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Age of Acquisition: Its Neural and Computational Mechanisms

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The acquisition of new skills over a life span is a remarkable human ability. This ability, however, is constrained by age of acquisition (AoA); that is, the age at which learning occurs significantly affects the outcome. This is most clearly reflected in domains such as language, music, and athletics. This article provides a perspective on the neural and computational mechanisms underlying AoA in language acquisition. The authors show how AoA modulates both monolingual lexical processing and bilingual language acquisition. They consider the conditions under which syntactic processing and semantic processing may be differentially sensitive to AoA effects in second-language acquisition. The authors conclude that AoA effects are pervasive and that the neural and computational mechanisms underlying learning and sensorimotor integration provide a general account of these effects.

Keywords: bilingualism, second language acquisition, age of acquisition, sensorimotor learning, computational modeling

Personal anecdotes and scientific evidence both confirm that it is important to learn a second language (L2) early. In the 125th anniversary Special Issue of *Science* (Kennedy & Norman, 2005), age of acquisition (AoA) and critical periods were included in a list of 100 important science questions to be addressed in the next few decades. Linguists, psychologists, and cognitive scientists have made significant progress in understanding AoA; however, important questions remain unanswered: What neural substrates underlie AoA, if any? Are AoA effects specific to L2 learning or are they present in language in general? And, how is AoA reflected in both linguistic and nonlinguistic domains? In this review, we approach these questions broadly and consider general computational and neural principles that may contribute to AoA effects in both linguistic and nonlinguistic domains.

What Is Age of Acquisition?

AoA, in its broadest sense, refers to the age at which a concept or skill is acquired. AoA effects have been addressed in at least three distinct literatures: the age at which skills are acquired in nonlinguistic domains, the age at which a lexical item is acquired in monolingual learners, and the age at which L2 learning begins. In the first and third literatures, researchers have attempted to understand how early versus late learning affects successful acquisition. This issue is often discussed in terms of a *critical period,* or *sensitive period,* of learning. In the second literature, researchers study the age at which lexical items are acquired in monolingual learners and before AoA effects on the processing of these items. Do these three types of AoA effects share a common mechanism? If so, what might that mechanism be? Our review attempts to provide an integrated answer to these questions.

Age of Acquisition in Nonlinguistic Domains

AoA effects have been found in many nonlinguistic domains. For example, early deprivation or alteration of sensory input leads to impaired sensory perception in many species. The most well-known examples involve binocular deprivation during a critical period leading to a reduction in stereoscopic depth perception among cats, monkeys, rats, mice, ferrets, and humans (Banks, Aslin, & Letson, 1975; Fagiolini, Pizzorusso, Berardi, Domenici, & Maffei, 1994; Harwerth, Smith, Duncan, Crawford, & von Noorden, 1986; Huang et al., 1999; Issa, Trachtenberg, Chapman, Zahs, & Stryker, 1999; Olson & Freeman, 1980). Critical periods are also found in the calibration of auditory maps by visual input (Brainard & Knudsen, 1998). Moreover, sensory deprivation can lead to problems in the motor system. For example, disruption of binocular experience adversely affects smooth pursuit of moving objects and diminishes stability of the eyes when viewing stationary targets (Norcia, 1996). Hence, problems in the sensory domain lead to abnormalities of motor function.

AoA also affects song learning in birds. Learning generally occurs in three phases: sensory, sensorimotor, and crystallized (Brainard & Doupe, 2002). During the sensory period, a bird listens to the song of a tutor and forms a template in memory. Lack of exposure to adult song during this phase leads to irregular songs that contain some species-specific characteristics. During the sensorimotor phase, the bird learns to match the song to the template. Songs are fine-tuned through practice; auditory feedback is crucial during this time (note that sensory and sensorimotor phases may overlap for some birds). In the final, crystallized phase, birds are

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mature and can produce a species-specific song, but they often cannot learn new songs. The fact that early acquisition of birdsong is characterized by sensory and sensorimotor processing is of particular importance in this review (see Doupe, Perkel, Reiner, & Stern, 2005).

Finally, AoA effects have been observed in high-level nonlinguistic functions. AoA effects are found in musicians at both the behavioral and the neural levels. Absolute pitch appears to be learned by speakers of nontonal languages only before the age of 7 years (Deutsch, Henthorn, Marvin, & Xu, 2006; Trainor, 2005). In addition, the ability to synchronize motor responses to a visually presented flashing square differs significantly between groups of professional musicians as a function of AoA, even when these groups are matched for years of musical experience, years of formal training, and hours of current practice (Watanabe, Savion-Lemieux, & Penhune, 2007). At the neural level, early musical training correlates with the size of digit representations in motor regions of the cortex (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995). Similarly, Schlaug, Jancke, Huang, Staiger, and Steinmetz (1995) found that the anterior corpus callosum was larger in musicians than nonmusicians and largest in those who learned to play before the age of 7 years. Hence, AoA effects on both behavior and neural representations in the music domain appear to reflect sensorimotor processing.

AoA effects are generally considered evidence for critical periods, time windows within which learning outcomes are optimal and after which the ability to learn drastically decreases. Critical periods, however, may be only one instantiation of AoA effects. A crucial aspect of these effects in nonlinguistic domains is that they impact both sensory and motor systems (for further discussion of critical and sensitive periods, see Knudsen, 2004).

Age of Acquisition in Monolingual Individuals

Researchers discovered over 30 years ago that early learned words are processed differently than late learned words (Carroll & White, 1973; Gilhooly & Watson, 1981); only recently, however, has this difference attracted significant interests among psycholinguists as an AoA effect. Using a number of experimental paradigms, researchers have shown that the age of word acquisition significantly affects the speed and accuracy with which a word is accessed and processed (Barry, Morrison, & Ellis, 1997; Cuetos, Ellis, & Alvarez, 1999; Ellis & Morrison, 1998; Gerhand & Barry, 1998, 1999; Gilhooly & Gilhooly, 1979; Lewis, 1999; Meschyan & Hernandez, 2002; Morrison, Chappell, & Ellis, 1997; Morrison & Ellis, 1995, 2000). Early learned words typically elicit faster response times than late learned words in word reading, auditory and visual lexical decision, picture naming, and face recognition. Researchers have not, however, agreed on the exact mechanisms underlying this AoA effect. The controversy lies in the identification of the locus of AoA effects, in particular, with regard to whether AoA reflects endogenous properties of the lexicon or exogenous properties of the learning process. We now turn to the various theoretical accounts.

Theoretical accounts of age of acquisition. Brown and Watson (1987) proposed a phonological completeness hypothesis to account for AoA effects in word learning. In this view, early learned words are stored and represented holistically, whereas late learned words are represented in a fragmented fashion and require reconstruction or reassembly before the whole phonological shape can be produced. Thus, early learned words are pronounced more quickly than late learned words. This hypothesis, however, has not been supported in a number of studies in several domains. First, the phonological completeness hypothesis has difficulty accounting for AoA effects in tasks that do not involve overt naming, such as face recognition (Moore & Valentine, 1998, 1999) and object processing (Moore, Smith-Spark, & Valentine, 2004). Second, reaction times are faster to early than to late learned words when participants are asked to perform a segmentation task (Monaghan & Ellis, 2002a). This pattern is contrary to what the hypothesis predicts. If late learned words are acquired in a fragmented form, they should be easier to segment than early learned words. These findings have led researchers to consider alternative hypotheses, in particular, hypotheses about whether lexical AoA effects are due to a more general mechanism.

Several general accounts of AoA effects have been proposed (for a recent review of the literature see Juhasz, 2005). The cumulative frequency hypothesis maintains that word frequency consists of additive effects across the lifetime of a word. Hence, early learned words will be encountered more times across many years of use than late learned words, even if they are low in frequency (Lewis, Gerhand, & Ellis, 2001). Lewis et al. have provided evidence for this hypothesis using mathematical modeling: However, research with old adults has not supported it. AoA effects should decrease as the language user becomes older. The difference, for example, between words learned at age 3 years versus words learned at age 8 years should be large when the learner reaches age 14 years (these words have been encountered for 11 and 6 years, respectively), but the difference should be smaller when the learner reaches age 60 years (the same words have been encountered for 57 and 52 years, respectively). Morrison et al. (Morrison, Hirsh, Chappell, & Ellis, 2002) found the standard AoA effect but also found that it did not increase with age. Such findings provide compelling evidence against the cumulative frequency hypothesis.[1]

The semantic locus hypothesis claims that early learned words have a semantic advantage over late learned words because they enter the representational network first and affect the semantic representations of later learned words (Brysbaert, Van Wijnendaele, & De Deyne, 2000; Steyvers & Tenenbaum, 2005). Brysbaert et al. (2000) found that participants generated associates faster to early learned words than to late learned words. Similarly, Morrison and Gibbons (2006) found AoA effects in a "living" versus "nonliving" semantic categorization task but only for the "living" items. Research with neural networks has found that early learned words have more semantic connections to other words than do late learned words (Steyvers & Tenenbaum, 2005) and that early learned words establish a basic semantic structure that allows later word learning to accelerate (for a discussion of the "vocabulary spurt" in lexical acquisition, see Li, Zhao, & MacWhinney,

[1] Recently, Zevin and Seidenberg (2004) have suggested a variant of the cumulative frequency hypothesis in which both cumulative frequency and frequency trajectory play an important role. Frequency trajectory, unlike cumulative frequency, refers to whether a word is encountered more frequently in childhood than in adulthood (e.g., *potty*, *stroller*) or vice versa (*fax*, *merlot*). In their view, AoA is difficult to quantify because it correlates highly with other types of information; hence, it may be impossible to isolate. According to Zevin and Seidenberg, frequency trajectory may be a more accurate measure of true AoA.

in press). Hence, AoA effects may be due, at least in part, to differences in semantic processing.

According to the semantic locus hypothesis, early learned words are conceptually more enriched than late learned words (e.g., have more semantic connections to other words) and these representations affect later learning.[2] In monolingual individuals, a linguistic form maps in a consistent and relatively straightforward manner to its corresponding conceptual representation. In bilingual indviduals, however, each concept maps to two forms, one for each language. Thus, the semantic locus hypothesis suggests that AoA effects should transfer to a second language.

Bilingual researchers have long argued for a unitary semantic store with separate lexical form representations for each language (Altarriba, 1992; Kroll & de Groot, 1997, 2005; Kroll & Tokowicz, 2005; Kroll, Tokowicz, & Nicol, 2001; Potter, So, von Eckardt, & Feldman, 1984; Schreuder & Weltens, 1993; Sholl, Sankaranarayanan, & Kroll, 1995). Furthermore, they have argued that connections between concepts and L2 lexical items are mediated initially through the learned first language. As proficiency (i.e., language ability) improves, connections between L2 and the conceptual store are strengthened. The conceptual/semantic processing of L2 items should reflect the overall organization of the conceptual system because semantic processing occurs at the conceptual level.[3] If AoA effects are purely a product of early items having more semantic connections to other items than do late items, then an L2 lexical item should inherit the L1's AoA

Empirical studies with L2 speakers, however, have not supported this prediction. Researchers have found that the speed of L2 lexical access is determined by the age at which words are acquired in the second language (L2 AoA) and not the age at which the corresponding words are learned in the native language (L1 AoA; Hirsh, Morrison, Gaset, & Carnicer, 2003; Izura & Ellis, 2004). Thus, these effects appear to be due to the order in which words enter a particular language, irrespective of when the language was learned (Hirsh et al., 2003). In order to account for this finding, the semantic locus hypothesis would have to assume separate semantic stores for each language. Researchers have not yet determined the exact mode of bilingual lexical representation (for a review, see French & Jacquet, 2004; Kroll & Tokowicz, 2005); however, most of the evidence favors a single semantic store. Thus, it seems reasonable to assume that AoA exerts its effects at the lexical level rather than at the semantic level (for further discussion along these lines with monolingual individuals, see Belke, Brysbaert, Meyer, & Ghyselinck, 2005).

Computational accounts of age of acquisition. Some connectionist models have been designed to explicitly capture mechanisms of AoA (Ellis & Lambon Ralph, 2000; Li, Farkas, & MacWhinney, 2004; M. A. Smith, Cottrell, & Anderson, 2001). Ellis and Lambon Ralph trained an auto-associative network on sets of words that were introduced at different times. They showed that the network displayed strong AoA effects, as indicated by lower recognition errors for early than for late learned words when the words were presented to the network in stages, that is, trained on one set of words before a second set was introduced. Using the same model without staged learning, M. A. Smith et al. (2001) showed that recognition errors decreased as a function of learning order; early learned words had lower final recognition errors than did late learned words. Li, Farkas, and MacWhinney (2004) further explored AoA effects using a self-organizing neural network relying on Hebbian learning. AoA effects appeared such that early and late acquired words showed structural differences in organization as a natural outcome of learning order. More recently, Lambon Ralph and Ehsan (2006) showed that their connectionist network could capture AoA effects as a function of the consistency or predictability in the input-to-output mapping relations: arbitrary mappings elicited larger AoA effects compared with less arbitrary mappings. In each case, AoA effects appeared to reflect increased rigidity (reduced plasticity) of the network as a result of the learning process. Early learned words influenced the structural organization of the distributed mental lexicon more than late learned words, and had better optimized representations (e.g., as captured by word density measures in Li, Farkas, & MacWhinney, 2004).[4]

These connectionist models provide a general account of AoA that is not specific to any particular domain (i.e., phonology, semantics, etc.); as such, the account is compatible with aspects of several hypotheses. For example, the semantic locus hypothesis also posits that early learned words help shape the (semantic) network. Similarly, the phonological completeness hypothesis conceptualizes early learned words as more complete than late learned words and posits that these words form a foundation for the less complete words acquired later. Hence, loss of plasticity may be a property of learning that is reflected in a number of domains.

Neuroimaging studies of age of acquisition. Relatively few studies have investigated the neural basis of AoA effects. Fiebach, Friederici, Müller, von Cramon, and Hernandez (2003) examined AoA with functional magnetic resonance imaging (fMRI), a technique that allows researchers to measure the oxygenation level of blood and thereby determine which neural areas are activated during a task. Participants were asked to make visual and auditory lexical decisions to words and pronounceable pseudowords during fMRI scanning. Results in both the visual and auditory modalities revealed increased activity for late relative to early learned words in the left inferior prefrontal cortex (IPFC; Brodmann's Area [BA] 45) extending to the lateral orbitofrontal cortex (BA 47/12). The precuneus was more activated for early learned relative to late learned words (see Figure 1). In addition, increased activity in the region of the left

[2] This is not true for some proposals based on statistical learning or neural networks. For example, Li et al. (in press) argued that semantic representations become enriched over time as a function of learning, much like filling holes in Swiss chess; initially, there may be more holes than cheese (shallow representations), but the holes fill quickly as the word context accumulates during learning (rich representations). This perspective, however, does not contradict the idea that early learned words establish the basic lexical–semantic structure.

[3] One could argue, however, that semantic structure is not equivalent to conceptual structure, with the former tied to specific properties of a given language and the latter more language independent (for further discussion see Lyons, 1977). Most bilingual lexical memory research does not make this fine-grained distinction, and considers semantic and conceptual structure at the same level.

[4] Zevin and Seidenberg (2002) have argued that AoA effects may be restricted to tasks in which early learned information does not aid in acquiring items introduced later. In the simulations discussed above, the networks must "memorize" each pattern. However, Zevin and Seidenberg have simulated reading acquisition and found that the practice effects can diminish AoA effects. Hence, AoA effects may be robust for tasks such as object naming and face recognition but may be small for skilled tasks such as reading (for additional evidence in favor of this view, see Lambon Ralph & Ehsan, 2006; Monaghan & Ellis, 2002b). Studies of AoA effects in transparent orthographies, however, call into question this "mapping" hypothesis (Raman, 2006).

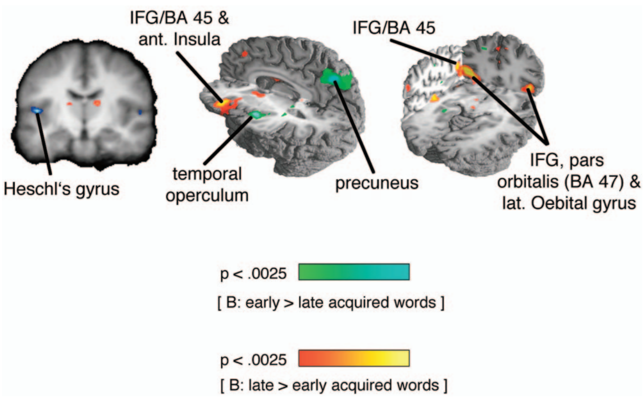

Figure 1. Neural activity associated with early and late learned words. Increased activity is evident for early and late learned words in monolingual German speakers. The blue-to-green scale represents areas of increased activity for early learned words. The red-to-yellow scale represents areas of increased activity for late learned words. BA = Brodmann's area; IFG = inferior frontal gyrus; ant. = anterior; lat. = lateral. From "Distinct brain representations for early and late learned words," by C. J. Fiebach, A. D. Friederici, K. Müller, D. Y. von Cramon, & A. E. Hernandez, 2003, *Neuroimage, 42,* p. 1631. Copyright, 2003 by Elsevier. Adapted with permission.

temporal operculum near Heschl's gyrus was observed for early relative to late learned words in the visual modality. Because auditory association cortices were activated, Fiebach et al. concluded that participants automatically coactivated auditory representations when making lexical decisions to early learned words that were visually presented, possibly to facilitate word recognition. The increase in inferior frontal activity during processing of late learned words is compatible with findings regarding the role of the left IPFC in semantic processing. Left IPFC appears to be critical in the effortful or strategic activation of information from the semantic knowledge system (Fiez, 1997; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). Hence, processing of late learned words, at least when making lexical decisions, is likely to involve complex semantic retrieval or selection processes instantiated by inferior frontal brain areas. An interesting implication of this result is that semantics may play a strong role in learning words late in life, whereas auditory processing may play a strong role in learning words early in life. This makes sense especially in light of our hypothesis regarding early sensorimotor integration in L2 acquisition (see discussions presented later in the section, Integration of Age of Acquisition Effects Across Domains).

Recent studies have extended Fiebach et al.'s (2003) research using word reading (Hernandez & Fiebach, 2006) and picture-naming tasks (Ellis, Burani, Izura, Bromiley, & Venneri, 2006). Ellis et al. (2006) found increased activity in separate portions of the middle occipital gyrus for early compared to late learned words, suggesting that both sets engage visual processing to a certain extent. Of particular interest, was the fact that late learned words elicited activity in the fusiform gyrus and early learned words elicited activity in the most inferior portions of the temporal lobe. Ellis et al. (2006) interpreted activity in the temporal pole for early learned items as reflecting the highly interconnected nature of these items. This inference is based on evidence that damage to the temporal poles leads to semantic dementia (Rogers, Lambon Ralph, Hodges, & Patterson, 2004; Thompson, Patterson, & Hodges, 2003). The increase in activity for late learned compared with early learned items in the fusiform gyrus reflects an increased need for visual form processing (Devlin, Jamison, Gonnerman, & Matthews, 2006; Price & Devlin, 2003). These results seem consistent with the view that early learned items have more semantic interconnections than do late learned items, whereas late learned items require more visual form processing than do early learned items during picture naming.

Hernandez and Fiebach (2006) asked participants to read single words during fMRI scanning. Increased activity to late as compared with early items was found in the left planum temporale (posterior superior temporal gyrus) and in the right globus pallidus, putamen, middle frontal gyrus (BA 9) and inferior frontal gyrus (BA 44). The authors suggested that late learned words engage brain areas in the left hemisphere that are involved in mapping phonological word representations and areas in the right hemisphere that aid articulatory and motor processing.

These results implicate neuroanatomical substrates that may be associated with plasticity. In all of the studies reviewed above, processing of late learned items involved brain areas thought to be involved in effortful retrieval, including effortful semantic retrieval in lexical decision, articulatory and motor processing during reading, and visual form processing in picture naming. By contrast, early learned words appeared to be strongly connected to semantics in picture naming and to auditory word representations in lexical decision. Together, these results are consistent with the notion that the neural substrate of early learned words is at a basic level, albeit semantic or auditory, depending on the task. Late learned words build on these representations and require additional processing during lexical tasks.

Age of Acquisition in Second-Language Learning

The term AoA has also been used by scholars of L2 acquisition. The meaning of the term, however, is different when researchers use it to describe L2 learning than when they use it to describe L1 processing. In L1 processing, AoA refers to a stimulus property of linguistic items (early vs. late learned words), whereas in L2 learning AoA usually refers to learner characteristics (early vs. late starting age for acquiring L2). In the L2 literature, AoA[5] is often examined along with other learner characteristics, such as level of L2 proficiency.[6]

Behavioral studies have long documented differences between early and late learners of a second language. They have consis-

[5] Some authors (e.g., Johnson & Newport, 1989) have used "age of arrival" rather than AoA to indicate the age at which L2 acquisition begins. The former term is conceptually relevant to immigrant learners whose L2 learning coincides with their arrival in the target language country, whereas the latter is a more general term. Here we use "L2 AoA" for consistency.

[6] Language proficiency can be defined as the degree of control one has over a language. Proficiency can be defined in four domains: listening, speaking, reading, and writing. These skills, although interrelated, are independent in that one skill may develop separately from the others. Cummins (1983) has argued that language proficiency has two levels: basic interpersonal communicative skills (BICS) and cognitive and academic language proficiency (CALP). BICS involves personal, face-to-face, "context-embedded" communication and typically requires 2 years to acquire, whereas CALP involves skills in understanding and using language in academic settings (context-reduced) and requires 5 to 7 years to acquire. Studies in the psycholinguistic and neuroimaging literature generally use some standardized test to assess proficiency; hence, proficiency involves CALP in Cummins's terminology.

tently found an AoA on the ultimate attainment of L2 (Flege, Munro, & MacKay, 1995; Flege, Yeni-Komshian, & Liu, 1999; Mackay & Flege, 2004; Munro, Flege, & MacKay, 1996).

Although critical period effects in L2 learning are still being debated (Hakuta, Bialystok, & Wiley, 2003; Harley & Wang, 1997; Johnson & Newport, 1989; Liu, Bates, & Li, 1992; Snow & Hoefnagel-Höhle, 1978), researchers generally agree that late compared with early learning of L2 is associated with lower ultimate proficiency, even though some individuals may achieve native-like proficiency (Birdsong, 1992). Moreover, behavioral work by Hernandez and colleagues suggests that proficiency, and not AoA, determines naming latencies in lexical tasks when L2 acquisition occurs early in life (Hernandez, Bates, & Avila, 1996; Hernandez & Kohnert, 1999; Hernandez & Reyes, 2002; Kohnert, Hernandez, & Bates, 1998). This is consistent with the view that L2 AoA affects the processing of syntax, morphology, and phonology more than it affects lexical and semantic processing (Johnson & Newport, 1989; Weber-Fox & Neville, 1996).

Evidence supporting the role of AoA in behavioral studies has been overwhelming; however, findings regarding the neural bases of L2 AoA effects have been mixed. First, language recovery in those with bilingual aphasia is not driven exclusively by L2 AoA (see Fabbro, 1999, for a review). Second, recent fMRI studies have yielded conflicting results, with some finding that AoA determines patterns of neural activity and others finding that language proficiency is the primary determinant. AoA modulates neural activity during sentence comprehension when proficiency is not taken into account (Perani et al., 1996). AoA effects diminish or disappear, however, when early and late learners are equated on proficiency: Proficient bilingual indviduals, whether early or late learners, show strikingly similar neural responses for both L1 and L2, whereas less proficient bilingual individuals have different activation patterns for the two languages, more so in comprehension than in production (for a review, see Abutalebi, Cappa, & Perani, 2001; see also Chee, 2006; Perani et al., 1998). Proficiency also plays a role in semantic and lexical tasks (Chee, Hon, Lee, & Soon, 2001; Chee, Soon, Lee, & Pallier, 2004; Elston-Guettler, Paulmann, & Kotz, 2005; Mechelli et al., 2004; Meschyan & Hernandez, 2006; Xue, Dong, Jin, Zhang, & Wang, 2004). Hence, considerable evidence suggests that proficiency has a crucial role in the neural activity underlying L2 processing. What remains unclear is how proficiency and AoA interact in the acquisition of different language processes, the topic of the next section.

Age of Acquisition, Proficiency, and Syntactic and Semantic Processing in Second-Language Learning

Age of Acquisition Versus Proficiency

Evidence for the relative importance of proficiency as opposed to AoA can be found in recent work with populations that are immersed in a second language early in life. One particularly intriguing finding involves Korean adoptees who experience exclusive L2 immersion after being adopted by French families. The research shows no neural or behavioral trace of L1 even when L2 immersion occurs as late as age 8 years (Pallier et al., 2003; Ventureyra, Pallier, & Yoo, 2004). Evidence to date is inconclusive as to whether AoA or proficiency determines the behavioral and neural patterns in L2 learning. The fact that proficiency seems more important than AoA in the neuroimaging research contradicts behavioral research in the L2 literature, as discussed above.

Syntactic Versus Semantic Processing

The lack of uniform support for AoA or proficiency as the primary determinant of neural activity may be a result of the fact that both factors play a role, perhaps differently for different language processes, as suggested by Hernandez et al. (2004; see earlier discussion). Indeed, some neuroimaging research has found that tasks involving syntactic processing show larger AoA effects than tasks involving semantic processing (Wartenburger et al., 2003; Weber-Fox & Neville, 1996). In a seminal study, Weber-Fox and Neville (1996) asked a group of Chinese–English bilingual individuals to read sentences that contained three different types of syntactic violations (phrase structure, specificity constraint, and subjacency constraint) and sentences that contained semantic violations. They used event-related potentials (ERPs) to measure participants' electrophysiological responses to a number of linguistic and nonlinguistic factors. Previous research has established that ERP components (e.g., N400, P600, and left anterior negativity [LAN]) are sensitive to semantic and syntactic violations (Atchley et al., 2006; Friederici, Hahne, & Mecklinger, 1996; Hagoort, 2003; Hagoort & Brown, 1999; Kutas & Hillyard, 1980; Kutas & Van Petten, 1988; Osterhout, Allen, McLaughlin, & Inoue, 2002). Weber-Fox and Neville found differences in the timing and distribution of the ERPs for both semantic and syntactic violations when L2 learners were compared with native speakers. Differences between L2 learners and native speakers appeared at different ages depending on whether the violation was syntactic or semantic. For syntactic violations, differences appeared between participants who learned English as early as age 2 years and native speakers. However, differences in the ERPs to semantic violations only appeared in participants who learned English after the age of 11 years. Although objective proficiency was not measured, participants who learned English after age 16 rated themselves as less proficient in English than in Chinese. These results are consistent with the view that AoA has an important role in determining the neural activity associated with grammatical violations, whereas proficiency has an important role in determining the neural activity associated with semantic violations.

In order to understand the neuroanatomical substrates that distinguish AoA and proficiency, Wartenburger et al. (2003) examined Italian–German bilingual indviduals as they monitored sentences for morphosyntactic violations (number, gender, or case) or semantic violations during fMRI scanning. Three groups were tested: early-acquisition bilingual individuals with high proficiency in L2 (EAHP), and late-acquisition bilingual individuals with either high (LAHP) or low (LALP) proficiency in L2. Increased brain activity in L2 relative to L1 was seen in all three groups for both semantic and syntactic violations. Late learners, relative to early learners, showed increased neural activity in areas associated with motor planning and articulatory effort when processing grammatical violations, even when both groups were matched in proficiency. In late learners, lower proficiency led to activity in areas closely associated with auditory and visual integration. A different pattern emerged for semantic processing. Proficiency modulated activity in areas of the brain devoted to memory and executive processing. However, the difference was between LAHP and LALP, unlike the results for syntactic processing. Together, these results suggest that AoA predicts activity in brain areas during syntactic processing, whereas proficiency predicts activity during semantic processing. Furthermore, the

AoA effects observed for the former appear to involve areas of the brain underlying sensorimotor processing.

A number of questions arise with regard to the finding that syntactic processing is more sensitive than semantic processing to AoA effects in bilingual indviduals. First, it is unclear why this should be so. One possibility is that semantic processes are more similar across a bilingual's two languages than are syntactic processes (at least the ones tested in these studies). A second possibility is that some processing component of syntax is particularly affected by AoA. The underlying cause of stronger AoA effects in L2 syntactic processing than L2 semantic processing may be revealed by considering various factors that modulate these effects.

Overlap Across Languages

As noted earlier, Zevin and Seidenberg (2002, 2004), as well as Monaghan and Ellis (2002b), argue that AoA effects should be large when early learning differs substantially from late learning (i.e., with little overlap between late and early learning). Although this hypothesis is inconsistent with findings in behavioral studies of AoA conducted with transparent orthographies (Raman, 2006), recent research suggests that it may play a role in L2 learning. Tokowicz and MacWhinney (2005) instructed English–Spanish bilingual indviduals to make grammaticality judgments for sentences that varied in the ways in which syntactic functions overlapped. The first function involved tense marking (noun–verb agreement), which is similar in English and Spanish. The second function involved determiner–noun agreement (*las casas* vs. *la casas*). Number in English, as in Spanish, is marked on the noun (*houses*). However, Spanish, unlike English, requires determiner–noun agreement (*la casa* vs. *las casas*). The third function involved gender agreement, a function that is unique to Spanish (*la casa* vs. *el casa*). ERP data were collected as participants made judgments about the sentences. Across all sentences, an interaction between function type and grammaticality was found for the P600, an electrophysiological index that is sensitive to grammatical violations in sentence contexts. Specifically, the difference in ERPs to grammatical and ungrammatical sentences was significant for subject–verb agreement, but not for determiner–number agreement. This finding is consistent with the view that cross-language overlap modulates sensitivity to grammatical processing in L2.

Chen, Shu, Liu, Zhao, and Li (in press) recently tested proficient late Chinese bilingual learners' ability to detect subject–verb agreement violations in English (e.g., *the price of the cars are too high*). In Chinese, unlike English and other Indo-European languages, grammatical morphology does not mark case, gender, or number; thus, subject–verb agreement in sentences is not required. The acquisition of subject–verb agreement is a major obstacle for Chinese learners of English. ERP responses from the L2 Chinese and the native English participants clearly showed distinct patterns, even though behavioral responses did not. Native speakers showed a typical LAN/P600 biphasic pattern in response to agreement violations, whereas this pattern was absent in the L2 learners. Instead, L2 learners showed an N400/N600 response pattern, indicating that even proficient L2 learners differ from native speakers when processing syntactic features that are absent in their native language. Together, these studies suggest that the overlap between native and nonnative languages affects syntactic processing in L2.

Regularity

Recent research in the psycholinguistic literature has focused on the difference between regular and irregular morphological markings, in particular, on the processing of English past tense. Researchers have debated whether irregular and regular verbs are processed in separate memory systems (Pinker, 1991; Pinker & Ullman, 2002; Ullman, 2001a, 2004) or in the same system, but relying differentially on semantic or phonological processes (Bird, Ralph, Seidenberg, McClelland, & Patterson, 2003; McClelland & Patterson, 2002; Patterson, Ralph, Hodges, & McClelland, 2001).

Although a large number of studies have investigated regularity in monolingual individuals, relatively few have examined the issue in bilingual indviduals. These few studies have found that late learners have difficulty learning irregular items (Birdsong & Flege, 2001; Flege et al., 1999). Recent neuroimaging work by Hernandez et al. (2004) examined AoA effects on the processing of regular and irregular grammatical gender. Two groups of early Spanish learners, one with high proficiency and one with low proficiency, were compared with a group of late learners. The results revealed increased activity in the inferior frontal gyrus for all three groups; however, the locus of activity varied. Early high-proficiency learners showed increased activity in the anterior insula, BA 44/45 and BA 44/6, as a function of irregularity (see Figure 2a). Each of these areas plays an important role in language processing (for a review, see Hagoort, 2005). BA 44/45 is activated in tasks that involve syntactic processing (Dapretto, Bookheimer, & Mazziotta, 1999; Friederici, Opitz, & von Cramon, 2000; Kang, Constable, Gore, & Avrutin, 1999; Moro et al., 2001) and in studies comparing gender monitoring to semantic monitoring (Miceli et al., 2002). Neuropsychological and neuroimaging studies have also demonstrated a link between the anterior insula

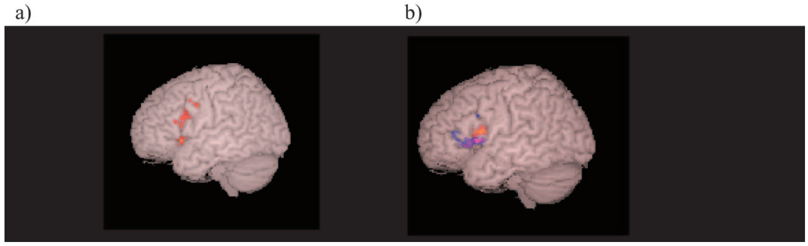

Figure 2. Difference between irregular and regular gender items for (a) monolingual Spanish speakers as well as (b) early and late learners of Spanish. Neural activity that varies in color from blue-to-pink represents results from late learners of Spanish. Results from early learners are represented in red-to-yellow color variations.

and articulation (Ackermann & Riecker, 2004; Bates et al., 2003; Dronkers, 1996; Shuster & Lemieux, 2005). BA 44/6 is involved in phonological processing (Poldrack et al., 1999) and activity is greater when German monolingual individuals are asked to generate a gender-marking determiner (*der*, *die* or *das*) for a picture than when they are asked to name the picture (Heim, Opitz, & Friederici, 2002). These results are consistent with the view that gender decisions for irregularly marked items, relative to regularly marked ones, involve more phonological and articulatory demands and more effortful syntactic computations.

Early and late learners of Spanish with matched proficiency showed different patterns of activity, although increased activity for the irregular items was observed for both groups. The late English–Spanish bilingual individuals showed a more distributed area of increased activity encompassing inferior portions of the inferior frontal gyrus, extending from the anterior insula into BA 47 (see Figure 2b). The early Spanish–English bilingual individuals showed more focused activity in BA 44/45 than did late learners. Direct comparisons between groups revealed increased activity in BA 47 for the late bilingual individuals. The results confirm that AoA modulates neural activity on grammatical tasks. Furthermore, they indicate that these differences are graded in nature. Group differences for regular items are very small, whereas larger differences are observed for irregular items. In summary, grammatical functions differ in their sensitivity to AoA, and inconsistent or irregular patterns in the grammar may affect bilingual learners to a greater extent than monolingual learners, especially as they age (see further discussion below in the section, Integration of Age of Acquisition Effects Across Domains).

A Declarative–Procedural Account

In the section, *Theoretical accounts of age of acquisition*, we described a number of theories that have been offered to account for AoA effects in monolingual individuals. Few theories, however, have been proposed to account for AoA effects in L2 except for a general learning plasticity based on computational modeling (see the section *Computational accounts of age of acquisition*). Ullman and colleagues (Ullman, 2001a, 2005) have proposed that L2 acquisition and use is constrained by the declarative and procedural (DP) memory systems. In the DP model, lexical learning and processing involve the declarative memory system, whereas grammatical acquisition and processing involve rule-governed combinatorial processes in the procedural memory system. Memory research supports the existence of these two systems (Eichenbaum, 2001; Squire & Zola, 1996), and neuroimaging research suggests that they have distinct neural bases. The declarative memory system underlies knowledge about facts and events, appears to be specialized for relational binding, and depends on a network of brain structures including regions of the medial temporal lobe. The procedural memory system underlies motor and cognitive skills, including "habits," may be specialized for sequences, and depends on a network of brain structures that include the frontal–basal ganglia circuitry. Ullman and colleagues have provided considerable evidence supporting their claim that grammatical and lexical processing rely on these different neural memory systems, respectively, including evidence from aphasia and Alzheimer's and Parkinson's diseases (Ullman et al., 1997; Ullman, 2005). Ullman (2005) has also shown that procedural learning decreases with age, whereas declarative learning may actually improve with age, possibly because of increased sex-hormone levels.

This framework sheds some light on why neural correlates of syntactic processing are more sensitive to AoA than are neural correlates of lexical processing. In the DP model, L2 learners, especially late learners, rely on declarative rather than procedural memory for grammatical processing. Evidence suggests that these learners memorize complex forms (e.g., "walked") as chunks, that is, forms that native speakers generally compose within the grammatical/procedural system. This reliance on declarative memory predicts that L2 learners will show more activity during grammatical processing than L1 learners in brain areas that are associated with declarative memory. As proficiency improves, L2 learners, especially early learners, should begin to rely on procedural memory; some recent evidence supports this prediction (Ullman, 2001b, 2005). The extent to which late learners can proceduralize their grammatical processing is still unclear, but late learners may rarely achieve L1-like levels of grammatical proficiency (Ullman, 2005).

Integration of Age of Acquisition Effects Across Domains

In the current review, we attempt to synthesize distinct literatures examining AoA in first- and second-language processing. It is worth noting, as we mentioned earlier, that no one would argue that AoA effects in L2 learning are the same as AoA effects involving vocabulary learning in monolingual individuals. However, these two types of AoA effects have interesting parallels raising a question about whether they rely, at least in part, on the same underlying mechanisms or processes. No current theory can explain both L1 and L2 AoA effects. Clearly, the DP model cannot account for AoA effects in monolingual lexical recognition and production. Similarly, the semantic locus and phonological completeness accounts do not predict L2 AoA effects as reflected in phonological, syntactic, and semantic processing.

The best candidate for a general account of AoA comes from computational models that attribute AoA effects to plasticity and stability across the life span, as suggested by Ellis and Lambon Ralph (2000); Li, Farkas, and MacWhinney (2004); Seidenberg and Zevin (2006); and Smith, Cottrell, and Anderson (2001). According to this account, AoA effects are due to the interactive dynamics with which items are learned. Early learning determines the structure of knowledge and shapes later learning, not only in the monolingual lexicon but also in other domains including phonological and grammatical development in both L1 and L2 learning (Kuhl, 2004). In other words, the learning process itself leads to AoA effects that are similar in L1 and L2.

If developmental constraints on learning are the underlying cause of AoA effects, how can one predict which domains will be most sensitive to AoA? This amounts to asking whether domains that show AoA effects share characteristics. One important characteristic that is shared among three domains showing AoA effects (nonlinguistic, L1, and L2) is the sensorimotor nature of processing. In L1, research suggests that early learned words are preferentially accessed using auditory information (Fiebach & Friederici, 2004), providing indirect evidence about the importance of sensory information for these items. In L2, late learners show reductions in phonological abilities and clear nonnative accents. In both cases, AoA is related to phonological processing, and in the latter, it is also related to motor planning and execution of speech. The association between AoA and sensorimotor processing is related to a broader theory that has been espoused by a number of scholars (Bates, Benigni, Bretherton, Camaioni, & Volterra, 1979; Lieberman, 2000; Zatorre, 1989), according to which language reflects a general sensorimotor ability in humans.

As discussed earlier, the frontal–basal ganglia circuitry underlies the procedural memory system. Recent neuroimaging research has shown that the basal ganglia plays an important role in cognitive and linguistic functions, including sensory acquisition and discrimination (Gao et al., 1996), lexical decision (Li, Jin, & Tan, 2004), and sequencing of articulatory activities. The development of the basal ganglia system is not well understood; however, it is possible that the crucial neural systems for sensorimotor learning and coordination, including the basal ganglia, undergo rapid organization and reorganization early in life; a loss of plasticity leads to difficulty in forming complex mappings later in life (Bates, 1999, Bates et al., 1997; Hensch, 2004; Pickett, Kuniholm, Protopapas, Friedman, & Lieberman, 1998). This view fits well with classic findings of a maturational constraint in sensory processing (Frenkel & Bear, 2004; Hensch, 2004; Hubel & Wiesel, 1965; Knudsen & Knudsen, 1990; Pettigrew, 1972; Smith & Greene, 1963; Stafford, 1984; Tees, 1967; Wiesel & Hubel, 1965).

If sensorimotor integration underlies AoA, then a unified account of linguistic and nonlinguistic patterns of development is possible. In nonlinguistic domains, we reviewed the acquisition of musical abilities and birdsong. In both these domains, evidence suggests that sensorimotor processing benefits from early exposure to the behavior of interest: and that the frontal-basal ganglia circuitry plays a significant role in this process (see Doupe et al., 2005). In the domain of language, phonological processing, particularly the articulation of speech sounds, is a sensorimotor process, and the accuracy of both L1 and L2 pronunciation depends on the speaker's precise control and temporal coordination of articulatory actions in the speech apparatus (tongue, lips, jaw, larynx, etc.). According to the motor theory of speech perception (Liberman & Mattingly, 1985), the perception of speech is based on our neural representation of the articulatory gestures associated with the generation of sounds: All speech sounds involve an invariant set of motor commands that are internally represented for articulation. In this view, speech production is the mirror image of speech perception. It involves fine-grained, high-speed sensorimotor control of sequences of muscle movements (Browman & Goldstein, 1989). Such activities must, to some extent, engage the frontal–basal ganglia neural circuitry that underlies the dynamic coordination of sequenced activities. If speech perception and articulatory coordination are developed early in life, as evidence seems to suggest (see Kuhl, 2000, 2004), then a sensorimotor account based on the dynamics of sequence acquisition may explain AoA effects in both L1 and L2.

Our sensorimotor view sheds light on several recent findings. For example, Izura and Ellis (2004) found that AoA effects in L2 are predicted by the order in which items enter L2, but not L1. The authors suggest that this finding supports computational models in which early learned items form initial links at the graphemic, phonological, and semantic level; these links constrain the acquisition of later items. Their argument is compatible with the sensorimotor hypothesis proposed here. Words encountered in L2 lead to the formation of new phonological and articulatory traces; these sensorimotor traces are unique to each language and do not transfer from L1 to L2, especially when L2 occurs late in life. The establishment of lexical structures in L1 may also adversely impact the representation of the L2 lexicon in addition to affecting phonology and articulation (see Hernandez, Li, & MacWhinney, 2005 for a review). Recent connectionist simulations that manipulate L1 and L2 AoA provide additional evidence about how the L2 lexicon, as a whole, may be affected when L2 learning is delayed; L1 will consolidate and will significantly (sometimes dramatically) affect the representation of L2. L2, for example, may be parasitic, with reduced lexical space and high rates of confusion during lexical retrieval (see Figure 3). These patterns may account for the observed "deficit" in lexical retrieval during word naming in L2 (Craik & Bialystok, 2006) and are consistent with the view that reduced plasticity and diminished structural reorganization underlie AoA effects.[7]

The sensorimotor hypothesis naturally accounts for the finding that syntax, especially morphosyntax, is more sensitive to AoA than semantics in both monolingual and bilingual individuals. Research suggests that young children use prosodic and phonological cues in early word learning (Morgan & Demuth, 1996a, 1996b). Most importantly, phonological cues appear to be crucial in the processing of syntax and morphosyntax (Christophe, Guasti, Nespor, Dupoux, & Van Ooyen, 1997; Jusczyk, Kemler Nelson, Morgan, & Demuth, 1996) and in lexical categorization (Shi, 2006; Shi, Morgan, & Allopenna, 1998). If phonological processing abilities develop early, and the learning of syntax and morphosyntax relies heavily on these abilities, then it would be no surprise to find that sensorimotor abilities underlie syntactic and morphosyntactic AoA effects. These effects should be especially large for irregular items and items that do not have overlapping characteristics across languages, as they will tax the phonological system to a greater extent. In contrast, semantic processing relies on the conceptual overlap across languages and should transfer readily; hence, it should be less susceptible to AoA than are syntactic and morphosyntactic processes.

Our working hypothesis is that AoA effects in nonlinguistic domains and in first- and second-language acquisition, although clearly distinct, share an underlying mechanism involving sensorimotor integration. This hypothesis is consistent with evidence about neural development. For example, Trainor (2005) showed that as an organism gains experience, its brain becomes more organized, leading to reduced plasticity because many connections have been functionally specified and are less open to change. This loss of plasticity can be described in neural terms by what some researchers call "experience-dependent synaptic change" (Bates, 1999) or "experience-mediated changes" (Trainor, 2005; Werker & Tees, 2005). Connectionist models provide computational principles that account for such changes (Elman, 1993; Elman, Bates, Johnson, & Karmiloff-Smith, 1996). Recent results from our self-organizing models clearly demonstrate such changes in mechanistic terms, as discussed earlier (Hernandez et al., 2005; Li & Farkas,

[7] The functional organization of the bilingual lexicon in development (as simulated by our model) should not be confused with the issue of neural representation of the two languages (as shown by fMRI work). Indeed, the early distinct representation of the two lexicons, as shown in Figure 3, would appear counterintuitive if it were pitted against the idea of a common neural machinery for both L1 and L2 in early or proficient bilingual individuals.

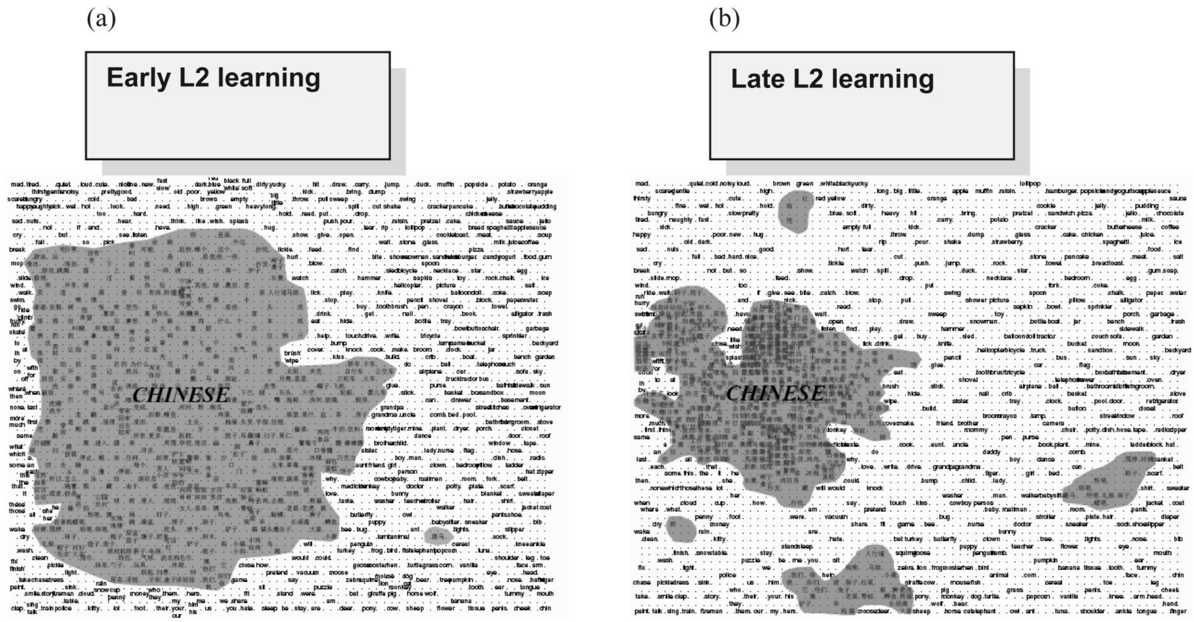

Figure 3. Lexical organization as a function of early versus late learning of a second language (L2). Shaded areas indicate L2 (Chinese) representations. From "A self-organizing connectionist model of bilingual lexical development" (p. 2639) by X. Zhao & P. Li. In *Proceedings of the 28th annual conference of the Cognitive Science Society* (2006). Mahwah, NJ: Erlbaum.

2002; Li, Farkas, & MacWhinney, 2004; Li, Zhao, & MacWhinney, 2007).

In conclusion, sensorimotor learning is an important milestone that determines AoA effects. Our sensorimotor account exemplifies the idea that learning shapes the course of development in monolingual, bilingual, and nonlinguistic domains. This view is consistent with recent views in developmental psychology and cognitive neuroscience that early learning leads to dedicated neural circuitry that affects the form of cognitive and neural structures at later stages of development (Elman, 2005; Elman et al., 1996; Kello, 2004; Kuhl, 2000, 2004; L. B. Smith & Thelen, 2003).

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