Review in Advance first posted online on September 17, 2014. (Changes may still occur before final publication online and in print.)

Critical Periods in Speech Perception: New Directions

Janet F. Werker[1,3] and Takao K. Hensch[2,3]

[1]Department of Psychology, University of British Columbia, Vancouver BC V6T 1Z4, Canada; email: jwerker@psych.ubc.ca

[2]Department of Molecular and Cellular Biology, Harvard University, Cambridge, Massachusetts 02138; email: hensch@mcb.harvard.edu

[3]Canadian Institute for Advanced Research, Toronto ON M5G 1Z8, Canada

Annu. Rev. Psychol. 2015. 66:23.1–23.24

The *Annual Review of Psychology* is online at psych.annualreviews.org

This article's doi: 10.1146/annurev-psych-010814-015104

Keywords

infancy, language acquisition, attention, GABA, parvalbumin, perineuronal net

Abstract

A continuing debate in language acquisition research is whether there are critical periods (CPs) in development during which the system is most responsive to environmental input. Recent advances in neurobiology provide a mechanistic explanation of CPs, with the balance between excitatory and inhibitory processes establishing the onset and molecular brakes establishing the offset of windows of plasticity. In this article, we review the literature on human speech perception development within the context of this CP model, highlighting research that reveals the interplay of maturational and experiential influences at key junctures in development and presenting paradigmatic examples testing CP models in human subjects. We conclude with a discussion of how a mechanistic understanding of CP processes changes the nature of the debate: The question no longer is, "Are there CPs?" but rather what processes open them, keeps them open, closes them, and allows them to be reopened.

Contents

INTRODUCTION

The ability to acquire human language is one of the quintessential characteristics of our species. Although many animals have communication systems, only human language allows the construction of an infinite number of new sentences not only to share needs and desires, but also to comment on the past and the future, to consider new possibilities, and to construct poetry and narrative. Human language is able to do this not only because humans have highly developed cognitive capabilities that support such complex thinking, but also because language itself has evolved to be richly structured, with multiple levels of interacting rules, from phonology through morphology, syntax, and semantics. Remarkably, by 4–5 years of age, young children have mastered nearly all of the rules of their native language and can produce and understand most structures, with subsequent development being primarily one of increasing vocabulary. Although infants don't begin canonical babbling until 7–10 months and don't typically produce their first words until this age or later, they begin life with biological biases that support the acquisition of language in general and have already begun—at birth—the process of acquisition of the native language via perception of the surface-level properties of the language(s) experienced.

In this article, we review the steps in perceptual development that support acquisition of the native language and examine these steps within the context of a critical (or sensitive) period framework (see also Doupe & Kuhl 1999, Friederici & Wartenburger 2010, Kuhl 2010, Werker & Tees 2005). We begin by defining the notion of a critical period at both a conceptual and more recent biological level. Then, in examining speech perception development, we first review the kinds of perceptual biases infants have for processing language prior to exposure to any specific language and the neural systems that are in place, even before birth, to direct and support language use.

Next, we describe how perceptual attunement to the properties of the native language unfolds, beginning with the most global rhythmical properties of the native language, the subsequent use of rhythm to segment continuous speech into different-sized units, and the perceptual narrowing

from broad-based to more language-specific discrimination of the speech sound differences that are used to distinguish one word from another in the native language(s). We describe briefly how the knowledge gained in perceptual attunement bootstraps acquisition of language proper. At each juncture, we consider the extent to which the system in question is subject to critical/sensitive period (hereafter referred to as CP) influences versus the extent to which it is open from the outset and remains open, and we discuss the consequences of openings and closings of CPs when development and functional use unfold in such a cascading fashion.

DEFINITION OF CRITICAL PERIODS

Conceptual Definition

CPs have been observed in various systems across species (Hensch 2004, Knudsen 2004). Primary sensory areas in particular—the brain's first filters to the outside world—exhibit especially striking examples of experience-induced plasticity during defined windows of early life. Such periods are needed to establish an optimal neural representation of the surrounding environment to guide future action. Given the extraordinary biological resources that must be devoted to rewiring neural circuitry, concentrating the construction of accurate, immutable maps early in life for use throughout adulthood may be an efficient strategy. However, this poses limitations on future revisions to the circuitry. Recent cellular and molecular insights indicate that biological mechanisms are expressed to ensure that adaptive changes are preferentially set in place early in life while leaving the door open for lifelong plasticity.

The classic notion of a CP is a window, typically in early development, during which a system is open to structuring or restructuring on the basis of input from the environment. Before and after this period, environmental influences cannot affect the sensitivity or response properties of that particular system. Although the timing of the initial opening of CPs is largely constrained by the maturation of underlying circuit readiness, early studies revealed that maturation is not the only contributing factor. Input is also necessary to trigger the opening of CPs: Animals reared in the dark remain open to visual influences until a later maturational age, beyond which there is eventually a closing (see Hensch 2005).

Almost as soon as the concept of CPs was introduced, it began to be modified. It was found that even in the visual system, experience can have an impact at time points outside of the CP, just not as profound. The alternate term, sensitive (or optimal) period, was coined to reflect the fact that windows do not always open and shut abruptly and may never close completely. Recent work showing that learning is possible throughout the life span (Bavelier & Davidson 2013), even in systems once thought to be CP-like, has added to the debate. Here we provide a mechanistic explanation of CPs that accounts for all of the above findings and hence changes the nature of the debate: The question no longer is, "Are there CPs?" but rather what processes open them, mediate their operation, and close (or reopen) them. We situate the age- and experience-related changes in speech perception within this framework.

Biological Definition

Perhaps the best-studied biological model of a CP is the enduring loss of responsiveness in primary visual cortex (V1) to a lazy or otherwise deprived eye. The behavioral consequence, amblyopia (poor visual acuity), afflicts 2–5% of the human population and remains without a known cure in adulthood (Holmes & Clarke 2006). From the initial discovery by Hubel and Wiesel 50 years ago, a biological picture has emerged wherein the inputs from the two eyes compete with each other

upon first converging onto individual neurons in V1 (Wiesel & Hubel 1963). Loss of connectivity underlies poor acuity and stereopsis. More recently, precise timing of this occular dominance CP has been shown to be essential for aligned binocular matching of orientation-selective neuronal responses, which typically mature earlier through each eye independently (Wang et al. 2010). Properly sequenced CPs are an essential part of acquiring higher-order functions such as language and birdsong (Doupe & Kuhl 1999).

Gamma-aminobutyric acid (GABA): the main inhibitory neurotransmitter in the central nervous system. CP onset is determined by the maturation of particular GABA circuits (PV cells)

Parvalbumin (PV): positive subtype of GABA neuron (notably the large basket cell) that acts as a pivotal plasticity switch underlying CPs. Optimal recruitment of E-I balance onto PV cells determines whether plastic changes are possible throughout life

Molecular tools have now begun to unravel the cellular mechanisms that control the onset and closure of such windows for cortical plasticity (for recent reviews, see Espinosa & Stryker 2012, Levelt & Hübener 2012, Takesian & Hensch 2013). These biological players are involved in the following key stages:

1. Molecular triggers to plasticity can shift neural circuits from an immature to plastic state, thereby opening a CP. The maturation of neural circuits that utilize the neurotransmitter gamma-aminobutyric acid (GABA) underlies the onset timing of plasticity, reflecting environmental input as well (Hensch 2004). Pharmacological agents that accelerate GABA circuit function (e.g., benzodiazepines) can trigger precocious onset, whereas genetic manipulations (e.g., deletion of genes involved in GABA synthesis) or environmental disruption (e.g., dark rearing, hearing loss) lead to a CP delay (Hensch 2005, Takesian & Hensch 2013). Environmental input needs to have some pattern for it to be effective: Under conditions in which sound space remains homogeneous across frequencies (white noise rearing), the tonotopic maps in primary auditory cortex (A1) remain immature and plasticity is delayed (Chang & Merzenich 2003, de Villers-Sidani et al. 2008).

   These manipulations are so powerful that they can determine whether an animal is before, at the peak of, or past a plastic window regardless of age. In other words, CP timing per se is plastic (see **Figure 1**). One particular subtype of inhibitory cell, the parvalbumin (PV) cell, serves as the pivotal plasticity switch (see sidebar, Biological Mechanisms Underlying Critical Periods) (Hensch 2005). PV cells provide lateral inhibition to the cell bodies of neighboring pyramidal cells, influencing their action potential firing, back propagation, and rhythmic oscillations (Sohal et al. 2009). Importantly, PV cells mature at different rates across brain regions (Condé et al. 1996)—potentially contributing to the cascading nature of CPs—and in response to a variety of intrinsic and external factors [e.g., brain-derived neurotrophic factor (BDNF), orthodenticle homeobox 2 (Otx2); see sidebar] (Takesian & Hensch 2013).

BIOLOGICAL MECHANISMS UNDERLYING CRITICAL PERIODS

The cellular substrates of CP plasticity (see **Figure 2**) as defined primarily in V1 include four sets of players: CP triggers, mediators, brakes, and reopeners. The PV cell serves as a pivotal plasticity switch, and its excitatory-inhibitory balance determines the timing of the CP. In the immature state, precocious plasticity is prevented by molecular brakes [such as polysialic acid/neural cell adhesion molecule (PSA-NCAM)]. The CP opens when molecular triggers (such as orthodenticle homeobox 2, BDNF)—in response to sensory input—promote PV cell maturation and GABA function. Rewiring is then mediated by physical pruning and homeostatic regrowth of synapses (by tPA, TNFα, protein synthesis). A consolidated state (CP closure) is finally maintained by molecular brakes, both functional (such as Lynx1, NgR1) and physical (such as PNN, myelin), which may limit plasticity by preventing further structural changes. Plasticity can be reopened, however, by lifting these brakes through epigenetic manipulation (HDAC inhibitors) or heightened attention (neuromodulators such as 5-HT, Ach, NE).

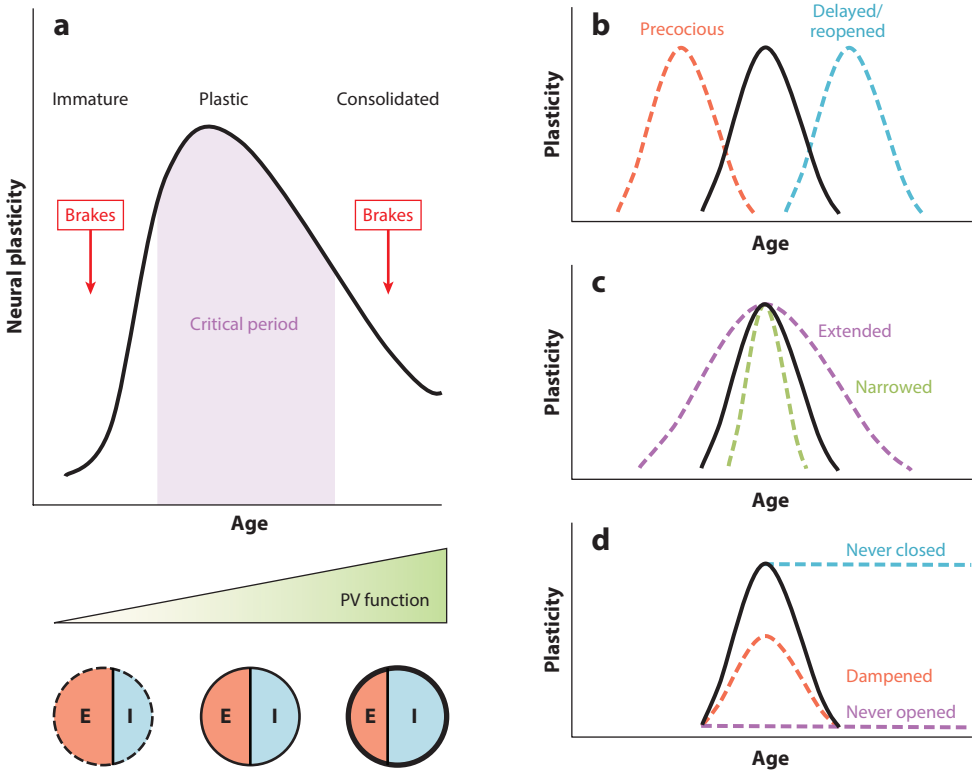

Figure 1

Recent biological insight into the time course of the critical period (CP). (*a*) The slow maturation of the excitatory-inhibitory (E-I) circuit balance [in particular that of parvalbumin (PV) cells] determines the initial onset and ultimate closure of a window of brain plasticity. (*b–d*) As a result, CP timing per se is malleable, allowing for precocious, delayed, extended, narrowed, dampened, or reopened plasticity. The latter involves the removal of molecular brakes that are expressed in adulthood to stabilize and consolidate otherwise plastic circuitry (see sidebar).

Timing of the events that lead to these triggers is constrained by maturation, but clearly experience is also necessary or the onset of plasticity will be delayed (**Figure 1*b***). How exactly GABA circuit maturation controls CP onset remains to be explored, but it has been proposed that inhibition may preferentially suppress responses to spontaneous intrinsic activity in favor of visually driven input, switching learning cues from internal to external sources (Toyoizumi et al. 2013).

2. Plasticity is mediated by molecular factors that enable rewiring of a neural circuit in response to sensory experience. During this open period, experience or the lack thereof can lead to significant (and sometimes rapid) changes in wiring; hence, this is a time of both opportunity and vulnerability. A biochemical sequence is triggered, initially freeing synaptic space through the action of secreted proteases [e.g., tissue-type plasminogen activator (tPA)] to cleave cell-adhesion molecules (see sidebar) (Hensch 2005). This first prunes away deprived inputs prior to sprouting of open eye connections in V1. Such delayed homeostatic growth requires protein synthesis and glial factors [e.g., tumor necrosis factor alpha (TNFα); Espinosa & Stryker 2012]. Directly disrupting intercellular adhesion molecules

Pyramidal cell: excitatory neurons of the cerebral cortex whose dendritic spines are pruned by experience during CP plasticity. The strength of inhibitory PV-to-pyramidal cell inputs increases (at a rate dependent on sensory experience) and eventually reaches an optimal threshold to promote plasticity

Table 1 Summary of the biological and experiential manipulations that alter critical period (CP) states

CP state	Biological manipulation	Experiential manipulation
Onset	■ Sensory deprivation (e.g., white noise, dark rearing) ■ E-I circuit maturation (e.g., GABA, BDNF, Otx2, PSA-NCAM)	■ Premature birth ■ SRI exposure ■ Maternal depression ■ Cochlear implant
Duration	■ Synapse pruning/homeostasis (e.g., tPA, TNFα, Icam5, protein synthesis) ■ Environmental enrichment	■ Bilingual experience ■ Diet
Closure	■ Molecular brakes (e.g., myelin, PNN, NgR1/PirB, Lynx1, HDAC) ■ Attentional arousal	■ Valproate exposure ■ Video games

Abbreviations: BDNF, brain-derived neurotrophic factor; E-I, excitatory-inhibitory; GABA, gamma-aminobutyric acid; HDAC, histone deacetylases; Icam5, intercellular adhesion molecule 5; NgR1/PirB, Nogo receptor 1/paired immunoglobulin-like receptor B; Otx2, orthodenticle homeobox 2; PNN, perineuronal net; PSA-NCAM, polysialic acid/neural cell adhesion molecule; SRI, serotonin reuptake inhibitor; TNFα, tumor necrosis factor alpha; tPA, tissue-type plasminogen activator.

(e.g., Icam5) shortens CP duration (Barkat et al. 2011), whereas enriched environments extend it (see **Figure 1*c***) (Brainard & Knudsen 1998, Sale et al. 2007).

3. Molecular brakes on plasticity eventually consolidate the neural circuit from a plastic to stable state, thereby closing the CP. Thus, the end of plasticity surprisingly involves active processes that preserve the changes that occurred during the plastic period. Several brake-like factors emerge after the CP to limit excessive circuit rewiring (see sidebar and **Table 1**) (Bavelier et al. 2010). Lifting any one of them through targeted genetic, pharmacological, or behavioral (e.g., attention training) manipulations can reinstate plasticity later in life (see Reopening Critical Periods section below) or extend the CP into adulthood (see **Figure 1*d***).

Brain-derived neurotrophic factor (BDNF): a secreted protein mediating growth of neurons and synapses. BDNF contributes to the opening of a CP by promoting maturation of PV cells

Orthodenticle homeobox 2 (Otx2): a protein that triggers the maturation and maintenance of PV cells upon accumulation in the cortex following sensory input. Thus, Otx2 enables plasticity and determines CP time course, by controlling both its opening and ultimate closure through PNNs

These brakes include structural obstacles to physically prevent synaptic pruning and outgrowth, such as perineuronal nets (PNNs) (Carulli et al. 2010, Miyata et al. 2012) or myelin-related signals including Nogo receptor 1 (NgR1) and the immune gene receptor paired immunoglobulin-like receptor B (PirB) (see **Figure 2**) (McGee et al. 2005, Syken et al. 2006). Other functional brakes (e.g., Lynx1, serotonin reuptake) dampen the neuromodulatory systems [e.g., acetylcholine (Ach), serotonin (5-HT)] that endogenously regulate excitatory-inhibitory (E-I) circuit balance (see sidebar) (Maya Vetencourt et al. 2008, Morishita et al. 2010). Finally, epigenetic modifications [e.g., histone deacetylases (HDACs)] silence gene programs necessary for synaptic rewiring (Maya Vetencourt et al. 2011, Putignano et al. 2007).

Windows of plasticity, therefore, arise between the maturation of an optimal E-I balance triggering the machinery of synaptic pruning and a later-emerging consolidating set of brake-like factors, which persistently limit rewiring throughout adult life (see **Figure 1*a***). With regard to speech perception in particular, the same principles derived from V1 are increasingly observed across brain regions. For example, in zebra finches, PNNs emerge in key nuclei as the multistep CP for song-learning closes. Social isolate rearing, which delays CP timing, then delays PNN formation and plasticity into older ages (Balmer et al. 2009). Adult mouse prefrontal cortex normally encodes acoustic preferences established during a CP early in life but can be rendered malleable later by NgR1 deletion or HDAC inhibitors (Yang et al. 2012). More recently, adult hippocampal

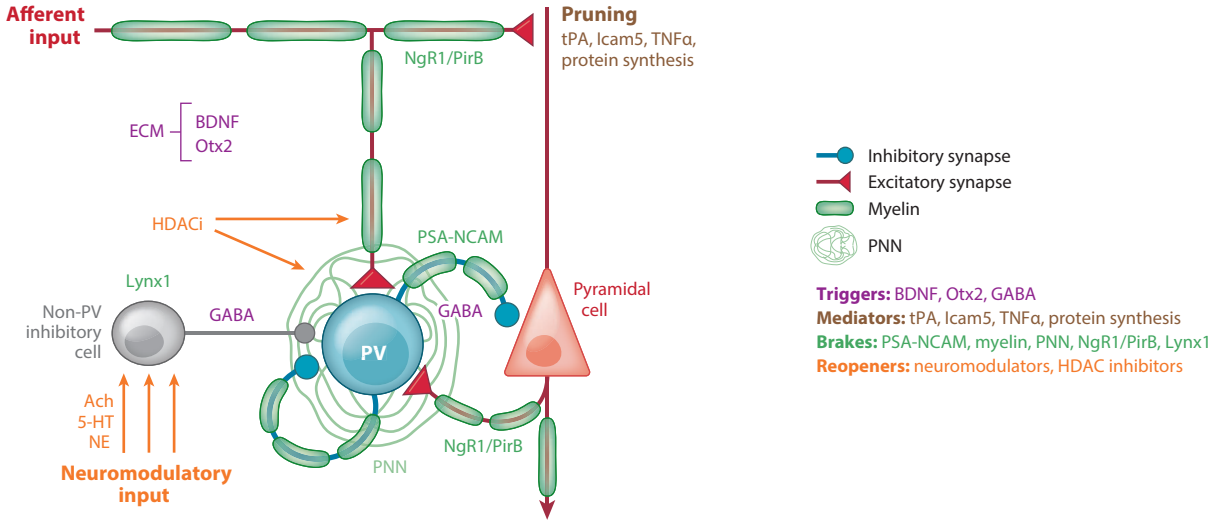

Figure 2

The biological processes involved in the onset, maintenance, and closing of critical periods. A detailed description is provided in the text. Abbreviations: 5-HT, serotonin; Ach, acetylcholine; BDNF, brain-derived neurotrophic factor; ECM, extracellular matrix; GABA, gamma-aminobutyric acid; HDAC, histone deacetylases; Icam5, intercellular adhesion molecule 5; NgR1/PirB, Nogo receptor 1/paired immunoglobulin-like receptor B; Otx2, orthodenticle homeobox 2; PSA-NCAM, polysialic acid/neural cell adhesion molecule; NE, norepinephrine; TNFα, tumor necrosis factor alpha; tPA, tissue-type plasminogen activator.

learning was found to reflect bistable PV cell states, under the control of non-PV inhibitory circuits, to focally recapitulate basic CP mechanisms throughout life (Donato et al. 2013).

CRITICAL PERIODS IN SPEECH PERCEPTION

The definitive examples of CPs involve fundamental sensory systems. Language, however, is an example of a higher-level cognitive system governed by CP phenomena. In his classic work, Lenneberg (1967) proposed a maturational model of language acquisition, with a critical period at the onset of puberty. Subsequently, it has become apparent that language acquisition is characterized by multiple critical and sensitive periods, with different onsets and offsets and different dynamics. There is a CP for the acquisition of syntax, for example, with a sharp dip after 7 years of age (Johnson & Newport 1989). There are even multiple sensitive periods for speech perception (which are discussed below) that open and close at different points in development. And there are some aspects of language, such as vocabulary acquisition, that remain open across the life span.

Speech processing shows both evolutionary- and experience-based influences (see Werker & Gervain 2013) from the earliest points in development at which the brain can support processing of such a complex signal. Anatomical organization that supports speech processing is evident in the human brain from as early as 29 weeks' gestation, even prior to specific listening experience (Dehaene-Lambertz et al. 2008), with ventral projections from temporal to prefrontal areas at birth but dorsal connections from the auditory cortex terminating in premotor cortex (Brauer et al. 2013). Functional imaging studies of newborn infants using both NIRS (Peña et al. 2003) and fMRI (Dehaene-Lambertz et al. 2002) reveal greater activation over classic temporal and frontal languages areas in response to continuous speech over nonspeech, with some studies revealing this specialization to be left-hemisphere dominant at birth, as it is in adults (Peña et al. 2003), and

Tissue-type plasminogen activator (tPA): an enzyme that prunes synaptic connections, thereby mediating early stages of CP plasticity. It is involved in cleaving cell-adhesion molecules on dendritic spines to free up synaptic space for growing axons and dendrites

Tumor necrosis factor alpha (TNFα): a cell-signaling protein released by astrocytes acting as a homeostatic regulator following disruptions of local E-I circuit balance, thereby mediating late stages of CP plasticity after initial pruning of inputs

other studies indicating it is initially bilateral with increased left hemisphere specialization over the next several months (Perani et al. 2011).

Importantly, although activation is greater to the native than to an unfamiliar language (May et al. 2011, Minagawa-Kawai et al. 2011), classic language areas in the brain are more activated to both forward familiar and unfamiliar language than to backward language (a nonspeech control stimulus; Peña et al. 2003) and/or to other kinds of nonlanguage but equally complex signals (for a review, see Price 2012). Similarly, the newborn brain reveals activation in classic speech processing areas in the left hemisphere in phonetic discrimination tasks (Dehaene-Lambertz & Gliga 2004). Indeed, even at 28–32 weeks' gestation, classic language areas in the Sylvian fissure are activated in the premature infant when discriminating phonemes (Mahmoudzadeh et al. 2013). Thus, at birth the marks of broad biological preparedness as well as specific experience are evident.

From the first moments of life, infant vocal behavior is influenced by prenatal listening experience (Mampe et al. 2009). Over the next several months of life, infants become increasingly attuned to other properties of the native language, and the link between perceptual attunement and higher-level processing becomes increasingly evident. As one example, at birth infants can discriminate languages from different rhythmical classes (Mehler et al. 1988). Prenatal listening experience also plays a role: Neonates show a preference for listening to languages that are from the same rhythmical class as those heard in utero (Mehler et al. 1988, Moon et al. 1993). It is only at 4–5 months of age that infants discriminate the native language from another language within the same rhythmical class and show a selective preference for the native language from another within the same rhythmical class (see Nazzi & Ramus 2003).

The timing of attunement to within-class rhythmical characteristics appears to be maturationally constrained. Infants born up to three months premature do not become capable of discriminating two languages from within the same rhythmical class until after eight months of age—the point at which they have reached the same gestational age as a 5-month-old full-term infant)—even though they have had three more months of postnatal listening experience by that time (Peña et al. 2010). These findings support the notion that the onset of this CP is constrained by maturation.

As infants become attuned to the rhythmical characteristics of the native language and use that attunement to pull out constituent units, perceptual attunement to finer properties of the native language ensues. By 7 months of age, infants show a preference for the stress (e.g., loud and long versus short and soft syllables), melody, and phonotactics (sequences of sounds that are allowed: English allows "rst" at the end but not the beginning of a word) used in the native language (see Jusczyk 2002). By this age infants can also use statistical regularities such as transitional probabilities to pull out probable units (Saffran et al. 1996). These sensitivities work together to enable infants to focus perceptual attention on individual words, and this in turn may support the perceptual narrowing to the speech sound categories of the native language.

Perineuronal net (PNN): a lattice-like structure of macromolecules that forms around PV cells and maintains their maturation by controlling the concentration of growth factors (e.g., BDNF, Otx2) and ions in the ECM. PNNs act as a physical brake on plasticity to close the CP

Myelin: a fatty insulation around neuronal axons promoting efficient electrical conduction; also enriched in proteins that inhibit axon growth, thereby limiting structural changes beyond the CP. Myelination thus acts as a physical brake to plasticity

Nogo receptor 1/paired immunoglobulin-like receptor B (NgR1/PirB): a complex that is a key mediator in myelin and PNN signaling. When proteins found in myelin or PNNs bind to these receptors, axonal sprouting and plasticity are limited, contributing to the closure of a CP

Phoneme Perception

The strongest evidence for CPs in perceptual attunement to the properties of the native language comes from work on phoneme discrimination. Although the standard understanding is that experience functions to induce or sharpen initial perceptual sensitivities—and this is indeed evident in speech perception development (for a review, see Kuhl 2010)—the vast majority of studies indicate that the ability to discriminate many of the consonant distinctions used across the world's languages is present in young infants prior to specific listening experience; the effect of listening experience is to maintain (and sharpen) sensitivity to those distinctions used in the native language and to show a decline in discrimination of nonnative ones (for a review, see Maurer & Werker

2014). Moreover, the onset of the opening of plasticity (of the CP) appears to be maturationally determined.

The languages of the world use different speech sound inventories to distinguish meaning. English, but not Japanese, distinguishes /r/ from /l/ in words such as "rate" versus "late," and Japanese adults have difficulty discriminating this distinction. At birth, infants can discriminate sounds such as /ba/ versus /da/ (a place of articulation difference) or /da/ versus /ta/ (a voicing distinction), and they do so using the same neural systems as activated in adult phoneme discrimination (Dehaene-Lambertz & Gliga 2004). More importantly, discrimination sensitivity extends to nonnative speech sound differences that the young infant has never before heard (Streeter 1976, Trehub 1976, Werker & Tees 1984).

The classic example of maintenance came from work reported by Werker and Tees in 1984. Young English-learning infants can discriminate two different "d" sounds that are used to contrast meaning in Hindi but not in English; however, by 10–12 months English-learning infants no longer succeed whereas Hindi-learning infants maintain sensitivity. This decline in nonnative perception and maintenance or improvement in native perception—which has now been shown to be ubiquitous across a wide variety of speech sound contrasts (Maurer & Werker 2014) as well as other aspects of perceptual development (Scott et al. 2007)—is referred to as perceptual narrowing. In consonant discrimination, narrowing is seen between 8 and 10 months of age. Up to 8 months of age, infants reliably discriminate both native and nonnative speech sound differences, but by 10–12 months of age, they have difficulty discriminating acoustically similar nonnative contrasts (for a review, see Maurer & Werker 2014). Similar effects have been shown for vowel discrimination (Polka & Werker 1994), for discrimination of lexical tone (Mattock et al. 2008), and for discrimination of the kinds of hand signs that are used in sign languages (Baker et al. 2005).

The fact that perception of so many different types of speech sound contrasts narrows at the same point in development is consistent with one of the characteristics of a CP. However, there is variability as well. Vowel perception may reorganize slightly earlier in development than consonant perception, with changes in the internal structure of vowel categories by 6–8 months of age (Kuhl et al. 1992) and the beginnings of recognition of familiar vowel sounds even at birth (Moon et al. 2013). Nonetheless, the decline in discrimination of two different nonnative vowels occurs closer to the 10-month age reported for narrowing of consonants (Polka & Werker 1994). Similarly, although the ability to discriminate between nonnative lexical tones appears to narrow only between 6–8 and 8–10 months of life (Mattock et al. 2008, Yeung et al. 2013), familiarity-based changes in preference are evident months earlier (Yeung et al. 2013). Thus the nervous system is accruing and registering experience, yet discrimination sensitivity—even of nonnative and never-before-heard speech sounds—is maintained until 10–12 months.

The 10- to 12-month time period appears to be under maturational control. Up to 10 months of age, infant perception of speech sounds is fairly easy to change. In a distributional learning paradigm, infants 6–8 months of age (Maye et al. 2002) show changes in speech sound categorization following as little as two minutes of exposure, with a bimodal frequency distribution during exposure leading them to bifurcate a continuum into two categories and a unimodal distribution to collapse it into one. At 10 months of age, however, once native speech sound categories have begun to solidify, double the exposure is needed to bring about the same amount of change (Yoshida et al. 2010). Thus, 10 months appears to coincide with the beginning of the consolidation period (see **Figure 1*a***).

As the system moves toward consolidation, experiences that are more engaging are better able to bring about perceptual change than are passive listening experiences. When exposed to Chinese speech in a contingent, interpersonal interaction, English infants 9–10 months of age maintain and reacquire sensitivity to Chinese (non-English) fricative contrasts (Kuhl et al. 2003) but do

Lynx1: a protein that dampens the effect of Ach on nicotinic receptors in GABA cells, ultimately shifting the local balance of excitation and inhibition. Lynx1 acts as a functional brake on plasticity, which can be reopened in adulthood by its removal

Acetylcholine (Ach): a neuromodulator released by enriched environmental input to engage non-PV cells, which then modulate PV cells as a functional mediator of plasticity

Serotonin (5-HT): a neuromodulator of E-I circuit balance. Once engaged by 5-HT, non-PV cells inhibit the PV cell and thus act as a functional mediator of plasticity

Histone deacetylases (HDACs): enzymes that cause DNA to be wrapped more tightly, ultimately limiting gene expression (also see definition of epigenetics). HDAC responds to environmental input and acts as a functional brake on plasticity; thus, HDAC inhibitors may result in CP reopening

not do so with equivalent noncontingent input. Similarly, if two nonnative consonant sounds are paired with two different objects in a quasi word-learning situation, infants 9–10 months of age also regain sensitivity to a nonnative speech sound contrast (Yeung & Werker 2009). Thus 10 months may mark the beginning of the decline in plasticity, but the closing appears to be gradual (for a discussion of such sensitive periods, see Knudsen 2004).

Non-PV inhibitory circuits: GABA circuits (e.g., containing vasoactive intestinal peptide) engaged by neuromodulators such as Ach or 5-HT inhibit PV cells and ultimately drive plasticity in adults

Once native speech sound categories are in place, infants are able to use them to segment words (Jusczyk & Aslin 1995) and to recognize familiar words (Swingley & Aslin 2002). Although there is instability in the first few months in infant's ability to use native phonological categories to guide the learning of new words (Stager & Werker 1997), they are able to succeed by 17 months (Werker et al. 2002) and can succeed at younger ages when the computational load is lighter (for a review, see Werker & Curtin 2005).

Audiovisual Matching and Integration

The mouth movements we make when we speak convey information that is consistent with that conveyed by the auditory signal. Adults integrate this seen information with what they hear. For example, it is easier to understand degraded speech if visual information from talking faces is also provided (Sumby & Pollack 1954).

Infants are sensitive to the visual information in speech (e.g., Rosenblum et al. 1997) and show neural integration of heard and seen speech from 10 weeks of age (Bristow et al. 2009, Kushnerenko et al. 2008). When presented with two side-by-side images of the same woman's face articulating "ee" and "ouu" respectively, infants of 4 months (Kuhl & Meltzoff 1982) and 2 months (Patterson & Werker 2003), and possibly even newborns (Aldridge et al. 1999), look longer to the side that is articulating the sound that they hear. Infants this young can also match heard and seen consonants (MacKain et al. 1983) and do so best when the matching face is on the right side, indicating involvement of the left hemisphere language areas.

Just as infants can discriminate speech sound differences they have never before heard, they can also match heard (auditory, A) and seen (visual, V) speech they have never before experienced (Pons et al. 2009). Moreover, there is perceptual narrowing by the end of the first year of life in AV matching just as there is in nonnative speech phonetic discrimination. In Spanish, there is not a distinction between /ba/ and /va/. Spanish-learning infants match heard and seen /ba/ and /va/ at 6 months but not at 10 months of age (Pons et al. 2009).

Young infants can also discriminate languages just by watching the articulatory movements in silent talking faces, and this capability also narrows in the first year of life. Following habituation to three bilingual French-English female speakers producing novel sentences in one of their native languages, and then testing with these same three speakers producing new sentences either in the old language (control condition) or the other language (the experimental condition), English-learning infants ages 4 and 6 months—but not 8 months—discriminate the change, as evident in a recovery of looking time in the experimental but not the control condition. However, infants growing up bilingual in English and French maintain sensitivity to the change in language at 8 months old (Weikum et al. 2007), consistent with the ubiquitous perceptual-narrowing pattern.

PROBING LANGUAGE CRITICAL PERIODS

Shifting Onset Timing

The most compelling evidence for a biologically determined onset to the sensitive period for phonetic attunement comes from a study with infants born approximately 12 weeks premature

but otherwise healthy. If perceptual narrowing to speech sound contrasts used only in the native language were driven entirely by amount of exposure, irrespective of age, one would predict that infants born premature would stop discriminating nonnative contrasts at a younger age than full-term infants. However, in an event-related potential (ERP) study of discrimination of the Hindi /da/-/Da/ distinction, Peña and colleagues (2012) reported that infants born premature continued discriminating the Hindi (nonnative) consonants until they reached a chronological age that was approximately 12 weeks older than that of the full-term infants; that is, when they had reached the same gestational age (time from conception) as had the full-term infants. Similarly, a recent ERP study indicates that when listening to consonant-vowel syllables, the spontaneous neural response to speech in premature infants does not show obvious effects of listening experience in the first several months after birth (Key et al. 2012). Thus, it appears that prior to a critical point in maturation—even when environmental input is provided—the developing human brain does not begin to settle on the native speech sound categories.

An understanding of the biological pathways that trigger the onset and offset of CPs positions one to probe those pathways to reinstate plasticity. In collaboration with W.M. Weikum and T.F. Oberlander, we did just that in a study of the timing of narrowing to the non-English, retroflex/dental (/da/-/Da/) distinction in English learning infants who had been exposed to different pharmacological or hormonal influences while in utero. We worked with a group of mothers who had experienced depression throughout their pregnancy and had chosen either to take an antidepressant [serotonin reuptake inhibitor (SRI)] or to seek treatment without SRIs, and we compared the speech perception development of their infants to the infants of a control group of mothers who had not experienced depression. The control infants discriminated the Hindi dental /da/ versus retroflex /Da/ at 6 but not 10 months of age, as in our previous work.

As in the work from other labs, at 36 weeks' gestation, when tested in utero using heart-rate decline as the dependent variable, fetuses discriminated a minimal pair-vowel contrast but did not discriminate a minimal pair-consonant difference, the voiced /da/ versus the voiceless /ta/. In the group of infants whose mothers had taken an SRI throughout their pregnancy, results indicated that prenatal exposure to SRIs had accelerated the entire speech perception trajectory: SRI-exposed fetuses, at 36 weeks' gestation, discriminated the vowel distinction but also already discriminated the /da/ versus /ta/ voicing contrast. Moreover, by 6 months of age, SRI-exposed infants had already stopped discriminating the Hindi dental /da/ versus retroflex /Da/ distinction. In comparison to the acceleration that SRI exposure seemed to cause, infants exposed to maternal depression that was not treated with SRIs continued to discriminate the Hindi dental /da/ versus retroflex /Da/ at 10 months of age (Weikum et al. 2012).

An identical effect was seen for visual language discrimination. The control infants, whose mothers were not depressed, discriminated visual French from visual English at 6 months but not at 10 months of age. Infants whose mothers had taken SRI medication had already stopped discriminating visual English and visual French at 6 months of age, whereas those infants whose depressed mothers had not taken SRIs continued to discriminate the change even at 10 months, which suggests that their CP had been extended.

Late gestational SRI exposure is known to disrupt auditory map formation in rodent A1 (Simpson et al. 2011). Developing circuits transiently express ectopic serotonergic receptors and transporters (Gaspar et al. 2003). Although the primary effect of SRIs is to regulate the serotonergic system, a secondary effect may be to boost receptor function in the neurotransmitter system that affects CP timing (e.g., GABA receptors) (see sidebar). Thus, exposure to SRIs in utero may have adjusted E-I circuit balance to open the CP at an earlier age (see **Figure 1*b***). It is more difficult to postulate why exposure to maternal depression not treated with SRIs led to a delay in perceptual narrowing. Maternal depression may have its own hormonal sequelae to slow

CP circuits from closing (see **Figure 1*d***). Alternatively, maternal depression may be like dark rearing. Highly engaging, contingent speech can boost learning of speech sounds (Kuhl 2007) and may even accelerate native-language category learning (Elsabbagh et al. 2013), but depressed mothers use less highly intoned and exaggerated infant-directed speech than do nondepressed mothers (e.g., Kaplan et al. 2001) and interact with their infants in a less engaging, less contingent manner. Thus, the infants of depressed mothers may not have had enough exposure to engaging speech to accrue the amount of experience necessary to trigger CP onset (see **Figure 1*b***).

Diet can also change CP timing. Exclusively breast-fed infants of vegetarian mothers who are missing essential fatty acids in their diet continue discriminating the nonnative dental /da/ versus retroflex /Da/ after 10 months of age (Innis et al. 2001; see also Pivik et al. 2012). Diet also influences syntax: At 5–7 years of age, children who lacked thiamine (vitamin B1) in their formula for only one month in the first year of life have been shown to have a number of deficits in the understanding of production of complex syntactic structures (Fattal et al. 2011). Thus, although CP onset is typically constrained by maturation, certain types of exposure/experience can accelerate or delay the opening of plasticity (see **Table 1**).

Early Enrichment: Bilingual Experience

Infants who grow up bilingual ultimately narrow on to two sets of phonemic categories, one for each of their languages (Burns et al. 2007). Most studies indicate such narrowing occurs in the same time frame as does narrowing for monolingual infants (Albareda-Castellot et al. 2011, Sundara et al. 2008), yet some studies suggest that bilingual-learning infants take longer to establish native phonetic categories (Bosch & Sebastián-Gallés 2003) and/or maintain sensitivity to nonnative speech sound differences until an older age than do monolingual infants (Petitto et al. 2012). Similarly, bilingual infants maintain the ability to discriminate two nonnative languages visually after the age that monolingual infants can no longer do so (Sebastián-Gallés et al. 2012).

A later age of perceptual narrowing could result from a delay in CP onset because of less input in each language for the bilingual infant (see **Figure 1*b***), or it could result from enhanced executive function and attentional focus. Some neuroimaging studies indicate that the neural circuitry supporting phonetic discrimination is less mature in bilingual than in same-aged monolingual infants (Garcia-Sierra et al. 2011) and/or is equally mature but involves different circuitry, specifically with greater connectivity to prefrontal areas (Petitto et al. 2012). Similarly, some behavioral studies suggest phonetic discrimination is boosted in bilingual infants by attentional, executive abilities (Conboy et al. 2008) that come from being bilingual (Kovács & Mehler 2009).

Unpublished data (W.M. Weikum, personal communication) are more consistent with an "attentional advantage" over an "impoverished input" explanation, as bilingual infants are not delayed in the decline in visual language discrimination. Rather, they continue to discriminate languages visually even months beyond the age at which monolingual infants fail. Perhaps neuromodulatory circuits that increase attention and engagement are more active in bilingual infants, hence preventing the placement of, or acting to remove, molecular brakes (see sidebar).

Early Deprivation: Deafness and Cochlear Implants

Under typical circumstances, the timing of opening of a CP determines the timing of its closing. However, as illustrated above with the visual system, both maturation and experience work together to bring about the end of a CP. This appears to be the case in speech perception as well.

Infants who are born deaf are at considerable risk for permanent language impairment. As is discussed below, although enormous variability exists across individuals, hearing aids and/or cochlear implants can enable many individuals to develop spoken language perception and

production skills close to those of the hearing population, particularly if provided early in life (for a review, see Lyness et al. 2013). Moreover, even without the reinstatement of hearing, the typical trajectory of language development can be achieved if a visual language (such as sign language) is provided early in life (Mayberry et al. 2002). Thus, successful language acquisition and its cascading CPs are independent of modality.

People who are born congenitally deaf and have their hearing reinstated via augmentation (hearing aids) or cochlear implants at some later point in development can have been deprived of listening experiences for several months. Both ERP measures of central auditory discrimination (Kral & Sharma 2012) and behavioral measures of speech discrimination (e.g., Faulkner & Pisoni 2013) indicate that plasticity may remain for a longer period than it does in infants who have been hearing from birth, with close to full recovery seen at the group level up to at least 3.5 years of age. Beyond that age, variability increases, with some children deriving benefit and others not from cochlear implants.

By adulthood, it is very rare for substantial benefit to occur, although some variability is still seen. On the other hand, infants who have only partial deafness, for example through recurrent ear infections, may receive just enough input to allow reorganization to occur but, in this case, with impoverished input and subsequent suboptimal phonetic perception (Clarkson et al. 1989). This may be akin to the distorting effects of noise versus silence on auditory organization in rats deprived of typical acoustic input in early life (Chang & Merzenich 2003, de Villers-Sidani et al. 2008).

Children who are born deaf have early access to visual, but not acoustic, speech. In comparison with hearing controls, a higher percentage of these individuals will become proficient lip readers (Auer & Bernstein 2007) and, as a group, will show a lifetime visual dominance in language processing and a lifetime deficit in auditory-visual speech integration if their hearing is not corrected by 2–3 years of age (Schorr et al. 2005). The advantage proffered is that across the life span, they maintain the ability to use visual information to augment a distorted (or masked) speech signal (Rouger et al. 2007).

In illustration, Schorr and colleagues compared children who had been hearing from birth with matched-age children 5–14 years old who had been born deaf but had received a cochlear implant at least one year prior to the time of testing. Children were tested on their ability to identify auditory-only, visual-only, and matching AV /pa/ and /ka/ as well as the nonmatching audio /pa/ with visual /ka/ (which results in a "ta" percept for most adults). Children in both groups reliably identified the correct syllable in the single modality and matching AV conditions, but significantly more children from the hearing than the early deaf group reported an integrated /ta/ AV percept. Moreover, within the early deaf group, only those children who received a cochlear implant after age 2.5 years showed significantly more difficulty in integration. And finally, when the hearing children failed to integrate, they showed auditory dominance and reported what they heard (audio /pa/), whereas when the early deaf children failed to integrate, they exhibited visual dominance and reported what they saw (visual /ka/) (Schorr et al. 2005).

The reason for this CP effect can be explained at many levels. Behaviorally, although overall infants have a preference for looking at eyes, between 6 and 10–12 months of age, there is a shift to longer looking to the mouth—a shift that arguably helps infants establish a better representation of the visual articulatory movements that coincide with heard speech (Lewkowicz & Hansen-Tift 2012). Indeed, the most significant difference in looking to the mouth over the eyes is evident when the heard and seen stimuli do not match (Tomalski et al. 2013). Without the opportunity to listen at the same time that they watched, infants who were unable to hear during this period of development would have missed the opportunity to improve integration.

There is also evidence from infants born deaf and later given cochlear implants that the CP for establishing higher-level auditory objects, such as phonological categories, may close earlier

than the CP for establishing native phonetic sensitivities. Specifically, the few studies that have tested the ability of toddlers to use phonological categories to guide word learning suggest a CP for implantation by 12–14 months (Houston et al. 2012). Infants given implants prior to age 12 months show no deficits in learning new words when taught and tested in standard laboratory tasks at 18–30 months of age (Houston et al. 2012), whereas infants given implants after 12–15 months perform significantly more poorly. Moreover, there are lasting effects. Across childhood, those children who were given implants prior to 1 year of age continue to achieve higher scores on both productive and receptive vocabulary tests than do children given implants even 6 months after that time (Houston et al. 2001). Thus, whereas sensitivities established at earlier ages facilitate the acquisition of higher-level aspects of language in hearing infants, the early establishment of impoverished or distorted categories can have negative cascading effects in infants born deaf and who fail to receive early auditory input.

A controversial question is the extent to which cross-modal plasticity in the auditory cortex, in particular activation by visual language input, compromises subsequent auditory plasticity. According to some studies, without either acoustic or visual language input, metabolic activity in the language areas of the auditory cortex remains low and, akin to dark rearing, keeps plasticity open. Exposure to any language stimulus, including visual (sign) language, increases metabolic activity, leading to commitment to that input and a subsequent decrease in openness to auditory language, and hence compromised success following cochlear implant (Lee et al. 2001). However, in the study conducted by Lee and colleagues (2001), the children were 4 years and older and therefore already beyond the optimal age for cochlear implants.

In more recent work, Lee and colleagues (2005) found that when degree of deafness, biological age, and age at implantation were controlled, hypermetabolic activity in prefrontal areas prior to implant (supporting executive, attentional processes), rather than hypometabolic activity in auditory cortex, was the best predictor of CI success. Moreover, many studies now indicate that rather than interfering with success, the cross-modal utilization of visual speech along with auditory speech is the best predictor of success in post-CP users of cochlear implants (Doucet et al. 2006).

THE LASTING IMPACT OF CRITICAL PERIOD DEVELOPMENT

Later Language Acquisition

Sensitivity to phonetic detail is necessary for learning the speech sound categories of the native language and ultimately for using those reorganized speech sound categories to guide language acquisition. Molfese & Molfese (1985), using ERPs, were the first to provide evidence that speech discrimination in neonates predicts language proficiency in later childhood. More recently, Tsao et al. (2004) found not only a positive relation between perception of native speech sound distinctions at 7 months of age and vocabulary growth at 18–24 months, but also a negative relation with sensitivity to nonnative phonetic contrasts. A similar relation has been reported between infant speech perception and later reading success (see Kuhl 2010). Importantly, the timing of this change and its lasting consequences may be mediated by the use of infant-directed speech (Ramírez-Esparza et al. 2014).

Relations also exist between the ability to use phonological categories to guide word learning at 18 months and language proficiency at 3–4 years (Bernhardt et al. 2007). As such, the relation between phonetic perception in infancy and later reading may not be direct but instead may be mediated through phonological processes (see **Figure 3**), as suggested in a recent review of neuroimaging data (Ramus 2014).

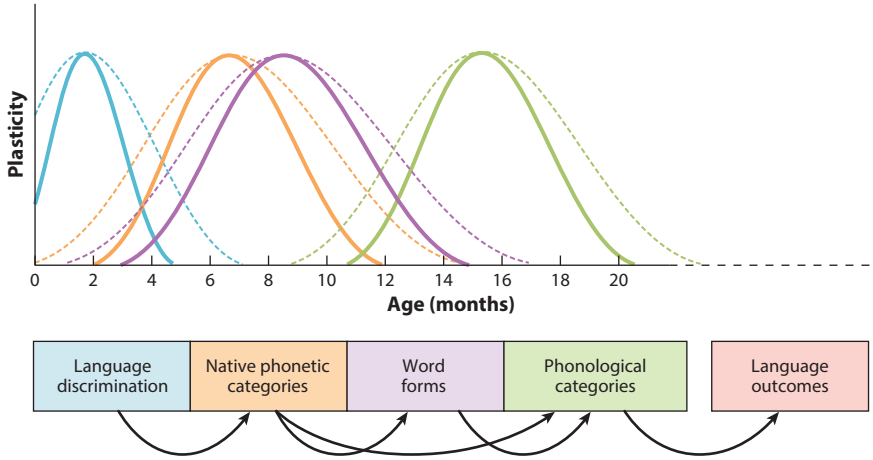

Figure 3

Illustration of the cascading nature (*arrows*) of the steps in perceptual development (*colored boxes*) that guide acquisition of the native language. Each step has a different critical (or sensitive) period (*solid lined curves*). The opening, closing, and duration of each of these periods can be altered by sensory deprivation, pharmacological exposure, and linguistic experience (*dashed lined curves*), ultimately influencing language outcomes (e.g., vocabulary size, reading).

Perceptual Savings

Animal studies have revealed that early sensory experience may leave lasting traces that can be tapped when similar environments are encountered later in life. Barn owls raised with prisms acquire novel maps of interaural timing difference to match the displaced visual scene; the novel maps revert to the original map when the prisms come off (Knudsen 2004). However, when faced with the same prisms in adulthood, the learned map is swiftly reengaged despite not having been used for years (Knudsen 1998). Similarly, a history of monocular vision enhances sensitivity of adult circuits to deprivation a second time even beyond the CP for amblyopia (Hofer et al. 2006).

It is difficult to test whether there are lasting effects of early language experience because, in most cases, there is interference from the first. However, studies of speech perception in adults who were adopted from one country to another as children provide one way to test for lasting effect. The results indicate that with only occasional exposure to the first language, no more than an hour or so a month, sensitivity to the speech sound distinctions of the native language can be maintained (Oh et al. 2003). However, if such exposure is not provided, there is little evidence of saving. Adults who had been adopted as children from Korea into French families in isolated villages—and thus had little further access to Korean after adoption—were no better than French adults at discriminating the voicing distinctions used in Korean (Ventureya et al. 2004).

On the other hand, when retraining procedures are used, evidence of a lasting effect is seen. Following only two weeks of Korean study at the university level, adult Americans who had been adopted from Korea before 1 year of age were better able to discriminate the lenis versus aspirated Korean consonant distinctions than were English-first-language speakers with the same amount of Korean training (Oh et al. 2010). Similar findings were shown for children who had been adopted from India into American English homes (Singh et al. 2011). We found similar results for adult students of Hindi who had had exposure to Hindi in the first few years of life via a short family stay in India or a grandmother living with them in the first two years of their lives (Tees & Werker 1984). Of interest, there may be an upper age limit beyond which reactivation of latent phonetic

sensitivity can be successful, with one study showing success in adults under but not over 40 years of age (Bowers et al. 2009).

The evidence is even clearer for a lasting effect of early experience on visual language discrimination. Although adults are much less able than infants to discriminate languages while watching silent talking faces, they do perform better than chance (Soto-Faraco et al. 2007). A recent study found that to achieve those levels of success, the adults needed to have learned one of the two languages in early childhood (Weikum et al. 2013).

Epigenetics: experience-dependent modifications of gene expression by altered accessibility to transcriptional machinery rather than changes to DNA sequence. Typical modifications include acetylation or phosphorylation of histones around which the DNA is tightly wound (chromatin) or methylation of particular sites on the DNA itself that limit transcription factor binding

REOPENING CRITICAL PERIODS

A continuing question is whether the age-related changes in phonetic perception involve a full loss of sensitivity. Those consonant contrasts that show the most robust evidence of perceptual attunement in infancy—such as the English /r/-/l/ and the Hindi /d/-/D/—are the same ones that show the most resistance to training in adulthood. With systematic training, however, significant improvement on discrimination of nonnative contrasts can be induced (e.g., Bradlow et al. 1997, Lively et al. 1994, McCandliss et al. 2002), particularly when feedback is provided (Lively et al. 1994) or the training progresses from the easiest to the most difficult tokens (Ingvalson et al. 2012). Although training seldom leads to improvements to the level of native speakers (e.g., Bradlow et al. 1997), there are large individual differences in performance following training (McCandliss et al. 2002), with one predictor of success the thickness of white matter tracts in Heschl's gyrus in the left hemisphere (Golestani et al. 2007).

Animal models now indicate that the mature brain is intrinsically plastic and actively stabilized by a variety of brake-like factors in adult life (see **Table 1**). As a result, it is possible to reopen CP levels of plasticity by judicious lifting of these brakes. Two potent pathways by which to do this involve focused attention and epigenetics (turning on or off genes), both of which can reestablish the E-I balance necessary for opening plasticity (see sidebar for further details). In the past, we would have explained the improvements in nonnative speech perception in adults as evidence that the CP had never fully closed and/or that there was thus some residual plasticity. Today we can investigate an equally plausible explanation: The training regimens that are most effective work by activating biological processes that remove molecular brakes.

The action of neuromodulators (such as the serotonin and nicotinic acetylcholine receptor signaling onto particular GABA neurons) acutely regulates E-I balance (Lee et al. 2010), effectively disinhibiting the local circuitry to enable adult learning (Brown et al. 2012, Donato et al. 2013, Letzkus et al. 2011). In adult barn owls, active hunting can extend CP plasticity (Bergan et al. 2005). Video games are particularly potent in engaging attentional mechanisms, which can be leveraged for enhanced learning (Bavelier & Davidson 2013). Highly engaging learning situations similarly may be more effective in improving speech perception in adults.

Stimulation of the basal forebrain or vagus nerve raises neuromodulatory tone to produce CP plasticity in adult A1 (Engineer et al. 2011, Kilgard & Merzenich 1998) sufficient to correct a rodent model of tinnitus. In V1, the Lynx1 protein was further identified as a brake-like factor that actively suppresses adult plasticity (see sidebar) (Morishita et al. 2010). Genetic removal of Lynx1 or acetylcholinesterase inhibitor treatment of adult wild-type animals restores CP plasticity, enabling recovery from amblyopia in adulthood. Likewise, phase 2 clinical trials with SRIs are proceeding for the treatment of amblyopia, as these drugs were found to rescue amblyopia in a rodent model by acutely perturbing E-I balance, perhaps epigenetically (Maya Vetencourt et al. 2008, 2011). Interestingly, contemplative practices to focus attention may also achieve plasticity enhancement noninvasively by engaging neuromodulatory systems (Slagter et al. 2011) as well as by producing epigenetic changes (Kaliman et al. 2014). This is another area for future study.

Epigenetic signatures such as DNA methylation, histone acetylation, and phosphorylation accompany the closure of CPs (Putignano et al. 2007). Thus, treating adult rodents with HDAC inhibitors such as valproic acid alters preference to paired acoustic stimuli (Yang et al. 2012) or reopens plasticity and rescues amblyopia in V1 (Silingardi et al. 2010). The same valproic acid treatment of healthy young adult humans enables the acquisition of absolute pitch, again when trained concurrently (Gervain et al. 2013). Elimination of inhibitory synapses is a major component of adult visual plasticity (Takesian & Hensch 2013, van Versendaal et al. 2012).

As noted at the beginning of this review, language is one of the few complex cognitive systems for which CPs exist. This may have implications for when and whether training of speech sound discrimination can improve language use. To date, the improvements reported at the level of speech sound (phonetic) discrimination seldom generalize to new syllables or new speakers (Ingvalson et al. 2011). Moreover, even when nonnative phonetic sensitivities improve with training, deficits still exist in how well the retrained categories facilitate the recognition of words in continuous speech (e.g., Pallier et al. 1997). In animal model work, prolonged sensory deprivation (such as dark rearing or white noise in adulthood) has been shown to change the E-I balance and reopen plasticity (Duffy & Mitchell 2013, He et al. 2006, Zhou et al. 2011). It remains to be determined whether comparable manipulations would similarly reopen CPs in language acquisition, but it is a theoretical possibility. Moreover, since input at all levels of the language system—not just phonetic perception—would be removed, perhaps higher-level use of speech perception sensitivities would also improve.

CONCLUSIONS AND FUTURE DIRECTIONS

In summary, infants begin life with a set of perceptual biases, learning mechanisms, and neural systems that orients them to language, provides an initial foundation for categorization, and allows them to learn the properties of the native language. Infants become attuned to these properties in a sequential fashion, beginning with the most global prosodic characteristics of the native language and eventually to detailed phonetic analysis. In at least some cases, the timing of attunement appears to under maturational control, suggesting the operation of a critical or sensitive period. The perceptual attunement to native language characteristics supports acquisition of the relevant structures, for example, of cues to word order or of word-meaning mappings. Moreover, attunement of the properties at each tier enables more focused attention to the next level of specificity.

It is often claimed that because there is lifetime plasticity, CPs are moot—but that misses the point. There are biologically verifiable CPs beyond which the brain works hard to maintain stability. By understanding the processes that function to maintain stability (molecular brakes), we may figure out how to remove those brakes and reopen plasticity. The opening and closing of a CP is like opening and then locking a door. Once a key is turned or a combination set, the door is locked. However, if one has the key or knows the combination, the door can be unlocked. The exciting work in neurobiology over the past 15 years has shed light on how that unlocking is done (Takesian & Hensch 2013).

New advances have brought within reach a more objective mechanistic definition of CP timing as a consequence of maturational state. Future directions include the combination of animal models with human work, as illustrated above. For example, despite the long-postulated parallels of birdsong and human language acquisition (Doupe & Kuhl 1999), only recently has mechanistic work been done with respect to CPs (Balmer et al. 2009). In the barn owl system, incremental training is effective in producing cumulative large changes in auditory maps (Linkenhoker & Knudsen 2002).

In addition, one can now carefully examine human populations with molecular markers in mind (see **Table 1**). Methods borrowed from experimental neuroscience, such as serendipitous pharmacology or epigenetic profiling, can be applied to track the trajectory of human language acquisition. Notably, many mental illnesses that include language impairment—such as schizophrenia and autism—are of neurodevelopmental origin and share defects in the triggers and brakes that normally regulate CP timing (Gogolla et al. 2009, Insel 2010, Rubenstein & Merzenich 2003). Interventions to restore CP mistiming are starting to yield promising therapeutic strategies in animal models (Gogolla et al. 2014).

In summary, in this article we have reviewed recent work on CPs in speech perception development within the mechanistic framework of understanding how sensory CPs work at a biological level. We are hopeful that by bringing new insights from neuroscience to one of the longest-standing debates in the language acquisition field, we can move beyond old strictures to better position scientists and clinicians across fields to gain a deeper understanding of how language development unfolds and to implement more effective interventions when development goes awry.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

The authors thank Dr. Padmapriya Kandhadai for the invaluable comments she provided on an earlier version of the manuscript and Savannah Nijeboer for her inspired contributions to the figures and glossary. The authors also gratefully acknowledge support from the Human Frontier Science Program (J.F.W. and T.K.H.), the National Sciences and Engineering Research Council of Canada (J.F.W.), the Bezos Family Foundation (T.K.H.), and the National Institute of Mental Health (T.K.H.).

LITERATURE CITED

Albareda-Castellot B, Pons F, Sebastián-Gallés N. 2011. The acquisition of phonetic categories in bilingual infants: new data from an anticipatory eye movement paradigm. *Dev. Sci.* 14:395–401

Aldridge MA, Braga ES, Walton GE, Bower TGR. 1999. The intermodal representation of speech in newborns. *Dev. Sci.* 2:42–46

Auer ET Jr, Bernstein LE. 2007. Enhanced visual speech perception in individuals with early-onset hearing impairment. *J. Speech Lang. Hear. Res.* 50:1157–65

Baker SA, Idsardi WJ, Golinkoff RM, Petitto LA. 2005. The perception of handshapes in American sign language. *Mem. Cogn.* 33:887–904

Balmer TS, Carels VM, Frisch JL, Nick TA. 2009. Modulation of perineuronal nets and parvalbumin with developmental song learning. *J. Neurosci.* 29:12878–85

Barkat TR, Polley DB, Hensch TK. 2011. A critical period for auditory thalamocortical connectivity. *Nat. Neurosci.* 14:1189–94

Bavelier D, Davidson RJ. 2013. Brain training: Games to do you good. *Nature* 494:425–26

Bavelier D, Levi DM, Li RW, Dan Y, Hensch TK. 2010. Removing brakes on adult brain plasticity: from molecular to behavioral interventions. *J. Neurosci.* 30:14964–71

Bergan JF, Ro P, Ro D, Knudsen EI. 2005. Hunting increases adaptive auditory map plasticity in adult barn owls. *J. Neurosci.* 25:9816–20

Bernhardt BM, Kemp N, Werker JF. 2007. Early word-object associations and later language development. *First Lang.* 27:315–28

Bosch L, Sebastián-Gallés N. 2003. Simultaneous bilingualism and the perception of a language-specific vowel contrast in the first year of life. *Lang. Speech* 46:217–43

Bowers JS, Mattys SL, Gage SH. 2009. Preserved implicit knowledge of a forgotten childhood language. *Psychol. Sci.* 20:1064–69

Bradlow A, Pisoni DB, Ahakane-Yamada R, Tokhura Y. 1997. Training Japanese listeners to identify English /r/ and /l/: IV. Some effects of perceptual learning on speech production. *J. Acoust. Soc. Am.* 101:2299–310

Brainard MS, Knudsen EI. 1998. Sensitive periods for visual calibration of the auditory space map in the barn owl optic tectum. *J. Neurosci.* 18:3929–42

Brauer J, Anwander A, Perani D, Friederici AD. 2013. Dorsal and ventral pathways in language development. *Brain Lang.* 127:289–95

Bristow D, Dehaene-Lambertz G, Mattout J, Soares C, Gliga T, et al. 2009. Hearing faces: how the infant brain matches the face it sees with the speech it hears. *J. Cogn. Neurosci.* 21:905–21

Brown CE, Sweetnam D, Beange M, Nahirney PC, Nashmi R. 2012. $\alpha 4^*$ Nicotinic acetylcholine receptors modulate experience-based cortical depression in the adult mouse somatosensory cortex. *J. Neurosci.* 32:1207–19

Burns TC, Yoshida KA, Hill K, Werker JF. 2007. The development of phonetic representation in bilingual and monolingual infants. *Appl. Psycholinguist.* 28:455–74

Carulli D, Pizzorusso T, Kwok JC, Putignano E, Poli A, et al. 2010. Animals lacking link protein have attenuated perineuronal nets and persistent plasticity. *Brain* 133:2331–47

Chang EF, Merzenich MM. 2003. Environmental noise retards auditory cortical development. *Science* 300:498–502

Clarkson RL, Eimas PD, Marean GC. 1989. Speech perception in children with histories of recurrent otitis media. *J. Acoust. Soc. Am.* 85:926–33

Conboy BT, Sommerville JA, Kuhl PK. 2008. Cognitive control factors in speech perception at 11 months. *Dev. Psychol.* 44:1505

Condé F, Lund JS, Lewis DA. 1996. The hierarchical development of monkey visual cortical regions as revealed by the maturation of parvalbumin-immunoreactive neurons. *Dev. Brain Res.* 96:261–76

Dehaene-Lambertz G, Dehaene S, Hertz-Pannier L. 2002. Functional neuroimaging of speech perception in infants. *Science* 298:2013–15

Dehaene-Lambertz G, Gliga T. 2004. Common neural basis for phoneme processing in infants and adults. *J. Cogn. Neurosci.* 16:1375–87

Dehaene-Lambertz G, Hertz-Pannier L, Dubois J, Dehaene S. 2008. How does early brain organization promote language acquisition in humans. *Eur. Rev.* 16:399–411

de Villers-Sidani E, Simpson KL, Lu YF, Lin RC, Merzenich MM. 2008. Manipulating critical period closure across different sectors of the primary auditory cortex. *Nat. Neurosci.* 11:957–65

Donato F, Rompani SB, Caroni P. 2013. Parvalbumin-expressing basket-cell network plasticity induced by experience regulates adult learning. *Nature* 50:272–76

Doucet ME, Bergeron F, Lassonde M, Ferron P, Lepore F. 2006. Cross-modal reorganization and speech perception in cochlear implant users. *Brain* 129:3376–83

Doupe AJ, Kuhl PK. 1999. Birdsong and human speech: common themes and mechanisms. *Annu. Rev. Neurosci.* 22:567–631

Duffy KR, Mitchell DE. 2013. Darkness alters maturation of visual cortex and promotes fast recovery from monocular deprivation. *Curr. Biol.* 23:382–86

Elsabbagh M, Hohenberger A, Campos R, Van Herwegen J, Serres J, et al. 2013. Narrowing perceptual sensitivity to the native language in infancy: exogenous influences on developmental timing. *Behav. Sci.* 3(1):120–32

Engineer ND, Riley JR, Seale JD, Vrana WA, Shetake JA, et al. 2011. Reversing pathological neural activity using targeted plasticity. *Nature* 470:101–6

Espinosa JS, Stryker MP. 2012. Development and plasticity of the primary visual cortex. *Neuron* 75:230–49

Fattal I, Friedmann N, Fattal-Valevski A. 2011. The crucial role of thiamine in the development of syntax and lexical retrieval: A study of infantile thiamine deficiency. *Brain* 134(6):1720–39

Faulkner KF, Pisoni DB. 2013. Some observations about cochlear implants: challenges and future directions. *Neurosci. Discov.* 1:9

Friederici AD, Wartenburger I. 2010. Language and brain. *Wiley Interdiscip Rev. Cogn. Sci.* 1:150–59
Garcia-Sierra A, Rivera-Gaxiola M, Conboy BT, Romo H, Percaccio CR, et al. 2011. Socio-cultural environment and bilingual language learning: A longitudinal event related potential study. *J. Phon.* 39:456–57
Gaspar P, Cases O, Maroteaux L. 2003. The developmental role of serotonin: news from mouse molecular genetics. *Nat. Rev. Neurosci.* 4:1002–12
Gervain J, Vines BW, Chen LM, Seo RJ, Hensch TK, et al. 2013. Valproate reopens critical-period learning of absolute pitch. *Front. Syst. Neurosci.* 7:102
Gogolla N, Leblanc JJ, Quast KB, Südhof TC, Fagiolini M, Hensch TK. 2009. Common circuit defect of excitatory-inhibitory balance in mouse models of autism. *J. Neurodev. Disord.* 1:172–81
Gogolla N, Takesian AE, Feng G, Fagiolini M, Hensch TK. 2014. Sensory integration in mouse insular cortex reflects GABA circuit maturation. *Neuron* 20:894–905
Golestani N, Molko N, Dehaene S, LeBihan D, Pallier C. 2007. Brain structure predicts the learning of foreign speech sounds. *Cereb. Cortex* 17:575–82
He HY, Hodos W, Quinlan EM. 2006. Visual deprivation reactivates rapid ocular dominance plasticity in adult visual cortex. *J. Neurosci.* 26:2951–55
Hensch TK. 2004. Critical period regulation. *Annu. Rev. Neurosci.* 27:549–79
Hensch TK. 2005. Critical period plasticity in local cortical circuits. *Nat. Rev. Neurosci.* 6:877–88
Hofer SB, Mrsic-Flogel TD, Bonhoeffer T, Hübener M. 2006. Prior experience enhances plasticity in adult visual cortex. *Nat. Neurosci.* 9:127–32
Holmes JM, Clarke MP. 2006. Amblyopia. *Lancet* 367:1343–51
Houston DM, Stewart J, Moberly A, Hollich G, Miyamoto RT. 2012. Word learning in deaf children with cochlear implants: Effects of early auditory experience. *Dev. Sci.* 15:448–61
Houston DM, Ying EA, Pisoni DB, Kirk KI. 2001. Development of pre-word-learning skills in infants with cochlear implants. *Volta Rev.* 303–26
Ingvalson EM, Holt LL, McClelland JL. 2012. Can native Japanese listeners learn to differentiate /r–l/ on the basis of F3 onset frequency? *Biling. Lang. Cogn.* 15:434–35
Ingvalson EM, McClelland JL, Holt LL. 2011. Predicting native English-like performance by native Japanese speakers. *J. Phonetics.* 39:571–84
Innis SM, Gilley J, Werker JF. 2001. Are human milk long-chain polyunsaturated fatty acids related to visual and neural development in breast-fed term infants? *J. Pediatr.* 139:532–38
Insel TR. 2010. Rethinking schizophrenia. *Nature* 468:187–93
Johnson JS, Newport EL. 1989. Critical period effects in language learning: The influence of maturational state on the acquisition of English as a second language. *Cogn. Psychol.* 21:60–99
Jusczyk PW. 2002. How infants adapt speech-processing capacities to native language structure. *Curr. Dir. Psychol. Sci.* 11:15–18
Jusczyk PW, Aslin RN. 1995. Infants' detection of the sound patterns of words in fluent speech. *Cogn. Psychol.* 29:1–23
Kaliman P, Alvarez-López MJ, Cosín-Tomás M, Rosenkranz MA, Lutz A, Davidson RJ. 2014. Rapid changes in histone deacetylases and inflammatory gene expression in expert meditators. *Psychoneuroendocrinology* 40:96–107
Kaplan PS, Bachorowski J, Smoski MJ, Zinser M. 2001. Role of clinical diagnosis and medication use in effects of maternal depression on infant-directed speech. *Infancy* 2:537–48
Key AP, Lambert EW, Aschner JL, Maitre NL. 2012. Influence of gestational age and postnatal age on speech sound processing in NICU infants. *Psychophysiology* 49:720–31
Kilgard MP, Merzenich MM. 1998. Cortical map reorganization enabled by nucleus basalis activity. *Science* 279:1714–18
Knudsen EI. 1998. Capacity for plasticity in the adult owl auditory system expanded by juvenile experience. *Science* 279:1531–33
Knudsen EI. 2004. Sensitive periods in the development of the brain and behavior. *J. Cogn. Neurosci.* 16:1412–25
Kovács ÁM, Mehler J. 2009. Cognitive gains in 7-month-old bilingual infants. *Proc. Natl. Acad. Sci. USA* 106:6556–60

Kral A, Sharma A. 2012. Developmental neuroplasticity after cochlear implantation. *Trends Neurosci.* 35:111–22

Kuhl PK. 2007. Is speech learning "gated" by the social brain? *Dev. Sci.* 10:110–20

Kuhl PK. 2010. Brain mechanisms in early language acquisition. *Neuron* 67:713–27

Kuhl PK, Meltzoff AN. 1982. The bimodal development of speech in infancy. *Science* 218:1138–41

Kuhl PK, Tsao FM, Liu HM. 2003. Foreign-language experience in infancy: Effects of short-term exposure and social interaction on phonetic learning. *Proc. Natl. Acad. Sci. USA* 100:9096–101

Kuhl PK, Williams KA, Lacerda F, Stevens KN, Lindblom B. 1992. Linguistic experience alters phonetic perception in infants by 6 months of age. *Science* 255:606–8

Kushnerenko E, Teinonen T, Volein A, Csibra G. 2008. Electrophysiological evidence of illusory audiovisual speech percept in human infants. *Proc. Natl. Acad. Sci. USA* 105:11442–45

Lee DS, Lee JS, Oh SH, Kim SK, Kim JW, et al. 2001. Cross-modal plasticity and cochlear implants. *Nature* 409:149–50

Lee HJ, Kang E, Oh SH, Kang H, Lee DS, et al. 2005. Preoperative differences of cerebral metabolism relate to the outcome of cochlear implants in congenitally deaf children. *Hear. Res.* 203:2–9

Lee S, Hjerling-Leffler J, Zagha E, Fishell G, Rudy B. 2010. The largest group of superficial neocortical GABAergic interneurons expresses ionotropic serotonin receptors. *J. Neurosci.* 30:16796–808

Lenneberg EH. 1967. *Biological Foundations of Language*. New York: Wiley

Letzkus JJ, Wolff SBE, Meyer EMM, Tovote P, Courtin J, et al. 2011. A disinhibitory microcircuit for associative fear learning in the auditory cortex. *Nature* 480:331

Levelt CN, Hübener M. 2012. Critical-period plasticity in the visual cortex. *Annu. Rev. Neurosci.* 35:309–30

Lewkowicz DJ, Hansen-Tift AM. 2012. Infants deploy selective attention to the mouth of a talking face when learning speech. *Proc. Natl. Acad. Sci. USA* 109:1431–36

Linkenhoker BA, Knudsen EI. 2002. Incremental training increases the plasticity of the auditory space map in adult barn owls. *Nature* 419:293–96

Lively SE, Pisoni DB, Yamada RA, Tohkura Y, Yamada T. 1994. Training Japanese listeners to identify English /r/ and /l/: III. Long-term retention of new phonetic categories. *J. Acoust. Soc. Am.* 96:2076–87

Lyness CR, Woll B, Campbell R, Cardin V. 2013. How does visual language affect crossmodal plasticity and cochlear implant success? *Neurosci. Biobehav. Rev.* 37:2621–30

MacKain K, Studdert-Kennedy M, Spieker S, Stern D. 1983. Infant intermodal speech perception is a left-hemisphere function. *Science* 219:1347–49

Mahmoudzadeh M, Dehaene-Lambertz G, Fournier M, Kongolo G, Goudjil S, et al. 2013. Syllabic discrimination in premature human infants prior to complete formation of cortical layers. *Proc. Natl. Acad. Sci. USA* 110:4846–51

Mampe B, Friederici AD, Christophe A, Wermke K. 2009. Newborns' cry melody is shaped by their native language. *Curr. Biol.* 19:1994–97

Mattock K, Molnar M, Polka L, Burnham D. 2008. The developmental course of lexical tone perception in the first year of life. *Cognition* 106:1367–81

Maurer D, Werker JF. 2014. Perceptual narrowing during infancy: a comparison of language and faces. *Dev. Psychobiol.* 56:154–78

May L, Byers-Heinlein K, Gervain J, Werker JF. 2011. Language and the newborn brain: Does prenatal language experience shape the neonate neural response to speech? *Front. Psychol.* 2:222

Maya Vetencourt JF, Sale A, Viegi A, Baroncelli L, De Pasquale R, et al. 2008. The antidepressant fluoxetine restores plasticity in the adult visual cortex. *Science* 18:385–88

Maya Vetencourt JF, Tiraboschi E, Spolidoro M, Castrén E, Maffei L. 2011. Serotonin triggers a transient epigenetic mechanism that reinstates adult visual cortex plasticity in rats. *Eur. J. Neurosci.* 33:49–57

Mayberry RI, Lock E, Kazmi H. 2002. Linguistic ability and early language exposure. *Nature* 417:38

Maye J, Werker JF, Gerken LA. 2002. Infant sensitivity to distributional information can affect phonetic discrimination. *Cognition* 82:B101–11

McCandliss BD, Fiez JA, Protopapas A, Conway M, McClelland JL. 2002. Success and failure in teaching the [r]-[l] contrast to Japanese adults: Tests of a Hebbian model of plasticity and stabilization in spoken language perception. *Cogn. Affect. Behav. Neurosci.* 2:89–108

McGee AW, Yang Y, Fischer QS, Daw NW, Strittmater SM. 2005. Experience-driven plasticity of visual cortex limited by myelin and Nogo receptor. *Science* 309:2222–26

Mehler J, Jusczyk PW, Lambertz G, Halsted N, Bertoncini J, Amiel-Tison C. 1988. A precursor of language acquisition in young infants. *Cognition* 29:143–78

Minagawa-Kawai Y, van der Lely H, Ramus F, Sato Y, Mazuka R, Dupoux E. 2011. Optical brain imaging reveals general auditory and language-specific processing in early infant development. *Cereb. Cortex* 21:254–61

Miyata S, Komatsu Y, Yoshimura Y, Taya C, Kitagawa H. 2012. Persistent cortical plasticity by upregulation of chondroitin 6-sulfation. *Nat. Neurosci.* 15(3):414–22, S1–2

Molfese DL, Molfese VJ. 1985. Electrophysiological indices of auditory discrimination in newborn infants: The bases for predicting later language development? *Infant Behav. Dev.* 8:197–211

Moon C, Cooper RP, Fifer WP. 1993. Two-day-olds prefer their native language. *Infant Behav. Dev.* 16:495–500

Moon C, Lagercrantz H, Kuhl PK. 2013. Language experienced in-utero affects vowel perception after birth: a two-country study. *Acta Paediatr.* 102:156–60

Morishita H, Miwa JM, Heintz N, Hensch TK. 2010. Lynx1, a cholinergic brake, limits plasticity in adult visual cortex. *Science* 330:1238–40

Nazzi T, Ramus F. 2003. Perception and acquisition of linguistic rhythm by infants. *Speech Commun.* 41:233–43

Oh JS, Au TKF, Jun SA. 2010. Early childhood language memory in the speech perception of international adoptees. *J. Child Lang.* 37:1123–32

Oh JS, Jun SA, Knightly LM, Au TK. 2003. Holding on to childhood language memory. *Cognition* 86:B53–64

Pallier C, Bosch L, Sebastián-Gallés N. 1997. A limit on behavioral plasticity in speech perception. *Cognition* 64:B9–17

Patterson ML, Werker JF. 2003. Two-month-old infants match phonetic information in lips and voice. *Dev. Sci.* 6:191–96

Peña M, Maki A, Kovacć D, Dehaene-Lambertz G, Koizumi H, et al. 2003. Sounds and silence: an optical topography study of language recognition at birth. *Proc. Natl. Acad. Sci. USA* 100:11702–5

Peña M, Pittaluga E, Mehler J. 2010. Language acquisition in premature and full-term infants. *Proc. Natl. Acad. Sci. USA* 107:3823–28

Peña M, Werker JF, Dehaene-Lambertz G. 2012. Earlier speech exposure does not accelerate speech acquisition. *J. Neurosci.* 32:11159–63

Perani D, Saccuman MC, Scifo P, Anwander A, Spada D, et al. 2011. Neural language networks at birth. *Proc. Natl. Acad. Sci. USA* 108:16056–61

Petitto LA, Berens MS, Kovelman I, Dubins MH, Jasinska K, Shalinsky M. 2012. The "Perceptual Wedge Hypothesis" as the basis for bilingual babies phonetic processing advantage: new insights from fNIRS brain imaging. *Brain Lang.* 121:130–43

Pivik RT, Andres A, Badger TM. 2012. Effects of diet on early stage cortical perception and discrimination of syllables differing in voice-onset time: a longitudinal ERP study in 3 and 6 month old infants. *Brain Lang.* 120:27–41

Polka L, Werker JF. 1994. Developmental changes in perception of nonnative vowel contrasts. *J. Exp. Psychol. Hum.* 20:421–35

Pons F, Lewkowicz DJ, Soto-Faraco S, Sebastián-Gallés N. 2009. Narrowing of intersensory speech perception in infancy. *Proc. Natl. Acad. Sci. USA* 106:10598–602

Price CJ. 2012. A review and synthesis of the first 20 years of PET and fMRI studies of heard speech, spoken language and reading. *NeuroImage* 62:816–47

Putignano E, Lonetti G, Cancedda L, Ratto G, Costa M, et al. 2007. Developmental down-regulation of histone post-translational modifications regulates visual cortical plasticity. *Neuron* 53:747–59

Ramírez-Esparza N, Garcia-Sierra A, Kuhl PK. 2014. Look who's talking: Speech style and social context in language input to infants are linked to concurrent and future speech development. *Dev Sci*. In press

Ramus F. 2014. Neuroimaging sheds new light on the phonological deficit in dyslexia. *Trends Cogn. Sci.* 18:274–75

Rosenblum LD, Schmuckler MA, Johnson JA. 1997. The McGurk effect in infants. *Percept. Psychophys.* 59:347–57

Rouger J, Lagleyre S, Fraysse B, Deneve S, Deguine O, Barone P. 2007. Evidence that cochlear-implanted deaf patients are better multisensory integrators. *Proc. Natl. Acad. Sci. USA* 104:7295–300

Rubenstein JL, Merzenich MM. 2003. Model of autism: increased ratio of excitation/inhibition in key neural systems. *Genes Brain Behav.* 2:255–67

Saffran JR, Aslin RN, Newport EK. 1996. Statistical learning by 8-month-old infants. *Science* 274:1926–28

Sale A, Maya Vetencourt JF, Medini P, Cenni MC, Baroncelli L, et al. 2007. Environmental enrichment in adulthood promotes amblyopia recovery through a reduction of intracortical inhibition. *Nat. Neurosci.* 10:679–81

Schorr EA, Fox NA, van Wassenhove V, Knudsen EI. 2005. Auditory-visual fusion in speech perception in children with cochlear implants. *Proc. Natl. Acad. Sci. USA* 102:18748–50

Scott LS, Pascalis O, Nelson CA. 2007. A domain-general theory of the development of perceptual discrimination. *Curr. Dir. Psychol. Sci.* 16:197–201

Sebastián-Gallés N, Albareda B, Weikum W, Werker JF. 2012. A bilingual advantage in visual language discrimination in infancy. *Psychol. Sci.* 23:994–99

Silingardi D, Scali M, Belluomini G, Pizzorusso T. 2010. Epigenetic treatments of adult rats promote recovery from visual acuity deficits induced by long-term monocular deprivation. *Eur. J. Neurosci.* 31:2185–92

Simpson KL, Weaver KJ, de Villers-Sidani E, Lu JYF, Cai Z, et al. 2011. Perinatal antidepressant exposure alters cortical network function in rodents. *Proc. Natl. Acad. Sci. USA* 108:18465–70

Singh L, Liederman J, Mierzejewski R, Barnes J. 2011. Rapid reacquisition of native phoneme contrasts after disuse: You do not always lose what you do not use. *Dev. Sci.* 14:949–59

Slagter HA, Davidson RJ, Lutz A. 2011. Mental training as a tool in the neuroscientific study of brain and cognitive plasticity. *Front. Hum. Neurosci.* 5:17

Sohal VS, Zhang F, Yizhar O, Deisseroth K. 2009. Parvalbumin neurons and gamma rhythms enhance cortical circuit performance. *Nature* 459:698–702

Soto-Faraco S, Navarra J, Weikum WM, Vouloumanos A, Sebastián-Gallés N, Werker JF. 2007. Discriminating languages by speech reading. *Percept. Psychophys.* 69:218–37

Stager CL, Werker JF. 1997. Infants listen for more phonetic detail in speech perception than in word learning tasks. *Nature* 388:381–82

Streeter LA. 1976. Language perception of 2-month-old infants shows effects of both innate mechanisms and experience. *Nature* 259:39–41

Sugiyama S, Di Nardo AA, Aizawa S, Matsuo I, Volovitch M, et al. 2008. Experience-dependent transfer of Otx2 homeoprotein into the visual cortex activates postnatal plasticity. *Cell* 134:508–20

Sumby WH, Pollack I. 1954. Visual contribution to speech intelligibility in noise. *J. Acoust. Soc. Am.* 26:212–15

Sundara M, Polka L, Molnar M. 2008. Development of coronal stop perception: Bilingual infants keep pace with their monolingual peers. *Cognition* 108:232–42

Swingley D, Aslin RN. 2002. Lexical neighborhoods and the word-form representations of 14-month-olds. *Psychol. Sci.* 13:480–84

Syken J, Grandpre T, Kanold PO, Shatz CJ. 2006. PirB restricts ocular dominance plasticity in visual cortex. *Science* 313:1795–800

Takesian AE, Hensch TK. 2013. Balancing plasticity/stability across brain development. *Prog. Brain Res.* 207:3–34

Tees RC, Werker JF. 1984. Perceptual flexibility: Maintenance or recovery of the ability to discriminate non-native speech sounds. *Can. J. Psychol.* 38:579–90

Tomalski P, Ribeiro H, Ballieux H, Axelsson EL, Murphy E, et al. 2013. Exploring early developmental changes in face scanning patterns during the perception of audiovisual mismatch of speech cues. *Eur. J. Dev. Psychol.* 10:611–24

Toyoizumi T, Miyamoto H, Yazaki-Sugiyama Y, Atapour N, Hensch TK, Miller KD. 2013. A theory of the transition to critical period plasticity: Inhibition selectively suppresses spontaneous activity. *Neuron* 80:51–63

Trehub SE. 1976. The discrimination of foreign speech contrasts by infants and adults. *Child Dev.* 47:466–72

Tsao FM, Liu HM, Kuhl PK. 2004. Speech perception in infancy predicts language development in the second year of life: a longitudinal study. *Child Dev.* 75:1067–84

van Versendaal D, Rajendran R, Saiepour MH, Klooster J, Smit-Rigter L, et al. 2012. Elimination of inhibitory synapses is a major component of adult ocular dominance plasticity. *Neuron* 7:374–83

Ventureya VAG, Pallier C, Yoo HY. 2004. The loss of first language phonetic perception in adopted Koreans. *J. Neurolinguist.* 17:79–91

Wang BS, Sarnaik R, Cang J. 2010. Critical period plasticity matches binocular orientation preference in the visual cortex. *Neuron* 65:246–56

Weikum WM, Oberlander TF, Hensch TK, Werker JF. 2012. Prenatal exposure to antidepressants and depressed maternal mood alter trajectory of infant speech perception. *Proc. Natl. Acad. Sci. USA* 109:17221–27

Weikum W, Vouloumanos A, Navarra J, Soto-Faraco S, Sebastián-Gallés N, Werker JF. 2007. Visual language discrimination in infancy. *Science* 316:1159

Weikum WM, Vouloumanos A, Navarra J, Soto-Faraco S, Sebastián-Gallés N, Werker JF. 2013. Age-related sensitive periods influence visual language discrimination in adults. *Front. Syst. Neurosci.* 7:86

Werker JF, Curtin S. 2005. PRIMIR: A developmental framework of infant speech processing. *Lang. Learn. Dev.* 1:197–234

Werker JF, Fennell CT, Corcoran K, Stager CL. 2002. Infants' ability to learn phonetically similar words: Effects of age and vocabulary size. *Infancy* 3:1–30

Werker JF, Gervain J. 2013. Speech perception in infancy. A foundation for language acquisition. In *The Oxford Handbook of Developmental Psychology*. Vol. 1: *Body and Mind*, ed. PD Zelazo, pp. 909–25. Oxford, UK: Oxford Univ. Press

Werker JF, Tees RC. 1984. Cross-language speech perception: Evidence for perceptual reorganization during the first year of life. *Infant. Behav. Dev.* 7:49–63

Werker JF, Tees RC. 2005. Speech perception as a window for understanding plasticity and commitment in language systems of the brain. *Dev. Psychobiol.* 46:233–51

Wiesel TN, Hubel DH. 1963. Single-cell responses in striate cortex of kittens deprived of vision in one eye. *J. Neurophysiol.* 26:1003–17

Yang EJ, Lin EW, Hensch TK. 2012. Critical period for acoustic preference in mice. *Proc. Natl. Acad. Sci. USA* 109:17213–20

Yeung HH, Chen KH, Werker JF. 2013. When does native language input affect phonetic perception? The precocious case of lexical tone. *J. Mem. Lang.* 68:123–39

Yeung HH, Werker JF. 2009. Learning words' sounds before learning how words sound: 9-month-olds use distinct objects as cues to categorize speech information. *Cognition* 113:234–43

Yoshida KA, Pons F, Maye J, Werker JF. 2010. Distributional phonetic learning at 10 months of age. *Infancy.* 15:420–33

Zhou X, Panizutti R, de Villers-Sidani E, Madeira C, Merzenich MM. 2011. Natural restoration of critical period plasticity in the juvenile and adult primary auditory cortex. *J. Neurosci.* 31:5625–34