The Neurobiology of Language: Looking Beyond Monolinguals

Ellen Bialystok & Judith F. Kroll

1. Introduction

The publication of *Biological Foundations of Language* in 1967 by Eric Lenneberg fundamentally changed the way we think about language. Chomsky brought language from the abstract realm of philosophy into the more grounded world of mind, and Lenneberg completed the process by rooting that mental view of language firmly in the brain. Without Lenneberg, it is difficult to imagine the immense amount of research over the past 50 years that has revealed its structure and function, its social and cognitive dimensions, and obviously, its neurobiology. For Chomsky, the biological basis of language was static, based on innate concepts that unfolded with experience and the reference to biology was largely metaphoric: "mental organ". For Lenneberg, the biological basis of language was real and dynamic. He was the first thinker to seriously understand language as part of human cognition: "[Words] stand for a cognitive process, that is, the *act* of categorization or the *formation* of concepts" (Lenneberg, 1967: 365, emphasis in original). This conception of language blossomed over the subsequent decades, leading to more sophisticated accounts of human language that were based on the use of new methodologies that Lenneberg was unlikely to even imagine. The expansion of technology for observing the brain, the explosion in the sheer amount of knowledge that was accumulated about the brain and its function, and the widespread access to these technologies that became available irrevocably changed the way that language research was conducted (Friederici 2017, Kemmerer 2015). Lenneberg's visionary ideas about the neurobiology of language set the stage for 50 years of exciting and productive study.

In parallel with Lenneberg's developing understanding of language as a biological system, another field began to emerge around the same time. There was growing interest in the process of learning a second language, particularly in adulthood, spawning the field of second-language acquisition (SLA). Much of this research was generated in response to practical needs. A salient example comes from the post-war efforts of The British Council to teach English in various corners of the British Empire by recruiting graduates from the top schools such as Oxford and sending them to distant lands. Armed with little more than intelligence and intuition, many of these teachers thought deeply about their experiences and began

Preparation of this manuscript was supported by in part by NIH Grants HD052523 and AG048431 and NSERC Grant A2559 to EB and NSF Grants BCS-1535124 and OISE- 1545900 and NIH Grant HD082796 to JFK.

ISSN 1450–3417
Biolinguistics 11.SI: 339–351, 2017
http://www.biolinguistics.eu

to uncover how to best teach foreign languages and by extension, how languages were learned. One leader in this effort was Pit Corder who had been teaching language and developing syllabus design in various countries for many years. His seminal paper proposed a new set of ideas about language teaching that freed SLA from the behaviorist roots by which it had long been constrained (Corder 1967). However, the predominant model for language subsequently adopted in SLA research was the nativist view of Chomsky, thereby limiting the dynamic component that connected language to cognitive structures and environmental constraints.

Both fields have matured over the past 50 years and yet, somewhat remarkably, remain largely distinct. The fiftieth anniversary of founding works in these fields is an opportunity to consider how more cross-fertilization might benefit our understanding of language. Language science is now deeply embedded in biological models and brain research (Kutas & Van Petten 1994). SLA has evolved through research in such areas as psycholinguistics and bilingualism that explore language-mind-brain connections when more than one language is involved (Kroll, Dussias, Bice, & Perrotti 2015). But Lenneberg had access to none of these insights; his theories and arguments were based on monolingual characterizations, with additional languages representing special cases that did not challenge the central theoretical claims. Our discussion will explore the implications of research with second-language learners and bilinguals for some of Lenneberg's most important claims.

Lenneberg did address the issue of foreign language learning to some extent. He acknowledged that second languages can be learned at any time, even after puberty and even at 40 years old, but asserted that there was no longer access to "automatic acquisition from mere exposure". Moreover, he noted that foreign accents were almost inevitable for languages learned after puberty. This observation is related to his claims for a critical period for (first) language acquisition, described below, but he saw no contradiction with the notion of a critical period because no further cerebral organization is required

> since natural languages tend to resemble one another in many fundamental aspects [...], the matrix for language skills is present.
>
> (Lenneberg 1967: 176)

Our view is that recent research in SLA, bilingualism, and psycholinguistics provides crucial evidence that requires a revision of these assumptions.

A central implication of situating language in the biology of the human brain is the acceptance of a framework based on maturation, leading irrevocably to the discussion of critical periods for language learning:

> Language cannot begin to develop until a certain level of physical maturation and growth has been attained. (Lenneberg 1967: 158)

He goes on to state that the years between 2-years old and the early teens are optimal for acquiring language and that language skills acquired after puberty remain "deficient for life". Before 2, there is inadequate brain development, and after puberty the brain loses its ability for reorganization. His argument that the critical period for language learning occurred in this window were based on his description of the structural, biochemical, and electrophysiological development of the brain during this period, all of which he believed were essential to support language, although the precise relations between these developments and language learning were not explained. His view is summarized as follows:

> The disequilibrium state called language-readiness is of limited duration. It *begins around two* and *declines with cerebral maturation* in the early teens. At this time, apparently a steady state is reached, and the cognitive processes are firmly structured, the capacity for primary language synthesis is lost, and *cerebral reorganization of functions is no longer possible*. (Lenneberg 1967: 376–377, emphasis added).

Evidence from SLA and bilingualism challenges each of these main points indicated in italics. We will address them by describing evidence from preverbal infants who are less than 2-years old, adults learning a foreign language, and reorganization of first language representations from second languages learned after the close of the critical period.

2. Language Learning Before Two

Biological developments in the form of critical periods are involved in aspects of the complex set of processes leading to language acquisition, but much has changed since Lenneberg's original description so the nature of that involvement is unlikely to be exactly as envisaged by him. Much of the revision of his ideas can be traced to the dramatic increase in our knowledge of brain structure and the neurobiological mechanisms that underlie human behavior, including language.

In a comprehensive review of speech perception in infancy, Werker & Hensch (2015) describe the multiple developments in the first two years of life and the biological mechanisms that provide the basis for language discrimination, phoneme perception, and audiovisual integration, all essential for language development. All these component developments are traced to specific critical periods that have clear onset and offset windows and in many cases, known biological bases. Crucially, however, they also examine factors that serve to maintain plasticity and avoid closing the critical period, even for these highly circumscribed abilities. One factor they discuss in this regard is bilingualism.

Despite being controlled by critical periods, several pre-linguistic landmarks in the first year of life evolve differently for infants being raised in monolingual or bilingual homes. Thus, even before the onset of Lenneberg's critical period for language learning at 2 years, monolingual and bilingual children are developing a different substrate for language acquisition, setting a different neural foundation for this process in the two language groups. An early example of this effect of experience was in infant phoneme perception. From birth, infants can discriminate between phonemic contrasts in consonants relevant to all (known) natural languages, making them in effect universal language learners (although the trajectory is different for vowels). By 10- to 12-months old, distinctions can only be perceived in the language they are learning, narrowing their perceptual focus and probably improving their ability to learn the environmental language. However, for infants being raised in bilingual environments, the ability to discriminate among all phonemic contrasts remains open, even after the critical period has closed for monolingual infants (Aslin, Pisoni, & Perey 1981, Best 2001, Werker & Tees 1984). Therefore, by the time of the first word, around one year old, the phonemic representation system is different for infants raised in different kinds of language environments.

A more dramatic example comes from studies showing the ability of infants in the first year to distinguish between languages being spoken on the basis of visual information alone. As with phonemic contrasts, monolingual infants can detect such changes until about 7 months old but then fail to make the discrimination. This is not the case for infants raised in bilingual environments. Infants were shown silent videos of a woman speaking French and then, after the infant has habituated, switching to English (or the reverse order). Monolingual infants older than 8-months old did not notice the change, but bilingual infants raised in French-English bilingual homes (Weikum et al. 2007) or Spanish-Catalan homes where they have never encountered either French or English (Sebastian-Galles, Albareda-Castellot, Weikum, & Werker 2012), were able to detect the switch from French to English.

Related to this ability to identify visual language is the way infants look at faces. For newborns, attention naturally focuses on the eyes, but by the end of the first year, preferential attention to faces shifts to the mouth. This new preference presumably supports their growing interest in language by focusing on the most relevant source of information. The shift is earlier for bilingual infants; by 8-months old, infants being raised in bilingual environments are more interested in looking at the mouth whereas infants in monolingual homes continue to focus on the eyes (Ayneto & Sebastian-Galles 2017, Pons, Bosch, & Lewkowicz 2015). By 12-months old, only bilingual infants continue to look at the mouth when both the native and non-native languages are spoken. By 12-months old, monolingual babies look at the mouth only for non-native speech.

These studies used behavioral methods. What happens when we look more directly at brain activity in young infants? Pettito et al. (2012) used functional near infrared spectroscopy (fNIRS) to investigate changes in brain activation for younger (4–6 months) and older (10–12 months) infants exposed to one language alone or more than one language. All the babies had been exposed to English but the bilingual babies had also been exposed to another language. Pettito et al. presented them with the sounds of Hindi, a language equally unfamiliar to the monolingual and bilingual infants. Critically, there was a difference in the pattern of brain activity between the older monolingual and bilingual babies. Consistent with the behavioral pattern reported by Werker & Tees (1984), at 10- to 12-months old the bilingually exposed babies continued to reveal brain activity in response to non-native phonetic contrasts while monolingual babies had lost that ability. They termed this phenomenon for bilinguals the "perceptual wedge" to suggest that bilingually exposed brains maintain greater openness to new language input. Other recent studies using the tools of cognitive neuroscience have examined the consequence of this special openness to speech in bilingual babies' developing brains. Using methods such as magnetoencephalography, they have demonstrated that there is not only increased openness for bilingually exposed babies, but also that there are consequences for the development of brain regions associated with cognitive control and executive function (e.g., Ferjan Ramírez, Ramírez, Clarke, Taulu, & Kuhl 2017). What is clear is that these are not simple effects of maturation but rather evidence for the powerful influence of environmental exposure on language development and the brain, even before the beginning of the critical period defined by Lenneberg.

Two generalizations from these findings challenge aspects of Lenneberg's original theory. First, language acquisition does not begin at 2 years when physical and neurological development has passed some maturational threshold but rather emerges from processes begun at least at birth and possibly in utero. In that sense, there is essentially no lower bound on the window for language acquisition. Second, the modifications found in these developments for children raised in bilingual homes demonstrate the plasticity of language learning even for simple perceptual processes such as phoneme discrimination and even during the crucial early stages of language acquisition. Although Lenneberg was open to a limited notion of plasticity and environmental influence, the evidence from infants in dual language environments speaks to a far greater interaction between biological and experiential contingencies than he imagined.

3. Too Old to Learn?

Critical periods are a common mechanism across species in which maturation requires receiving specific input or experience during a window of maximum sensitivity so that development can proceed. These critical periods are generally used to describe low-level processes such as perception that are part of the foundation for higher-level processes, such as visual interpretation or cognition. This distinction applies as well to critical periods in humans where such low-level maturationally-timed developments in vision (Lewis & Maurer 2005) underlie higher-level visual processing, and low-level developments in speech perception (Werker & Hensch 2015) set the stage for language acquisition. But is there also a maturational restriction on the higher-level processes involved in language acquisition, including mastery of syntax and morphology?

Lenneberg was careful to restrict his deterministic notions of a critical period to primary language acquisition, acknowledging that foreign language learning could take place later in life although it would proceed through different mechanisms. He also limited the degree of proficiency that could be expected for older second-language learners and noted that a foreign accent was likely to occur. Others, however, have made broader claims and essentially argued that all language learning was curtailed after the close of the critical period (e.g., Johnson & Newport 1989). The time that marks the close of the critical period is also different in various accounts: for Lenneberg it was puberty, for Penfield & Roberts (1959) it was 9 years old, and for Johnson & Newport (1989) it was late teens. Throughout these views, however, there is consensus that the close of the critical period is a turning point that either ends the possibility of learning a second language (e.g., Johnson & Newport 1989) or changes its learning mechanism and reduces its expected outcome (e.g., Lenneberg). Therefore, it is important to establish what the evidence is for a biological restriction on this high-level process and whether it applies to all language learning after the close of the critical period or only to acquisition of the first language or only to aspects of the first language.

The challenge in evaluating the role of a critical period for a high-level process such as language acquisition is to determine what evidence is appropriate to test the hypothesis. With the exception of rare cases of abused or feral children, children are unlikely to be completely deprived of language until the close of the critical period. Lenneberg's approach was to investigate children's language acquisition following a brain lesion or acquired aphasia from brain injury and compare the prognosis as a function of the age at which the trauma occurred. His observation was that for children less than 3-years old, when language acquisition resumed it followed the usual stages, possibly proceeding more rapidly than usual. The older children were when the aphasia occurred, the more effortful the recovery, up to puberty which Lenneberg called "a turning point", after which language impairments from aphasia never completely clear up. A similar pattern was noted for patients undergoing the removal of the entire left cerebral hemisphere because, as Lenneberg states,

> language learning can take place, at least in the right hemisphere, only between the age of two to about thirteen. (Lenneberg 1967: 153)

These data are necessarily fragmentary and brain lesions are never identical for different individuals, so comparisons are difficult. However, the pattern is that injury to language acquisition with increasing age is increasingly disruptive, and that injury after puberty cannot restore the language system.

Newport and her colleagues have taken a different approach to examining the possibility for a critical period in first language acquisition and studied the acquisition of American Sign Language (ASL) by congenitally deaf children (summary in Newport 1990). These children can be first exposed to ASL at different ages, providing a natural manipulation to test the hypothesis. In practice, however, children are not first exposed at any time but rather at specific points that mark experiential landmarks, such as starting school. Therefore, their studies typically compared children whose first exposure to ASL was native (from birth), early (4- to 6-years old), or late (after 12 years old). Across studies and measures, outcomes were different for the three groups, with earlier exposure leading to the best mastery of ASL.

In both the investigations of language acquisition following brain lesion and acquisition of ASL at different ages, the evidence shows that older ages are associated with poorer outcomes. In both cases as well, the interpretation is that puberty is a juncture after which language acquisition will be compromised, leading the researchers to conclude that this is caused by the close of the critical period. However, in both cases, the interpretation of a critical period with a qualitative change at puberty is inferential because the data do not include a continuous sampling of ages.

A more direct test of the critical period hypothesis comes from examining second-language acquisition but here, too the evidence is mixed. In a comprehensive review of children acquiring a second-language between the ages of one and 3-years old or between 4- and 7-years old, Unsworth (1916) reported no significant difference between these groups in several aspects of language proficiency, including vocabulary and morphosyntax. However, Newport examined this question and arrived at a different conclusion. In a study comparing English proficiency in second-language learners who began using English at different ages, Johnson & Newport (1989) reported a relation between age and proficiency with better outcomes for those who began learning at a younger age. The relation was shown as a significant linear function across all ages, with a stronger correlation for those who began learning English before the age of 17 years than for those who began after 17. Their conclusion was that the pattern in which a critical period marked the close of a capacity to learn language extended to the acquisition of a second language.

Johnson & Newport's (1989) study was based on data from 46 individuals. In a substantially larger-scale investigation, Hakuta, Bialystok, & Wiley (2003) examined census data from 2.3 million immigrants to the U.S. whose first language was Spanish or Chinese. The census asked respondents to provide a self-rating of their English proficiency, so these scores were analyzed in terms of the number of years they had lived in the U.S. on the assumption that on average that would indicate the age at which they began learning English. The ages of initial acquisition ranged from birth until around 80 years old, and the results showed a significant linear relation between age and proficiency across the entire spectrum, similar to the pattern reported by Johnson and Newport.

There are two problems with the conclusion that evidence for a linear relation between age of acquisition and proficiency supports a critical period for language acquisition. First, if the critical period defines the optimal window for learning to occur, then the variation in learning outcomes within that window should be relatively minor and certainly less than variation in outcomes when comparing learning within and outside of the critical period. Johnson & Newport (1989) argued that their data did show that pattern in that the correlation between age and proficiency was not significant considering only the 23 learners who were more than 17 years old at the time of acquisition, but the overall correlation was significant and the sample was very small. Hakuta et al. (2003) demonstrated that by removing only one participant from the Johnson & Newport data who did not line up on the regression curve, the correlation between age and proficiency for the learners who were over 17 years old became significant. Using the much larger data reported by Hakuta et al. (2003), the relation between these variables was statistically equivalent inside and outside the critical period.

Second is the related point that the definition of a critical period presumes an abrupt change in learning potential following the close of that window. This abrupt change was clearly not found in the Hakuta et al. data, but to confirm that interpretation, the authors compared the correlation before and after specific juncture points of 15 and 20 years old. No change in slope was detected. Importantly as well, the Hakuta et al. study included participants at every age along the continuum, whereas the other studies sampled from specific points making the interpretation of a linear function more inferential than real. Similarly, if the critical period begins at 2-years old, then there should be no difference in outcomes for those who begin language learning at 2 years, 3 years, or 4 years. Yet in the lesion data, the ASL data, and the second-language acquisition data, these onset ages are all associated with declining success.

There is no doubt that age is a crucial factor in determining language learning outcomes for both a first and second language. The question is whether these age-related patterns support the interpretation of a critical period for overall proficiency. Evidence from second-language acquisition is more in line with a gradual decline in the success of language learning than a biological barrier that interferes with its potential. Regarding first language acquisition, there is simply inadequate evidence to conclude there is a critical period. The most compelling evidence is that reported by Newport and colleagues regarding the acquisition of ASL at different ages, but again the pattern is inferential. The late learners certainly had poorer outcomes than the early learners, but the early learners also had poorer outcomes than the native learners. That should not happen if both those groups were within the critical period for language acquisition. Instead, it may be that this pattern again follows the lifelong linear relation reported for second-language acquisition in which older acquisition ages are associated with poorer outcomes in a continuous function. This relation still needs to be explained, but if it is indeed continuous across the lifespan then it is more likely a reflection of gradual changes in cognition, learning and memory. These are important changes, but they are not captured by critical periods.

4. Language Learning, Reorganization, and Processing Beyond the Critical Period

Two predictions drawn from a strict interpretation of the critical period hypothesis have been widely tested. One is that second language learning past the critical period necessarily relies on mechanisms that differ from those that had been available initially for the first language. The second is that past the critical period, the native language is largely stable, remaining unchanged when adult learners acquire and use a second language. In each case, recent findings require a revision of the idea that hard constraints determine the trajectory and outcome of late second language learning.

The question of whether late second language learners can fully acquire the nuances of the second language grammar beyond any putative critical period has been the focus of a great deal of research. To account for the reduced ability for adult to acquire native-like sensitivity to second language grammar, some have argued that late learners exploit semantic and pragmatic information rather than strictly syntactic or morpho-syntactic information, relying on mechanisms available only via explicit learning (e.g., Clahsen & Felser 2006, Ullman 2001). Although a full consideration of the evidence on this issue is beyond the scope of the present discussion, we note that recent studies using neuroscience methods have shown that it is possible for late learners to acquire native-like sensitivity to a range of grammatical structures in the second language. A critical observation concerning the previous behavioral research on this issue is that it suffered from an inevitable confounding between age of acquisition (AoA), length of time spent learning the second language, and second language proficiency (Steinhauer 2014). However, when the performance of highly proficient late second language learners is examined, the neural networks that are activated when processing even subtle aspects of the second language grammar are largely the same as those that are activated by native speakers of the language (e.g., Berken et al. 2015, Caffarra, Molinaro, Davidson, & Carreiras 2015; Morgan-Short et al. 2012, Roncaglia-Denissen & Kotz 2016). These similar patterns suggest common processes and underlying mechanisms.

The evidence on late learners does not refute the observation central to Lenneberg's claim that there may be an effect of AoA for the grammar. The circumstances of learning for adults clearly differ from those for young children and adult second language learning is not as reliably successful as child language learning. Critically, what the new data do show is that when that process is successful, either because learners have been immersed in a second language context or because they have acquired the control mechanisms that enable them to regulate the native language, it reflects the same underlying networks used by native speakers of the language (e.g., Perani & Abutalebi 2005). In all cases, there appears to be much greater plasticity for adult learners than was known at the time of Lenneberg's original claims about the critical period.

The research on acquiring the second-language grammar past the critical period focuses primarily on acquired language abilities in the second language itself. A more recent line of investigation has asked how the native language changes in the process of acquiring and using a second language as an adult learner. Evidence for such changes would indicate reorganization of the first language. Contrary to the view that the native language is stable past an early critical period for language learning, the recent research demonstrates that the native language is both more variable than previously understood, even for monolingual speakers (e.g., Pakulak & Neville 2010), and that the process of learning and using a second language proficiently comes to have profound influences on the native language. Those changes can be seen at the level of the phonology (Chang 2013), the lexicon (Ameel et al. 2005), and the grammar (Dussias & Sagarra 2007). The bilingual's two languages are influenced by each other, with changes that not only reflect transfer from the native language to the second language, the direction of influence that characterized most early research on this topic, but also from the second language to the first. The consequence is that the native language of proficient bilingual speakers is not precisely like the native language of monolingual speakers of the same language. That observation itself requires a reassessment of the native speaker model that has characterized research on second language learning and bilingualism.

Changes to the native language can be observed in long-term studies of language attrition (Schmid 2010) but they can also be seen during briefer periods of immersion in the second language (Linck et al. 2009), and in the laboratory when speakers use the native language after a very brief exposure to the second language (Misra et al. 2012). Contrary to the view that maturation alone determines the presence of sensitivity to the syntax of the second language, recent studies show that the form of language usage, such as whether bilinguals code switch across their two languages, comes to affect the way they process each language and influences the observed patterns of brain activity in both comprehension and production (Beatty-Martinez & Dussias 2017, Green & Wei 2016). The brain networks that support cognitive control are engaged by these language processes and come to shape the relationship between language and cognition.

The plasticity revealed by the new research is evident not only in proficient bilinguals but also in adult learners at early stages of acquiring the second language. The second language quickly comes to affect the native language (e.g., Bice & Kroll 2015) and what is not yet well understood is what these changes might predict about success in second-language learning. Studies using electrophysiological methods have shown remarkable sensitivity to emerging learning, with the brain outpacing behavior and suggesting important sources of individual variation in the process (e.g., McLaughlin et al. 2004, Tanner et al. 2014). Given the deterministic nature of critical periods, such evidence for lifelong plasticity is a significant challenge to explanations in which language acquisition is constrained by a critical period.

5. Conclusion

The research since Lenneberg (1967), illustrated by the findings we have discussed, shows that there is variation in how constrained or plastic different aspects of language acquisition may be. Infants tune to the speech of the language or languages to which they are exposed within the first year of life. In a sense, that process is more constraining than Lenneberg imagined. At the same time, studies of dual language exposure show that early exposure to two or more languages has profound consequences for creating a broader bandwidth for new language learning for young infants exposed to more than one language. The process of tuning to speech happens quickly and much earlier than one might expect from Lenneberg's account. If any aspect of language learning is open to hard constraints, it may be speech, with rapid changes in the first year of life and late exposure producing accents that be difficult or impossible to overcome. The evidence we have considered on acquiring grammar suggests that there may be soft constraints that are modulated by the context in which language is learned and used but that the hard constraints that were thought to be associated with a critical period can be overcome. A crucial point in our review is that it is only by examining how a second language comes into play that these features of language learning can be identified.

In 2005, on the occasion of the 125th anniversary of *Science*, Kennedy & Norman wrote an editorial in which they identified the top 125 questions to be answered in all of science in the following 25 years. One of these questions was the biological basis of second-language learning. In the time since 2005, there has been an explosion of studies on this topic, reflecting many of the themes we have discussed in this paper. The intensive effort to uncover the neural mechanisms engaged by language learning across the lifespan is an enduring tribute to Lenneberg. While the findings since Lenneberg largely refute the notion of a strict critical period for language, and the new evidence for plasticity fails to match the junctures in development that he first identified, the spirit of this new work is congenial with his visionary commitment to a biology of language.

References

Ameel, Eef, Gert Storms, Barbara C. Malt, Steven A. Sloman. 2005. How bilinguals solve the naming problem. *Journal of Memory and Language* 53, 60–80.

Aslin, Richard N., David B. Pisoni, Beth L. Hennessy, Alan J. Percy. 1981. Discrimination of voice onset time by human infants: New findings and implications for the effects of early experience. *Child Development* 52, 1135–1145.

Ayneto, Alba & Nuria Sebastian-Galles. 2017. The influence of bilingualism on the preference for the mouth region of dynamic faces. *Developmental Science* 20, e12446.

Beatty-Martínez, Anne L. & Paola E. Dussias. 2017. Bilingual experience shapes language processing: Evidence from codeswitching. *Journal of Memory and*

Language 95, 173–189.

Berken, Jonathan A., Xiaoqian Chai, Jen-Kai Chen, Vincent L. Gracco, & Denise Klein. 2016. Effects of early and late bilingualism on resting-state functional connectivity. *Journal of Neuroscience* 36, 1165–1172.

Best, Catherine T. 2001. Discrimination of non-native consonant contrasts varying in perceptual assimilation to the listener's native phonological system. *Journal of the Acoustical Society of America* 109, 775.

Bice, Kinsey & Judith F. Kroll. 2015. Native language change during early stages of second language learning. *NeuroReport* 26, 966–971.

Caffarra, Sendy, Nicola Molinaro, Doug Davidson, Manuel Carreiras. 2015. Second language syntactic processing revealed through event-related potentials: An empirical review. *Neuroscience & Biobehavioral Reviews* 51, 31-47.

Chang, Charles B. 2013. A novelty effect in phonetic drift of the native language. *Journal of Phonetics* 41, 520–533.

Clahsen, Harald & Claudia Felser. 2006. Grammatical processing in language learners. *Applied Psycholinguistics* 27, 3–42.

Corder, S. Pit 1967. The significance of learner's errors. *International Review of Applied Linguistics in Language Teaching* 5, 161–170.

Dussias, Paola E. & Nuria Sagarra. 2007. The effect of exposure on syntactic parsing in Spanish-English bilinguals. *Bilingualism: Language and Cognition* 10, 101–116.

Friederici, Angela D. 2017. *Language in Our Brain: The Origins of a Uniquely Human Capacity*. Cambridge, MA: MIT Press.

Ferjan Ramírez, Naja, Rey R. Ramírez, Maggie Clarke, Samu Taulu, & Patrica K. Kuhl. 2017. Speech discrimination in 11-month-old bilingual and monolingual infants: A magnetoencephalography study. *Developmental Science* 20, e12427.

Green, David W. & Li Wei. 2016. Code-switching and language control. *Bilingualism: Language and Cognition* 19(5), 883–884.

Hakuta, Kenji, Ellen Bialystok, & Edward Wiley. 2003. Critical evidence: A test of the critical-period hypothesis for second-language acquisition. *Psychological Science* 14(1), 31–38.

Johnson, Jacqueline S. & Elissa L. Newport. 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, 60–99.

Kemmerer, David (2015). *Cognitive Neuroscience of Language*. New York, NY: Psychology Press.

Kennedy, Donald & Colin Norman. 2005. What don't we know? *Science* 309, 75–75.

Kroll, Judith F., Paola E. Dussias, Kinsey Bice, & Lauren Perrotti. 2015. Bilingualism, mind, and brain. *Annual Review of Linguistics* 1, 377–394.

Kutas, Marta & Cyma K. Van Petten. 1994. Psycholinguistics electrified. In Morton Ann Gernsbacher (ed.), *Handbook of Psycholinguistics* 83–143. San Diego, CA: Academic Press.

Lenneberg, Eric H. 1967. *Biological Foundations of Language*. New York, NY: Wiley.

Lewis, Terri L. & Daphne Maurer. 2005. Multiple sensitive periods in human visual development: Evidence from visually deprived children. *Developmental Psychobiology* 46, 163–183.

Linck, Jared A., Judith F. Kroll, & Gretchen Sunderman. 2009. Losing access to the native language while immersed in a second language: Evidence for the role of inhibition in second language learning. *Psychological Science* 20, 1507–1515.

McLaughlin, Judith, Lee Osterhout, & Albert Kim. 2004. Neural correlates of second-language word learning: Minimal instruction produces rapid change. *Nature Neuroscience* 7, 703–704.

Misra, Maya, Taomei Guo, Susan C. Bobb, & Judith F. Kroll. 2012. When bilinguals choose a single word to speak: Electrophysiological evidence for inhibition of the native language. *Journal of Memory and Language* 67, 224–237.

Morgan-Short, Kara, Karsten Steinhauer, Cristina Sanz, & Michael T. Ullman. 2012. Explicit and implicit second language training differentially affect the achievement of native-like brain activation patterns. *Journal of Cognitive Neuroscience* 24, 933–947.

Newport, Elissa L. 1990. Maturational constraints on language learning. *Cognitive Science* 14, 11–28.

Pakulak, Eric & Neville, Helen J. 2010. Proficiency differences in syntactic processing of monolingual native speakers indexed by event-related potentials. *Journal of Cognitive Neuroscience* 22, 2728–2744.

Penfield, Wilder & Lamar Roberts. 1959. *Speech and Brain Mechanisms*. Princeton, NJ: Princeton University Press.

Perani, Daniela & Jubin Abutalebi. 2005. The neural basis of first and second language processing. *Current Opinion in Neurobiology* 15, 202–206.

Petitto, Laura-Ann, Melody S. Berens, Ioulia Kovelman, Matt H. Dubins, Kaja K. Jasińska, & Mark H. Shalinsky. 2012. The "Perceptual Wedge Hypothesis" as the basis for bilingual babies' phonetic processing advantage: New insights from fNIRS brain imaging. *Brain and Language* 121, 130–143.

Pons, Ferran, Laura Bosch, David J. Lewkowicz. 2015. Bilingualism modulates infants' selective attention to the mouth of a talking face. *Psychological Science* 26, 490–498.

Roncaglia-Denissen, M. Paula & Sonja A. Kotz. 2016. What does neuroimaging tell us about morphosyntactic processing in the brain of second language learners? *Bilingualism: Language and Cognition* 19, 665–673.

Schmid, Monika S. 2010. Languages at play: The relevance of L1 attrition to the study of bilingualism. *Bilingualism: Language and Cognition* 13, 1–7.

Sebastián-Gallés, Núria, Bàrbara Albareda-Castellot, Whitney M. Weikum, Janet F. Werker. 2012. A bilingual advantage in visual language discrimination in infancy. *Psychological Science* 23, 994–999.

Steinhauer, Karsten. 2014. Event-related potentials (ERPs) in second language research: a brief introduction to the technique, a selected review, and an invitation to reconsider critical periods in L2. *Applied Linguistics* 35, 393–417.

Tanner, Darren, Kayo Inoue, & Lee Osterhout. 2014. Brain-based individual differences in online L2 grammatical comprehension. *Bilingualism: Language and Cognition* 17, 277–293.

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

Unsworth, Sharon. 2016. Early child L2 acquisition: Age or input effects? Neither, or both? *Journal of Child Language* 43, 608–634.

Weikum, Whitney M. , Athena Vouloumanos, Jordi Navarra, Salvador Soto-Faraco, Núria Sebastián-Gallés, Janet F. Werker. 2007. Visual language discrimination in infancy. *Science* 316, 1159.

Werker, Janet F. & Takao K. Hensch. 2015. Critical periods in speech perception: New directions. *Annual Review of Psychology* 66, 173–196.

Werker, Janet F. & Richard C. Tees. 1984. Phonemic and phonetic factors in adult cross-language speech perception. *The Journal of the Acoustical Society of America* 75, 1866–1878.

Ellen Bialystok
York University
Department of Psychology
4700 Keele Street
Toronto, Ontario M3J 1P3
Canada

ellenb@yorku.ca

Judith F. Kroll
University of California, Riverside
Department of Psychology
Riverside, CA 92521
United States of America

judith.kroll@ucr.edu