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Author
Robbins, Scarlett L.

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A Neurobiological Model of Procedural Linguistic Skill Acquisition

Scarlett L. Robbins
University of California, Los Angeles

This paper presents a neurobiologically inspired model of one aspect of adult second language acquisition (SLA): procedural linguistic skill acquisition. Procedural linguistic skills are defined as the speaker/learner's implicit, unstatable knowledge regarding the formal linguistic (i.e., syntactic, phonological, and morphological) properties of the second language (L2). Unlike declarative linguistic knowledge (i.e., semantic and lexical knowledge and explicit knowledge of the L2 linguistic system), which can be readily displayed through verbal report or description, procedural linguistic skills are best demonstrated through performance. The proposed acquisition model crucially involves the neural circuitry of the neocerebellum. The neocerebellum is a brain structure which, although traditionally associated with purely motor activity, has recently been implicated in higher cognitive and, potentially, linguistic functions. The model provides for a potential unification of the competing cerebral (Ojemann, 1991; Loritz, 1991) and cerebellar (Rumelhart & McClelland, 1986: Sokolik, 1990) theories of linguistic function by integrating the unique contributions of both regions of the cerebral cortex (e.g., Broca's expressive speech area and the prefrontal cortex responsible for cognitive planning and monitoring functions) and regions of the cerebellum (an enormous capacity parallel processor responsible for the integration of cognitive and sensory information). The proposed model also offers a principled account of how explicit formalized grammar instruction might potentially serve as an effective metacognitive strategy for the L2 learner's acquisition of procedural linguistic skills.

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INTRODUCTION

This paper presents a neurobiological model of one aspect of adult second language acquisition (SLA): procedural linguistic skill acquisition.[1] Procedural linguistic skills are defined for present purposes as the speaker/learner's implicit, unstatable knowledge of the structure and form of the second language (L2), including knowledge of the so-called "abstract rules" of the syntax, phonology, and morphology of the L2. Procedural linguistic skills concern those aspects of the L2 linguistic system which speaker/learners "know" only in the sense that they are able to produce grammatical strings in the L2 which both reflect and obey these underlying rules, principles and constraints; "naive" speaker/learners are largely unable to describe this knowledge in significant detail or with much accuracy. I refer to this type of "knowledge" as a skill precisely because it is best demonstrated through performance, rather than through verbal or written report. Not all knowledge about language, however, is implicit and unstatable; speaker/learners also have a significant amount of explicit knowledge about the L2. This explicit and statable knowledge is referred to as declarative linguistic knowledge; examples include lexical and semantic knowledge, and explicit formally learned knowledge of the syntactic, phonological, and morphological properties of the L2. As an illustrative example consider the phonological and morphological knowledge that speaker/learners of English have about the noun "house." They possess explicit declarative knowledge that the plural form of the noun is "houses" (/hauzɪz/), but they also have implicit procedural linguistic knowledge of the Obligatory Contour Principle (a constraint which essentially forbids adjacent identical elements or features within a phonological constituent) which, in this case, forces the epenthesis (insertion) of the default vowel /ɪ/ to separate the two adjacent identical consonants.[2]

Essentially, the proposed model assumes that the acquisition of procedural linguistic skills in an L2 involves the gradual, stage-wise formulation and refinement of detailed execution programs within the neural circuitry of the neocerebellum and related structures. Adult procedural linguistic skill acquisition is represented within this model as the operationalization of "abstract" or conceptual linguistic plans originating in Broca's expressive speech region under the monitoring and strategic planning influence of the frontal cortex. Through its integration of diverse brain

structures including regions of both the cerebral hemispheres and the cerebellum the model presented here offers a potential unification of the currently competing cerebral (Ojemann, 1991; Loritz, 1991) and cerebellar (Rumelhart & McClelland, 1986: Sokolik, 1990) models of linguistic function.

I would like to begin this paper by making explicit a number of assumptions and theoretical preferences which underlie the proposed model of adult L2 procedural linguistic skill acquisition. Then, I will briefly describe the neurobiological processes involved in the acquisition and storage of knowledge (i.e., learning and memory) and offer a general sketch of a larger inclusive neurobiological model of SLA into which the present model of procedural linguistic skill acquisition might fit. Finally, I will present the model and discuss the potential contributions of this avenue of research to the overall understanding of the processes involved in adult SLA.

Underlying Assumptions of Proposed Model

First, the proposed model is neurobiologically inspired; it relies crucially on Squire's neurobiological theory of memory (Squire, 1982, 1985, 1986, 1987; Squire & Zola-Morgan, 1991) and is based upon neurobiological models of voluntary motor activity (Ghez, 1991) and procedural motor skill learning (McCormick & Thompson, 1984; Thompson, 1986, 1989; Harrington, Haaland, Yeo & Marder, 1990; Bloedel, Bracha, Kelly & Wu, 1991; Greenough & Anderson, 1991). As Jacobs & Schumann (1992) argue, it is important that any model or theory which purports to account for language acquisition (either primary or second) be at least neurobiologically plausible. If we are ever ultimately to understand how human language is acquired, we must begin to consider how the human brain, given what we know of its anatomical structure and its physiological function, might acquire language.

Secondly, much of the neuroscientific research upon which the present model is based is concerned with non-linguistic learning and memory (i.e. the acquisition and storage of knowledge) in both non-human and human subjects. I maintain, however, that it is valid to build a model of linguistic skill acquisition upon this research for the following reasons. First, a number researchers have argued that adult SLA is in many ways similar to the acquisition of other complex cognitive skills and is, to a significant extent, dependent upon "general" cognitive learning processes

which are not specific to language (Bialystok & Ryan, 1985; Faerch & Kasper, 1985; McLaughlin, 1987; O'Malley & Chamot, 1990). Second, although much current neuroscientific research is performed on non-human subjects, the findings are to a surprising degree generalizable to human subjects and the data available from cross-species comparisons support the notion that the "*fundamental neurobiological structure and principles* remain the same across mammalian species" (Jacobs & Schumann, 1992: 285, emphasis theirs). I want to emphasize, however, that although I agree with Klein's assertion that "the capacity to acquire and use a language is a species-specific genetic endowment" (Klein, 1990: 219), the present model makes no assumptions regarding the issue of the innateness of linguistic ability in humans and is entirely consistent with both the environmentalist (cf. Jacobs, 1988; Greenfield, 1991) and the nativist-constructivist (cf. Crain, 1991; Karmiloff-Smith & Johnson, 1991) views of language acquisition.

Third, the present model of procedural linguistic skill acquisition presupposes a larger model/theory of SLA in which the acquisition of competence in an L2 is assumed to involve the acquisition of at least the following four distinct components: a motor skill component responsible for phonetic speech output; a general cognitive component concerned with cognitive skills related to the use of language which are not specifically linguistic, such as reasoning, development of plans for behavior, and the strategic use of available resources and capacities to achieve a goal; a declarative linguistic skill component which consists of the speaker/learner's explicit knowledge of the linguistic system; and a procedural linguistic skill component which comprises the speaker/learner's implicit knowledge of the structure and form of the language.

Fourth, although this model presumes the existence of a localized and distinct neural system devoted to language function, the proposed system is less modular and restrictive than traditional neurolinguistic models such as those presented by Geschwind (1970) and Ojemann (1987) which concern themselves primarily with strictly defined regions of the left cerebral hemisphere (i.e. Broca's and Wernicke's areas). The present model postulates a neural system which is self-contained yet distributed within a circular loop across several distinct brain regions including both the cerebral and the cerebellar hemispheres (for discussion of the role of additional brain structures in language function see Lem, this volume and Sato & Jacobs, this volume). The present model is not only a more plausible representation of the functional organization of the brain than the strictly modular traditional neurolinguistic models[3]

but also offers a possible compromise between two currently competing theories of linguistic representation: the symbolist, or cerebral theories proposed by researchers such as Loritz (1991) and Ojemann (1987) and the connectionist, or cerebellar theories such as those of Rumelhart and McClelland (1986) and Sokolik (1990).[4]

Neurobiology of Learning and Memory

Memory is assumed to consist of information, or knowledge, which is stored and retrieved through the patterns of synapses (i.e., communicative connections between neurons) existing within a given neuronal network (Squire, 1987; Kupfermann, 1991; Thompson, 1987). Knowledge is stored, or acquired, through local changes occurring within a particular neural network. Local changes, which constitute the neural mechanism for learning, may involve either morphological or chemical alterations. Morphological alterations include the formation of new synapses and the structural modification of preexisting synapses. Chemical changes involve the alteration of the membrane properties of neurons, which in turn may influence the functional properties of potential or preexisting synapses.

Given that learning involves the formation of new synapses and/or the morphological or chemical modification of synapses, the acquisition of novel information crucially depends upon the existence of "plasticity" within the relevant neuronal circuitry. Plasticity is defined as the capacity of a given neuronal network to create new synaptic connections or modify preexisting ones in response to novel input from the environment, either external or internal (i.e., the capacity to learn). Plasticity has been documented within numerous neural systems including those relevant to the present discussion: the cerebral cortex and the cerebellum (Purves & Litchman, 1980); the hippocampus and related cortical areas (Squire & Zola-Morgan, 1991); and the red nucleus, a brain stem structure receiving massive projections from the neocortex (the most recently evolved portion of the cerebral cortex) (Tsukahara, 1984). The importance of plasticity within each of these functional neural systems will be discussed in greater detail in later sections.

OUTLINE OF LARGER INCLUSIVE MODEL OF ADULT SLA

Motor Speech Component

One aspect of SLA involves the acquisition and fine-tuning of the purely motor skills required for fluent and accurate phonetic speech production. The realization of the L2 linguistic system as phonetic speech output requires the formulation and automaticization of highly detailed motor programs that encode the precisely timed and coordinated neuronal impulses which ultimately result in a complex set of muscle movements. Although the motor neurons which directly innervate the muscles of the speech organs are located in Brodmann's areas 4 & 6 of the cerebral cortex[5], research suggests that the cerebellum plays an integral role in the acquisition and orchestration of motor speech activity (Figure 1).

Although research in this area remains speculative, it is generally accepted that the basal ganglia, the cerebellum, and related neural circuitry are responsible for the acquisition and storage of certain types of procedural motor skills (Harrington, Haaland, Yeo & Marder, 1990; Bloedel, Bracha, Kelly & Wu, 1991; Ghez, 1991). The structures of the basal ganglia are reportedly involved in the facilitation and inhibition of movement, as well as the regulation of movement speed (Ghez, 1991); the cerebellum is reportedly responsible for the acquisition and storage of the detailed motor activity programs which underlie a restricted subset of procedural motor skills: those which crucially require the neural circuitry of the cerebellum for their execution (McCormick & Thompson, 1984; Thompson, 1986, 1989; Bloedel, Bracha, Kelly & Wu, 1991; Greenough & Anderson, 1991). Research suggests that the cerebellum is indeed crucially involved in phonetic speech production (Ivry & Keele, 1989; Raichle, 1990) and may therefore be responsible for the acquisition and storage of the procedural motor speech programs which are responsible for modulating and orchestrating motor speech activities. In fact, it has been suggested that the evolutionary development of phonetic speech ability (an ability which depends upon high-speed processing and the integration of mental and motor activity) in humans was largely the result of the phylogenetic enlargement of regions of the neocerebellum (Leiner, Leiner & Dow, 1987: 429).

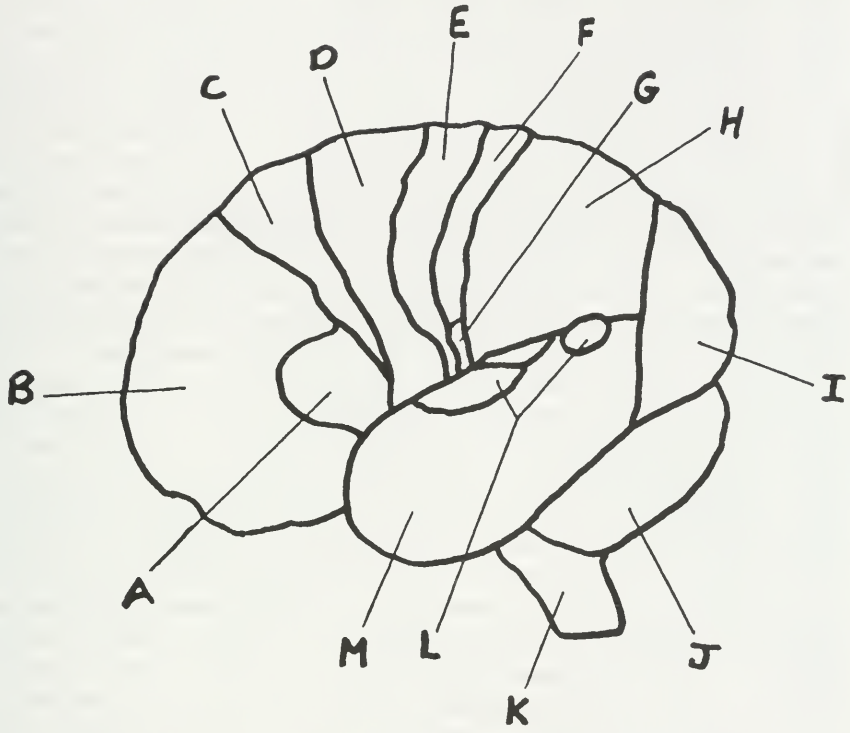

Figure 1. Sketch of lateral view of human brain identifying numerous functional and anatomical regions. A=Broca's Area 44 & 45, B=Frontal Lobe, C=Area 8, Prefrontal Cortex, D=Area 6, Supplementary Motor Cortex, E=Area 4, Primary Motor Cortex, F=Primary Sensory Cortex, G=Secondary Sensory Cortex, H=Parietal Lobe, I=Occipital Lobe, J=Cerebellum, K=Brain Stem, L=Wernicke's Area 22 & 42, M=Temporal Lobe.

General (Non-Linguistic) Cognitive Component

Certain aspects of the acquisition and production of a second language are assumed to be extra-linguistic, involving general cognitive capacities such as reasoning, the development of plans for future actions, and the strategic direction and integration of available resources towards a specified goal. The prefrontal region of the cerebral cortex (cf. Figure 1) is generally acknowledged to be responsible for the cognitive functions of abstract reasoning, weighing the consequences of future actions, and planning

accordingly (Fuster, 1988, 1992; Kupferman, 1991). It is likely that the prefrontal cortex is also responsible for the acquisition of these same skills as they relate to the use of a second language. Research supports the notion that the prefrontal cortex is responsible for the reasoning and planning activities required for the utilization of language to conceptualize, elaborate, and express our thoughts (Novoa & Ardila, 1987). After reviewing the substantial clinical and experimental research, Stuss and Benson (1984) conclude that frontal lobe lesion studies support a role for the frontal lobe in organization and sequential planning, monitoring of behavior, directed attention, and error detection. Numerous studies document the following impairments in patients following frontal lesions: (1) an inability to use verbalized (i.e., declarative) knowledge to guide motor activity, (2) an impaired ability to organize sequential behaviors, (3) an impaired capacity to direct and maintain attention, and (4) an impaired ability to monitor on-going activity (Stuss & Benson, 1984: 22-23). Patients with prefrontal damage are typically observed to display generally intact formal linguistic systems and yet are significantly impaired in their ability to use their linguistic resources strategically to accomplish desired linguistic behaviors or achieve communicative goals (Novoa & Ardila, 1987). These findings have led researchers to conclude that the linguistic impairments observed in patients with prefrontal damage are not due to deficits in specifically linguistic functions, but are instead the result of their generally impaired ability to exercise control over behavior, focus voluntary attention appropriately, and develop plans which direct their activities towards a specified goal (Novoa & Ardila, 1987: 207).

Specifically Linguistic Components

The current model fundamentally assumes a distinction between two types of linguistic knowledge and proposes two separate components devoted to specifically linguistic knowledge: one involving declarative linguistic knowledge and the other procedural linguistic skills. This proposed distinction between declarative and procedural knowledge originated within the fields of artificial intelligence (Winograd, 1975) and cognitive psychology (Anderson, 1976) and was recently applied to specifically linguistic knowledge by a number of researchers interested in SLA (Anderson, 1980, 1985; Bialystok & Ryan, 1985; Faerch & Kasper, 1985; O'Malley & Chamot, 1990). For instance, Faerch and Kasper (1985) classified semantic knowledge of word meaning

and explicitly "learned" rules of grammar as declarative, and strategies and procedures used to implement declarative knowledge as procedural knowledge; O'Malley and Chamot (1990) described declarative linguistic knowledge as knowledge "about" how to use language and procedural knowledge as the skills required to actually use language as a communicative tool. Unfortunately, despite obvious implications for research and theory, SLA researchers have generally been hesitant to pursue this distinction, perhaps because of the imprecise and confounding way in which the terms "declarative" and "procedural" are often used. Among those who have addressed the topic there has been significant debate concerning the extent to which these two types of knowledge differ in the nature of their representation in memory, the degree to which one type of knowledge can be transformed into the other type, and even the feasibility of accurately classifying knowledge as being either declarative or procedural (Anderson, 1980, 1985; Bialystok & Ryan, 1985; Faerch & Kasper, 1985; O'Malley & Chamot, 1990). It is interesting to note that the question of whether and how declarative knowledge might be transformed into procedural knowledge is reminiscent of the longstanding debate in SLA research concerning the possible facilitatory role of "learned" linguistic knowledge in the subsequent "acquisition" of that knowledge (Lamendella, 1979; Krashen, 1981; Gregg, 1984; McLaughlin, 1987).

The declarative/procedural distinction has also been adopted by neurobiological researchers and incorporated within their theories of learning and memory (Cohen & Squire, 1980, 1981; Squire, 1982, 1985, 1986, 1987; Tulving, 1987; Kupfermann, 1991; Squire & Zola-Morgan, 1991). Researchers working within this neurobiological paradigm have been able to formulate more precise and theoretically constrained definitions of each type of knowledge, offer substantial clinical and experimental evidence supporting the validity of the proposed declarative/procedural distinction, and clarify the possible facilitative role of declarative linguistic knowledge in the acquisition of procedural linguistic knowledge. Squire and Zola-Morgan (1991), for example, have developed a taxonomy of knowledge types which distinguishes between declarative (factual and episodic) knowledge and non-declarative knowledge. Non-declarative knowledge comprises several distinct sub-types of knowledge including: procedural skill knowledge, priming, simple classical conditioning, and non-associative knowledge. Only two of these sub-types of knowledge are relevant

to the present discussion: declarative knowledge, and procedural skill knowledge.

For present purposes I will assume that declarative linguistic knowledge refers to the speaker/learner's lexical and semantic knowledge and explicit, formally "learned" knowledge of the rules of the L2 grammar (e.g., memorized and statable knowledge of grammatical rules), while procedural linguistic skills consist of the speaker/learner's implicit knowledge of the "abstract rules" related to the sequencing, coordination, and combination of linguistically relevant units (phonemes, morphemes, words, phrases, etc.) into grammatical configurations as required for the actual use of the L2 in real-time as a communicative tool. Thus, a defining characteristic which can help to identify knowledge as being either declarative or procedural in nature is the means by which it can be demonstrated: declarative knowledge can be explicitly verbalized and procedural skills can be performed. However, this distinction does not preclude the possibility of learners acquiring declarative knowledge related to the performance of an essentially procedural skill, perhaps even without adequately acquiring the procedural aspects required for the performance of the skill. This may, in fact, be precisely what is happening to learners who are able to demonstrate accurate grammatical knowledge of the L2 "declaratively," yet are unable to *use* this knowledge "procedurally."

As an additional example of each type of linguistic knowledge consider what speaker/learners of English know about the word "give." Declarative linguistic knowledge of "give" includes the fact that "give" symbolically encodes the following concept: the transfer of possession or ownership of some object or entity from one party to another, as a result of some action of the first party. Procedural linguistic skills related to "give" include the speaker/learner's implicit, encoded knowledge that "give" must appear in syntactic constructions as the head of a verb phrase containing two arguments (a direct and an indirect object), assigns inherent case, and thereby licenses dative alternation of its direct and indirect objects.[6] It is worth emphasizing that speaker/learners may possess significant amounts of procedural knowledge related to the syntactic, phonological, and morphological properties of a word and yet be largely or entirely unable to express this knowledge verbally, as in the case of untutored, naturalistic L2 learners who have little if any declarative knowledge of the L2 system beyond their semantic and lexical knowledge.

The validity of the distinction between declarative and procedural knowledge types rests primarily on the extensive clinical

and experimental research performed with human amnestics and lesion studies performed upon laboratory animals. Patients with lesions localized to the medial temporal lobe of the cerebral cortex, resulting either from surgery or injury, have been reported to demonstrate a significant loss of prior declarative memory (retrograde amnesia) in addition to a severely impaired capacity to acquire declarative knowledge (anterograde amnesia) (Milner, 1966; Warrington & Weiskrantz, 1982; Squire, 1986; Squire & Zola-Morgan, 1991). Although the extent to which prior memories are lost varies considerably, most patients retain a significant portion of their remote memory (i.e., memory stored many years prior to damage). The capacity of these patients to acquire and retrieve procedural knowledge, however, remains remarkably intact (Warrington & Weiskrantz, 1982; Squire, 1986; Tulving, 1987). Despite an inability to remember even the simplest facts, amnestics demonstrate a normal ability to acquire novel, complex procedural skills such as reverse mirror reading (Cohen & Squire, 1980). Thus, the defining characteristics of human amnesia, a significant impairment of declarative memory in conjunction with spared procedural memory, support the existence of separate memory/knowledge systems that are dependent upon distinct neuroanatomical structures for their acquisition and storage (Squire, 1986; Tulving, 1987; Kupfermann, 1991; Squire & Zola-Morgan, 1991).

In the sections below, I will briefly present what are currently considered the most plausible neuroanatomical substrates for each type of linguistic knowledge. However, I would like to point out that the fundamentally distinct character of these two types of knowledge, declarative being a chunk of information and procedural a detailed program for activity, as well as their dependence upon distinct neuroanatomical systems, make it entirely inconceivable that knowledge of one type could ever be "transformed" into knowledge of the other type. However, this does not preclude the possibility that previously acquired knowledge of one type may facilitate the subsequent acquisition of related knowledge of the other type, which is essentially what I will propose in a later section of this paper.

Anatomical substrate for declarative linguistic knowledge/memory

Recent research on human amnestics and non-human primates provides compelling evidence that the medial temporal lobe

system (consisting of the hippocampus, the parahippocampal gyrus, and the entorhinal and perirhinal cortices) is primarily responsible for and crucially involved in the acquisition and storage of declarative knowledge, although the actual site of long-term memory storage most likely lies outside of this region (Squire & Zola-Morgan, 1991; Plummer, 1991).

The acquisition of declarative knowledge (including specifically linguistic declarative knowledge) involves the shift of memory stores from short-term, working memory to long-term memory and the subsequent consolidation with previously acquired knowledge and transfer to a location independent of the medial temporal lobe system. The neocortex is presumed to play a significant, as yet undefined, role in the transfer of declarative memory from semi-permanent storage sites within the medial temporal lobe system to long-term storage sites, which can then be accessed and retrieved independently (Squire & Zola-Morgan, 1991). The remote declarative memory spared in medial temporal lobe amnesia is presumed to be that which has been transferred to this independent long-term storage site (Squire, 1987).

Anatomical substrate for procedural linguistic knowledge/memory

Procedural knowledge is generally considered to involve an aggregate of distinct skills which are acquired and stored in a number of distinct neuroanatomical systems (Squire, 1987; Harrington, Haaland, Yeo & Marder, 1990; Squire, Zola-Morgan, Cave, Haist, Musen & Suzuki, 1990; Bloedel, Bracha, Kelly & Wu, 1991). As discussed previously, the cerebellum and the basal ganglia may be responsible for the acquisition and orchestration of those procedural motor skills responsible for phonetic speech activity. Research involving the acquisition of the procedural skills underlying complex cognitive and linguistic activities has traditionally focused upon the cerebral cortex, but researchers have recently argued that the neocerebellum may also participate in the modulation, integration, and acquisition of these skills (Leiner, Leiner & Dow 1986, 1987, 1989, 1991; Schmahmann, 1991).[7]

The neocerebellum forms a significant portion of what researchers have identified as an extensive and phylogenetically enlarged "learning loop" (Leiner, Leiner & Dow, 1987). This proposed "learning loop" is essentially a circular neural circuitry system which connects the newly evolved regions of a number of brain structures including the cerebral neocortex, the neocerebellar

nuclei and cortex, and the red nucleus. The system is assumed to contribute substantially to the rapid and fluent acquisition and performance of procedural motor, cognitive, and linguistic skills in humans (Leiner, Leiner & Dow, 1986, 1987, 1989, 1991). The current proposal, which asserts that the neocerebellum is largely responsible for the acquisition of procedural linguistic skills, relies upon exactly these extensive connections with newly evolved regions of the human brain and areas of the cerebral cortex traditionally associated with language function, in addition to the cerebellum's enormous computational capacity. The proposed involvement of the neocerebellum and related neural circuitry in the acquisition of procedural linguistic skills will be discussed in detail in the section which follows.

PROPOSED MODEL OF PROCEDURAL LINGUISTIC SKILL ACQUISITION

The model of procedural linguistic skill learning presented here is based upon proposals made by Thompson (1984, 1986, 1989), Bloedel, Bracha, Kelly & Wu (1991), Ghez (1991), and Greenough & Anderson (1991) concerning cerebellar involvement in voluntary movement and motor skill learning. Current models of voluntary movement propose that the cerebellum is responsible for integrating the sensory input from the environment with the conceptual motor activity plans of the prefrontal association cortex and ultimately producing detailed, precisely timed and coordinated programs for the execution of motor activity which are then relayed to the relevant musculature by way of the motor neurons of the cerebral cortex (Ghez, 1991). Essentially, the model below proposes a similar involvement for the neocerebellum in the formulation and acquisition of (non-motor) linguistic programs. Although the cerebellum has not traditionally been assumed to play a significant role in the acquisition or production of language (aside from its strictly motor involvement in phonetic speech production), I suggest that it is in fact uniquely suited for its proposed role in the acquisition of procedural linguistic skills for several reasons. First, the cerebellar cortex contains an enormous number of neurons, similar to that of the cerebral cortex, enabling it to perform large quantities of precise computations quickly and accurately (Leiner, Leiner & Dow, 1987: 434). Second, because of the highly

structured, parallel organization of its dendritic and axonal networks which are easily and continuously modified by experience, the cerebellar cortex is capable of the immense quantities of high-speed parallel processing that are required for the acquisition and production of language.[8] Finally, because of its ability to integrate incoming ascending sensory and descending cortical information with ongoing motor activities and its extensive connections with areas of the cerebral cortex implicated in language function (e.g. frontal and parietal association areas, prefrontal cortex, Broca's area, Wernicke's area, and motor speech cortex) the neocerebellum appears ideally suited to the task of orchestrating ongoing linguistic activity while acquiring or fine tuning novel procedural linguistic skills (Leiner, Leiner & Dow; 1986, 1987, 1989, 1991; Schmahmann, 1991).

Because the organization of information flowing into and out of the cerebellum is of central importance in understanding precisely how it might initially acquire and subsequently improve and refine performance of novel linguistic skills, I briefly summarize the relevant aspects of the neuroanatomical (structural) and neurophysiological (functional) organization of the neocerebellum below.

Anatomy and Physiology of the Neocerebellum

The cerebellum is located posterior to the pons and medulla and inferior to the cerebral hemispheres (cf., Figure 1). As a whole the cerebellum is responsible for the maintenance of equilibrium and balance, posture and muscle tone, and the initiation, coordination, and modulation of motor activities; responsibility for initiation and temporal coordination is presumably shared with the structures of the basal ganglia. The cerebellum is organized such that information from distinct functional systems (e.g., those devoted to equilibrium, posture, coordination) is directed towards different cerebellar nuclei and different regions of the cerebellar cortex for processing. Processed information and stimuli are then conveyed to related functional anatomical systems in other areas of the nervous system. In this manner functional systems are localized within specific regions of anatomical structures and yet distributed among networks of connections which span several anatomical systems.

The following description of the flow of information into and out of the cerebellum (Figure 2) is true of both the cerebellum as a whole and the region of primary concern to the current discussion: the neocerebellum.

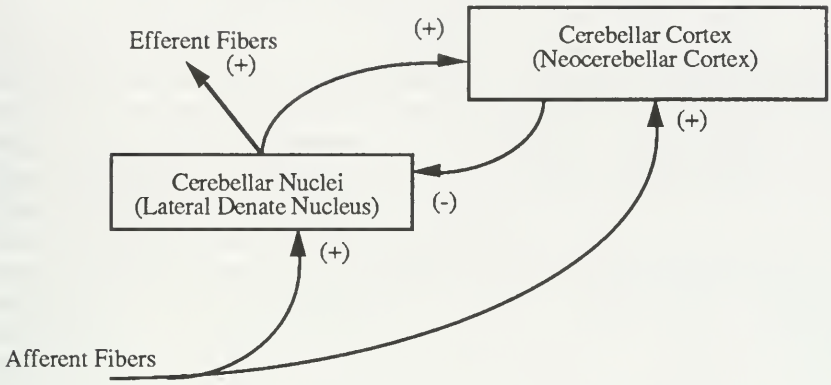

Figure 2. Highly schematized illustration of the flow of incoming and outgoing information in the cerebellum. Plus signs (+) represent excitatory connections, minus signs (-) inhibitory connections.

Information enters the cerebellum by way of large bundles of fibers (cerebellar peduncles) which ultimately terminate in predetermined regions of the cortex. En route to the cortex these afferent (incoming) fibers send branching (secondary) collateral fibers to the relevant cerebellar nucleus. Thus, the cerebellar nuclei and the cerebellar cortex are essentially responding to the same incoming stimuli but in a distinct manner. The efferent (outgoing) fibers of the cerebellar nuclei are excitatory in nature (i.e., they carry signals which facilitate activity), whereas the efferent fibers of the cerebellar cortex are inhibitory (i.e., they carry signals which inhibit or suppress activity). The efferent fibers from the cerebellar cortex all terminate in the cerebellar nuclei, suppressing the firing activities of those nuclei and indirectly suppressing motor activity. The efferent fibers from the cerebellar nuclei are the only fibers which actually leave the cerebellum and they fire under the modulating influence of the cerebellar cortical neurons. The fibers from the cerebellar nuclei ascend through the thalamus to terminate in predetermined regions of the cerebral motor cortex (Brodmann's areas 4 & 6) and convey impulses which stimulate the firing activity of the cortical motor neurons. The motor neurons of the cerebral cortex are responsible for conveying the excitatory stimuli to the musculature which result in motor activity. Thus, although the excitatory stimuli which ultimately result in motor activity originate

in the cerebellar nuclei, these impulses can be directly suppressed by the inhibitory impulses of the cells of the cerebellar cortex.

afferents to the neocerebellum: Two important sources of afferent (incoming) fibers to the neocerebellum are the fibers descending from the cerebral cortex (via the corticopontocerebellar tract) and the fibers originating in the olivary nucleus. These tracts connect the neocerebellum with several cortical structures implicated in language function including: the frontal cortical association areas (abstract reasoning and planning), prefrontal cortex (planning and monitoring), Broca's expressive speech area (areas 44 & 45), motor speech cortex (areas 4 & 6) and Wernicke's receptive speech area (areas 22 & 42). The corticopontocerebellar tract consists of efferent fibers originating in each of the four lobes of the cerebral cortex which descend through the pontine nuclei and decussate (i.e., cross) to enter the contralateral cerebellar hemisphere. In this manner the right cerebellar hemisphere receives information regarding the activities of the right side of the body from the left cerebral hemisphere, and the left cerebellar hemisphere from the right cerebral cortex. The climbing fibers from the olivary nucleus constitute a second source of afferent fibers to the neocerebellum. The significance of these fibers is twofold. First, the olivary nucleus receives the majority of the efferent fibers from the red nucleus which is a brainstem structure receiving massive projections from the neocortex. Second, the cells of the red nucleus are reported to exhibit remarkable plasticity (Tsukahara, 1984). As previously mentioned, researchers have speculated that the red nucleus may play a considerable role in a newly evolved and enlarged learning loop within the human brain (Leiner, Leiner & Dow, 1986). A third important source of afferent fibers are those of the ascending spinal tracts. These fibers convey sensory and proprioceptive (related to position and movement of muscles) information from the external environment and the musculature directly to the cerebellum. It is this continuously up-dated information concerning the changing environment and ongoing motor activity which enables the cerebellum to effectively monitor and orchestrate smooth and balanced movement.

efferents from the neocerebellum: As discussed above, efferent fibers from the neocerebellar cortex terminate exclusively in the lateral dentate nucleus, which in turn serves as the unique source of efferent fibers leaving the neocerebellum. A small percentage of efferent fibers from the dentate nuclei return to the cerebellar cortex

forming a circular feedback loop crucial to the cerebellum's function in continuously monitoring and modifying ongoing activity. However, the majority of the efferent fibers from the dentate nucleus leave the cerebellum and project to the thalamus (ventral lateral and ventral anterior nuclei). The efferent fibers from these thalamic nuclei subsequently project to diverse regions of the cerebral cortex including: the frontal motor areas of the cerebral cortex (areas 4 & 6), the prefrontal cortex (area 8), the frontal association cortex, Broca's expressive speech area (areas 44 & 45), and Wernicke's receptive speech area (areas 22 & 42) (cf. Figure 1).

In summary, the neocerebellar cortex and the dentate nuclei receive identical stimuli from the cerebral cortex and the environment, enabling the dentate nuclei to respond directly to sensory, proprioceptive, and cerebrocortical stimuli while simultaneously being monitored and influenced (i.e., inhibited) by the neurons of the neocerebellar cortex. The information conveyed to the neocerebellum from the cerebral cortex includes stimuli from several areas with identified language related functions including the frontal cortical association areas involved in abstract reasoning and planning, the prefrontal cortex responsible for planning and monitoring, Broca's expressive speech area, the motor speech cortex, and Wernicke's receptive speech area. Given its extensive, highly organized and neuron-dense networks, the neocerebellar cortex is able to process the incoming information at high speeds. It then performs the computations required to integrate input from the cerebrocortical, sensory, and motor systems and produce a detailed program for the execution of the desired linguistic behavior. On the basis of this program, the neocerebellar cortex is then able to monitor, in an "informed" manner, the firing of the dentate nuclei which ultimately (by way of the thalamus) convey excitatory stimuli to the motor neurons of the cerebral cortex resulting in the motor activity of the speech organs. Thus, although the signals conveyed to the cortical motor neurons originate in the cells of the dentate nuclei, the firing of these cells is crucially guided by the activity of the neurons of the cerebellar cortex, which are thereby capable of determining the outcome of motor speech activity by suppressing (inhibiting) undesired behaviors and allowing (disinhibiting) desired behaviors.

Model of Procedural Linguistic Skill Acquisition

The model presented here proposes that procedural linguistic skill acquisition occurs essentially as follows. To begin, general

linguistic plans or behavior structures regarding desired future linguistic activity are sent to the cerebellum from the expressive speech area of the cerebral cortex (Broca's area) and, presumably under the guidance and monitoring influence of the prefrontal cortex, they are operationalized within the neocerebellar cortical networks and the related neural circuitry (Figure 3).[9] The operationalization of these general, conceptual linguistic plans or behavior structures involves extensive and high-speed parallel processing and the integration of motor and cognitive activities, and results in the production of detailed, precisely timed programs for the execution of linguistic activity. The newly created programs are then relayed back to the expressive speech region of the cerebral cortex and can ultimately be used to orchestrate and oversee motor speech activity. During the acquisition process on-going linguistic activity is monitored and evaluated by the neocerebellum and the prefrontal cortex, and information concerning the relative success or failure of the performance of the novel skill is used to create appropriate cognitive and linguistic plans for future action and to help direct focused attention to aspects of the developing program which require improvement and fine-tuning. Subsequent performances of the novel skill result in gradual and incremental long-term gains in the accuracy of the cerebellar program and the speed with which it is executed.

In such a model, the role of the prefrontal cortex would be most essential during the early stages of skill acquisition when the novel linguistic plans fare first conveyed and refined into detailed, precisely timed cerebellar programs for linguistic activity. In fact, this assumption is generally in accordance with what is known about the involvement of the prefrontal cortex during the acquisition of novel skills. Fuster (1992) reviews a large body of clinical and experimental evidence which suggests that "the prefrontal cortex is essentially involved in the formation of behavior structures" and of crucial importance when those behavior structures are either "novel to the organism or unusually complex in their sensory or motor aspects" (Fuster, 1988, 1992: 352). Research also suggests that frontal cortical planning activities may be responsible for ensuring that attention is directed towards selected aspects of the incoming linguistic and sensory information (Lem, this volume) enabling input to be transformed into intake (Sato & Jacobs, this volume), and may result in what is experienced by the learner as consciousness (cf. Bridgeman, 1992). According to the proposed model, once the neocerebellum has successfully acquired (i.e.,

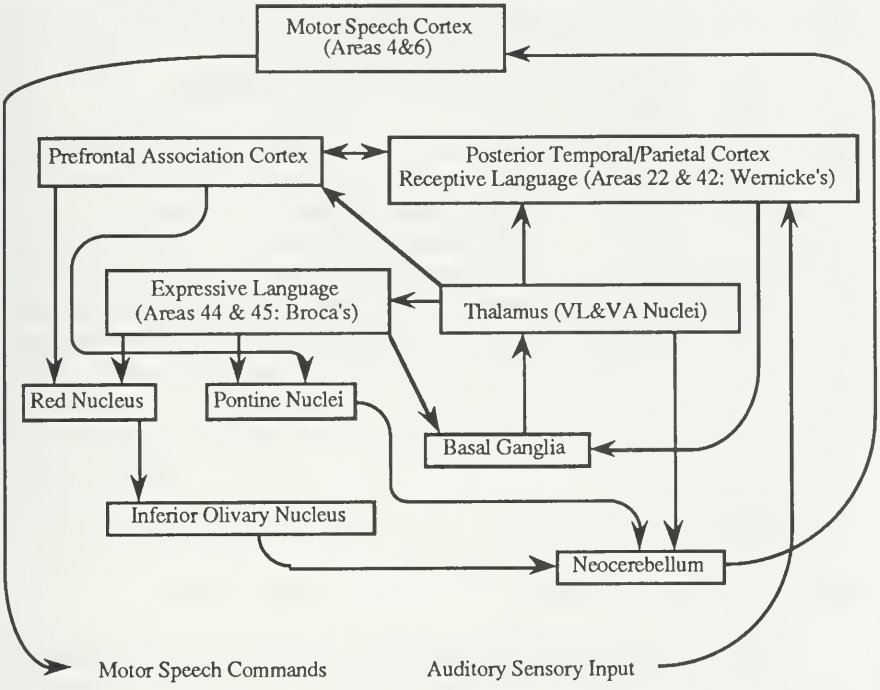

Figure 3. Schematic representation of the proposed model of procedural linguistic skill acquisition illustrating directional flow of information and anatomical connections between relevant brain regions.

operationalized and refined) the detailed procedural activity programs required for the execution of a given cerebral linguistic plan, the monitoring activities of the prefrontal cortex are no longer required to ensure accurate performance and cease to be routinely involved in the performance of the procedural linguistic skills. Decreasing involvement of frontal cortical planning activities is experienced as a gradual fading of conscious awareness of the task and decreasing need for focused selective attention during procedural skill execution, and it effectively allows prefrontal planning capacities to be devoted to higher-order communicative goals.[10] This decreasing need for the involvement of prefrontal planning and monitoring activities as once-novel skills are gradually acquired may be considered a neurobiological correlate of what SLA researchers have referred to as automaticization. A number of SLA researchers have argued that the successful acquisition of a second

language, or any other complex cognitive skill, requires the gradual integration of the individual sub-components of a complex skill which occurs over time as processes that were initially "controlled" (i.e., highly cognitively demanding) become "automatized" (i.e., less cognitively demanding) (Faerch & Kasper, 1985; McLaughlin, 1987). Attempting to apply the current neurobiological framework to cognitive theories of acquisition, "controlled" processes can be equated with procedural linguistic skills in the process of being acquired, still requiring frontal cortical monitoring to ensure accurate performance, and "automatic" processes with procedural skills which have been fully acquired (i.e., operationalized and refined) and are executed within the circuitry of the cerebellum and related neural systems without prefrontal involvement. Inconsistencies observed in the performance of skills being acquired are therefore considered a result of the limited capacities of the prefrontal region of the cerebral cortex, which can only plan for and direct focused selective attention to a limited number of tasks at one time.

Stages in the Acquisition of a Procedural Skill

The neurobiological process of acquiring a procedural linguistic skill is a gradual and incremental one which, according to the current model, involves three stages: formulation, evaluation, refinement (Table 1).

Formulation: As suggested by this model, the initial acquisition stage begins when the general cognitive and conceptual linguistic plans that serve as a model of desired activity or behavior is first conveyed to the cerebellum from regions of the prefrontal and frontal cortex and Broca's expressive speech area. This stage involves the integration of desired linguistic behaviors with incoming sensory information concerning the external environment and on-going activity. During this initial formulation stage, the dense networks of the cerebellar cortex and the circuitry involving related neural systems are assumed to perform the computations necessary to operationalize general cortical linguistic plans and to produce a detailed, precisely timed program for the execution of linguistic activity.

Evaluation: During the evaluation stage the developing program is presumably conveyed back to Broca's area and ultimately results in motor speech output which is closely monitored by both the

Table 1:
Procedural Skill Acquisition Stages

Formulation:

—General cognitive and conceptual linguistic plans for future action conveyed to cerebellum from Broca's area and prefrontal and frontal association cortex;

—Integration, processing and computation of information in neocerebellar circuits and related neural systems (e.g., basal ganglia);

—Formulation of detailed execution program for linguistic activity.

Evaluation:

—Execution of program with simultaneous monitoring and evaluation of actual performance, as compared with desired behavior within the cerebellar circuitry and the prefrontal cortex;

—Using information concerning relative success or failure in execution, the prefrontal cortex responds with new plans for future activity designed to improve performance and inform direction of selective attention to relevant linguistic features of input/output.

Refinement:

—Subsequent performances of skill benefit from updated prefrontal planning and enhanced perception of relevant linguistic features involved in execution;

—Detailed program gradually becomes more accurate and coordinated;

—Requirements of cortical planning and selective attention to the task decrease, and frontal association cortex and attentional systems gradually cease involvement during the execution of the skill.

cerebellum and the prefrontal cortex. The continuous monitoring of the on-going activity and comparison with the desired behaviors which occurs within the cerebellum and the prefrontal cortex result in an evaluation of the relative success of initial attempts to perform the novel skill. Based upon this evaluation, the prefrontal cortex can then respond by generating appropriate plans for future action designed to improve subsequent performance and direct attentional

systems to focus selected attention on relevant features of the linguistic input/output.

The evaluation and ensuing plans may be communicated to and stored within the medial temporal lobe system, resulting in a declarative memory of the learning experience and/or explicit knowledge of one's strengths and weaknesses with respect to the skill being acquired (Kleiter & Schwarzenbacher, 1989). This explicit declarative knowledge related to the acquisition process may prove to be invaluable to the speaker/learner's effective use of cognitive and metacognitive learning strategies and may serve as the primary basis upon which they judge their relative success or failure as learners.[11]

Refinement: Finally, during the refinement stage, the updated cognitive and linguistic cortical plans can serve to facilitate the subsequent refinement and debugging of the execution programs of the cerebellum. The gradual improvement and fine-tuning of the cerebellar execution programs during the refinement stage of acquisition can then result in long-term gains in the speed, consistency, and accuracy of the performance of the newly acquired procedural skill. The gradually increasing accuracy and ease with which the skill is executed by the neocerebellar circuitry accounts for the decreasing involvement of prefrontal cortical monitoring activity results in a gradually fading conscious awareness of, and focussed attention during, performance of the procedural linguistic skill.

SUPPORT FOR THE PROPOSED MODEL

PET Studies

Research conducted with positron emission tomography (PET) imaging technology has attempted to identify the neural structures activated during the performance of a limited subset of linguistic functions: semantic word association tasks (Raichle, 1990; Peterson, Fox, Posner, Mintun & Raichle, 1989). By asking subjects to (1) look at or listen to a word, (2) say that word aloud, and (3) provide another word which was semantically associated in a predetermined manner to the original word, researchers were able to identify the neuroanatomical systems actively involved in the linguistic task of semantic association. In addition, by tracking the brain activity of subjects over time they were able to distinguish

between those structures presumably responsible for performance of the linguistic skill of word association and those involved only in the acquisition of the skill. The results of these PET studies confirm a role for the neocerebellum in procedural linguistic activity which is distinct from its traditionally assigned motor speech role. The right lateral portion of the neocerebellum was active during both the initial acquisition and the subsequent performance of the word association task. Significantly, the right hemicerebellum communicates with the left (language dominant) cerebral hemisphere, further suggesting that the neocerebellum is actively involved in specifically linguistic functions. Regions of the frontal cerebral cortex and the anterior cingulate gyrus (implicated in focused selective attention) were also actively involved during the acquisition phase but, significantly, were not involved in later performance of the task. These findings, although far from conclusive, are consistent with the current proposal that the planning and monitoring activities of the frontal association cortex and the selective attentional capacity of the anterior cingulate gyrus are required only during the acquisition process when the task is novel and requires focussed selective attention, whereas the activity of the neocerebellum is involved throughout the acquisition process and required for execution even after the skill has been successfully acquired.

William's Syndrome

Research conducted on patients with William's Syndrome provides additional support for the proposed role of the neocerebellum in the acquisition and execution of procedural linguistic skills (Bellugi, Bihrle, Jernigan, Trauner & Doherty, 1990). William's Syndrome (WS) is a rare neurological disorder which is characterized by a marked reduction in cerebral volume (80% of normal size) with no significant reduction in cerebellar volume (99% of normal). When compared with age and IQ matched Down's Syndrome (DS) subjects, WS subjects performed significantly better on linguistic tasks, demonstrating remarkably preserved syntactic abilities (Bellugi, Bihrle, Jernigan, Trauner & Doherty, 1990: 117). These results are perhaps even more striking in light of the fact that DS subjects show significant reduction in both cerebral (77% of normal) and cerebellar (69% of normal) volume. Researchers have speculated that the remarkable preservation of formal linguistic abilities in WS subjects in contrast to the general retardation of their other cognitive capacities may be a reflection of the concurrent reduction in cerebral volume and relative

preservation of cerebellar volume, assuming of course that the cerebellum plays a significant role in linguistic function (Bellugi, Bihrle, Jernigan, Trauner & Doherty, 1990; Leiner, Leiner & Dow, 1991).[12]

Deficits Associated with Cerebellar Lesions

Evidence is accumulating from lesion studies that damage restricted to some regions of the cerebellum does not result in the typically observed motor deficits, but instead in significant cognitive impairment (Leiner, Leiner & Dow, 1987, 1989, 1991). In one study five patients with cerebellar damage were reported to demonstrate substantially impaired performance on almost all tests administered when compared with ten control subjects (Bracke-Tolkmitt *et. al.*, 1989). Significantly, subjects with cerebellar damage were impaired on all measures of IQ, including both verbal IQ and general ability (Bracke-Tolkmitt *et. al.*, 1989: 443). Thus far, there have been no reports of significant, specifically linguistic (non-motor) impairments as a result of cerebellar damage. However, given what is known of the diffuse and distributed nature of memory representation in the cerebellar circuitry, generalized impairment of formal linguistic capacities would require rather extensive cerebellar lesions and would most likely result in damage to motor and general cognitive capacities as well.

IMPLICATIONS OF THE PROPOSED MODEL: DECLARATIVE "LEARNING" AS A METACOGNITIVE STRATEGY FOR PROCEDURAL LINGUISTIC SKILL ACQUISITION

SLA researchers have, for many years, debated the questions of whether, to what extent, and in precisely what manner language teachers ought to incorporate formal, explicit grammar instruction into their ESL curriculum (see Celce-Murcia, 1992 and Krashen, 1992 for current perspectives on this debate). The current proposal can contribute to a future resolution by offering a new conceptualization of the problem, in addition to a potential, if only partial, solution. Although, as Celce-Murcia (1992) asserts, formalized grammar instruction is probably essential if post-pubescent adolescents and adults are to ever acquire near-native linguistic competence in an L2 and must be embedded within the

meaningful and contextualized use of language, there remains significant skepticism regarding the limited usefulness of such instruction.

Krashen (1992), for instance, concludes that because of the fundamental distinction between conscious "learning" and unconscious "acquisition" processes, the effects of formal grammar instruction are unavoidably destined to be "peripheral and fragile". However, McLaughlin (1990) contends that the notion of consciousness is entirely too vague to be of much use in theories of SLA and should be avoided in favor of more strictly defined concepts such as automatic and controlled processes and restructuring.

I propose that considering these facts from a neurobiological perspective might provide both new insight into the nature of the problem and a potential conceptual framework within which to develop a solution. Essentially, I suggest that traditional approaches to formalized grammar instruction may have proved of limited usefulness because they generally resulted in students acquiring declarative knowledge related to procedural linguistic skills rather than the procedural linguistic skills themselves. Although explicit declarative knowledge of the L2 linguistic system may be useful when taking a written exam or consulting a pedagogical grammar text, this type of knowledge is an insufficient basis for the fluent and spontaneous use of the L2 for communicative purposes. What has yet to be determined is how formalized grammar instruction can be effectively incorporated into ESL curriculum so as to facilitate learner's acquisition of procedural linguistic skills.

Although the neurobiological theories of learning and memory presented above support the claim that declarative knowledge (i.e., "learning") cannot be directly transformed into procedural skills (i.e., "acquisition"), they do not preclude the possibility that the prior acquisition of related declarative knowledge may under restricted circumstances serve as an effective metacognitive strategy to enhance the subsequent acquisition of procedural linguistic skills (cf. O'Malley & Chamot, 1991). The term metacognitive strategy is intended to refer to a strategy for learning which involves conscious, implicit consideration and planning related to the learning process itself. The above scenario is possible only if the declarative knowledge related to the novel procedural linguistic skill is used to inform and improve the planning and monitoring activities of the prefrontal cortex and to enhance the direction of focussed selected attention to the relevant features of the linguistic system in both the environmental input and

the behavioral output. The contribution of explicit declarative knowledge of the L2 linguistic system to the successful acquisition of procedural linguistic skills thus lies in its potential contribution to the learner's use of effective metacognitive strategies to facilitate the learning process itself. This contribution, however, requires active and informed involvement on the part of both the L2 learner and the language instructor in the development and use of cognitive and metacognitive learning strategies as well as a general level of awareness regarding the nature of learning itself. The intentional and strategic use of declarative linguistic knowledge in the process of acquiring a second language as an adult has also been advocated on independent grounds by other researchers including Celce-Murcia (1992), Wenden (1991), and Widdowson (1990).

CONCLUSION

In this paper, I have presented a model of procedural skill acquisition which crucially involves the circuitry of the neocerebellum, Broca's area, and regions of the frontal and prefrontal cerebral cortex. This model, although it remains largely speculative, is a plausible neurobiological account of the acquisition of procedural linguistic skills and offers a potential means of unifying competing cerebral and cerebellar theories of language function. In addition, the model provides a conceptual framework for further investigation of the potential facilitatory contribution of explicit, formally learned declarative linguistic knowledge to the successful acquisition of procedural linguistic skills. However, much remains to be done in terms of clarifying and more precisely characterizing the neurobiological processes involved, more thoroughly addressing the nature of the linguistic knowledge and its representation, and incorporating pragmatic and discourse related knowledge.

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NOTES

[1] I have chosen to focus on adult SLA, rather than PLA, to avoid the confounding influences of neurological and cognitive development.

[2] See Pinker & Prince, 1988 for additional discussion of the linguistic processes involved in pluralization.

[3] Ojemann himself acknowledges that subcortical structures such as the thalamus are likely to be involved in linguistic function (Ojemann, 1991).

[4] See Bialystok, 1990 for discussion of the benefits of such a compromise.

[5] Brodmann's areas are a numerical representation of designated regions of the cerebral cortex devised by Brodmann (1909).

[6] Dative alternation refers to the movement of the indirect object (IO) of a small class of verbs such as "give" to a preposition-less position immediately following the verb as an alternative to the IO appearing as the object of a preposition following the direct object.

[7] The neocerebellum is the most recently evolved portion of the cerebellum and comprises the posterior and lateral portions of the cerebellar cortex and the lateral dentate nucleus.

[8] See Loritz, 1991 for discussion of the demand for parallel, rather than serial, processing.

[9] No assumptions are made concerning the origin of these linguistic commands. It is conceivable that they are either predominantly learned (i.e., abstracted from the incoming linguistic data perhaps by regions of frontal association cortex) or predominantly innate (i.e., unlearned principles and parameters of Universal Grammar). For detailed discussion of this topic see Jacobs (1988), Crain (1991), and Jacobs & Schumann (1992).

[10] See Levelt, 1978, 1989, for a hierarchy of communicative goals.

[11] See O'Malley & Chamot, 1990 for discussion of effective use of learning strategies in SLA.

[12] An alternative explanation might be that WS subjects, unlike DS subjects, have an essentially intact perisylvian cortex and thus display preserved linguistic abilities.

References

Anderson, J. (1976). *Language, memory, and thought*. Hillsdale, NJ: Erlbaum.

Anderson, J. (1980). *Cognitive psychology and its implications*. San Francisco: Freeman.

Anderson, J. (1985). *Cognitive psychology and its implications*. New York: Freeman.

Bellugi, U., Bihrle, A., Jernigan, T., Trauner, D. & Doherty, S. (1990). "Neuropsychological, neurological, and neuroanatomical profile of Williams syndrome" *American Journal of Medical Genetics Supplement, 6*, 115-125.

Bloedel, J., Bracha, V., Kelly, T. & Wu, J. (1991). Substrates for motor learning: Does the cerebellum do it all? *Annals of the New York Academy of Sciences, 627*, 305-318.

Bialystok, E. & Ryan, E. (1985). Toward a definition of metalinguistic skill. *Merrill-Palmer Quarterly, 31*, 229-51.

Bialystok, E. (1990). The competence of processing: Classifying theories of second language acquisition. *TESOL Quarterly, 24,* 635-648.

Bracke-Tolkmitt, R., Linden, A., Canavan, A. G., Rockstroh, B., Scholz, E., Wessel, K. & Diener, H. C. (1989). The cerebellum contributes to mental skills. *Behavioral Neuroscience, 103,* 442-446.

Bridgeman, B. (1992). Conscious vs unconscious processes: The case of vision. *Theory & Psychology, 2,* 73-88.

Celce-Murcia, M. (1992). Formal grammar instruction: An educator comments... *TESOL Quarterly, 26,* 406-409.

Cohen, N. & Squire, L.R. (1980). Preserved learning and retention of pattern analyzing skill in amnesia: A dissociation of knowing how and knowing that. *Science, 210,* 207-210.

Cohen, N. & Squire, L.R. (1981). Retrograde amnesia and remote memory impairment. *Neuropsychologia, 19,* 337-356.

Crain, S. (1991). Language acquisition in the absence of experience. *Behavioral and Brain Sciences, 14,* 597-611.

Faerch, C. & Kasper, G. (1985). Procedural knowledge as a component of foreign language learners' communicative competence. In H. Boete & W. Herrlitz (Eds.), *Kommunikation im (Sprach-) Unterricht* (pp. 169-99). Utrecht: University of Utrecht.

Fuster, J. M. (1988). *The prefrontal cortex.* New York: Raven Press.

Fuster, J. M. (1992). Prefrontal neurons and the cognitive foundation of motor action. *Advances in Neurology, 57,* 351-360.

Geschwind, N. (1970). The organization of language and the brain. *Science, 170,* 940-944.

Ghez, C. (1991). Voluntary movement. In E. Kandel, J. Schwartz & T. Jessell (Eds.), *Principals of Neural Science* (pp. 609-625). New York: Elsevier Science.

Greenfield, P. (1991). Language, tools, and brain: The development and evolution of hierarchically organized sequential behavior. *Brain and Behavioral Sciences, 14,* 531-550.

Greenough, W. & Anderson, B. (1991). Cerebellar synaptic plasticity. *Annals of the New York Academy of Sciences, 627,* 231-247.

Gregg, K. (1984). Krashen's monitor and Occam's razor. *Applied Linguistics, 5,* 79-100.

Harrington, D., Haaland, K., Yeo, R. & Marder, E. (1989). Procedural memory in Parkinson's disease: Impaired motor but not visuoperceptual learning. *Journal of Clinical and Experimental Neuropsychology, 12* (2), 323-339.

Ivry, R.B. & Keele, S.W. (1989). Timing functions of the cerebellum. *Journal of Cognitive Neuroscience, 1,* 136-152.

Jacobs, B. (1988). Neurobiological differentiation of primary and secondary language acquisition. *Studies in Second Language Acquisition, 10,* 303-37.

Jacobs, B. & Schumann, J. (1992). Language acquisition and the neurosciences: Towards a more integrative perspective. *Applied Linguistics, 13,* 282-301.

Karmiloff-Smith, A. & Johnson, M.H. (1991). Constructivism without tears. *Behavioral and Brain Sciences, 14,* 565-565.

Klein, W. (1990). A theory of language acquisition is not so easy. *Studies in Second Language Acquisition, 12,* 219-231.

Kleiter, G.D. & Schwarzenbacher, K. (1989). Beyond the answer: Post-error processes. *Cognition, 32,* 255-277.

Krashen, S.D. (1981). *Second language acquisition and second language learning*. Oxford, UK: Pergamon Press.

Krashen, S.D. (1992). Formal grammar instruction: Another educator comments... *TESOL Quarterly, 26,* 409-412.

Kupfermann, I. (1991). Learning and memory. In E. Kandel, J. Schwartz & T. Jessell (Eds.), *Principals of Neural Science* (pp. 997-1008). New York: Elsevier Science.

Lamendella, J. (1979). The neurofunctional basis of pattern practice. *TESOL Quarterly, 13*, 5-19.

Leiner, H. C., Leiner, A. L. & Dow, R. S. (1986). Does the cerebellum contribute to mental skills? *Behavioral Neuroscience, 100*, 443-454.

Leiner, H. C., Leiner, A. L. & Dow, R. S. (1987). Cerebro-cerebellar learning loops in apes and humans. *Italian Journal of Neurological Sciences, 8*, 425-436.

Leiner, H. C., Leiner, A. L. & Dow, R. S. (1989). Reappraising the cerebellum: What does the hindbrain contribute to the forebrain? *Behavioral Neuroscience, 103*, 998-1008.

Leiner, H. C., Leiner, A. L. & Dow, R. S. (1991). The human cerebro-cerebellar system: Its computing, cognitive, and language skills. *Behavioural Brain Research, 44*, 113-128.

Loritz, D. (1991). Cerebral and cerebellar models of language learning. *Applied Linguistics, 12*, 299-318.

McClelland, J. L., Rumelhart, D. E., & the PDP Research Group Eds.). (1986). *Parallel distributed processing: Explorations in the microstructure of cognition* (vol.2: *Psychological and biological models*). Cambridge, MA: MIT Press.

McCormick, D. & Thompson, R. F. (1984). Cerebellum: Essential involvement in the classically conditioned eyelid response. *Science Washington D.C., 223*, 296-299.

McLaughlin, B. (1987). *Theories of second language learning*. London: Edward Arnold.

McLaughlin, B. (1990). "Conscious" versus "unconscious" learning. *TESOL Quarterly, 24*, 617-634.

Milner, B. (1966). Amnesia following operation on the temporal lobes. In C. Whitty & O. Zangwill (Eds.), *Amnesia* (pp.109-133). London: Butterworth.

Novoa, O. P. & Ardila, A. (1987). Linguistic abilities in patients with prefrontal damage. *Brain and Language, 30*, 206-225.

Ojemann, G. A. (1987). Language, Neurology of. *Encyclopedia of Neuroscience* (pp.556-558) Boston, MA: Birkhauser.

Ojemann, G. A. (1991). Cortical organization of language. *The Journal of Neuroscience, 11*, 2281-2287.

O'Malley, J. & Chamot, A. (1990). *Learning strategies in second language acquisition*. Cambridge: Cambridge University.

Peterson, S., Fox, P., Posner, M., Mintun, M. & Raichle, M. (1989). Positron emission tomographic studies of the processing of single words. *Journal of Cognitive Neuroscience, 1*, 153-170.

Pinker, S. & Prince, A. (1988). On language and connectionism: Analysis of a parallel distributed processing model of language acquisition. *Cognition, 28*, 73-193.

Plummer, J. R. (1991). LTP as a mechanism for memory of language. Unpublished manuscript. University of California, Los Angeles.

Purves, D. & Lichtman, J. W. (1980). Elimination of synapses in the developing nervous system. *Science Washington DC, 210,* 153-157.

Raichle, M. (1990). Anatomical explorations of mind: Studies with modern imaging techniques. *Cold Spring Harbor Symposia on Quantitative Biology,* 983-986.

Schmahmann, J. (1991). An emerging concept: The cerebellar contribution to higher function. *Archives of Neurology, 48,* 1178-1187.

Sokolik, M. E. (1990). Learning without rules - PDP and a resolution of the adult language learning paradox. *TESOL Quarterly, 24,* 685-696.

Squire, L. R. (1982). The neuropsychology of human memory. *Annual Review of Neuroscience, 5,* 241-273.

Squire, L. R. (1985). Memory: Neural organization and behavior. In J. Brookhart & V. Mountcastle (Eds.), *Handbook of physiology: The nervous system V* (pp. 295-371). Bethesda, MD: American Physiological Society.

Squire, L. R. (1986). The neuropsychology of memory dysfunction and its assessment. In I. Grant & K. Adams (Eds.), *Neuropsychological assessment of neuropsychiatric disorders* (pp. 268-299). New York: Oxford University.

Squire, L. R. (1987). *Memory and brain.* New York: Oxford University.

Squire, L. R., Zola-Morgan, S., Cave, C. B., Haist, F., Musen, G. & Suzuki, W. A. (1990). Memory: Organization of brain systems and cognition. *Cold Spring Harbor Symposia on Quantitative Biology, LV,* 1007-1023.

Squire, L. R. & Zola-Morgan, S. (1991). The medial temporal lobe memory system. *Science, 253,* 1380-1386.

Stuss, D. T. & Benson, D. F. (1984). Neuropsychological studies of the frontal lobes. *Psychological Bulletin, 95,* 3-28.

Thompson, R. F. (1986). The neurobiology of learning and memory. *Science, 233,* 941-947.

Thompson, R. F. (1987). Learning and memory, neural mechanisms. *Encyclopedia of Neuroscience* (pp.574-576). Boston, Massachusetts: Birkhauser.

Thompson, R. F. (1989). The cerebellum: Motor skills, procedural learning, and memory and hyperactivity. In T. Sagvolden & T. Archer (Eds.), *Attention deficit disorder: Clinical and basic research* (pp. 339-351). New Jersey: Laurence Erlbaum Associates.

Tsukahara, N. (1984). Classical conditioning mediated by the red nucleus: An approach beginning at the cellular level. In G. Lynch, J. McGaugh & N. Weinberger (Eds.), *Neurobiology of learning and memory* (pp. 165-180). New York: Guilford Press.

Tulving, E. (1987). Multiple memory systems and consciousness. *Human Neurobiology, 6,* 67-80.

Warrington, E. & Weiskrantz, L. (1982). Amnesia: A disconnection syndrome? *Neuropsychologia, 20,* 233-248.

Wendon, A. (1991). *Learner strategies for learner autonomy.* New York: Prentice-Hall International.

Widdowson, H. G. (1990). *Aspects of language teaching*. Oxford, UK: Oxford University Press.

Winograd, T. (1975). Computer memories: A metaphor for memory organization. In C. Cofer (Ed.), *The structure of human memory* (pp.485-506). San Francisco, CA: Freeman.

Scarlett Robbins is a Ph.D. student in the Applied Linguistics program at UCLA. She holds an M.A. in Linguistics from the University of California, Santa Cruz. Her research interests include: first and second language acquisition, the neurobiology of memory and learning, and phonology.