FIVE

A Cognitive Neuroscience Perspective on Second Language Acquisition: The Declarative/Procedural Model

MICHAEL T. ULLMAN

KEY WORDS

Aphasia ▪ basal ganglia ▪ Broca's area ▪ critical period ▪ declarative memory ▪ ERP ▪ estrogen ▪ explicit ▪ fMRI ▪ frontal lobe ▪ grammar ▪ implicit ▪ language ▪ language processing ▪ lexicon ▪ morphology ▪ neuroimaging ▪ PET ▪ procedural memory ▪ puberty ▪ second language ▪ second language acquisition (SLA) ▪ syntax ▪ temporal lobe.

1. Introduction

The neural, cognitive, and computational (i.e., neurocognitive) bases of second language acquisition and processing are still not well understood. There has been surprisingly little empirical work in this area. Data informing the specific neural substrates of second language and the relations between its neural, cognitive, and computational underpinnings have been especially sparse (e.g., what brain structures play which computational roles and how do they interact?). Given this lack of data, it is not surprising that there have been few attempts to offer integrative neurocognitive theories of second language, particularly in the context of first language and of our broader understanding of the mind and brain.

In this chapter, I discuss a neurocognitive model that begins to address these theoretical gaps. According to this perspective, both first and second languages are acquired and processed by well-studied brain systems that are known to subserve particular nonlanguage functions. These brain systems are posited to play analogous roles in their nonlanguage and language functions. So our independent knowledge of the cognitive, computational, neuroanatomical, physiological, cellular, endocrine, and pharmacological bases of these systems leads to specific testable predictions about both first and second language. The model thus brings the knowledge base and empirical approaches of cognitive neuroscience to bear on the study of second language acquisition (SLA).

This chapter begins by discussing the broader linguistic and neurocognitive issues, along with the neurocognitive model as it pertains to normal early-learned first language (L1). Next, the background, theory, and extant empirical evidence regarding the acquisition and processing of second and subsequent languages are presented, with a focus on later-learned languages, particularly those learned after puberty. (Note that the term *L2* is used in this chapter to refer only to such later-learned languages.) Finally, the chapter concludes with comparisons between the model and other perspectives and with a discussion of implications and issues for further study.

2. The Neurocognition of Lexicon and Grammar

Language depends upon two mental abilities (Chomsky, 1965; Pinker, 1994). First, all idiosyncratic information must be memorized in some sort of mental dictionary, which is often referred to as the mental lexicon. The lexicon necessarily includes all words with arbitrary sound-meaning pairings, such as the noncompositional ("simple") word *cat.* It must also contain other irregular—that is, not entirely derivable—word-specific information, such as whether any arguments must accompany a verb (e.g., *hit* requires a direct object) and whether a word takes any unpredictable related forms (e.g., *teach* takes the irregular past tense *taught*). The mental lexicon may comprise other distinctive information as well, smaller or larger than words: bound morphemes (e.g., the *-ed* or *-ness* suffixes, as in *walked* or *happiness*) and complex linguistic structures whose meanings cannot be transparently derived from their parts (e.g., idiomatic phrases, such as *kick the bucket*) (Di Sciullo and Williams, 1987; Halle and Marantz, 1993).

But language also consists of regularities, which can be captured by rules of grammar. The rules constrain how lexical forms combine to make complex representations and allow us to interpret the meanings of complex forms even if we have not heard or seen them before. Meanings can be derived by rules that underlie the sequential orders and hierarchical relations of lexical items and of abstract categories such as *verb phrase.* Such rule-governed behavior is found in various aspects of language, including phrases and sentences (syntax) and complex words such as *walked* or *happiness* (morphology). The rules are a form of mental knowledge in that they underlie our individual capacity to produce and comprehend complex forms. The learning and use of this knowledge are generally implicit—that is, not available to conscious awareness. Last, although complex representations (e.g., the regular past tense form *walked*) could be computed anew each time (e.g., *walk* + *-ed*), they could in principle also be stored in the mental lexicon.

Numerous theories and empirical studies have probed the neurocognitive bases of lexical and grammatical abilities in L1 (e.g., Damasio and Damasio, 1992; Elman et al., 1996; Friederici, 2002; Gleason and Ratner, 1998; Goodglass, 1993; Pinker, 1994). This research has addressed several interrelated issues, including the following: (a) separability: Do lexicon and grammar depend on distinct components that rely on separable neurocognitive correlates? (b) mechanisms: What mechanisms underlie the learning, representation, computation, and processing of the two linguistic capacities? (c) domain specificity: Are the underlying neurocognitive substrates dedicated to language (domain specific) or do they also subserve nonlanguage functions (that is, are they domain independent)? (d) biological correlates: What are the biological correlates of lexicon and grammar, be they brain structures, neural circuits, or molecular systems? What is the temporal order of their involvement during processing and how do they interact?

Here I focus on one theoretical perspective—the declarative/procedural (DP) model (Ullman, 2001a, 2001c; Ullman, 2004; Ullman et al., 1997)—which addresses these and related issues. The basic premise of the DP model is that aspects of the lexicon-grammar distinction are tied to the distinction between two well-studied brain memory systems (Ullman, 2001c; Ullman, 2004), declarative and procedural memory, that have been implicated in nonlanguage functions in humans and other animals (Mishkin, Malamut, and Bachevalier, 1984; Schacter and Tulving, 1994; Squire and Knowlton, 2000; Squire and Zola, 1996). In the following two sections, I first discuss the nature of the two memory systems and then present the claims and predictions of the DP model as they pertain to L1.

3. Declarative and Procedural Memory

The *declarative memory system* underlies the learning, representation, and use of knowledge about facts (semantic knowledge) and events (episodic knowledge) (Eichenbaum and Cohen, 2001; Mishkin et al., 1984; Schacter and Tulving, 1994; Squire and Knowlton, 2000). This system may be particularly important for learning arbitrary relations (e.g., that fact that Ouagadougou is the capital of Burkina Faso) (Eichenbaum and Cohen, 2001). The knowledge learned in declarative memory is at least partly (but not completely; Chun, 2000) explicit, that is, available to conscious awareness. The memory system is subserved by medial temporal lobe regions (e.g., the hippocampus), which are connected extensively with temporal and parietal neocortical regions (Suzuki and Amaral, 1994). The medial temporal structures consolidate, and possibly retrieve, new memories (Eichenbaum and Cohen, 2001; Mishkin et al., 1984; Schacter and Tulving, 1994; Squire and Knowlton, 2000). Memories seem to eventually become independent of these

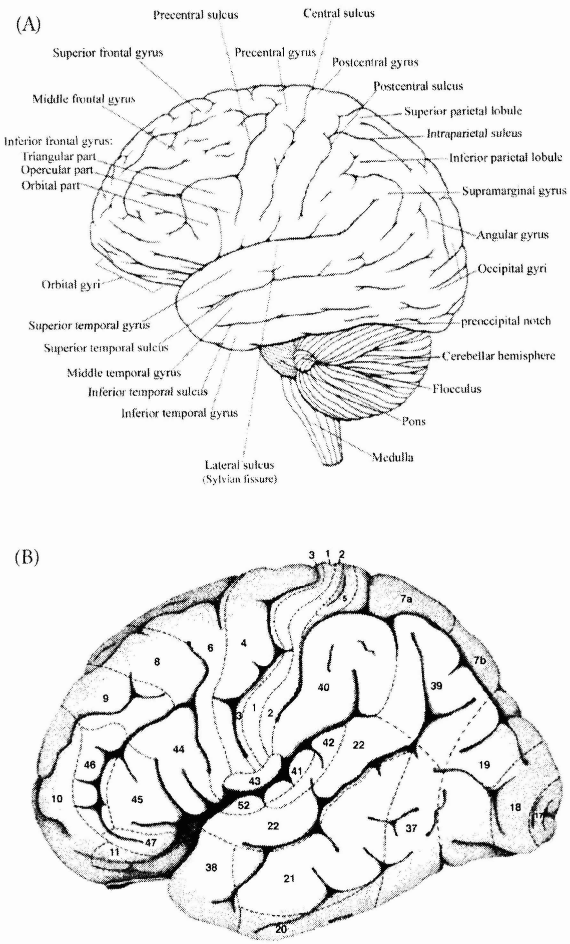
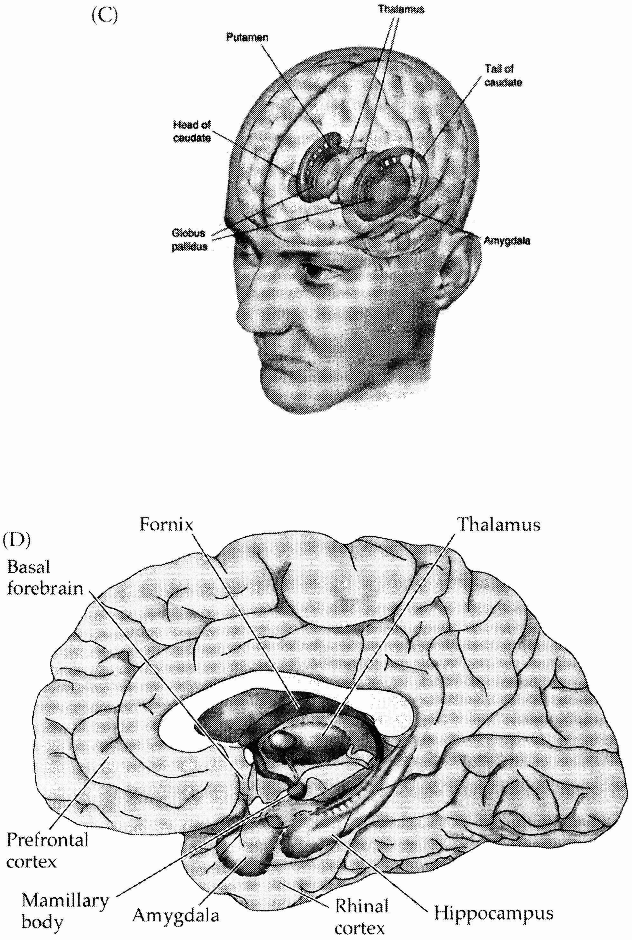


FIGURE 5.1. *Structures and regions of the brain: (A) A lateral view of anatomical structures in the left hemispheres of the cerebrum and the cerebellum. The same structures are found on the right side. There are four lobes in each hemisphere of the cerebrum. The frontal lobe lies anterior to (in front of) the central sulcus, above the lateral sulcus. The temporal lobe lies inferior to (below) the lateral sulcus, going back to the occipital lobe at the back of the brain. The parietal lobe lies posterior to (behind) the central sulcus and superior to (above) the temporal lobe. (B) Brodmann's areas of the lateral aspect of the left hemisphere. The same areas are found in the right hemisphere. Not shown are the Brodmann's areas of the medial aspect of the cerebrum. (C) A whole-head view of certain subcortical structures, including the basal ganglia. In each hemisphere, the basal ganglia consist of several substructures, of which the caudate, putamen, and*



globus pallidus are indicated here. (D) A medial view of the cerebrum, including the hippocampus and various structures to which it is closely connected. Figure 5.1A from the public domain. Figure 5.1B from The human brain: Surface, three-dimensional sectional anatomy, and MRI *(p. 44), by Henri M. Duvernoy, New York: Springer. Copyright 1991. Reprinted with permission. Figure 5.1C from "Human diencephalon," by Jacob L. Drisen, http:// www.driesen.com/ basalganglia-2.jpg. Copyright 2005 by Jacob L. Driesen, PhD. Reprinted with permission. Figure 5.1D from* Neuroscience *(2nd ed.), "Brain areas associated with declarative memory disorders," by Dale Purves, George J. Augustine, David Fitzpatrick, Lawrence C. Katz, Anthony-Samuel LaMantia, James O. McNamara, and S. Mark Williams (Eds.). Sunderland, MA.: Sinauer Associates. Copyright 2001. Reprinted with permission.*

structures and dependent on neocortical regions, particularly in the temporal lobes (Hodges and Patterson, 1997; Martin, Ungerleider, and Haxby, 2000). Other brain structures also play a role in declarative memory. Portions of ventro-lateral prefrontal cortex (corresponding largely to Brodmann's area [BA] 45 and BA 47) seem to play a role in the selection or retrieval of declarative memories, while parts of the right cerebellum may underlie searching for this knowledge (Buckner and Wheeler, 2001; Desmond and Fiez, 1998; Ivry and Fiez, 2000; Wagner et al., 1998). Note that I use the term *declarative memory system* to refer to the entire system involved in the learning and use of the relevant knowledge (Eichenbaum, 2000), not just to those structures underlying memory consolidation.

The declarative memory system has been intensively studied not only from functional and neuroanatomical perspectives but also at cellular and molecular levels (H. V. Curran, 2000; Lynch, 2002). The neurotransmitter acetylcholine plays a particularly important role in declarative memory and hippocampal function (Freo, Pizzolato, Dam, Ori, and Battistin, 2002; Packard, 1998). (Neurotransmitters are molecules that allow communication between neurons.) Evidence also suggests that the declarative memory system is affected by estrogen (Phillips and Sherwin, 1992; Sherwin, 1988), perhaps via the modulation of acetylcholine (Packard, 1998; Shughrue, Scrimo, and Merchenthaler, 2000). For example, estrogen improves declarative memory in women (Maki and Resnick, 2000; Sherwin, 1998) and men (Kampen and Sherwin, 1996; Miles, Green, Sanders, and Hines, 1998), and strengthens the cellular and molecular correlates of long-term hippocampal learning (McEwen, Alves, Bulloch, and Weiland, 1998; Woolley and Schwartzkroin, 1998). Moreover, testosterone, which is the main source of estrogen in men, also improves their memory (Cherrier et al., 2001).

The *procedural memory system* is implicated in the learning of new, and in the control of long-established, motor and cognitive skills and habits, especially those involving sequences (Aldridge and Berridge, 1998; Boecker et al., 2002; Mishkin et al., 1984; Schacter and Tulving, 1994; Squire and Knowlton, 2000; Willingham, 1998). Neither the learning nor the remembering of these procedures appears to be accessible to conscious memory. Thus the system is often referred to as an *implicit memory* system. (I use the term *procedural memory* to refer only to one type of implicit, nondeclarative memory system, Squire and Zola, 1996, not to all such systems; see also section 8 below.) The system is composed of a network of several interconnected brain structures (De Renzi, 1989; Heilman, Watson, and Rothi, 1997; Hikosaka et al., 2000; Jenkins, Brooks, Nixon, Frackowiak, and Passingham, 1994; Mishkin et al., 1984; Rizzolatti, Fogassi, and Gallese, 2000; Schacter and Tulving, 1994; Squire and Zola, 1996). It depends especially on structures in the left hemisphere of the cerebrum (De Renzi, 1989; Heilman et al., 1997; Schluter, Krams, Rushworth, and Passingham, 2001) and is rooted in neural circuits that encompass the frontal lobes and the basal ganglia, which are subcortical structures that are strongly connected to frontal cortex. Evidence suggests that particular neurotransmitters of these circuits, especially dopamine, underlie aspects of procedural learning (Harrington, Haaland, Yeo, and Marder, 1990; Nakahara, Doya, and Hikosaka, 2001; Saint-Cyr, Taylor, and Lang, 1988). Within frontal cortex, two areas play particularly important roles: premotor areas, especially the region of the supplementary motor area (SMA and pre-SMA); and Broca's area, especially posterior portions of this region, corresponding largely to BA 44 (Broca's area is defined here as a part of inferior frontal cortex, including and perhaps limited to cortex corresponding to BA 44 and 45; Amunts et al., 1999). Other brain structures also form part of the procedural system network, including portions of inferior parietal cortex and the cerebellum (Hikosaka et al., 2000; Rizzolatti, Fogassi, and Gallese, 2001; Schacter and Tulving, 1994; Squire and Zola, 1996; Ullman, 2004; Willingham, 1998). Note that I use the term *procedural memory system* to refer to the entire system involved in the learning and use of motor and cognitive skills, not just to those brain structures underlying their acquisition.

The declarative and procedural memory systems interact in a number of ways. Essentially, the systems together form a dynamically interacting network that yields both cooperative and competitive learning and processing, such that memory functions may be optimized (Poldrack and Packard, 2003). First of all, the two systems can complement each other in acquiring the same or analogous knowledge, including knowledge of sequences. As was initially shown in the amnesic patient H.M., the declarative memory system need not be intact for the procedural memory system to learn (Corkin, 1984; Eichenbaum and Cohen, 2001; Squire and Knowlton, 2000). However, when both systems are functioning, they can be used cooperatively to learn a given task (Willingham, 1998). The declarative memory system may be expected to acquire knowledge initially, thanks to its rapid learning abilities, while the procedural system may gradually learn the same or analogous knowledge (Packard and McGaugh, 1996; Poldrack and Packard, 2003). Interestingly, the time course of this shift from declarative to procedural memory can be modulated pharmacologically (Packard, 1999).

Second, animal and human studies suggest that the two systems also interact competitively (for reviews, see Packard and Knowlton, 2002; Poldrack and Packard, 2003; Ullman, 2004). This leads to a "see-saw effect" (Ullman, 2004), such that a dysfunction of one system results in enhanced learning in the other or that learning in one system depresses the functionality of the other (Halbig et al., 2002; McDonald and White, 1993; Mitchell and Hall, 1988; Packard, Hirsh, and White, 1989; Poldrack and Packard, 2003; Poldrack et al., 2001; Poldrack, Prabhakaran, Seger, and Gabrieli, 1999; Schroeder, Wingard, and Packard, 2002; Ullman, 2004). The see-saw effect may be explained by a number of factors (Ullman, 2004), including direct anatomical projections between the two systems (Sorensen and Witter, 1983) and a role for acetylcholine, which may not only enhance declarative memory but might also play an inhibitory role in brain structures underlying procedural memory (Calabresi, Centonze, Gubellini, Marfia et al., 2000). Estrogen may also contribute to the see-saw effect, perhaps via the modulation of acetylcholine (Ullman, 2004).

The two memory systems display variability in their functioning across individuals. That is, individuals differ in their ability to learn or use knowledge in one or the other system. Of particular interest here is that evidence suggests sex differences in the functionality of the two systems. Women show an advantage over men at verbal memory tasks (Halpern, 2000; Kimura, 1999; Kramer, Delis, Kaplan, O'Donnell, and Prifitera, 1997), which depend on declarative memory (Squire and Knowlton, 2000; Wagner et al., 1998). This sex difference does not seem surprising in light of the higher levels of estrogen in girls and (premenopausal) women than in boys and men (Cutler Jr., 1997; K. Klein, Baron, Colli, McDonnell, and Cutler, 1994; Wilson, Foster, Kronenberg, and Larsen, 1998). Conversely, evidence suggests that men show superior performance at a variety of tasks, such as aimed throwing and mental rotation (Kimura, 1999), which are expected to depend on the procedural system network (Ullman and Pierpont, 2005). Intriguingly, across the menstrual cycle in females, performance on some of these "male" tasks decreases with increasing estrogen and increases with decreasing estrogen (Hampson, 1990; Kimura, 1999), strengthening the view that estrogen may play a role in the see-saw effect.

4. The DP Model and L1

According to the DP model, in L1 the declarative memory system underlies the mental lexicon, whereas the procedural memory system subserves aspects of the mental grammar. (For additional discussion, see Ullman, 2001a, 2001c; Ullman, 2004; Ullman et al., 1997). Each of the two memory systems is posited to play analogous roles in its nonlinguistic and linguistic functions. Declarative memory is an associative memory that stores not only information about facts and events but also lexical knowledge, including the sounds and meanings of words. Learning new words relies largely on medial temporal lobe structures. Eventually the knowledge of words becomes largely independent of the medial temporal lobe and depends upon neocortical areas, particularly in temporal and temporo-parietal regions. Middle and inferior aspects of the temporal lobe may be particularly important for storing word meanings, whereas superior temporal and temporo-parietal regions may be more important in storing phonological word forms and possibly also for stored complex morphological and syntactic structures. These latter regions could thus serve as one type of interface between the declarative and procedural systems. Ventrolateral prefrontal cortex underlies the retrieval or selection of lexical representations stored in the temporal brain regions, while portions of the right cerebellum may underlie searching for that knowledge. Thus these frontal and cerebellar structures may be less important in receptive than in expressive language. Finally, pharmacological manipulations of acetylcholine, and endocrine manipulations of estrogen, should modulate aspects of lexical memory.

The procedural system network of brain structures subserves the implicit learning and use not only of motor and cognitive skills but also aspects of a rule-governed combinatorial grammar. The system is expected to play computationally analogous roles across grammatical subdomains, including morphology, syntax, and possibly phonology. It may be especially important in grammatical structure building—that is, the sequential and hierarchical combination of stored lexical forms (e.g., *walk* + *-ed*) and abstract representations (e.g., verb phrase) into complex structures. Pharmacological manipulations of dopamine, and possibly the modulation of estrogen and acetylcholine, may be expected to affect the acquisition of grammatical knowledge.

The two systems should interact both cooperatively and competitively in the acquisition and use of language. For example, young children should initially learn both idiosyncratic and complex forms in declarative memory, while the procedural system gradually acquires the grammatical knowledge underlying rule-governed combinations. Increased functionality in one system may depress the other and vice versa. Thus the improvements found in declarative memory during childhood (Di Giulio, Seidenberg, O'Leary, and Raz, 1994; Kail and Hagen, 1977; Ornstein, 1978) should not only facilitate lexical acquisition but may also eventually depress the procedural learning of grammatical knowledge.

Individual differences in the acquisition and use of lexical and grammatical knowledge, including sex differences, are expected. Thanks to their advantage at declarative memory, females should show superior lexical abilities as compared to males. In contrast, males may demonstrate better performance at aspects of grammar that depend on the procedural system. This difference in the functionality of the two systems also leads to the prediction that females will tend to memorize complex forms (e.g., *walked*) that men generally compute compositionally in the grammatical-procedural system (e.g., *walk* + *-ed*) (Ullman, 2004; Ullman et al., 2002).

Thus the DP model posits that lexical and grammatical functions are largely separable and are associated with distinct computational and neural substrates that are not dedicated to language but are rather domain independent. These substrates are well-studied brain memory systems, whose functionality may be modulated by particular pharmacological and endocrine substances and which vary with some degree of predictability across the lifespan of and between individuals.

This view contrasts with two competing theoretical frameworks. Although it shares the view of traditional "dual system" or "modular" theories that lexicon and grammar are subserved by two or more distinct systems (Chomsky, 1995; Fodor, 1983; Grodzinsky, 2000; Levelt, 1989; Pinker, 1994), it diverges from their claims that domain-specific components underlie each of the capacities. (For further discussion of the issue of domain specificity, see Ullman, 2004). Conversely, while the DP model agrees with "single mechanism" (e.g., connectionist) theories that the two capacities are subserved by domain-independent mechanisms, it diverges from their claim that both capacities are linked to a single computational mechanism with broad anatomic distribution (Bates and MacWhinney, 1989; Elman et al., 1996; MacDonald, Pearlmutter, and Seidenberg, 1994; Rumelhart and McClelland, 1986; Seidenberg, 1997).

The DP model alone predicts the following double dissociations: One set of links is expected among neurocognitive markers (e.g., neuroimaging activation patterns) of stored linguistic representations, conceptual-semantic knowledge, and declarative memory brain structures. A distinct set of links is expected among neurocognitive markers of grammar (across subdomains, including morphology and syntax), motor and cognitive skills, and procedural memory brain structures. My colleagues and I have previously argued in some depth that converging evidence from a wide range of psycholinguistic, developmental, neurological, electrophysiological, and neuroimaging studies largely supports this view (Ullman, 2001a, 2001c; Ullman, 2004; Ullman et al., 1997).

5. Late-Learned L2

People who learn a language at later ages, particularly after puberty, do not generally acquire the language to the level of proficiency attained by younger learners (Birdsong, 1999; Hyltenstam and Abrahamsson, 2003; Johnson and Newport, 1989; Newport, 1990; Oyama, 1982). However, late language learning does not seem to cause equal difficulties for lexical and grammatical functions. In L1, studies of language-deprived children have shown that late exposure to language results in an apparently irreversible inability to acquire aspects of grammar (particularly in morphology and syntax), whereas lexical acquisition remains relatively spared (S. Curtiss, 1989; S. R. Curtiss, 1977). In L2 the picture appears to be similar. A number of studies have shown that late L2 learning negatively affects the acquisition and/or processing of grammar

(Coppieters, 1987; DeKeyser, 2000; Hahne and Friederici, 2001; Johnson and Newport, 1989; Newport, 1993; Oyama, 1982; Patkowski, 1980; Wartenburger et al., 2003; Weber-Fox and Neville, 1996), while leaving lexical accretion (Eubank and Gregg, 1999) and lexical-conceptual processing (Hahne and Friederici, 2001; Wartenburger et al., 2003; Weber-Fox and Neville, 1996) relatively intact. However, it does not appear to be the case that late learning necessarily precludes nativelike attainment, even of grammatical abilities. Rather, a number of studies have suggested that such attainment is not in fact all that rare, given sufficient exposure to the L2 (Birdsong, 1992; Birdsong and Molis, 2001; Cranshaw, 1997; Van Wuijtswinkel, 1994; White and Genesee, 1996).

6. The DP Model and L2

The DP model makes a somewhat different set of claims and predictions for late-learned L2 than for L1 (see also Ullman, 2001b; Ullman, 2004). At least during early adulthood (see below for a discussion of L2 learning later in the lifespan), the acquisition of grammatical-procedural knowledge is expected to be more problematic than the acquisition of lexical-declarative knowledge, as compared to language learning in young children. This may be due to one or more factors that directly or indirectly affect one or both brain systems, including decreased rule-abstraction abilities due to augmented working memory capacity (see Newport, 1993), the attenuation of procedural memory, and the enhancement of declarative memory. Evidence from humans and animals suggests that motor skill learning associated with the procedural system is subject to early critical period effects (Fredriksson, 2000; Schlaug, 2001; Walton, Lieberman, Llinas, Begin, and Llinas, 1992; Wolansky, Cabrera, Ibarra, Mongiat, and Azcurra, 1999). In contrast, there are clear improvements in declarative memory during childhood, with a possible plateau in adolescence (Campbell and Spear, 1972; Di Giulio et al., 1994; Kail and Hagen, 1977; Meudell, 1983; Ornstein, 1978; Siegler, 1978). The changes in both procedural and declarative memory may be at least partly explained by the increasing levels of estrogen that occur during childhood/adolescence (in boys as well as girls, though estrogen levels are higher in girls) (Ankarberg and Norjavaara, 1999; Cherrier et al., 2001; Cutler Jr., 1997; K. Klein et al., 1994; Klein, Martha, Blizzard, Herbst, and Rogol, 1996), since estrogen may somehow inhibit the procedural memory system as well as enhance declarative memory (Calabresi, Centonze, Gubellini, Pisani, and Bernardi, 2000; Packard, 1998; Phillips and Sherwin, 1992; Sherwin, 1988; Shughrue et al., 2000; Ullman, 2004) (also see discussion above). Additionally, the competitive interaction between the two memory systems, such that learning in one system depresses functionality of the other, leads to the possibility that the improvements in declarative memory during childhood may be accompanied by an attenuation of procedural learning abilities.

Thanks to their relative facility at declarative as compared to procedural learning, young adult L2 learners should tend to rely heavily on declarative memory, even for functions that depend upon the procedural system in L1. In particular, L2 learners should tend to memorize complex linguistic forms (e.g., *walked*) that can be computed compositionally by L1 speakers (e.g., *walk* + *-ed*). Associative properties of lexical memory (Hartshorne and Ullman, in press; Pinker, 1999; Prasada and Pinker, 1993) may lead to productivity in L2. L2 learners can also learn rules in declarative memory (e.g., in a pedagogical context), providing an additional source of productivity. Note that such rules do not depend at all upon grammatical-procedural computations; indeed, what they specify could in principle differ radically from the grammatical-procedural rules of native speakers of the target language.

Memorizing complex forms and rules in declarative memory may be expected to lead to a fairly high degree of proficiency, the level of which should vary according to a number of factors. These include the amount and type of L2 exposure and individual subject differences regarding declarative memory abilities. Thus women's advantage at declarative memory should provide them with advantages at L2 learning. However, not all types of "grammatical" knowledge should be equally learnable in declarative memory. Certain complex forms will be easier to memorize than others, such as those that are shorter or more frequent. Constructions that cannot be easily memorized, such as those that involve long-distance dependencies, should cause particular difficulties. Similarly, not all declarative-memory based rules should be equally easy to learn or apply. The limitations of lexical-declarative memory lead to the expectation that this system alone is unlikely to provide full grammatical proficiency. That is, by itself this system is not predicted to supply all functions subserved by the grammatical-procedural system in L1, and so reliance on this system alone should not lead to nativelike proficiency in all aspects of grammar.

Crucially, however, the complete dysfunction of the grammatical system in L2 is *not* expected. Rather, in accordance with multiple studies of the adult acquisition of nonlinguistic skills by procedural memory (Mishkin et al., 1984; Schacter and Tulving, 1994; Squire and Knowlton, 2000; Squire and Zola, 1996), practice should lead to procedural learning and improved performance. Thus with sufficient experience with L2, the language is expected to become L1-like in its grammatical dependence on the procedural system, with the potential for a high degree of proficiency. Whether or not a given individual acquires a given set of grammatical knowledge in the procedural system will depend on factors such as the type of grammatical knowledge being learned, the nature of the L2 exposure, and characteristics of the learner, such as intrinsic procedural learning abilities. Thus, whereas women should tend to show a faster learning rate than men during early stages of L2 learning (due to females' superior declarative memory abilities), men may show an advantage in later stages (due to a possible male advantage at procedural memory).

The claims and predictions laid out above for young adults differ somewhat for older adults. The ability to learn new information in declarative memory begins to decline in early adulthood, with more notable losses in old age (Park et al., 2002; Prull, Gabrieli, and Bunge, 2000). This pattern may be at least partly explained by the fact that estrogen levels decline with age in both sexes, especially during later years and especially in women (i.e., postmenopausal declines) (Carlson and Sherwin, 2000; Carr, 1998; Ferrini and Barrett-Connor, 1998; Sherman, West, and Korenman, 1976). To complicate matters further, while some forms of procedural learning are spared with aging, others, such as the learning of sequences containing higher level structure, appear to decline gradually across the adult years (Churchill, Stanis, Press, Kushelev, and Greenough, 2003; T. Curran, 1997; Feeney, Howard, and Howard, 2002; Howard, Howard, Dennis, Yankovich, and Vaidya, 2004; Prull et al., 2000). Therefore older adults may have more difficulty than young adults with procedural as well as declarative aspects of L2 acquisition.

Thus the age-of-exposure effects in L2 acquisition that are predicted to occur across childhood and adolescence differ qualitatively from those expected to take place during adulthood. Whereas in the former case the decline in language-learning ability is predicted from a decreasing reliance on procedural memory relative to declarative memory, in the latter case the decline follows primarily from problems with declarative memory, which may be further aggravated by difficulties with procedural memory. Thus age-of-exposure effects in language learning may be explained by more than one mechanism, with different mechanisms at play during different periods of the lifespan.

In sum, at lower levels of L2 experience, declarative memory is posited to subserve the learning and use not only of idiosyncratic lexical knowledge but also of complex linguistic representations. During early adulthood, women should show an advantage at L2 acquisition as compared to men. Due to the attenuation of declarative memory, older learners (especially postmenopausal women) should have particular difficulty acquiring an L2 even to low proficiency. At higher levels of L2 experience, the procedural system should be able to acquire grammatical knowledge (although again, this may be more difficult for older L2 learners), resulting in a neurocognitive pattern similar to that of L1—that is, with idiosyncratic lexical knowledge stored in declarative memory, while rule-governed complex forms are composed by the procedural system.

So dissociations between simple and complex forms are expected in high-experience L2 and in L1 but less so or not at all in low-experience L2. In direct comparisons between L1 and L2 *within* subjects, the use of complex forms should depend more on declarative memory brain structures in low-experience L2 than in L1 or high-experience L2, in which complex forms should show a greater dependence on procedural memory brain structures. In contrast, idiosyncratic lexical knowledge should be stored in declarative memory in all individuals, and therefore no lexical dissociations between L1 and either low- or high-experience L2 are expected.

7. Empirical Evidence on the Neurocognition of L2

Here I present several lines of neurocognitive evidence which speak to a number of the L2-related claims and predictions of the DP model. For further discussion on some of these data, see Ullman (2001b).

Aphasia generally refers to language impairments that result from relatively circumscribed lesions to the brain. In L1, adult-onset damage to neocortical temporal regions often leads to impaired lexical abilities, while the use of grammatically appropriate complex structures remains relatively spared. In contrast, frontal and basal ganglia lesions often produce impaired performance at grammar (across linguistic domains, including syntax and morphology), leaving lexical knowledge largely intact (Goodglass, 1993; Ullman, 2004; Ullman et al., 1997; Ullman et al., 2005).

Brain damage in L2 speakers yields a different pattern. First of all, relatively circumscribed temporal lobe damage can lead to worse grammatical performance in L2 than in L1 (Ku, Lachmann, and Nagler, 1996; Ullman, 2001b). More importantly, left basal ganglia and left frontal lobe lesions have been shown to produce greater grammatical impairments in L1 than L2, as well as in the more proficient L2 as compared to the less proficient L2 (Fabbro, 1999; Fabbro and Paradis, 1995; Ullman, 2001b). This pattern is particularly striking because the damage leads to more severe problems in the earlier learned and the more proficiently spoken languages. However, left frontal or basal ganglia damage does not appear to lead to differences in *lexical* performance between L1 and L2 or between high- and low-proficiency L2s, even in the same patients who show worse grammatical performance in L1 than L2 or in the more proficient L2 (Fabbro, 1999; Fabbro and Paradis, 1995; Ullman, 2001b). Thus frontal and basal ganglia damage appears to be at least somewhat selective, resulting in particular impairments of grammar in L1 and proficient L2.

Positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) measure changes in blood flow or oxygenation levels in the brain. Since these changes are related to changes in neural activity, the techniques provide an indirect method for pinpointing the brain structures that are active during specific cognitive tasks. The representation and/or processing of both lexical knowledge in L1 and nonlinguistic conceptual-semantic information (i.e., knowledge about the world around us) is strongly linked to activation in temporal and temporo-parietal regions (Damasio, Grabowski, Tranel, Hichwa, and Damasio, 1996; Martin et al., 2000; Newman, Pancheva, Ozawa, Neville, and Ullman, 2001; Ullman, 2004). The selection or retrieval of this knowledge reliably leads to activation in ventro-lateral prefrontal cortex, especially in BA 45 and BA 47 (Buckner, 2000; Fiez, 1997; Poldrack, Wagner et al., 1999; Thompson-Schill, D'Esposito, Aguirre, and Farah, 1997). A wide range of tasks designed to probe syntactic processing in both receptive and expressive language have elicited preferential activation in Broca's area, especially in the region of BA 44 (Caplan, Alpert, and Waters, 1998; Embick, Marantz, Miyashita, O'Neil, and Sakai, 2000; Friederici, 2002; Friederici, 2004; Indefrey, Hagoort, Herzog, Seitz, and Brown, 2001; Moro et al., 2001; Ni et al., 2000; Stromswold, Caplan, Alpert, and Rauch, 1996).

In later-learned second languages, tasks that involve *only* lexical-conceptual processing have been found not to yield more activation in L2 than L1 (Chee, Tan, and Thiel, 1999; Illes et al., 1999; Klein, Milner, Zatorre, Zhao, and Nikelski, 1999; Pillai et al., 2003), suggesting a common neurocognitive basis. Such tasks have also elicited greater activation in L2 than L1 in regions that may reflect the greater demands of the less-well learned L2 on articulation (putamen: Klein, Milner, Zatorre, Meyer, and Evans, 1995; Klein, Zatorre, Milner, Meyer, and Evans, 1994), on working memory (left superior BA 44 and SMA: Chee, Hon, Lee, and Soon, 2001), or on lexical retrieval and selection (left BA 45 and BA 47: Chee et al., 2001; De Bleser et al., 2003).

Tasks that are expected to involve grammatical processing (e.g., sentence comprehension) have generally elicited different activation patterns in L2 and L1, in particular in temporal lobe regions, suggesting a greater dependence on these structures in L2 than in L1. Perani et al. (1996) found greater activation in L2 than L1 only in the parahippocampal gyrus, bilaterally. Similarly, in Perani et al. (1998), the only areas of activation that were found in L2 (as compared to baseline) and not in L1 were in the parahippocampal gyrus (bilaterally) and the left middle temporal gyrus. Dehaene et al. (1997) observed greater activation in L2 than in L1 in several right hemisphere temporal neocortical regions, in the left middle temporal gyrus, and in frontal regions implicated in the retrieval of declarative memories (see above; Buckner and Wheeler, 2001; Ullman, 2004). Note that although Kim, Relkin, Lee, and Hirsch (1997) did not discuss temporal lobe activation differences, the paper reported no data outside left posterior superior temporal cortex. Even early L2 learners have shown a pattern of greater temporal lobe involvement in L2 as compared to L1 (e.g., parahippocampal cortex activation in Perani et al., 1998). However, as would be expected if early-acquired L2 relies on similar neurocognitive correlates as L1, some studies have found no activation differences at all between L1 and very early-acquired L2 (Chee et al., 1999; Wartenburger et al., 2003). Finally, other than the frontal regions associated with retrieval found by Dehaene et al. (1997), greater frontal lobe activation in L2 than L1 has generally *not* been observed (Chee et al., 1999; Kim et al., 1997; Perani et al., 1996; Perani et al., 1998, in neither experiment; Wartenburger et al., 2003, who observed greater frontal activation in late- but not early-acquired L2, as compared to L1, in a grammaticality judgment task).

Intriguingly, a recent fMRI study examining the adult acquisition of an artificial language found that early on during learning, syntactic processing involved the left hippocampus and neocortical temporal regions, including the left middle temporal gyrus (Opitz and Friederici, 2003). However, activation in these brain structures decreased across the experiment (i.e., as experience and proficiency increased), while activation increased in BA 44 within Broca's area. This finding directly supports the DP model's prediction of a shift from the declarative to the procedural system during late L2 learning.

Event-related potentials (ERPs) are scalp-recorded electrical potentials that reflect the real-time electrophysiological brain activity of cognitive processes that are time locked to the presentation of target stimuli, such as words. Lexical processing in L1 and nonlinguistic conceptual processing elicit central-posterior bilateral negativities (N400s) that peak about 400 milliseconds after the presentation of the stimulus (Barrett and Rugg, 1990; Kutas and Hillyard, 1980). The N400 component depends at least in part on temporal lobe structures (McCarthy, Nobre, Bentin, and Spencer, 1995; Nobre, Allison, and McCarthy, 1994; Simos, Basile, and Papanicolaou, 1997) and has been posited to involve the declarative memory system (Ullman, 2001b, 2001c). Lexical stimuli that elicit N400 components in L1 also consistently elicit them in L2, in both low- and high-proficiency speakers (Hahne, 2001; Hahne and Friederici, 2001; McLaughlin, Osterhout, and Kim, 2004; Weber-Fox and Neville, 1996), strengthening the view that lexical-declarative memory is largely available to L2 learners.

In L1, tasks involving the processing of grammatical violations often yield left anterior negativities (LANs) (Friederici, Pfeifer, and Hahne, 1993; Neville, Nicol, Barss, Forster, and Garrett, 1991). LANs have been linked to left frontal cortex and to automatic grammatical processing (Friederici, 2002; Friederici, Hahne, and Mecklinger, 1996; Friederici, Hahne, and von Cramon, 1998). It has been posited that LANs reflect processing by the grammatical-procedural system (Ullman, 2001b, 2001c). In lower proficiency L2, LANs are not found, even when the same violation elicits a LAN in L1 (Hahne, 2001; Hahne and

Friederici, 2001; Weber-Fox and Neville, 1996). Instead of LANs, either no negativities are observed (Hahne, 2001; Hahne and Friederici, 2001), or subjects show more posterior negativities that resemble N400s more than LANs (Ullman, 2001b; Weber-Fox and Neville, 1996). N400s have also been found in very low-proficiency L2 learners for grammatical anomalies that do not elicit a LAN (or an N400) in L1 (Osterhout and McLaughlin, 2000). Together, these findings suggest that grammatical processing in lower proficiency L2 is subserved by brain structures that are at least partially distinct from those subserving grammar in L1 and that overlap, in at least some cases, with those subserving lexical-conceptual processing.

In contrast, an ERP study of adults acquiring an artificial language found that grammatical violations elicited a LAN in highly proficient learners (Friederici, Steinhauer, and Pfeifer, 2002), as would be expected after proceduralization of grammatical knowledge. Similarly, it appears that the only LAN that has been found in a natural language learned as an L2 was elicited by subjects who were proficient in the L2 (Hahne, Muller, and Clahsen, 2003).

Finally, it is interesting to note that the late positive P600 ERP component, which is linked to controlled (that is, not automatic) late syntactic processing in L1 (Friederici et al., 1996) and is *not* posited to depend on procedural processing (Ullman, 2001b, 2001c), is (unlike the LAN) generally displayed by L2 speakers (Hahne, 2001; Osterhout and McLaughlin, 2000; Weber-Fox and Neville, 1996). Its absence in one experiment has been attributed to floor effects, due to higher amplitude positivities in the correct condition in L2 (Hahne and Friederici, 2001).

8. Discussion

In summary, the DP model posits that in the late acquisition of second or subsequent languages, learning grammar in procedural memory is more problematic than learning lexical or other linguistic knowledge in declarative memory, as compared to L1 acquisition. Thus adult second language learners rely particularly heavily on declarative memory, depending on this system not only for storing idiosyncratic lexical knowledge, but also for memorizing complex forms and "rules." However, with sufficient experience with the language, the procedural system should be able to acquire much or perhaps even all of the grammatical knowledge that it subserves in L1. Differences in L2 acquisition abilities are expected across the adult years and between individuals; because learning in declarative memory and possibly procedural memory becomes more problematic with aging during adulthood, particularly in later years, one should find increasing problems with L2 acquisition during this period. Women should tend to be faster than men at L2 acquisition, at least during initial learning stages, thanks to their advantages at declarative memory, although such advantages may be eliminated following menopause. Estrogen is expected to play an important role in a number of these effects.

Existing behavioral evidence, as well as neurocognitive data from brain-damaged patients, neuroimaging, and event-related potentials, largely supports this perspective. However, many gaps in the data remain. For example, neurocognitive experiments have not probed the relation between L2 and either sex differences or the underlying hormonal status and have ignored changes in L2 acquisition abilities later in the lifespan. Moreover, it is important to point out that not all evidence appears to be consistent with the predictions of the DP model. Corpora studies and some research examining highly proficient L2 learners suggest that late L2 acquisition may impact irregular inflected forms and idiosyncratic language features as much as or more than regular inflected forms and abstract grammatical structure (Birdsong, 1992; Birdsong and Flege, 2001; Flege, Yeni-Komshian, and Liu, 1999; Gass and Selinker, 1994). Moreover, whereas a number of studies suggest an L2 performance advantage of females over males, in measures of general language proficiency (Boyle, 1987; Wen and Johnson, 1997), vocabulary memorization (Gardner and Lambert, 1972; Nyikos, 1990), and reading (Chavez, 2001), other investigations have found no sex differences in listening comprehension (Bacon, 1992), in reading comprehension (Phakiti, 2003), and in overall measures of achievement (Spurling and Ilyin, 1985). Still others have reported an advantage for males in certain vocabulary measures (Boyle, 1987; Scarcella and Zimmerman, 1998) and in reading (Bügel and Buunk, 1996). For further discussion on sex differences in SLA, see Bowden, Sanz, and Stafford (this volume, chapter 4).

These empirical gaps and inconsistencies indicate the need for further studies, in particular for ones that are specifically designed to directly test and potentially falsify the L2-related predictions of the DP model. Crucially, these must probe not only performance but also a range of measures of the neurocognitive correlates of the learning and use of L2. Such studies should control for a variety of item, task, and subject factors that are posited to play important roles in the DP model, such as the idiosyncracy versus regularity of items and the sex, age of acquisition, years of exposure, and hormonal status of subjects.

The DP perspective can be directly compared to and contrasted with a number of previous SLA hypotheses. Moreover, it leads to a number of issues for further discussion, has several implications, and suggests a range of questions for further investigation.

First, it is important to emphasize that the model's claims and predictions regarding L2 are largely motivated by our *independent* knowledge of other areas of study, in particular of L1 and cognitive neuroscience, broadly defined. Our understanding of these areas, including the cognitive, computational, anatomical, physiological, cellular, and molecular bases of the two brain systems lead to a wide array of testable predictions. This offers far greater predictive power than hypotheses whose motivations and claims are largely restricted to language itself. Moreover, the two brain systems can be examined with a range of reliable techniques that are widely used in cognitive neuroscience, complementing and greatly strengthening those methods that have traditionally been employed in the study of SLA. Together, the theoretical and empirical advantages of the perspective presented in this chapter provide the potential to make substantial and rapid advances in our understanding of L2 acquisition and processing.

Second, the DP model offers a novel explanatory framework for age-of-exposure effects—that is, for the greater difficulty in learning languages during later years. The model explains these effects largely in terms of biologically based mechanisms that affect one or both memory systems and that vary both with age and across individuals. Importantly, distinct sets of changes are posited to occur prior to and during adulthood, although in both cases the two memory systems are affected, at least in part, as a consequence of modulation by the endocrine system. This testable neurocognitive perspective differs substantially from previous explanations for age-of-exposure effects (Birdsong, 1999), such as the loss of language-specific learning mechanisms (Bley-Vroman, 1990; Pinker, 1994) and earlier learned languages interfering with L2 learning (MacWhinney, 1987; Rohde and Plaut, 1999).

Third, the model's claims that L2 learners can ultimately become L1-like in their proficiency, as well as in their underlying neurocognitive correlates, contradicts the strong form of the critical period hypothesis, which denies both of these assertions (Bley-Vroman, 1990; Clahsen and Muysken, 1986; Hyltenstam and Abrahamsson, 2003; Johnson and Newport, 1989; Meisel, 1991). Importantly, the prediction of L1-like ultimate attainment in both performance and neurocognition is clearly testable using a number of well established methods.

Fourth, the model strongly emphasizes variation in L2 learning aptitude, both within and across individuals. Within individuals, L2 acquisition abilities are expected to vary not only over the lifespan but even across shorter periods. Thus daily as well as seasonal fluctuations in the level of sex hormones (Kimura, 1999) should affect L2 learning and use. Differences across individuals should vary both between groups (e.g., males vs. females) and between individuals within a group, as a consequence of individual variation in the population in factors such as hormone levels. These claims allow one to make specific predictions regarding the rapidity and ultimate attainment of L2 acquisition. Such predictions may be made not only on the basis of general patterns regarding how the memory systems differ over time and between groups but also on the basis of neurocognitive and performance measures of the two memory systems and their biological correlates (e.g., sex hormone levels) in individual subjects. Moreover, this knowledge of group and individual subject characteristics should allow one to make distinct testable predictions for declarative and procedural aspects of L2 acquisition. For example, whereas young women may tend to show more rapid learning than men during early stages of L2 learning, as well as higher eventual levels of idiosyncratic lexical knowledge, young men might be more likely to reach L1-like levels of grammatical proficiency.

Fifth, because the functional and biological characteristics of the two memory systems are reasonably well understood, one should be able to predict how to manipulate them in order to improve the rate and ultimate proficiency levels of L2 learning. For example, one should be able to exploit the functional characteristics of declarative memory, such as promoting learning in rich semantic contexts (Schacter and Tulving, 1994). The DP model also underscores the view that nativelike attainment may be achieved only through extensive practice (i.e., experience). The amount and type of experience that may be necessary to achieve this, and how experience relates to other factors, such as individual subject learning characteristics, remain to be determined. However, one should be able to optimize L2 acquisition by scheduling learning to take advantage of natural fluctuations in the endocrine system (e.g., daily, monthly, seasonal). The model also suggests a potential role for pharmacological agents in SLA. Cholinergic interventions, which can enhance declarative memory (Freo et al., 2002; Packard, 1998), may facilitate the initial stages of learning posited to depend on this system. Dopaminergic interventions, which under certain circumstances can enhance the procedural system (Gerfen, 1995; Jankovic and Tolosa, 1993), might be helpful in promoting the acquisition of grammatical rules by this system. Moreover, as discussed above, the time course of the shift from declarative to procedural memory can also be modulated pharmacologically (Packard, 1999). Further research is clearly needed to investigate these issues.

Sixth, the model may contribute to our understanding of the much-studied distinction between explicit and implicit knowledge in SLA (Bialystok, 1978, 1979; DeKeyser, 2003; N. C. Ellis, 1994, 2002; Krashen, 1985; Krashen, Scarcella, and Long, 1982; Norris and Ortega, 2001). At first blush, this distinction may seem to correspond quite closely to the declarative-procedural distinction proposed by the DP model, given that declarative memory has been claimed to underlie explicit knowledge while procedural memory subserves implicit knowledge. However, there are a number of critical differences. First of all, the DP model is based on claims about neurocognitive systems, whereas the explicit-implicit distinction is premised on claims about awareness. This latter distinction is somewhat problematic in that awareness is difficult not only to define but also to test (DeKeyser, 2003; Doughty, 2003; Schmidt, 1994). In contrast, the distinction between the declarative and procedural brain systems is relatively clear, and the dichotomy can be tested with a variety of methodological approaches.

It is also important to note that the mapping between declarative-procedural memory on the one hand, and explicit-implicit knowledge on the other, is by no means isomorphic (one-to-one). Information stored in declarative memory may very well be explicit (accessible to conscious awareness in some sense), but there is no requirement that it must be, and recent data suggest that at least certain kinds of knowledge acquired by the declarative memory system are not explicit (Chun and Phelps, 1999; Chun, 2000). Additionally, evidence suggests the existence of more than one nondeclarative implicit memory system (Eichenbaum and Cohen, 2001; Squire and Knowlton, 1995). Procedural memory, as it is defined in the DP model and by many memory researchers, refers only to one type of nondeclarative memory system (Eichenbaum and Cohen, 2001; Squire and Knowlton, 1995; Ullman, 2001c; Ullman, 2004; Ullman and Pierpont, 2005). Unfortunately, the term *procedural memory* has sometimes been used interchangeably with *implicit memory,* resulting in quite a confusing situation (Eichenbaum and Cohen, 2001; Schacter and Tulving, 1994). Finally, most previous treatments of explicit-implicit memory in SLA have not focused on, or even clearly acknowledged, the distinction between lexicon and grammar (Bialystok, 1978; N. C. Ellis, 2002; Gass, 1997; Krashen et al., 1982). In sum, it is difficult to draw simple parallels between the explicit-implicit and declarative-procedural distinctions. Nevertheless, the clear and testable dichotomy between declarative and procedural memory and the examination of how these two brain systems relate to lexicon and grammar, across different periods of the lifespan and across individuals, may encourage SLA researchers to consider how these factors relate to the constructs of explicit and implicit knowledge.

Seventh, the DP model can be directly compared to and contrasted with other neurocognitive perspectives of SLA. The model is perhaps most similar to the view espoused by Friederici and her colleagues on the basis of their fMRI and ERP data. They have concluded that low-proficiency L2 learners do not have the neurocognitive abilities of native speakers for automatic parsing and syntactic structure building in sentence comprehension, which are assumed to depend on BA 44 and certain other structures in L1 (Friederici et al., 2002; Hahne, 2001; Hahne and Friederici, 2001; Opitz and Friederici, 2003). Instead, low-proficiency learners initially depend on medial and lateral temporal lobe structures, and possibly on strategy-dependent compensatory right-hemisphere processes (Hahne and Friederici, 2001; Opitz and Friederici, 2003). However, as L2 proficiency increases (with experience with the language), medial and lateral temporal lobe involvement decreases, while BA 44 involvement increases (Opitz and Friederici, 2003). In contrast, conceptual-semantic integration seems to remain largely L1-like in L2 learners (Hahne and Friederici, 2001). Friederici's data and conclusions are thus highly compatible with the DP model. The two views seem to diverge in a number of the details (e.g., the role of the basal ganglia) and in that Friederici's perspective is primarily driven by data from L2 studies, whereas the DP model's claims and predictions follow largely from our independent knowledge of the two memory systems.

The DP model can also be directly compared to the view embraced by Paradis. He has proposed a model that links SLA notions of explicit and implicit knowledge to specific neural structures (Paradis, 1994, 1995, 1997, 1999, 2004). Like the DP model, Paradis emphasizes a greater dependence on declarative than procedural memory in L2 as compared to L1 and in low-proficiency L2 as compared to high-proficiency L2. However, unlike the DP model, Paradis seems to assume a direct correspondence between explicit knowledge and declarative memory and between implicit knowledge and procedural memory (Paradis, 1994, 2004). Moreover, Paradis discusses the increased reliance on procedural memory (in L1 and high-proficiency L2) largely in terms of greater automatization and implicitness across various domains of language, including at least portions of the lexicon. For Paradis, only consciously accessible lexical elements are declarative, in both L1 and L2. This seems to correspond largely to vocabulary items—that is, consciously accessible knowledge of the sound-meaning pairings of words. More abstract lexical knowledge (i.e., lexicalized knowledge of grammatical properties, such as argument structure) is not declarative (Paradis, 2004). Even vocabulary items do not depend on declarative memory when they are processed implicitly (nonconsciously) in sentence contexts (Paradis, 1994). Thus Paradis' claims for the lexicon differ at least partly from those of the DP model: Whereas the DP model assumes that *all* lexical knowledge resides in declarative memory (whether or not the knowledge is available to conscious awareness), Paradis takes seriously the divide between explicit and implicit knowledge, and claims that only the conscious use of lexical knowledge depends on declarative memory. Paradis also diverges somewhat from the DP model with respect to neuroanatomy. He focuses on medial temporal lobe structures for declarative memory and on the basal ganglia, cerebellum, and neocortex for procedural memory; particular neocortical regions do not appear to be implicated, other than left perisylvian areas (Paradis, 1999, 2004). Finally, unlike the DP model, Paradis does not seem to make further predictions based on our independent knowledge of the two memory systems, such as sex differences or modulation by sex hormones. Together these predictions enable Paradis' view to be empirically distinguished from the DP model.

Finally, it is important to point out that a number of theoretical gaps remain to be addressed in the DP perspective of L2 acquisition and processing. For example, the precise relation between late SLA on the one hand, and both native language acquisition and early SLA on the other, remains to be determined. In all cases, declarative memory is predicted to acquire information much faster than procedural memory. Thus even in very young children learning their native language, complex forms as well as idiosyncratic knowledge are predicted to be memorized in declarative memory before grammatical rules are abstracted in procedural memory. Indeed, at least some evidence appears to be consistent with this view (e.g., Marcus et al., 1992). Second and subsequent languages learned during early childhood should follow much the same pattern. However, in both of these cases, the fact that language acquisition occurs early, prior to the posited changes in the two memory systems, leads to the prediction that the grammar will be acquired with greater facility than would occur in later years, particularly following puberty. Other issues, such as the rapidity of vocabulary learning during childhood (Bloom, 2000) and the role of transfer or interference from previously learned languages, also remain to be investigated.

9. Summary

The DP perspective constitutes a novel alternative to previously proposed explanatory hypotheses of SLA. It leads to an array of specific predictions that are largely generated by our independent knowledge of the two memory systems and are directly testable using a range of widely used behavioral and neurocognitive methods. The predictions allow the model to be directly compared against alternative accounts and provide the means for it to be both falsified and further specified. Thus the DP model may provide a useful paradigm for the study of SLA.

10. Exercises

The following exercises are designed to increase your understanding of the neurocognition of SLA.

10.1 QUESTIONS

1. Briefly describe an experiment, using any methodology that you feel is appropriate, that could test one or more of the L2-related predictions of the DP model.

2. According to the DP model, might individual differences in working memory capacity lead to individual differences in SLA? Explain your answer.
3. A monolingual adult male suffers from a stroke that leads to damage to Broca's area, the basal ganglia, and surrounding structures, and to the onset of Broca's aphasia and agrammatism in his L1. Should he be able to learn an L2? Explain your answer. How might pharmacological agents improve his SLA?
4. Adult-onset bilateral damage limited to medial temporal lobe structures leads to an inability to learn new knowledge in declarative memory—that is, information about facts, events, and words. In contrast, such amnesic patients are generally able to acquire new motor and cognitive skills and other procedures, even though they do not remember the individual testing sessions. Should such patients be impaired at SLA? Explain your answer.
5. Specific Language Impairment (SLI) is a congenital disorder that affects language. It generally compromises grammatical abilities more than lexical abilities. It is also associated with a variety of impairments of nonlinguistic functions that are linked to the procedural memory system, while declarative memory appears to be relatively spared (Ullman and Pierpont, 2005). Thus it has been suggested that many individuals with SLI may suffer from abnormalities of brain structures underlying the procedural memory system (Ullman and Pierpont, 2005). Do you think that such individuals should show age-of-exposure period effects in language learning? Why or why not?

10.2 GUIDED CRITIQUE

To practice your skills at reading and critiquing articles on the neurocognition of SLA, please read the following article and answer the questions below.

Weber-Fox, C. M., and Neville, H. J. (1996). Maturational constraints on functional specializations for language processing: ERP and behavioral evidence in bilingual speakers. *Journal of Cognitive Neuroscience, 8*(3), 231–256.

1. Motivations and hypotheses
   a. What are the primary motivations and goals of the study?
   b. What hypothesis or hypotheses are the authors testing?
2. Methodology
   a. ERPs. What are ERPs? What do they reveal about neural and cognitive processes? What are their strengths and weaknesses as compared to other neurocognitive methods?

   b. Subjects. What subject groups were examined? What factors (e.g., age, education, etc.) are the subject groups matched or not matched on? Are there confounds between the subject factors of interest (e.g., age of exposure and length of exposure to the L2)?
   c. Materials and procedure. Why were both behavioral and ERP measures acquired? Why was only receptive language examined with ERPs? Do you think that 14 electrodes were sufficient in this study? What advantages or disadvantages might such a small number of electrodes confer?
   d. List the main strengths and weaknesses of the methods of this study.
3. Results.
   a. Explain the main behavioral results. What do you think are the most important results, and why?
   b. Explain the main ERP results. What do you think are the most important results, and why?
   c. Did one or more of the subject groups yield a pattern of results that was particularly different from that of the others? Why might this be?
4. Discussion and conclusions.
   a. What conclusions do the authors draw from their results?
   b. Are all of their conclusions justified by the data?
   c. Do their data suggest additional questions for study? Suggest one or more experiments to investigate any additional questions of interest.

Further Reading

Birdsong, D. (2004). Second language acquisition and ultimate attainment. In A. Davies & C. Elder (Eds.), *Handbook of Applied Linguistics* (pp. 82–105). Oxford, UK: Blackwell.

Opitz, B., & Friederici, A. D. (2003). Interactions of the hippocampal system and the prefrontal cortex in learning language-like rules. *Neuroimage, 19*(4), 1730–1737.

Paradis, M. (2004). *A neurolinguistic theory of bilingualism.* Amsterdam: John Benjamins.

Ullman, M. T. (2004). Contributions of memory circuits to language: The declarative/procedural model. *Cognition, 92*(1–2), 231–270.

Acknowledgments

This chapter was written with support from NSF SBR-9905273, NIH MH58189, and research grants from the National Alliance for Autism Research, the Mabel Flory Trust, and Pfizer, Inc. I thank David Birdsong, Claudia Bonin, Harriet Wood Bowden, Ivy Estabrooke, Shira Fischer, Matthew Moffa, Kara Morgan-Short, Michel Paradis, Cristina Sanz, Matthew Walenski, and Robbin Wood for helpful comments.

References

Aldridge, J. W., & Berridge, K. C. (1998). Coding of serial order by neostriatal neurons: A "natural action" approach to movement sequence. *The Journal of Neuroscience, 18*(7), 2777–2787.

Amunts, K., Schleicher, A., Burgel, U., Mohlberg, H., Uylings, H., & Zilles, K. (1999). Broca's region revisited: Cytoarchitecture and intersubject variability. *Journal of Comparative Neurology, 412*(2), 319–341.

Ankarberg, C., & Norjavaara, E. (1999). Diurnal rhythm of testosterone secretion before and throughout puberty in healthy girls: Correlation with 17 beta-estradiol and dehydroepiandrosterone sulfate. *Journal of Clinical Endocrinology and Metabolism, 84*(3), 975–984.

Bacon, S. M. (1992). The relationship between gender, comprehension, processing strategies, and cognitive and affective response in foreign language listening. *The Modern Language Journal, 76*(2), 160–178.

Barrett, S. E., & Rugg, M. D. (1990). Event-related potentials and the semantic matching of pictures. *Brain and Cognition, 14*(2), 201–212.

Bates, E., & MacWhinney, B. (1989). Functionalism and the competition model. In B. MacWhinney & E. Bates (Eds.), *The crosslinguistic study of sentence processing* (pp. 3–73). Cambridge, UK: Cambridge University Press.

Bialystok, E. (1978). A theoretical model of second language learning. *Language Learning, 28*(1), 69–83.

Bialystok, E. (1979). An analytical view of second language competence: A model and some evidence. *The Modern Language Journal, 63,* 257–262.

Birdsong, D. (1992). Ultimate attainment in second language acquisition. *Language, 68,* 706–755.

Birdsong, D. (Ed.). (1999). *Second language acquisition and the critical period hypothesis.* Mahwah, NJ: Lawrence Erlbaum.

Birdsong, D., & Flege, J. E. (2001). Regular-irregular dissociations in the acquisition of English as a second language. In A. H.-J. Do, L. Domínguez, & A. Johansen (Eds.), *BUCLD 25: Proceedings of the 25th Annual Boston University Conference on Language Development* (pp. 123–132). Boston, MA: Cascadilla Press.

Birdsong, D., & Molis, M. (2001). On the evidence for maturational constraints in second-language acquisition. *Journal of Memory and Language, 44,* 235–249.

Bley-Vroman, R. (1990). The logical problem of foreign language learning. *Linguistic Analysis, 20,* 3–49.

Bloom, P. (2000). *How children learn the meanings of words.* Cambridge, MA: MIT Press.

Boecker, H., Ceballos-Baumann, A. O., Bartenstein, P., Dagher, A., Forster, K., Haslinger, B., et al. (2002). A H215O positron emission tomography study on mental imagery of movement sequences—the effect of modulating sequence length and direction. *Neuroimage, 17,* 999–1009.

Boyle, J. P. (1987). Sex differences in listening vocabulary. *Language Learning, 37*(2), 273–284.

Buckner, R. L. (2000). Neuroimaging of memory. In M. S. Gazzaniga (Ed.), *The new cognitive neurosciences* (pp. 817–828). Cambridge, MA: MIT Press.

Buckner, R. L., & Wheeler, M. E. (2001). The cognitive neuroscience of remembering. *Nature Review Neuroscience, 2*(9), 624–634.

Bügel, K., & Buunk, B. P. (1996). Sex differences in listening vocabulary. *The Modern Language Journal, 80*(1), 15–31.

Calabresi, P., Centonze, D., Gubellini, P., Marfia, G. A., Pisani, A., Sancesario, G., et al. (2000). Synaptic transmission in the striatum: From plasticity to neurodegeneration. *Progress in Neurobiology, 61,* 231–265.

Calabresi, P., Centonze, D., Gubellini, P., Pisani, A., & Bernardi, G. (2000). Acetylcholine-mediated modulation of striatal function. *Trends in Neurosciences, 23*(3), 120–126.

Campbell, B., & Spear, N. (1972). Ontogeny of memory. *Psychological Review, 79,* 215–236.

Caplan, D., Alpert, N., & Waters, G. (1998). Effects of syntactic structure and propositional number on patterns of regional cerebral blood flow. *Journal of Cognitive Neuroscience, 10*(4), 541–552.

Carlson, L. E., & Sherwin, B. B. (2000). Higher levels of plasma estradiol and testosterone in healthy elderly men compared with age-matched women may protect aspects of explicit memory. *Menopause, 7*(3), 168–177.

Carr, B. R. (1998). Disorders of the ovaries and female reproductive tract. In J. D. Wilson, D. W. Foster, H. M. Kronenberg, & P. R. Larsen (Eds.), *Williams textbook of endocrinology* (9th ed.). Philadelphia: W. B. Saunders.

Chavez, M. (2001). *Gender in the language classroom.* New York: McGraw-Hill.

Chee, M. W., Caplan, D., Soon, C. S., Sriram, N., Tan, E. W., Thiel, T., et al. (1999). Processing of visually presented sentences in Mandarin and English studied with fMRI. *Neuron, 23*(1), 127–137.

Chee, M. W., Hon, N., Lee, H. L., & Soon, C. S. (2001). Relative language proficiency modulates BOLD signal change when bilinguals perform semantic judgments. *Neuroimage, 13*(6), 1155–1163.

Chee, M. W., Tan, E. W., & Thiel, T. (1999). Mandarin and English single word processing studied with functional magnetic resonance imaging. *Journal of Neuroscience, 19*(8), 3050–3056.

Cherrier, M. M., Asthana, S., Plymate, S., Baker, L., Matsumoto, A. M., Peskind, E., et al. (2001). Testosterone supplementation improves spatial and verbal memory in healthy older men. *Neurology, 57*(1), 80–88.

Chomsky, N. (1965). *Aspects of the theory of syntax.* Cambridge, MA: MIT Press.

Chomsky, N. (1995). *The minimalist program.* Cambridge, MA: MIT Press.

Chun, M. M. (2000). Contextual cueing of visual attention. *Trends in Cognitive Science, 4*(5), 170–178.

Chun, M. M., & Phelps, E. (1999). Memory deficits for implicit contextual information in amnesic subjects with hippocampal damage. *Nature Neuroscience, 2*(9), 844–847.

Churchill, J. D., Stanis, J. J., Press, C., Kushelev, M., & Greenough, W. T. (2003). Is procedural memory relatively spared from age effects? *Neurobiology of Aging, 24*(6), 883–892.

Clahsen, H., & Muysken, P. (1986). The availability of universal grammar to adult and child learners—a study of the acquisition of German word order. *Second Language Research, 2,* 93–119.

Coppieters, R. (1987). Competence differences between native and near-native speakers. *Language, 63*(3), 544–573.

Corkin, S. (1984). Lasting consequences of bilateral medial temporal lobectomy: Clinical course and experimental findings in H. M. *Seminars in Neurology, 4*(2), 249–259.

Cranshaw, A. (1997). *A study of Anglophone native and near-native linguistic and metalinguistic performance.* Unpublished doctoral dissertation, Université de Montréal.

Curran, H. V. (2000). Psychopharmacological approaches to human memory. In M. S. Gazzaniga (Ed.), *The new cognitive neurosciences* (pp. 797–804). Cambridge, MA: MIT Press.

Curran, T. (1997). Effects of aging on implicit sequence learning: Accounting for sequence structure and explicit knowledge. *Psychological Research, 60*(1–2), 24–41.

Curtiss, S. R. (1977). *Genie: A psycholinguistic study of a modern-day "wild child."* New York: Academic Press.

Curtiss, S. R. (1989). *The case of Chelsea: A new test case of the critical period for language acquisition.* Unpublished manuscript, University of California, Los Angeles.

Cutler, G. B., Jr. (1997). The role of estrogen in bone growth and maturation during childhood and adolescence. *Journal of Steroid Biochemistry and Molecular Biology, 61*(3–6), 141–144.

Damasio, A. R., & Damasio, H. (1992). Brain and language. *Scientific American, 267*(3), 88–95.

Damasio, H., Grabowski, T., Tranel, D., Hichwa, R., & Damasio, A. (1996). A neural basis for lexical retrieval. *Nature, 380*(6574), 499–505.

De Bleser, R., Dupont, P., Postler, J., Bormans, G., Spellman, D., Mortelmans, L., et al. (2003). The organization of the bilingual lexicon: A PET study. *Journal of Neurolinguistics, 16,* 439–456.

De Renzi, E. (1989). Apraxia. In F. Boller & J. Grafman (Eds.), *Handbook of neuropsychology* (Vol. 2, pp. 245–263). New York: Elsevier Science.

Dehaene, S., Dupoux, E., Mehler, J., Cohen, L., Paulesu, E., Perani, D., et al. (1997). Anatomical variability in the cortical representation of first and second language. *Neuroreport, 8*(17), 3809–3815.

DeKeyser, R. M. (2000). The robustness of critical period effects in second language acquisition. *Studies in Second Language Acquisition, 22,* 499–533.

DeKeyser, R. M. (2003). Implicit and explicit learning. In C. J. Doughty & M. H. Long (Eds.), *The handbook of second language acquisition* (pp. 313–348). Oxford, UK: Blackwell.

Desmond, J. E., & Fiez, J. A. (1998). Neuroimaging studies of the cerebellum: Language, learning, and memory. *Trends in Cognitive Science, 2*(9), 355–362.

Di Giulio, D. V., Seidenberg, M., O'Leary, D. S., & Raz, N. (1994). Procedural and declarative memory: A developmental study. *Brain and Cognition, 25*(1), 79–91.

Di Sciullo, A. M., & Williams, E. (1987). *On the definition of word.* Cambridge, MA: MIT Press.

Doughty, C. J. (2003). Instructed SLA: Constraints, compensation, and enhancement. In C. J. Doughty & M. H. Long (Eds.), *The handbook of second language acquisition* (pp. 256–310). Oxford, UK: Blackwell.

Eichenbaum, H. (2000). A cortical-hippocampal system for declarative memory. *Nature Review Neuroscience, 1*(1), 41–50.

Eichenbaum, H., & Cohen, N. J. (2001). *From conditioning to conscious recollection: Memory systems of the brain.* Oxford, UK: Oxford University Press.

Ellis, N. C. (Ed.). (1994). *Implicit and explicit learning of languages.* New York: Academic Press.

Ellis, N. C. (2002). Reflections on frequency effects in language processing. *Studies in Second Language Acquisition, 24,* 297–339.

Elman, J. L., Bates, E. A., Johnson, M. H., Karmiloff-Smith, A., Parisi, D., & Plunkett, K. (1996). *Rethinking innateness: A connectionist perspective on development.* Cambridge, MA: MIT Press.

Embick, D., Marantz, A., Miyashita, Y., O'Neil, W., & Sakai, K. L. (2000). A syntactic specialization for Broca's area. *Proceedings of the National Academy of Sciences, 97,* 6150–6154.

Eubank, L., & Gregg, K. R. (1999). Critical periods and (second) language acquisition: Divide et impera. In D. Birdsong (Ed.), *Second language acquisition and the critical period hypothesis* (pp. 65–99). Mahwah, NJ: Lawrence Erlbaum.

Fabbro, F. (1999). *The neurolinguistics of bilingualism.* Hove, UK: Psychology Press.

Fabbro, F., & Paradis, M. (1995). Differential impairments in four multilingual patients with subcortical lesions. In M. Paradis (Ed.), *Aspects of bilingual aphasia* (Vol. 3, pp. 139–176). Oxford, UK: Pergamon.

Feeney, J. J., Howard, J. H., & Howard, D. V. (2002). Implicit learning of higher order sequences in middle age. *Psychology and Aging, 17*(2), 351–355.

Ferrini, R., & Barrett-Connor, E. (1998). Sex hormones and age: A cross-sectional study of testosterone and estradiol and their bioavailable fractions in community-dwelling men. *American Journal of Epidemiology, 147*(8), 750–754.

Fiez, J. A. (1997). Phonology, semantics, and the role of the left inferior prefrontal cortex. *Human Brain Mapping, 5*(2), 79–83.

Flege, J. E., Yeni-Komshian, G. H., & Liu, S. (1999). Age constraints on second language acquisition. *Journal of Memory and Language, 41,* 78–104.

Fodor, J. A. (1983). *The modularity of mind: An essay on faculty psychology.* Cambridge, MA: MIT Press.

Fredriksson, A. (2000). Maze learning and motor activity deficits in adult mice induced by iron exposure during a critical postnatal period. *Developmental Brain Research, 119*(1), 65–74.

Freo, U., Pizzolato, G., Dam, M., Ori, C., & Battistin, L. (2002). A short review of cognitive and functional neuroimaging studies of cholinergic drugs: Implications for therapeutic potentials. *Journal of Neural Transmission, 109*(5–6), 857–870.

Friederici, A. D. (2002). Towards a neural basis of auditory sentence processing. *Trends in Cognitive Science, 6*(2), 78–84.

Friederici, A. D. (2004). The neural basis of syntactic processes. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences III* (pp. 789–801). Cambridge, MA: MIT Press.

Friederici, A. D., Hahne, A., & Mecklinger, A. (1996). The temporal structure of syntactic parsing: Early and late effects elicited by syntactic anomalies. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22*(5), 1219–1248.

Friederici, A. D., Hahne, A., & von Cramon, D. Y. (1998). First-pass versus second-pass parsing processes in a Wernicke's and a Broca's aphasic: Electrophysiological evidence for a double dissociation. *Brain and Language, 62*(3), 311–341.

Friederici, A. D., Pfeifer, E., & Hahne, A. (1993). Event-related brain potentials during natural speech processing: Effects of semantic, morphological, and syntactic violations. *Cognitive Brain Research, 1*(3), 183–192.

Friederici, A. D., Steinhauer, K., & Pfeifer, E. (2002). Brain signatures of artificial language processing: Evidence challenging the critical period hypothesis. *Proceedings of the National Academy of Sciences, 99*(1), 529–534.

Gardner, R. C., & Lambert, W. E. (1972). *Attitudes and motivation in second language learning.* Rowley, MA: Newbury House.

Gass, S. M. (1997). *Input, interaction, and the second language learner.* Mahwah, NJ: Lawrence Erlbaum.

Gass, S. M., & Selinker, L. (1994). *Second language acquisition.* Mahwah, NJ: Lawrence Erlbaum.

Gerfen, C. R. (1995). Dopamine receptor function in the basal ganglia. *Clinical Neuropharmacology, 18,* S162–S177.

Gleason, J. B., & Ratner, N. B. (Eds.). (1998). *Psycholinguistics* (2nd ed.). Fort Worth, TX: Harcourt Brace College.

Goodglass, H. (1993). *Understanding aphasia.* New York: Academic Press.

Grodzinsky, Y. (2000). The neurology of syntax: Language use without Broca's area. *Behavioral and Brain Sciences, 23*(1), 1–71.

Hahne, A. (2001). What's different in second-language processing? Evidence from event-related brain potentials. *Journal of Psycholinguist Research, 30*(3), 251–266.

Hahne, A., & Friederici, A. D. (2001). Processing a second language: Late learners' comprehension strategies as revealed by event-related brain potentials. *Bilingualism: Language and Cognition, 4,* 123–141.

Hahne, A., Muller, J., & Clahsen, H. (2003). Second language learner's processing of inflected words: Behavioral and ERP evidence for storage and decomposition. *Essex Research Reports in Linguistics, 45,* 1–42.

Halbig, T. D., Gruber, D., Scherer, P., Kopp, U. A., Trottenberg, T., & Kupsch, A. (2002). *Subthalamic high frequency stimulation differentially modulates declarative and nondeclarative memory.* Paper presented at the Society for Neuroscience Annual Meeting, Orlando, FL.

Halle, M., & Marantz, A. (1993). Distributed morphology and the pieces of inflection. In K. Hale & S. J. Keyser (Eds.), *The view from Building 20* (pp. 111–176). Cambridge, MA: MIT Press.

Halpern, D. F. (2000). *Sex differences in cognitive abilities* (3rd ed.). Mahwah, NJ: Lawrence Erlbaum.

Hampson, E. (1990). Variations in sex-related cognitive abilities across the menstrual cycle. *Brain and Cognition, 14*(1), 26–43.

Harrington, D. L., Haaland, K. Y., Yeo, R. A., & Marder, E. (1990). Procedural memory in Parkinson's disease: Impaired motor but not visuoperceptual learning. *Journal of Clinical and Experimental Neuropsychology, 12*(2), 323–339.

Hartshorne, J. K., & Ullman, M. T. (in press). Why girls say "holded" more than boys. *Developmental Science.*

Heilman, K. M., Watson, R. T., & Rothi, L. G. (1997). Disorders of skilled movements: Limb apraxia. In T. E. Feinberg & M. J. Farah (Eds.), *Behavioral neurology and neuropsychology* (pp. 227–235). New York: McGraw-Hill.

Hikosaka, O., Sakai, K., Nakahara, H., Lu, X., Miyachi, S., Nakamura, K., et al. (2000). Neural mechanisms for learning of sequential procedures. In M. S. Gazzaniga (Ed.), *The new cognitive neurosciences* (pp. 553–572). Cambridge, MA: MIT Press.

Hodges, J. R., & Patterson, K. (1997). Semantic memory disorders. *Trends in Cognitive Sciences, 1*(2), 68–72.

Howard, J. H., Jr., Howard, D. V., Dennis, N. A., Yankovich, H., & Vaidya, C. J. (2004). Implicit spatial contextual learning in healthy aging. *Neuropsychology, 18,* 124–134.

Hyltenstam, K., & Abrahamsson, N. (2003). Maturational constraints in SLA. In C. J. Doughty & M. H. Long (Eds.), *The handbook of second language acquisition* (pp. 539–588). Oxford, UK: Blackwell.

Illes, J., Francis, W. S., Desmond, J. E., Gabrieli, J. D., Glover, G. H., Poldrack, R., et al. (1999). Convergent cortical representation of semantic processing in bilinguals. *Brain and Language, 70*(3), 347–363.

Indefrey, P., Hagoort, P., Herzog, H., Seitz, R., & Brown, C. (2001). Syntactic processing in left prefrontal cortex is independent of lexical meaning. *Neuroimage, 14*(3), 546–555.

Ivry, R. B., & Fiez, J. A. (2000). Cerebellar contributions to cognition and imagery. In M. S. Gazzaniga (Ed.), *The new cognitive neurosciences* (pp. 999–1011). Cambridge, MA: MIT Press.

Jankovic, J., & Tolosa, E. E. (1993). *Parkinson's disease and movement disorders.* Baltimore: Williams and Wilkins.

Jenkins, I. H., Brooks, D. J., Nixon, P. D., Frackowiak, R. S., & Passingham, R. E. (1994). Motor sequence learning: A study with positron emission tomography. *Journal of Neuroscience, 14*(6), 3775–3790.

Johnson, J. S., & Newport, E. L. (1989). Critical period effects in second language learning: The influence of maturational state on the acquisition of English as a second language. *Cognitive Psychology, 21*(1), 60–99.

Kail, R. V., & Hagen, J. W. (1977). *Perspectives on the development of memory and cognition.* Mahwah, NJ: Lawrence Erlbaum.

Kampen, D. L., & Sherwin, B. B. (1996). Estradiol is related to visual memory in healthy young men. *Behavioral Neuroscience, 110*(3), 613–617.

Kim, K. H. S., Relkin, N. R., Lee, K.-M., & Hirsch, J. (1997). Distinct cortical areas associated with native and second languages. *Nature, 388,* 171–174.

Kimura, D. (1999). *Sex and cognition.* Cambridge, MA: MIT Press.

Klein, D., Milner, B., Zatorre, R. J., Meyer, E., & Evans, A. C. (1995). The neural substrates underlying word generation: A bilingual functional-imaging study. *Proceedings of the National Academy of Sciences of the United States of America, 92*(7), 2899–2903.

Klein, D., Milner, B., Zatorre, R. J., Zhao, V., & Nikelski, J. (1999). Cerebral organization in bilinguals: A PET study of Chinese-English verb generation. *Neuroreport, 10*(13), 2841–2846.

Klein, D., Zatorre, R. J., Milner, B., Meyer, E., & Evans, A. C. (1994). Left putaminal activation when speaking a second language: Evidence from PET. *Neuroreport, 5*(17), 2295–2297.

Klein, K., Baron, J., Colli, M., McDonnell, D., & Cutler, G. (1994). Estrogen levels in childhood determined by an ultrasensitive recombinant cell bioassay. *Journal of Clinical Investigation, 94*(6), 2475–2480.

Klein, K., Martha, P., Blizzard, R., Herbst, T., & Rogol, A. (1996). A longitudinal assessment of hormonal and physical alterations during normal puberty in boys. II. Estrogen levels as determined by an ultrasensitive bioassay. *Journal of Clinical Endocrinology and Metabolism, 81*(9), 3203–3207.

Kramer, J. H., Delis, D. C., Kaplan, E., O'Donnell, L., & Prifitera, A. (1997). Developmental sex differences in verbal learning. *Neuropsychology, 11*(4), 577–584.

Krashen, S. D. (1985). *The input hypothesis.* London: Longman.

Krashen, S. D., Scarcella, R. C., & Long, M. H. (Eds.). (1982). *Child-adult differences in second language acquisition.* Rowley, MA: Newbury House.

Ku, A., Lachmann, E. A., & Nagler, W. (1996). Selective language aphasia from herpes simplex encephalitis. *Pediatric Neurology, 15*(2), 169–171.

Kutas, M., & Hillyard, S. A. (1980). Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science, 207*(1), 203–205.

Levelt, W. J. M. (1989). *Speaking: From intention to articulation.* Cambridge, MA: MIT Press.

Lynch, G. (2002). Memory enhancement: The search for mechanism-based drugs. *Nature Neuroscience, 5*(Supplement), 1035–1038.

MacDonald, M. C., Pearlmutter, N. J., & Seidenberg, M. S. (1994). Lexical nature of syntactic ambiguity resolution. *Psychological Review, 101*(4), 676–703.

MacWhinney, B. (1987). Applying the competition model to bilingualism. *Applied Psycholinguistics, 8,* 415–431.

Maki, P. M., & Resnick, S. M. (2000). Longitudinal effects of estrogen replacement therapy on PET cerebral blood flow and cognition. *Neurobiology of Aging, 21*(2), 373–383.

Marcus, G. F., Pinker, S., Ullman, M., Hollander, M., Rosen, T. J., & Xu, F. (1992). Overregularization in language acquisition. *Monographs of the Society for Research in Child Development, 57*(4, Serial No. 228), 1–165.

Martin, A., Ungerleider, L. G., & Haxby, J. V. (2000). Category specificity and the brain: The sensory/motor model of semantic representations of objects. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 1023–1036). Cambridge, MA: MIT Press.

McCarthy, G., Nobre, A. C., Bentin, S., & Spencer, D. D. (1995). Language-related field potentials in the anterior-medial temporal lobe: I. Intracranial distribution and neural generators. *The Journal of Neuroscience, 15*(2), 1080–1089.

McDonald, R., & White, N. (1993). A triple dissociation of memory systems: Hippocampus, amygdala, and dorsal striatum. *Behavioral Neuroscience, 107*(1), 3–22.

McEwen, B. S., Alves, S. E., Bulloch, K., & Weiland, N. G. (1998). Clinically relevant basic science studies of gender differences and sex hormone effects. *Psychopharmacology Bulletin, 34*(3), 251–259.

McLaughlin, J., Osterhout, L., & Kim, A. (2004). Neural correlates of second-language word learning: Minimal instruction produces rapid change. *Nature Neuroscience, 7*(7), 703–704.

Meisel, J. M. (1991). Principles of Universal Grammar and strategies of language use: On some similarities and differences between first and second language acquisition.

In L. Eubank (Ed.), *Point counterpoint: Universal Grammar in the second language* (pp. 231–276). Amsterdam: John Benjamins.

Meudell, P. R. (1983). The development and dissolution of memory. In A. Mayes (Ed.), *Memory in animals and humans.* New York: Van Nostrand-Reinhold.

Miles, C., Green, R., Sanders, G., & Hines, M. (1998). Estrogen and memory in a transsexual population. *Hormones and Behavior, 34*(2), 199–208.

Mishkin, M., Malamut, B., & Bachevalier, J. (1984). Memories and habits: Two neural systems. In G. Lynch, J. L. McGaugh, & N. W. Weinburger (Eds.), *Neurobiology of learning and memory* (pp. 65–77). New York: Guilford Press.

Mitchell, J. A., & Hall, G. (1988). Caudate-putamen lesions in the rat may impair or potentiate maze learning depending upon availability of stimulus cues and relevance of response cues. *Quarterly Journal of Experimental Psychology B, 40*(3), 243–258.

Moro, A., Tettamanti, M., Perani, D., Donati, C., Cappa, S. F., & Fazio, F. (2001). Syntax and the brain: Disentangling grammar by selective anomalies. *Neuroimage, 13*(1), 110–118.

Nakahara, H., Doya, K., & Hikosaka, O. (2001). Parallel cortico-basal ganglia mechanisms for acquisition and execution of visuomotor sequences—a computational approach. *Journal of Cognitive Neuroscience, 13*(5), 626–647.

Neville, H., Nicol, J. L., Barss, A., Forster, K. I., & Garrett, M. F. (1991). Syntactically based sentence processing classes: Evidence from event-related brain potentials. *Journal of Cognitive Neuroscience, 3*(2), 151–165.

Newman, A. J., Pancheva, R., Ozawa, K., Neville, H. J., & Ullman, M. T. (2001). An event-related fMRI study of syntactic and semantic violations. *Journal of Psycholinguistic Research, 30*(3), 339–364.

Newport, E. L. (1990). Maturational constraints on language learning. *Cognitive Science, 14*(1), 11–28.

Newport, E. L. (1993). Maturational constraints on language learning. In P. Bloom (Ed.), *Language Acquisition* (pp. 543–560). Cambridge, MA: MIT Press.

Ni, W., Constable, R. T., Menci, W. E., Pugh, K. R., Fulbright, R. K., Shaywitz, S. E., et al. (2000). An event-related neuroimaging study distinguishing form and content in sentence processing. *Journal of Cognitive Neuroscience, 12*(1), 120–133.

Nobre, A. C., Allison, T., & McCarthy, G. (1994). Word recognition in the human inferior temporal lobe. *Nature, 372,* 260–263.

Norris, J. M., & Ortega, L. (2001). Does type of instruction make a difference? Substantive findings from a meta-analytic review. *Language Learning, 51*(1), 157–213.

Nyikos, M. (1990). Sex-related differences in adult language learning: Socialization and memory factors. *The Modern Language Journal, 74*(3), 273–287.

Opitz, B., & Friederici, A. D. (2003). Interactions of the hippocampal system and the prefrontal cortex in learning language-like rules. *Neuroimage, 19*(4), 1730–1737.

Ornstein, P. A. (1978). *Memory development in children.* Mahwah, NJ: Lawrence Erlbaum.

Osterhout, L., & McLaughlin, J. (2000). *What brain activity can tell us about second-language learning.* Paper presented at the 13th Annual CUNY Conference on Human Sentence Processing, La Jolla, CA.

Oyama, S. (1982). The sensitive period and comprehension of speech. In S. D. Krashen, R. C. Scarcella, & M. H. Long (Eds.), *Child-adult differences in second language acquisition* (pp. 39–51). Rowley, MA: Newbury House.

Packard, M. G., Hirsh, R., & White, N. (1989). Differential effects of fornix and caudate nucleus lesions on two radial maze tasks: Evidence for multiple memory systems. *The Journal of Neuroscience, 9*(5), 1465–1472.

Packard, M. G. (1998). Posttraining estrogen and memory modulation. *Hormones and Behavior, 34*(2), 126–139.

Packard, M. G. (1999). Glutamate infused posttraining into the hippocampus or caudate-putamen differentially strengthens place and response learning. *Proceedings of the National Academy of Sciences of the United States of America, 96*(22), 12881–12886.

Packard, M. G., & Knowlton, B. J. (2002). Learning and memory functions of the basal ganglia. *Annual Review of Neuroscience, 25,* 563–593.

Packard, M. G., & McGaugh, J. L. (1996). Inactivation of hippocampus or caudate nucleus with lidocaine differentially affects expression of place and response learning. *Neurobiology of Learning and Memory, 65*(1), 65–72.

Paradis, M. (1994). Neurolinguistic aspects of implicit and explicit memory: Implications for bilingualism and SLA. In N. C. Ellis (Ed.), *Implicit and explicit learning of languages* (pp. 393–419). New York: Academic Press.

Paradis, M. (1995). Introduction: The need for distinctions. In M. Paradis (Ed.), *Aspects of bilingual aphasia* (Vol. 3, pp. 1–9). Oxford, UK: Pergamon.

Paradis, M. (1997). The cognitive neuropsychology of bilingualism. In A. M. B. de Groot & J. F. Kroll (Eds.), *Tutorials in bilingualism: Psycholinguistic perspectives* (pp. 331–354). Mahwah, NJ: Lawrence Erlbaum.

Paradis, M. (1999). *Neuroimaging studies of the bilingual brain: Some words of caution.* Paper presented at the 25th Lacus Forum, University of Alberta, Edmonton, Canada.

Paradis, M. (2004). *A neurolinguistic theory of bilingualism.* Amsterdam: John Benjamins.

Park, D. C., Lautenschlager, G., Hedden, T., Davidson, N., Smith, A. D., & Smith, P. (2002). Models of visuospatial and verbal memory across the adult life span. *Psychology and Aging, 16,* 299–320.

Patkowski, M. S. (1980). The sensitive period for the acquisition of syntax in a second language. *Language Learning, 30*(2), 449–472.

Perani, D., Dehaene, S., Grassi, F., Cohen, L., Cappa, S. F., Dupoux, E., et al. (1996). Brain processing of native and foreign languages. *Neuroreport, 7*(15–17), 2439–2444.

Perani, D., Paulesu, E., Galles, N. S., Dupoux, E., Dehaene, S., Bettinardi, V., et al. (1998). The bilingual brain. Proficiency and age of acquisition of the second language. *Brain, 121*(10), 1841–1852.

Phakiti, A. (2003). A closer look at gender and strategy use in L2 reading. *Language Learning, 53*(4), 649–702.

Phillips, S. M., & Sherwin, B. B. (1992). Effects of estrogen on memory function in surgically menopausal women. *Psychoneuroendocrinology, 17*(5), 485–495.

Pillai, J. J., Araque, J. M., Allison, J. D., Suthuraman, S., Loring, D. W., Thiruvaiy, D., et al. (2003). Functional MRI study of semantic and phonological language processing in bilingual subjects: Preliminary findings. *NeuroImage, 19,* 565–576.

Pinker, S. (1994). *The language instinct.* New York: William Morrow.

Pinker, S. (1999). *Words and rules: The ingredients of language.* New York: Basic Books.

Pinker, S., & Ullman, M. T. (2002). The past and future of the past tense. *Trends in Cognitive Sciences, 6*(11), 456–463.

Poldrack, R. A., & Packard, M. G. (2003). Competition among multiple memory systems: Converging evidence from animal and human brain studies. *Neuropsychologia, 41*(3), 245–251.

Poldrack, R. A., Clark, J., Pare-Blagoev, E. J., Shohamy, D., Moyano, J. C., Myers, C., et al. (2001). Interactive memory systems in the human brain. *Nature, 414,* 546–550.

Poldrack, R. A., Prabhakaran, V., Seger, C. A., & Gabrieli, J. D. (1999). Striatal activation during acquisition of a cognitive skill. *Neuropsychology, 13*(4), 564–574.

Poldrack, R. A., Wagner, A. D., Prull, M. W., Desmond, J. E., Glover, G. H., & Gabrieli, J. D. (1999). Functional specialization for semantic and phonological processing in the left inferior prefrontal cortex. *NeuroImage, 10*(1), 15–35.

Prasada, S., & Pinker, S. (1993). Generalization of regular and irregular morphological patterns. *Language and Cognitive Processes, 8*(1), 1–56.

Prull, M. W., Gabrieli, J. D. E., & Bunge, S. A. (2000). Age-related changes in memory: A cognitive neuroscience perspective. In F. I. M. Craik & T. A. Salthouse (Eds.), *The handbook of aging and cognition* (2nd ed.). Mahwah, NJ: Lawrence Erlbaum.

Rizzolatti, G., Fogassi, L., & Gallese, V. (2000). Cortical mechanisms subserving object grasping and action recognition: A new view on the cortical motor functions. In M. S. Gazzaniga (Ed.), *The new cognitive neurosciences* (pp. 539–552). Cambridge, MA: MIT Press.

Rizzolatti, G., Fogassi, L., & Gallese, V. (2001). Neurophysiological mechanisms underlying the understanding and imitation of action. *Nature Review Neuroscience, 2*(9), 661–670.

Rohde, D. L., & Plaut, D. C. (1999). Language acquisition in the absence of explicit negative evidence: How important is starting small? *Cognition, 72*(1), 67–109.

Rumelhart, D. E., & McClelland, J. L. (1986). On learning the past tenses of English verbs. In J. L. McClelland, D. E. Rumelhart, & PDP Research Group (Eds.), *Parallel distributed processing: Explorations in the microstructures of cognition* (Vol. 2, pp. 216–271). Cambridge, MA: MIT Press.

Saint-Cyr, J. A., Taylor, A. E., & Lang, A. E. (1988). Procedural learning and neostriatal dysfunction in man. *Brain, 111*(4), 941–959.

Scarcella, R., & Zimmerman, A. (1998). Academic words and gender: ESL student performance on a test of academic lexicon. *Studies in Second Language Acquisition, 20,* 27–49.

Schacter, D. L., & Tulving, E. (Eds.). (1994). *Memory systems 1994.* Cambridge, MA: MIT Press.

Schlaug, G. (2001). The brain of musicians: A model for functional and structural adaptation. *Annals of the New York Academy of Sciences, 930*(1), 281–299.

Schluter, N. D., Krams, M., Rushworth, M. F. S., & Passingham, R. E. (2001). Cerebral dominance for action in the human brain: The selection of actions. *Neuropsychologia, 39*(2), 105–113.

Schmidt, R. (1994). Implicit learning and the cognitive unconscious: Of artificial grammars and SLA. In N. C. Ellis (Ed.), *Implicit and explicit learning of languages* (pp. 165–209). New York: Academic Press.

Schroeder, J. A., Wingard, J., & Packard, M. G. (2002). Post-training reversible inactivation of the dorsal hippocampus reveals interference between multiple memory systems. *Hippocampus, 12,* 280–284.

Seidenberg, M. S. (1997). Language acquisition and use: Learning and applying probabilistic constraints. *Science, 275,* 1599–1603.

Sherman, B. M., West, J. H., & Korenman, S. G. (1976). The menopausal tradition: Analysis of LH, FSH, estradiol, and progesterone concentrations during menstrual cycles of older women. *Journal of Clinical Endocrinology and Metabolism, 42,* 629–636.

Sherwin, B. B. (1988). Estrogen and/or androgen replacement therapy and cognitive functioning in surgically menopausal women. *Psychoneuroendocrinology, 13*(4), 345–357.

Sherwin, B. B. (1998). Estrogen and cognitive functioning in women. *Proceedings of the Society for Experimental Biology and Medicine, 217*(1), 17–22.

Shughrue, P. J., Scrimo, P. J., & Merchenthaler, I. (2000). Estrogen binding and estrogen receptor characterization (ERalpha and ERbeta) in the cholinergic neurons of the rat basal forebrain. *Neuroscience, 96*(1), 41–49.

Siegler, R. S. (Ed.). (1978). *Children's thinking: What develops?* Mahwah, NJ: Lawrence Erlbaum.

Simos, P. G., Basile, L. F. H., & Papanicolaou, A. C. (1997). Source localization of the N400 response in a sentence-reading paradigm using evoked magnetic fields and magnetic resonance imaging. *Brain Research, 762*(1–2), 29–39.

Sorensen, K., & Witter, M. (1983). Entorhinal efferents reach the caudato-putamen. *Neuroscience Letters, 35*(3), 259–264.

Spurling, S., & Ilyin, D. (1985). The impact of learner variables on language test performance. *TESOL Quarterly, 19,* 283–301.

Squire, L. R., & Knowlton, B. J. (1995). Memory, hippocampus, and brain systems. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 825–837). Cambridge, MA: MIT Press.

Squire, L. R., & Knowlton, B. J. (2000). The medial temporal lobe, the hippocampus, and the memory systems of the brain. In M. S. Gazzaniga (Ed.), *The new cognitive neurosciences* (pp. 765–780). Cambridge, MA: MIT Press.

Squire, L. R., & Zola, S. M. (1996). Structure and function of declarative and nondeclarative memory systems. *Proceedings of the National Academy of Sciences of the United States of America, 93,* 13515–13522.

Stromswold, K., Caplan, D., Alpert, N., & Rauch, S. (1996). Localization of syntactic comprehension by positron emission tomography. *Brain and Language, 52,* 452–473.

Suzuki, W. A., & Amaral, D. G. (1994). Perirhinal and parahippocampal cortices of the macaque monkey: Cortical afferants. *Journal of Comparative Neurology, 350*(4), 497–533.

Thompson-Schill, S. L., D'Esposito, M., Aguirre, G. K., & Farah, M. J. (1997). Role of left inferior prefrontal cortex in retrieval of semantic knowledge: A reevaluation.

Proceedings of the National Academy of Sciences of the United States of America, 94(26), 14792–14797.

Ullman, M. T. (2001a). The declarative/procedural model of lexicon and grammar. *Journal of Psycholinguistic Research, 30*(1), 37–69.

Ullman, M. T. (2001b). The neural basis of lexicon and grammar in first and second language: The declarative/procedural model. *Bilingualism: Language and Cognition, 4*(1), 105–122.

Ullman, M. T. (2001c). A neurocognitive perspective on language: The declarative/procedural model. *Nature Reviews Neuroscience, 2,* 717–726.

Ullman, M. T. (2004). Contributions of memory circuits to language: The declarative/procedural model. *Cognition, 92*(1–2), 231–270.

Ullman, M. T., Corkin, S., Coppola, M., Hickok, G., Growdon, J. H., Koroshetz, W. J., et al. (1997). A neural dissociation within language: Evidence that the mental dictionary is part of declarative memory, and that grammatical rules are processed by the procedural system. *Journal of Cognitive Neuroscience, 9*(2), 266–276.

Ullman, M. T., Estabrooke, I. V., Steinhauer, K., Brovetto, C., Pancheva, R., Ozawa, K., et al. (2002). Sex differences in the neurocognition of language. *Brain and Language, 83,* 141–143.

Ullman, M. T., Izvorski, R., Love, T., Yee, E., Swinney, D., & Hickok, G. (2005). Neural correlates of lexicon and grammar: Evidence from the production, reading, and judgment of inflection in aphasia. *Brain and Language, 93*(2), 185–238.

Ullman, M. T., & Pierpont, E. I. (2005). Specific Language Impairment is not specific to language: The procedural deficit hypothesis. *Cortex, 41,* 399–433.

Van Wuijtswinkel, K. (1994). *Critical period effects on the acquisition of grammatical competence in a second language.* Unpublished BA thesis, Katholieke Universiteit, Nijmegen, The Netherlands.

Wagner, A. D., Schacter, D. L., Rotte, M., Koutstaal, W., Maril, A., Dale, A. M., et al. (1998). Building memories: Remembering and forgetting of verbal experiences as predicted by brain activity. *Science, 281*(5380), 1188–1191.

Walton, K. D., Lieberman, D., Llinas, A., Begin, M., & Llinas, R. R. (1992). Identification of a critical period for motor development in neonatal rats. *Neuroscience, 51*(4), 763–767.

Wartenburger, I., Heekeren, H. R., Abutalebi, J., Cappa, S. F., Villringer, A., & Perani, D. (2003). Early setting of grammatical processing in the bilingual brain. *Neuron, 37,* 159–170.

Weber-Fox, C. M., & Neville, H. J. (1996). Maturational constraints on functional specializations for language processing: ERP and behavioral evidence in bilingual speakers. *Journal of Cognitive Neuroscience, 8*(3), 231–256.

Wen, Q., & Johnson, R. K. (1997). L2 learner variables and English achievements: A study of tertiary-level English majors in China. *Applied Linguistics, 18,* 27–48.

White, L., & Genesee, F. (1996). How native is near-native? The issue of ultimate attainment in adult second language acquisition. *Second Language Research, 12*(3), 233–265.

Willingham, D. B. (1998). A neuropsychological theory of motor skill learning. *Psychological Review, 105*(3), 558–584.

Wilson, J. D., Foster, D. W., Kronenberg, H. M., & Larsen, P. R. (Eds.). (1998). *Williams textbook of endocrinology* (9th ed.). Philadelphia: W. B. Saunders.

Wolansky, M. J., Cabrera, R. J., Ibarra, G. R., Mongiat, L., & Azcurra, J. M. (1999). Exogenous NGF alters a critical motor period in rat striatum. *Neuroreport, 10*(13), 2705–2709.

Woolley, C. S., & Schwartzkroin, P. A. (1998). Hormonal effects on the brain. *Epilepsia, 39*(8), S2–8.