically organized, with segregated circuitries dedicated to highly specific purposes. There is general agreement that different subregions, or modules of the cerebellum, perform analogous computations on whatever neural information it receives, dependent upon each module's set of inputs and outputs (Koziol et al., 2013; Stoodley & Schmahmann, 2010; Stoodley, Valera, & Schmahmann, 2012). The basal ganglia are topographically organized with reciprocal connections among specific regions of cortical association areas (Alexander, DeLong, & Strick, 1986; Arsalidou, Duerden, & Taylor, 2013; Middleton, 2003). Both basal ganglia and cerebellar output influence motor and nonmotor functions (Middleton & Strick, 1996; Sarvestani, Lindahl, Hellgren-Kotaleski, & Ekeberg, 2011). The cerebellum and the basal ganglia also are communally connected (Bostan, Dum, & Strick, 2010; Bostan & Strick, 2010). This anatomy provides the neuroanatomically situated substrate for cerebellar involvement in nonmotor functions mediated by the anterior frontal and posterior sensory/association cortices as well as in functions associated with the basal ganglia, including the relevant "subsets" of frontal-striatal systems (Bostan, Dum, & Strick, 2013). The cerebellum, neocortex, and basal ganglia operate as an integrated unit, but all the operations of this system are beyond the scope of this selected review. For the purposes of this discussion, we consider the integrity of the cerebellum as absolutely critical for the *acquisition, timing, automation, and adaptation* that are inherent in all subsets of linguistic processing across all situations and contexts. This is analogous to, and biologically consistent with, the operations it performs on motor behavior (Njiokiktjien, 2010).

CLASSIFICATION OF DEVELOPMENTAL LANGUAGE DISORDERS

Nomenclatures for identifying developmental language disorders are described within overarching categories. The Diagnostic and Statistical Manual of Mental Disorders, 5th edition (American Psychiatric Association, 2013), general category of Neurodevelopmental Disorders includes the terminology of "Communication Disorders." This "umbrella category" includes "Language Disorder," which essentially combines expressive and mixed receptive-expressive language disorders. These conditions manifest as limited vocabulary, errors in tense when speaking, word retrieval difficulties, and underdeveloped sentence production, which includes limited sentence length or complexity; the diagnostic criteria indicate these types of symptoms occur against the background of adequate intelligence and appropriate receptive language development (as measured by standardized tests). However, these standards seem to consider these symptoms *in isolation from other relevant aspects of neurocognition.* Receptive-expressive language impairment includes difficulty in understanding words, sentences, or even specific types of words such as *spatial terms.* A separate category exists for the substitutions of one sound for another, omissions of sounds, and extends to encompass difficulties with articulation. The subcategory "childhood-onset fluency disorder" manifests through any of the characteristics observed in "stuttering," and includes the symptoms of sound and syllabic repetitions, prolongations of sounds, pauses within a word, and "blocking" such as audible (filled) or silent (unfilled) pauses in speech. And word substitutions/circumlocutions serve the purpose of avoiding words that are particularly difficult to initiate. Therefore, even these subcategories are characterized by a broad range of seemingly unrelated symptoms, and in this way, the term "developmental language disorder" is so generalized that it can never have a readily agreed upon meaning. The diagnostic criteria are primarily exclusionary in the sense that an absence of these symptoms rules out the "diagnosis." There is little evidence to support the notion that any of these symptoms represent discrete "subtypes" or entities with distinct, unrelated etiologies, with the possible exception of specific language impairment (SLI) as understood within the declarative-procedural model, a "unique" descriptive term not specifically recognized within observational, categorically defined diagnostic systems (Bishop, 1994; Bishop, North, & Donlan, 1995). An additional issue concerns the fact that there is often significant variability in the cognitive profile for the same child at different ages. For example, in many

settings, a diagnosis of language disorder requires a "significant discrepancy" between language ability and *nonverbal intelligence.* However, early language difficulties influence *nonverbal development* (Fisher, Lai, & Monaco, 2003). The fact remains that the population of typically developing children develop speech and language skills effortlessly, without formal instruction.

Speech and language pathologists generally characterize developmental language disorders symptomatically as well. Apraxia of speech is observed relatively frequently, in perhaps the earliest onset speech problems, but it is rarely seen in isolation, in the absence of other concomitant language problems (Yorkston, Beukelman, Strand, & Hakel, 2010). SLI is frequently assigned to developmental language disorders that do not have any identifiable neurological, psychological, or social etiology, and its indicators include a wide range of symptoms. In this way, the term SLI becomes a heterogeneous disorder. However, as reviewed by Ullman, a homogeneous group of people with SLI has been identified (Ullman, 2001). This "subtype," primarily characterized by grammatical, syntactic deficits, is believed to be of familial/genetic origin (Graham & Fisher, 2013). This heredity conclusion remains controversial and has been challenged by a larger scale study that focused upon the relationship between disruptive gene mutations and variability in structural neuroanatomy (Hoogman et al., 2014). However, as reviewed by Ackermann (2008), numerous studies conclude that distinct mutations of a specific regulatory gene (FOXP2) promoted the emergence of articulate speech during the course of evolution. It has been concluded that FOXP2 protein generated changes within phylogenetically older brain networks, including reciprocal cerebrocerebellar connections engaged in upper limb motor control, which eventually supported the structural brain changes necessary for vocal elaboration. This provides one important link between motor and speech processes.

The cerebellum is implicated in dysarthria, mutism, and speech apraxia (Paquier & Mariën, 2005). Once they identified the cerebellar cognitive affective syndrome (CCAS), Schmahmann and Sherman (1998) were arguably the first to propose a functional specialization of cerebellar structures for language and communication. This syndrome features executive dysfunction, visuospatial functional deficits, linguistic impairment, and affective dysregulation, and is observed in both adults and children (Schmahmann, 2004; also see Schmahmann, this volume). Therefore, the CCAS also supports a paradigm that fractionates "cognition" into various "domains." When investigating the cognitive, emotional, and behavioral characteristics observed in posterior fossa syndrome, which frequently include language

impairment, Riva and Giorgi (2000) also observed these features of CCAS in children. Comprehensive reviews of cerebellar functional organization in language and communication processes are also presented by Riva and colleagues, Travano and Borgatti, and Steinlin (Riva et al., 2010; Steinlin, 2007; Tavano & Borgatti, 2010). These investigators summarized a wide range of conditions in both congenital and acquired neurodevelopmental disorders in which language disturbances were observed. In aggregate, these reviews characterize the cerebellum as serving a *modulatory* role in speech and language processes, but not playing a role in *generating* these functions. In the interest of moving forward, we see no reason to "rehash," rephrase, or even review this material because these days, the preponderance of cerebellum researchers agree with this basic tenet. There does not appear to be a unique entity such as "developmental language disorder," but instead, *symptoms of developmental language pathology.* These symptoms do not occur in isolation (Bates & Dick, 2002), which brings us to the topic of how language is traditionally investigated.

LANGUAGE SCIENCE AND BRAIN SYSTEMS

Our understanding of developmental language disorders is impeded or encumbered because the study of language is fractionated (Walenski & Ullman, 2005). Language is often studied as a *domain*, as if it existed within a vacuum, *separate* from other cognitive functions. We contend that the artificial compartmentalization among various cognitive domains results in an enormous, critical loss of information. It is becoming increasingly clear that the vertebrate brain is characterized by large-scale brain systems (Yeo et al., 2011). However, a brain network dedicated specifically to language functions is yet to be identified. This does not mean that a left-hemisphere lateralized "subnetwork" that supports language does not exist. In fact, Broser, Groeschel, Hauser, Lidzba, and Wilke (2012) recognized the limitations of applying functional magnetic resonance imaging (fMRI) technologies to young children, and confirmed the presence of a left hemisphere, structurally lateralized corticocortical language "network" in children as young as 8 years of age. However, this "subsystem" was connected (*unilaterally and bilaterally*) to other cortical and subcortical brain regions as well, and these regions have multiple functions with varying degrees of functional specialization. In this regard, we believe it is particularly notable that the occipital-parietal-frontal pathway (the superior longitudinal fasciculus), a subsystem that can be considered an aspect of a network we will later refer to as the

dorsal network, is not only involved in the canonical language system, but in a variety of other praxic behaviors as well (Fadiga, Craighero, & D'Ausilio, 2009). Brain regions never function in seclusion. Any given cortical region is characterized by a certain degree of information processing specificity for a particular cognitive ability or facet of cognitive operations (Friston, 2002; Johnson, 2005). This defines "functional specialization." The successful performance of any given task is characterized by the "functional integration" of distal brain regions. This integration refers to transient, dynamic, context-specific interactions that convey information via subsets of anatomical connections among a limited handful of brain regions engaged by a particular cognitive process (Koziol & Stevens, 2012). Aspects of language functions, and the brain regions that support them, are often recruited in the performance of a range of cognitive/behavioral tasks (Hillert, 2014). However, neither receptive nor expressive speech/language is totally specific or "localized" within any particular region such as Broca and/or Wernicke areas. Areas within these brain regions are also enlisted by many other tasks. Language functions are dependent upon the conscription of a group of distributed brain systems and their dynamically changing interactions. *This defines the construct of language as having both localized and widely distributed brain network properties*. Similarly, disciplines such as psychology, cognitive science, neurolinguistics, speech pathology, and other neurosciences investigate speech, language, or aspects of these functions from the viewpoint of the specific "niche" of each field. There is little translational communication among these disciplines. This makes it impossible to develop an integrated theory of developmental language disorders. Merging on a "common ground" to include brain systems and networks in language-related processes is vital. So the question we pose is this: how can anyone identify, characterize, and describe how a "disorder" contributes to the inability to attain a goal, such as a language system, if that system, and its neurobiological substrates, cannot be established? Similarly, we are not at all certain whether or not we have been asking the right questions about how linguistic functions are organized within the cerebrum and the cerebellum, with respect to both adults and children. If our questions have been based upon the possibility of false assumptions about cerebral and cerebellar lateralization of cognitive functions as in the neuropsychological "verbal–nonverbal" and/or "verbal–visuospatial" dichotomies, then the hypotheses, conclusions, and further questions that have been generated have been misleading, and we must agree with deductions drawn from *The Consensus Paper: Language and the Cerebellum* (Mariën et al., 2014) that the role of the cerebellum in

linguistic processes remains obscure or enigmatic. However, we believe that when such persistent ambiguity persists and becomes too complicated and perplexing, it just might make more sense to stop and wonder if we have been asking the relevant questions.

For example, what exactly is "cognition?" We have used the term on several occasions in this chapter; the word seems to capture the essence of the generally accepted definition of *the act or process of knowing* (Merriam-Webster's online dictionary, n.d.). However, what are the neuroanatomic correlates of this term? Simply put, there are none! This term has no discrete reality within the brain. As Cromwell and Panksepp (2011) have stated, the words *cognition or cognitive* are arguably the most frequently used terms in behavioral neuroscience, despite any readily agreed upon meaning. These words are both overused and misused, and actually might have hindered our understanding of how brain–behavior relationships develop and are organized within the brain. How can terms without precise meaning promote interdisciplinary communication? One of the biggest challenges of contemporary neuroscience is to develop a clear-cut meaning of cognitive processes, specifically as related to large-scale brain networks (Hastings et al., 2014). And, in trying to validate the term cognition, some rely upon tradition to compartmentalize cognitive, emotional, and motor functions into domains and even subdomains. In our opinion, this only serves the superficial purpose of maintaining the status quo. Furthermore, apportioning "cognition" into the domains of attention, executive functions (and its various proposed subsystems), language, visuospatial functions, etc., is really no better. Why do we challenge these generally accepted constructs? They are all defined arbitrarily and operationally, and can never be assessed by any other means than according to the tests that are purported to measure them (Wasserman & Wasserman, 2013). And if any of these constructs were a neuroscientific reality, why is it that a specific, dedicated brain network has never been identified as a neurobiologic substrate to support any of the constructs in question? Instead, we find *changing patterns of dynamic brain network interactions* (Cole et al., 2013). Similarly, it has been proposed that there is essentially no difference between movement and thought, with the primary substantive difference between planning an activity and executing its motor counterpart is the actual execution of that behavior (Frank, Loughry, & O'Reilly, 2001; Hazy, Frank, & O'Reilly, 2007; Ito, 1993; Jeannerod, 1994, 2001; Koziol, Budding, & Chidekel, 2012; Stocco, Lebiere, & Anderson, 2010). Finally, perhaps it should be a generally accepted principle by now that behavioral representations, which include "thoughts," are

retained within the same neural circuitry systems that were activated when first experienced (Cisek & Kalaska, 2010). So, feasibly, it is time to ask the question about why should the proposed domain of language be any different? We have already defined the language system as consisting of both localized and widely distributed functional processes, whereas many of these same brain regions are recruited by nonlanguage tasks. And, if language tasks enlist changing patterns of functional connectivity within different brain networks, what "clues" might this provide about understanding the role of the cerebellum in linguistic functioning and in developmental language processes?

LARGE-SCALE BRAIN SYSTEMS

Using MRI-measured brain anatomy and functional connectivity from 1000 healthy adults, Yeo et al. (2011) recently observed the remarkable replicability of the same seven patterns of cortical networks within the human brain. These same networks are identified in adults, adolescents, children, and even in infants as assessed through resting-state neuroimaging technologies (Menon, 2013). Many brain regions within these networks are involved in both nonlanguage related and language processes. Our "bullet point" is that specific "hubs" or "nodes" within these cortical regions have reciprocal connections with different modules within the cerebellum and nodes within basal ganglia (Buckner, personal communication, April 3, 2014; Habas et al., 2009; Middleton & Strick, 1996). (Many subsystems and networks can be identified; we focus upon this model for the purpose of illustration, since this model has been the subject of a preponderance of investigations.)

These large-scale cortical systems include frontoparietal networks (FPNs) commonly engaged during effortful cognitive task performance requiring information or rules to be held in mind for purposeful, goal-directed behavioral guidance. FPNs consist of the dorsolateral prefrontal cortex, the anterior cingulate cortex, the anterior prefrontal cortex, the lateral cerebellum, the anterior insula, the caudate nucleus, and the inferior parietal lobe. The left hemisphere FPN is responsible for internally guided behavior; the right hemisphere FPN is activated by external influences when situations are unfamiliar and require the development of new problem-solving strategies. The dorsal and ventral attention networks are involved in goal-directed executive control processes and salience evaluations respectively, which are necessary operations for the control of spatial

attention and the orientation of attention to a specific area of interest. The ventral attention network (VAN) includes the temporoparietal junction, the supramarginal gyrus, the frontal operculum, and the anterior insula. The focus of the VAN is primarily upon *allocentric* space, or knowing about objects that lie beyond immediate reach, including information about *what* those objects are used for. The dorsal attention network (DAN) is anchored in the intraparietal sulcus and the frontal eye fields. The DAN includes a focus upon *egocentric space* to generate sensory-motor information about functions such as reaching, grasping, the "data" that are important for knowing about *how* to use objects. The occipital lobe, the lateral temporal region, and the superior parietal lobule, making up the visual network (VN), interact with the DAN and VAN to sustain attention and to suppress attention to extraneous, irrelevant variables. Therefore, these are critical components of the brain's "action control" system, and as we will demonstrate throughout this chapter, certain hubs within these regions are involved in linguistic functions. The limbic network interacts with these systems to generate motivational and reward influences. The sensory motor network (SMN) consists of the primary motor cortex, the primary and secondary sensory cortices, the supplementary motor cortex, the ventral premotor cortex, the putamen, the thalamus, and the cerebellum. These regions are involved in language, and in certain motor abnormalities that are also observed in developmental disorders. In addition, a default mode network (DMN) whose activity is high until active, goal-directed cognitive processing is required is anchored in two regions, the anterior medial prefrontal cortex and the posterior cingulate cortex as well as two additional systems, the dorsomedial prefrontal system and the medial temporal lobe memory system. The DMN is less active during the performance of cognitive tasks in normal control subjects, but it is considerably more active in various psychopathologies (Sandrone, 2012). (This chapter is a selective review of brain networks specifically involved in language; for comprehensive reviews and illustrations, see www.humanconnectomeproject.org.)

Simply put, what this "distributed network" perspective implies is that it is no longer appropriate to think of language as a single or unitary entity, given the complexity of the neural systems involved. The brain regions involved in many of these networks participate in multiple brain functions, *including* linguistic processes. Language cannot be viewed as a dedicated domain that resides separate from any other aspect of cognition, regardless of how cognition is operationalized. This emerging network-based appreciation of the complexity of brain–behavior relationships clearly goes well

beyond the "canonical" or generally accepted, traditional model of receptive and expressive language functions as well as other aspects of thinking and behavior that are often considered a specific functional domain. Large-scale networks and even smaller, more modularized subnetworks are believed to have strong degrees of specialization for certain behavioral functions and operations (Castellanos & Proal, 2012; Cortese et al., 2012). On the one hand, this might superficially seem to replace a strict localizationist perspective (i.e., one brain region = one cognitive function) with a similar framework that substitutes a single brain region for a group of regions. However, this initial conclusion is misleading. These specific regions, hubs, or nodes within large-scale brain networks interact with the learning, inhibitory, and modulatory influences provided by vertically organized, subcortical systems (Koziol, 2014; Koziol, Budding, & Chidekel, 2013). These interactions allow for the critical understanding of all distributed cognitive processes. This includes the intrinsic relationship between language and other distributed functional brain-behavioral systems, all of which are dependent upon corticocortical and cortical–subcortical interactions. Language and communication disorders can be better appreciated and understood within this integrated framework.

The simplified seven-network parcellation proposed by Yeo et al. (2011) features numerous brain regions that are recruited by linguistic tasks. For example, language tasks recruit the anterior PFC, the caudate nucleus, and the parietal lobe of the left-lateralized FPN, and the bilateral DLPFC; within the VAN, the temporal–parietal junction, upper regions of the superior temporal sulcus (STS), the frontal operculum of the left hemisphere, and right-lateralized supramarginal gyrus are all known to be involved in language functioning; the intraparietal sulcus of the DAN and the lateral temporal and superior parietal lobule of the VN are activated in language tasks as well as the medial temporal lobe system of the DMN. Nearly all hub regions of the SMN are recruited in language functioning (Hillert, 2014; Lieberman, 2000; Mariën, Engelborghs, Fabbro, & DeDeyn, 2001; Murdoch & Whelan, 2009; Ullman, 2004; this listing represents an introductory sampling, not intended to be interpreted as complete or exhaustive).

Therefore, most components of cortical hub regions are multifunctional with subregions that contribute to various functional processes. These hubs are not totally dedicated to any specific behavioral process. The neurologic substrates of language are perhaps best characterized by *neural multifunctionality* (Cahana-Amitay & Albert, 2014). This means that the evolving brain slowly incorporated functions that initially were nonlinguistic to support a

language system that required dynamic, ongoing interactions between neural networks that subserve praxic, affective, "thinking," and behavioral functions. Aspects of these networks became specialized for semantic classification, language comprehension, lexical word retrieval, and discourse, conversational processing. The most critical questions concern how these networks and nodes share their resources and how they communicate and coordinate their functions to provide the integration necessary to complete language tasks. The specific recruitment of a brain region in language is determined by patterns of connectivity; in other words, there is significance in the nature or kind of interaction with other regions. This distributed network perspective is critical in attempting to understand all features of language functioning; in this regard, language can no longer be considered apart from other aspects of thinking or behavior. Language needs to be understood within the context of shared neuroanatomic resources and correlates for language and nonlanguage functions; these include attention, the operations of multiple memory systems, audition and vision, motor functions, and even affect/emotion. Although all of these processes cannot be included in this selective review, the basic framework has been established and a few subtle features are illustrated by two simple neuropsychological testing–type examples. In our opinion, these critical points are seldom even considered in attempts to understand linguistic processing.

First, on a study of the California Verbal Learning Test, second edition (Delis, Kramer, Kaplan, & Ober, 2000), in a word list acquisition task, the left hemisphere was clearly activated as observed by fMRI imaging. However, the immediate memory trial, novel, or unfamiliar words, additionally activated the *right* hemisphere anterior hippocampus. Across all trials, including a recognition condition, the overall best "verbal learners" were those subjects who recruited the highest levels of *right* hemisphere DLPFC and *right* anterior hippocampal activity (Johnson, Saykin, Flashman, McCallister, & Sparling, 2001). In another study that assessed the analysis of metaphors (such as the expression, "I'm having a rough day" or a "hard time") fMRI studies identified *bilateral* brain activation of those regions necessary for "texture" processing, but not "visual" processing, or areas for processing other sensory modalities (Sathian et al., 2011). These (and other) studies clearly reveal that a "fixed hemispheric assignment" is erroneous to conclude for any brain function, that a distributed brain network perspective is absolutely necessary for understanding linguistic processing, and that language simply cannot be understood as an isolated domain residing only in the *left cerebral hemisphere,* apart from other motor and nonmotor functions.

THE NOVELTY-ROUTINIZATION PRINCIPLE: NEUROBIOLOGIC CONSISTENCY AND THE VERTEBRATE BRAIN

If the traditional left versus right hemisphere dichotomy is simply reduced to a verbal–nonverbal principle of brain organization, then we are forced to ignore the well-documented neurobiologic consistency of the vertebrate brain. And, if we accept this consistency over 500 million years of phylogeny, we are compelled to reexamine the "fixed" assignment viewpoint that language resides within the left hemisphere, which emphasizes the uniqueness of the human brain because of specialized linguistic systems. It is impossible to have it both ways. We believe that if we ask good questions, we are led to good answers; if we ask questions that might overlook a clue here and there, our answers or solutions can be misleading, taking us off course, in the wrong direction. So, what clues can we explore to help generate a better understanding of language and its disorders, particularly for addressing the "enigma" of the role of the cerebellum in language and its development?

In our opinion, the novelty-routinization principle of vertebrate brain organization is the critical game-changer (Goldberg & Costa, 1981; Mac-Neilage, Rogers, & Vallortigara, 2009), and we are at a total loss in trying to explain why certain disciplines and clinical neuropsychology in particular have never "paid attention" to it! This overlooked principle of lateralized brain functioning is the underpinning for a deeper understanding of distributed brain functions and large-scale brain networks and systems. The left hemisphere is specialized for the control and execution of well-established patterns of behavior under ordinary, familiar circumstances; the right hemisphere is specialized for detecting and responding to novel, unfamiliar, or unexpected stimuli. Dynamically changing brain interactions are inherent in this lateralization principle because every vertebrate survives by continuously interacting within a changing environment. The left hemisphere exploits predictable, routine features of the world by responding in an automatic way. The underpinning of automatic behavior always involves a predictable sequence of motor behavior or action. Few situations are completely predictable, and many circumstances are completely novel. This requires novelty detection and the modification of a known behavioral sequence or the development of a new adaptive response (Toates, 2006). The fundamental job of any brain is to learn behaviors that are adaptive, and the more frequently these learned responses are used or practiced, the more automatic they become (Ito, 2008). This allows for biologically economic

functioning, conserving precious biologic resources; automatic behaviors are adaptive, even elegant, and almost effortless (Bruya, 2010; Saling & Phillips, 2007). Developing and learning completely new behaviors is arduous, it requires energy expenditure, and is typically slow. That said, it would be expected that behaviors are organized along a hierarchy, which also assists in understanding certain individual differences; what is new for one person might be routine for another. This is particularly important for understanding pediatric development because knowledge and action are grounded in interaction with the environment and are gradually acquired over a protracted period (Pezzulo, 2011). This pattern of hemispheric organization is also biologically consistent across vertebrate phylogeny (see Podell, Lovell, & Goldberg, 2001 for a comprehensive review).

If this principle is true, there must be an identifiable functional neuroanatomy that maintains this system. Goldberg and Costa (1981) were arguably the first to identify this framework. Recent studies of large-scale brain systems and operative specialization refine the initially proposed anatomic substrate and support predictions that might be made from our knowledge about brain networks. The FPN is highly specialized in both hemispheres (Wang, Buckner, & Liu, 2014). The FPN and the DMN are the most specialized within the left hemisphere, whereas the VN, VAN, and SMN are the least specialized. This supports the fact that the cognitive control of novel problem-solving, recruiting the left hemisphere FPN, is preferentially connected to the DMN, for the effortful cognitive task performance that requires information/knowledge, or rules to be held in mind for the *internal* guidance of behavior. This is the left hemisphere network that is critical for guiding behavior according to the content of what one is thinking about for contextually dependent functioning. And, the fact that the VN, VAN, and SMN are the least specialized makes good sense because automatic or routine behaviors and the operations of the VN/VAN are not particularly relevant for guiding behaviors according to what a person thinking about. The FPN, VAN, and DAN are preferentially and highly specialized within the right hemisphere—in other words, what might be termed a global attention system. The right hemisphere FPN functional specialization profile is the substrate for broadly defined "behavioral" selections driven by the *external* environment for context independent behavior, necessary for identifying and orienting to task novelty. FPNs are highly specialized in both hemispheres, whereas collectively, they rapidly and flexibly recruit and update whatever brain systems are necessary for any particular context or

situation (Cole et al., 2013). Importantly, as reported by Wang et al. (2014), *the cerebellum parallels this cerebral hemispheric functional specialization pattern, but in the contralateral cerebellar hemisphere.* (We return to this critical point later when we discuss previously reported findings concerning the cerebellar contribution to linguistic processing.)

The Broca area, a node within the left hemisphere FPN, is activated when information is expressed through language. And, because this system is driven internally by what one is thinking about, the quality of the linguistic expression might be expected to be literal. Although the medial temporal lobe memory system is a "hub" within the DMN, it would be predicted that factual and even personal autobiographical recollection would be concrete and literal, an inherent property of this type of information. However, right hemisphere networks process many types of linguistic information. This includes the resolution of ambiguity when words have multiple meanings, metaphorical understanding, appreciating humor, and judging and expressing affective language prosody as well as processing the figurative and pragmatic aspects of language because all of the functions are driven by external factors that are independent of personal context. For example, novelty, at least to some degree, is an inherent property of conversational discourse, which includes *external* factors. The left hemisphere processes literal, detailed, routinized and automatic information; the right hemisphere is specialized for processing closely related words as specific to the external context, appropriate affect, and the semantic integration required for the particular "novel" circumstances for the specific external situation, all of which have been demonstrated clinically and experimentally (Bryan & Hale, 2001). The right hemisphere is clearly not irrelevant to the linguistic system. Therefore, by divesting language of its cardinal role in left hemispheric specialization, and reinvestigating the novelty–routinization principle of hemispheric brain organization, we open the door for incorporating phylogenetic consistency, we rid ourselves of the limitations inherent in any "fixed assignment" processing of any brain function, we can understand a dynamic instead of a static view of linguistic organization, we can see how a pattern of hemispheric specialization might be different at changing stages of development, and we can understand how the locus of control shifts from one hemisphere to the other during the course of behavioral, and linguistic, skill development, while all of these conclusions are supported by our knowledge about the functions of large-scale brain systems. Within this framework, left hemisphere specialization for language is a "specific instance" of the sequencing and routinization inherent in left hemisphere

information processing. This principle far surpasses any understanding of language that might be achieved through a simplistic left hemisphere assignment.

THE DECLARATIVE-PROCEDURAL MODEL OF LANGUAGE

The initial, perhaps most comprehensive presentation of this language model was arguably offered by Ullman (2004). However, only a summary is presented here to allow for a subsequent focus upon the role of the cerebellum in modulating a broad scope of developmental language processes. In a nutshell, the Declarative-Procedural model is dependent upon interactions between cortical and basal ganglia regions. The architecture of segregated cortico-striatal–pallidal-thalamo-cortical "loops" allows the cortex and basal ganglia to operate as a modulatory unit. *Basal ganglia functioning can never be viewed independently or separate from cortical functioning* (Broser et al., 2012). The nature of evolution and the consistency of the structure of the vertebrate brain across 500 million years of phylogeny clearly imply that the uniqueness of language depends upon brain systems that subserve other functions (Reiner, 2010).

   The term "declarative" in this model refers to the declarative memory system. Its underpinning is the medial temporal lobe, hippocampal memory network. However, this system extends to include the VAN, the ventral stream of information processing. The most critical functions of this "what" pathway concern "object identification." However, assigning worth, salience, or broadly defined hierarchical reward value to objects out there in the world is mediated by the VAN. It can be argued that the primary reason for identifying objects is to recognize their worth and what they can be used for (Cisek & Kalaska, 2010). In addition to reciprocal cortical connections to the hippocampus, the temporal lobes also are reciprocally connected with the caudate, which has been identified as a critical underpinning of implicit reward–based category learning (Seger, 2013). These connections, in aggregate, form the neurobiologic substrate for explicit-implicit learning system interactions, even though only differences between these learning and memory systems have historically been emphasized (Ashby & Crossley, 2012). It is well-recognized that the medial temporal lobe supports the critical function of associative/contextual "binding," acquiring facts, semantic knowledge, and episodic memory; further, it involves linking features of "events" that combine as a unit. However, in language, "declarative" literally means that everything identified through the activation of this pathway is

expressed through "words," or information that can be declared (Squire, 1987).

Declarative memory is an associative system for retaining facts and events, including the brain's dictionary of words and the sounds and meanings of words (Ullman, 2001). Learning new words activates this system. This "lexicon" includes the learning of all new, irregular word forms, such as knowing the past tense of teach is "taught" and not "teached." It includes the pronunciations of spellings of irregular word forms such as "yacht." It has also been proposed that this system includes disambiguation, which, for example, is an inherent property of homophones (words with similar or even the exact same sounds, but with different spellings and meanings), and deriving the appropriate interpretation of idioms, such as the subtle, abstract saying, "he bought the farm," which we have already documented as initially recruiting right hemisphere activation. Once acquired, these peculiarities of the English language system become automatic and are expressed implicitly (i.e., without conscious thought). The VAN seems to store word meanings, and its temporoparietal junction likely retains word sounds. However, as our examples demonstrate, the "declarative" component of this model implies hemispheric interactions.

The procedural memory system refers to one type of implicit memory and not all implicit systems. The system is operationalized as subserving the acquisition of new sensorimotor and cognitive habits, skills, and other procedures that require the "chunking" of sequences (Ullman, 2004). Within this implicit system, the learning of the knowledge, including the knowledge itself, is typically unavailable to conscious access. The learning and memory of this system is observed and/or measured through improvement in task performance. Aspects of learning new procedures might require initial input of conscious cortical control and the FPN system; but once acquired, automaticity is achieved, and the conscious input of the declarative system actually interferes or competes with successful performance (Packard & Knowlton, 2002; Poldrack & Packard, 2003). The "procedural" component refers to the instrumental learning system of the basal ganglia, which governs contextually dependent, rule-like, stimulus–response sequences. Learning new sequences tends to be gradual; it occurs in an ongoing way, and the successions are rule-like and operate quickly and automatically. This progression is very robust and not easily influenced by other presumably consciously controlled brain systems. This helps explain why the language system develops slowly, tending to follow the trajectory of the procedural learning system (Lum, Gelgee, & Conti-Ramsden, 2010).

The anatomy of procedural learning is a network of brain structures rooted in the cortico-striatal–pallidal–thalamo-cortical circuitry system. This includes frontal-striatal, parietal-striatal, and temporostriatal modulatory "loops" (Seger & Miller, 2010). Every reciprocally connected and segregated "prototypical circuit" within this system plays a significant role in aspects of procedural learning. Importantly, it also includes much of the cerebrocerebellar circuitry system: *intersecting within the thalamus*, and then projecting back to the "hub" region (usually a cortical area) where these parallel, corticobasal ganglia and cerebrocerebellar functionally segregated circuits originated (Houk et al., 2007). *Without these hub region connections to the cerebellum, long-range transmission of information occurs significantly more slowly* (Hwang, Hallquist, & Luna, 2012). These two "vertically organized" systems also intersect with ventral cortical frontal regions. These cortical and thalamic linkages are also part of a neurobiologically situated substrate, so that declarative and procedural systems share the same retrieval mechanisms/resources (Dew & Cabeza, 2011; Oberauer, Souza, Druey, & Gade, 2013). Importantly, this also reveals that *nature recruited and incorporated nonlinguistic mechanisms and functions to support language processes.*

This linguistic system, by definition, requires all sorts of *interactions*. The procedural system is a motor system. It is generally accepted that this system builds complex *sequences*. It learns by chunking or linking together aspects of action patterns to acquire new rule-governed sequences, including grammar and syntax. Although much of this learning is implicit and it unfolds by interacting with others over the course of development, all exceptions to the rules of grammatical and syntactical linkages must select items from the declarative dictionary to modify these rules (such as taught versus teached). That is, the learning process is both automatic and self-correcting. Similarly, these items must be retrieved, maintained, restructured, and recoupled with previous sequences through *working memory* processes, well-known to be dependent upon cortical-basal ganglia interactions (McNab & Klingberg, 2008; Moore, Li, Tyner, Hu, & Crosson, 2013). Similarly, the STS, along with its role in retaining mental representations of movement ideas, can provide the anatomic substrate for cortical input for the procedural system through its connections with the caudate and the thalamic nuclei; this same region of the STS (the upper bank, Schmahmann & Pandya, 1997) sends projections to the cerebellum, which in turn, after cerebellar refinement, projects to thalamic nuclei via the feedback limb (see Schmahmann, this volume). The hypothesis that similar or even the same types of knowledge can be acquired by both systems is inherent in these interactions and has been

clearly supported by several investigations (Ashby & Crossley, 2010, 2012; Paul & Ashby, 2013). Finally, eye movements during *listening* are directly, yet implicitly linked to spontaneous grammatical processing (Huette, Winter, Matlock, & Spivey, 2012). The STS, concerned with both visual and auditory processing, and the adjacent temporal–parietal region, together representing a sensorimotor integration system (Hillert, 2014) have well-established connections with the cerebellum and the thalamus. These connections provide the neurobiologically situated substrate, a key perceptual component to grammatical comprehension, and include the cerebellar contribution to eye movement spontaneously recruited by listening (Ito, 2011). We find it remarkable that listening/comprehending activates this entire subset of systems, including spontaneous eye movement, which often orients an aspect of attention (DAN).

Four integrative networks across corticobasal ganglia loops and the role of the thalamus have been identified and described as critical underpinnings for ongoing adaptation (Haber, 2011; Haber & Calzavara, 2009). There is very strong evidence that the thalamus, the caudate, the entire cingulate cortex, the inferior parietal lobe, and the prefrontal cortex are recruited for high-level aspects of language processing. Examples include accurate ambiguity resolution, such as when different semantic meanings converge upon a homonym, as in the meaning assigned to a "*pool of water*" versus *"the game of pool"* (Ketteler, Kastrau, Vohn, & Huber, 2008). These identified nodes have specific inputs to, and outputs from, the cerebrocerebellar and basal ganglia-cerebellar circuitry systems (Bostan et al., 2013; Schmahmann & Pandya, 2008). Although all of these circuitry profiles include projections to the thalamus, cortico-thalamo-cortical networks, initially described by Haber (2011) and Haber and Calzavara (2009), they also appear to be heavily involved in the selection of one language unit, or word, over another in the expression of a concept, and act in concert with basal ganglia loops (Crosson, 2013). These data are entirely consistent with our description of a linguistic system that operates within a novelty-routinization principle of hemispheric organization, including the role of right hemisphere processing in linguistic processing (as illustrated previously with several practical and neuropsychological testing examples).

This interactive neuroanatomy makes perfect common sense. For another simple example, the VAN labels objects or nouns that carry meaning or salience, hence, limbic network activation. The DAN, with anteroposterior parietal hubs, specify the parameters for action, or movement, and attach speech sounds to speech musculature *sequences* for anterior, frontal expression,

activating the Broca area. When we are interrupted from relaxing, i.e., doing nothing and suddenly then asked a question, we activate the DMN and SMN. Even one simple example illustrates the logic behind these shared network interactions, although we need to imagine that practically, we would not be consciously aware of these processes as we interact in real time.

THE ROLE OF THE CEREBELLUM IN LANGUAGE FUNCTIONS

Therefore, although it was previously thought that language functions were based upon cortico-centric processes, it has become increasingly recognized that the linguistic system is best understood within a dual-tiered model that requires cortical–subcortical interactions. Furthermore, the Declarative-Procedural model is primarily derived from *adult* subjects, using anatomical lesion, neuroimaging, and other clinical data. Our understanding of this model is far from complete. Data concerning how this system *develops* are absent to sparse and are primarily based upon observation. An additional drawback concerns the obvious fact that experimental paradigms with animals cannot be developed. As previous chapters reveal, recently established functional neuroimaging techniques are starting to provide new insights into the neurobiologic substrates of linguistic systems. Our understanding of how these systems develop rests far off on the horizon. However, the developing infant and the child are not at all passive learners, and language acquisition requires a sort of practice, or *action*, reflected during different periods of development. For example, it is generally accepted that "babbling" occurs between 6 and 8 months; content words are expressed between 9 and 18 months; two-word phrases with semantic relationships (perhaps the forerunner of sentences) are observed between 18 and 24 months; and multiword phrases with morphemes are evident at 30+ months. Figurative language with more elaborate expression is observed between 6 and 10 years of age, and irony, idiomatic, and more sophisticated figurative, abstract, non-literal language develops even later. It seems obvious that linguistic development follows the trajectory of brain development (Fisher et al., 2003, previously cited; Tau & Peterson, 2010). However, our understanding of brain maturation within the context of large-scale brain systems remains in its infancy (Menon, 2013; Supekar, Musen, & Menon, 2009).

   Habas et al. (2009) have described distinct cerebellar contributions to intrinsic connectivity networks in adults and the same systems are observed in children. The vestibulocerebellum is mature at the time of full-term birth,

the cerebellar cortex already exhibits its well-known architecture, and all the Purkinje cells are presumably present, as are the climbing fibers that synapse with the cell bodies (Altman & Bayer, 1997). Studies of newborn babies and infants reveal that reciprocal cerebellar-vestibular interconnections are fully myelinated, notwithstanding the limitations of the neurotechnologies that were applied (Rorke & Riggs, 1969). Importantly, more recently, sophisticated MRI morphometric technologies identified a remarkable postnatal growth during infancy in the *ventral pons* (an action region). Cell proliferation is at its peak during infancy, corresponding with a significant increase in myelination (Tate et al., 2015). Cerebrocerebellar circuitry very closely resembles adult circuitry during the course of development (Power, Fair, Schlaggar, & Petersen, 2010). By 4 years of age, pontine-cerebellar tracts attain adult appearance (Yakovlev & Lecours, 1967). Cerebellar adult volume can be observed between the ages of 7–12 years, despite gender differences (Giedd & Rapoport, 2010; Power et al., 2010). It also has been proposed that cerebellar integrity might actually be an important *driver* in overall developmental brain processes (Wang et al., 2014). Therefore, concurrent with full-term birth, and rapid postnatal development, the cerebellum is already in neuroanatomic position and "primed" to support the systems that are necessary for "bottom-up" language development and ongoing, increasingly refined language capacities.

Many things can go wrong within this complex system, and question remains as to *how* the cerebellum contributes to language, *in our opinion, if only conceptualized as an artificially defined, compartmentalized domain*. The most agreed upon conclusions concern a repeated modular organization within the cerebellum that reflects a repeating functional organization, which is to say the cerebellum performs a common function whether in support of movement or nonmotor functions. Clearly, there is a topographic organization of function within the cerebellum. However, according to Wang et al. (2014), this organization parallels the cerebral organization of the FPN, VAN, DAN, VN, limbic network, DMN, and SMN, *which is certainly not the same as the way traditional constructs and domains have been historically conceptualized*. Reductions in cerebellar activity accompany automaticity and learning, regardless of the function in question. Increases in cerebellar activity are accompanied by errors computed as a result of disparities between intended versus actual outcomes. In total, these conclusions support the view that the cerebellum performs a modulatory function in all motor and nonmotor skills, including language. This involves a transition from controlled to automatic processing as well as adaptation across contexts, as reflected in error

correction. These processes might be oversimplified by stating the cerebellum predicts and corrects errors in behavioral outcomes, and through the feedback limb of the cerebrocerebellar circuit, allows the cortex to store, or retain, the most efficient representation of any and all behaviors, including linguistic processes (Doyon et al., 2002; Galea, Vazquez, Pasricha, de Xivry, & Celnik, 2011; Koziol et al., 2013; Shadmehr, Smith, & Krakauer, 2010).

This fundamental process therefore can be applied to every symptom of language pathology. This approach is fully consistent with the proposal that nature's oldest solutions to complex problems of adaptation have never relied upon sophisticated cognitive processes (Ito, 1997), and that an intimate link exists between all predictive and learning processes within the brain (Grossberg, 2009). Nature does not reinvent the wheel. Instead, it very efficiently applies an adaptive mechanism to another system. That said, we reiterate the basic paradigm that the brain evolved to meet the needs of interactive behavior. The environment is not static, but instead, dynamically changing and characterized by episodes of recruiting routinized, automatic behaviors that exploit the predictable features of the environment, alternating with episodes of controlled behaviors, which are characterized by modifying or adapting known behaviors or developing new ones to meet novel situational changes. And, it follows that all behaviors must be characterized by a sort of "action–perceptual/ideational" linkage, in which case a similar connection must inherently characterize language and communication. Language and communication are specific instances of a coupling of perception–action and or action–perception linkages. This again takes us back to the concept of "embodiment" and not specific domains because knowledge is developmentally grounded in sensory-motor interactions (Koziol et al., 2013). This knowledge is represented or retained in the same distributed brain systems that were recruited when the specific situations were encountered, which is the essence, or definition, of the term "embodiment." Within the human species, language is an inherent property of that embodied sensory-motor circuitry. This is entirely consistent with the manner in which large-scale brain systems are organized within the brain at the cerebral level, which is paralleled by the representation of these same systems within the organization of the contralateral cerebellum, as reported by Wang et al. (2014).

Intact "action–perceptual/ideational" linkages are dependent upon the integrity of the cerebellum (Christensen et al., 2014). Through a process of cerebellum lesion–symptom "mapping," these investigators identified distinct regions in the dentate nucleus and both lateral hemispheres of the

cerebellum as causally involved in action–perception coupling. They concluded that the cerebellum was the critical neuroanatomic substrate for establishing time-dependent *multisensory representations* at numerous levels that are relevant for motor (action) control as well as supporting action perception. This can easily be related to the novelty-routinization principle, revealing the neuroanatomic organization that can explain individual differences. In other words, providing the underpinning for understanding how and why a task might be novel for one person but "routine" or "automatic" for another, as revealed by the integration of multisensory representations/retention of information at many different levels as task mastery proceeds from novel to routine. Importantly, they identified *ipsilateral* motor representations within the cerebellum as critical for supporting somatosensory state estimates, or *prediction of feedback*, of ongoing movements which are necessary for adapting behaviors across contexts. Just as significantly, the ventral dentate and the contralateral posterior cerebellum were identified as the substrate for generating *multisensorimotor integration,* a critical component for the chemistry or orchestration of embodiment. In other words, data from studies of large-scale brain systems reported here reveal that functions, or *constructs, including language,* that should be unified are actually distributed throughout the brain, and those that should be distinct, often involve the *same regions. And this makes sense, since words are actually stored or retained in semantic networks, which is fully consistent with the distributed system perspective*. Because it follows that this information must be rapidly integrated to serve the needs of nearly constant interaction with a complicated and ever-changing environment (including the world of conversational discourse), there must be continuous modification of ongoing actions, including language, through feedback control, and the continuous evaluation, likely through predictive mechanisms to operate in "real time." The cerebrocerebellar system is positioned to provide that integration of information for rapid adaptation. The modular organization of the cerebellum because it mimics the pattern of cortical organization within the contralateral hemisphere, is not so much "organized" by constructs or domains, but instead, according to the *input* it receives from cortical networks. Language is an inherent function distributed within these systems. Furthermore, this viewpoint actually assists in explaining why the broad range of "domain-like" symptoms observed in syndromes such as the CCAS (Schmahmann, 2004) do not occur in isolation, even with focal lesions and/or malformations of the cerebellum. Relatively focal lesions do not affect only one function in segregation (for a review, see Tavano & Borgatti, 2010).

BOTTOM-UP DEVELOPMENT: EARLY PREDICTION OF LANGUAGE OUTCOMES

Individual differences and right-left asymmetry, originally thought to be unique to the human neocortex, are also evident at the level of the brain-stem and cerebellum (Baizer, 2014). Although at least five differences have been reported, two of these appear particularly important for developing linguistic functioning. The principal nucleus of the inferior olive and the dentate nucleus both demonstrate significant differences as compared with other primates. In humans, the entire medulla has expanded outward to contain the enlarged principal nucleus of the inferior olive, and is shifted more toward the right, which is the sole source of climbing fibers believed to play a significant role in error correction. Baizer believed this was perhaps driven by handedness (yet to be confirmed; see Mazoyer et al., 2014). Although the sample size was small, the basic "template" Baizer described included variability in the pattern of folding, and similar left-right differences as well within the dentate nucleus. In this regard, the brainstem is lateralized. These differences may be particularly important because perhaps they generate further support for the concept of the "lateralized cerebellum," initially proposed by Mariën and colleagues (Mariën et al., 2001).

This notion recognizes hemispheric differences at the levels of both neocortex and cerebellum, and includes the process of cerebral diaschisis. Cortical language areas of the left cerebral hemisphere may in fact be affected by reduced or deficient *input* from right-sided cerebellar and perhaps brainstem pathology. Further, compromised *output* from cortical speech regions can impact upon the functioning of the cerebellar nodes receiving this neural information (Mariën et al., 2007). Therefore, cortical, cerebellar, or even the connecting white matter tracts can generate similar symptoms. However, there also is evidence that the left cerebellar hemisphere assists in coordinating linguistic systems, not only by managing affect and/or prosody but also for high-level linguistic tasks, including word-finding fluency, complex sentence formulation, and lexical-semantic manipulation tasks. These findings were also linked to the expanded role of the thalamus, which we described previously (Whelan & Murdoch, 2005). Therefore, consistent with the known novelty-routinization principle of brain organization, left-lateralized cerebellar activation can be interpreted to reflect recruitment of the right cerebral hemisphere-left cerebellar "ensemble" on the basis of the novelty of the task (see Koziol, 2014 for review of lateralization of brain functions, pp. 27–31). This has particular relevance for child populations,

because by definition, the learning of words and the complexities of language are indeed *novel* tasks. This is critically important to consider because once again, the principles of functional specialization and integration that reflect the *dynamically changing* recruitment of distributed brain networks argue against any "fixed assignment" of particular tasks to one or the other hemisphere (Podell et al., 2001). Certain language skills initially require right hemisphere cortical processes and gradually shift to left hemisphere routinization (Bakker, 1983). However, the linguistic system requires two cerebral and two cerebellar hemispheres, lateralized for different functions. Just as the right cerebral hemisphere is not irrelevant to language, the left hemisphere of the cerebellum is similarly relevant to linguistic processes.

Cerebellar vermis and brainstem regions, medial in location, have their major impact on oromotor abilities such as articulatory processes and dysarthric-type symptoms and aspects of verbal working memory processes (Tavano & Borgatti, 2010; also see Marvel & Desmond, 2013 & Marvel, this volume). Reflexive suck, which *anticipates* nurturance, presumably mediated by brainstem/cerebellar regions, has been related to important behaviors such as eating, speaking, and gesturing. Overlapping networks of brainstem, subcortical, and cortical regions encode, modify, and refine neural signals for the musculature that supports initial suck, feeding, and later speech-language production. Any form of sensory modification and/or motor restriction can potentially disrupt development of the cerebellum and the motor cortex to which it projects and this is critical for sensorimotor control. Any orofacial apparatus such as feeding and/or oxygen tubes can potentially limit movement and sucking. Therefore, anomalous sucking cycles and feeding (early motor behaviors) predict neuromotor integrity and are sensitive predictors of speech-language delays and disorders (Poore & Barlow, 2009). In fact, the link between movement and language is inexorable. Children with pre- or perinatal unilateral brain lesions do not demonstrate the same levels of gesturing as typically developing children by the age of 18 months, and eventually experience language delay (Sauer, Levine, & Goldin-Meadow, 2010). All movement is purposeful, related to language, and as we previously implied, to any other function; the critical "game-changer" is the recognition that the brain's primary duty is "action control" for purposeful interaction within a dynamically changing environment. Absence of early gesture can be considered another at-risk factor predicting linguistic delay (Iverson & Thelen, 1999). Similarly, it is notable to review that automatic, acquired, purposeful gestures activate the left cerebral hemisphere, while novel gestures, including the learning of sign language, activate the right cerebral hemisphere (Bates & Dick, 2002; cited above).

Unfortunately, the intimate interrelationships between all these functions are beyond the scope of this selected review (see Budding & Chidekel, 2012, and Koziol & Lutz, 2013 for summaries). Perhaps the best summary we can provide is to conclude that distinctions between domains are arbitrary, since all functions serve the ultimate goal of achieving action and work together. This requires a paradigm shift characterized by "embodied cognition" which serves the purpose of the control of action (Glenberg & Gallese, in Cortex, 2012), coupled with a working knowledge of large-scale brain systems and interactions within them. Choice and decision-making, which traditional constructs refer to as executive functioning, can also easily be understood within this framework, which is remarkably consistent with currently understood functional neuroanatomic networks. And, within the general network system, the "visuospatial" domain is understood as reflecting the momentary, changing "geometry" of instances of novelty. Although this is a documented, evidence-based conclusion, a comprehensive discussion is unfortunately beyond the more "selective review" focus of this chapter (Cisek & Kalaska, 2010; Cisek & Pastor-Bernier, 2014; Friston et al., 2014).

LINGUISTIC DEVELOPMENT AND DISORDERS OF LANGUAGE

Based upon these findings, along with the fact that general development proceeds from *proximal to distal* regions, it is predicted that "delays" in babbling would represent a manifestation of anomalous development within brainstem and vermal regions founded upon its contribution to oromotor control. The vermis and adjacent intermediate cerebellar hemispheric zones are the most likely candidates in early onset articulation difficulties (assuming the peripheral aspects of the speech apparatus are intact). Aspects of this early linguistic processing appear to be dependent upon the phylogenetically ancient motor system consisting of aspects of the anterior cingulate cortex and adjacent medial frontal regions, via reciprocal connections with the midbrain and pons, common to primates and retained in humans. Ackermann (2008) has described this system as well as a second motor pathway supporting vocal behavior. This system, unique to humans, includes many frontal lobe regions traversing the basal ganglia and the cerebellum, and appears to represent the principle difference between subhuman and human primates. Throughout the course of development, and during adulthood, the predictive and corrective mechanisms of the cerebellum generate the coordination and automation of the sequencing of sounds and syllables into fast, rhythmically organized, "smooth" speech utterances resulting in words. These

"words" are retained in cortical brain regions, as described in the summary of the Declarative-Procedural model. Speech-sound combinations (words) and object linkages require at least the initial support of cortical–cerebellar interactions. The cerebellum copies the cortical content, traditionally termed "working memory," to form these associations. The working memory content of the cerebellum always appears to be a copy of the current cortical state or content (Ito, 2011). Therefore, in this way, the cerebellum also provides an underpinning for word retention. For example, one of the main problems for children with SLI concerns the rapid initial cortical encoding of information that requires phonological processing (Alt, 2011). Therefore, the cerebellum has little cortically processed phonological information to copy for the purpose of performing its modulatory function. This contributes to the lexical, vocabulary learning deficits seen in children with SLI.

SLI has been described as a manifestation of impairment in the procedural learning system. However, as we stated previously, all "procedural learning" is not the same. In this regard, children with SLI demonstrate deficits in learning procedures only if the task requires the acquisition of *sequential relationships between discrete elements* (Hsu & Bishop, 2014). For example, an experimental paradigm based upon sequential relationships is the Serial Reaction Time Task, and children and adolescents with SLI clearly learn this task slowly and inefficiently (Tomblin, Mainela-Arnold, & Zhang, 2007). However, individuals with SLI do not demonstrate learning deficits on skill learning tasks such as the rotor pursuit task. This task is independent of sequential relationships, but remains dependent upon the integrity of the cerebellum for task performance improvement, or automation (Dean et al., 2014).

Because rotor pursuit does not require learning new sequential relationships, SLI, which requires the learning of the sequential relationships of the rule-governed grammatical system, does not reflect impairment at the level of the cerebellum. Again, as in the cerebellar relationship with phonological working memory, the cerebellum is unable to automate and adjust grammatical sequences on the basis of its receipt of defective input, as the principle of Mariën's crossed cerebrocerebellar diaschisis implies. This is actually the expected finding in view of our description of the Declarative-Procedural language model.

SUMMARY AND CONCLUSIONS

We have made an attempt to demonstrate the role of the cerebellum as it pertains to the language system. In doing so, we provided a review for the classification systems of language disorders that focus upon symptoms.

In contrast to the fractionation inherent in language science, with an inclination to consider language as an isolated functional domain, we provided an integrated model of language functioning that is parasitic upon large-scale brain systems and the integrity of corticobasal ganglia and cerebrocerebellar circuitry networks. Within that model, on the basis of its predictive and correctional learning mechanisms, we applied the universal function of the cerebellum, which we defined as a modulator that serves the role of automating and adapting behavior across contexts. We provided only a very selective review, and we realize we were unable to address all subtopics such as mutism, word retrieval, the *prediction* inherent in pragmatic social communication, and other aspects of language functioning. We did not discuss linguistic facets such as the cerebellar role in language perception, comprehension, and aspects of language expression such as stuttering. Describing such a complete characterization of every feature of language processing is a far too demanding task for any single brief chapter, so our aim was more modest. Perhaps these critical functions could be presented in a subsequent manuscript. However, we have provided much more than a general outline that includes examples of how a uniform cerebellar function might apply to all aspects of linguistic processing. We demonstrate how the cerebellum participates within a well-organized language system, and this should establish sufficient groundwork to develop testable hypotheses for the investigation of all language-related and communicational functions as they relate to developmental disorders.

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