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Speech Perception as a Window for Understanding Plasticity and Commitment in Language Systems of the Brain

ABSTRACT: *In this article, we provide a critical review of the literature on speech perception and phonological processing in infancy, and in populations with different experiential histories as a window to understanding how the notion of critical periods might apply to the acquisition of one part of language: the sound system. We begin by suggesting the use of the term "optimal period" because (a) both the onset (opening) and offset (closing) of openness to experience is variable rather than absolute and (b) phonological acquisition involves the emergence of a series of nested capabilities, each with its own sensitive period and each best explained at one of several different levels of specificity. In support, we cite evidence suggesting that to fully understand plasticity and commitment in phonological acquisition, it is necessary to consider not only the biological and experiential factors which may contribute to the onset and the offset of openness to experience but also how the sequentially developing parts of phonology constrain and direct development. In summary, we propose a nested, cascading model wherein biology, experience, and functional use each contribute. © 2005 Wiley Periodicals, Inc.* Dev Psychobiol 46: 233–251, 2005.

Keywords: *speech perception; phonological processing; critical period; plasticity*

INTRODUCTION

In a *Scientific American* article outlining what was then known about the ontogeny of speech perception, Peter Eimas (1985) proposed that human infants are born with the capacity to discriminate speech-sound contrasts from all of the worlds' languages, and that experience listening to one versus another language functions to maintain those distinctions that are heard. Research in the decade following provided support for initial organization, followed by loss without specific listening experience. Moreover, this subsequent research indicated that the effect of experience might operate in infancy (Werker & Tees, 1984a). By the late 1980s, infant speech perception work was taken as an example, par excellence, of how lack of use (via lack of relevant experience) can lead to selective pruning of neural connections (e.g., Greenough, Black, & Wallace, 1987; Kolb, 1989). Although maintenance is now viewed as only one of many ways in which experience influences initial organization (discussed later), this initial theorizing served to illustrate how speech perception could serve as a model system linking multiple levels of explanation.

In the past decade, knowledge of age-related changes in infant speech perception has expanded dramatically. Research on phonetic perception has become increasingly sophisticated. As well, the research focus has broadened from trying to answer the question of how infants perceive the individual sounds of their language to studying how infants perceive each of the properties of language—each with its own initial organization and subsequent changes in response to listening experiences. Concurrently, there have been tremendous advances in understanding the

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mechanisms by which experience impacts perceptual competences and their underlying neural organizations. In this article, we revisit and reinterpret findings in speech perception in light of these new advances, and reflect on how this may deepen our understanding of critical-period-type notions.

WHAT IS A CRITICAL PERIOD?

The notion of a critical period (CP) has been influential in biobehavioral research for close to a century (e.g., Bateson, 1979; Scott, 1962; Scott & Marston, 1950). In essence, it proposes that there is a biologically determined, specific and ''fixed'' or invariant period of time during development during which an organism's neural functioning (and related behavioral competence) is open to effects of external experiential input. In its classic conception, while there are constraints on the nature of the environmental input that can modify or influence the organism, the beginning, end, and length of this window of time are invariant: Prior to, and after, this ''critical'' point in development, the system cannot be altered by experience. Indeed, the onset and end of the ''critical'' period are the consequences of some internal clock that keeps time independent of what happens during the window of time. Such CPs are both points of ''opportunity'' during which a particular system can be optimally tuned to the ''requirements'' of the environment as well as points of ''vulnerability'' during which aberrant input, or the lack of adequate input, can have permanent, deleterious consequences for the biobehavioral system in question (see Tees, 2001) This is graphically illustrated in Figure 1.

Decades of research have confirmed that in some instances, particular systems do indeed show clear evidence of critical developmental time windows, with relatively abrupt onsets and rather complete closures. Apparent examples of these include the emergence of characteristic barrel arrangements of cell types in the somatosensory cortex of rodents from early tactual input from facial vibrissae (Woolsey, Durham, Harris, Simons, & Valentino, 1981), masculinizing influences on the brain of early androgen exposure in rodents (Plapinger & McEwen, 1978), and loss of the neural substrate of visual stereopsis without early binocular experience (Timney, 1990); however, many other biobehavioral systems have elasticity in either (or both) the onset and the offset (Bateson, 1979, 1987). Indeed, there is considerable evidence showing that the endpoint of apparent CPs can often be ''extended'' under explicitly designed exposure and retraining conditions (e.g., Cynader, Timney, & Mitchell, 1980; Mitchell, Pitto, & Lepore, 1994).

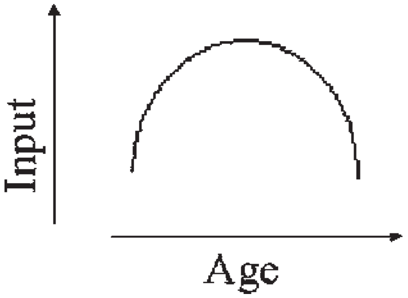

FIGURE 1 Schematic illustration of the concept of an invariant critical period in early development with its abrupt onset and offset in the sensitivity of a perceptual system to particular sensory experiences.

Because the onset, length, and offset (endpoint) of the periods during which biobehavioral systems can be altered by experience are often more variable than surmised in the classic conception of a ''critical period,'' the term ''sensitive period'' (SP) has often been substituted (Bateson, 1979; Michel & Moore, 1995). In the field of language acquisition, unfortunately, many researchers use the terms ''critical period'' and ''sensitive period'' interchangeably, thus clouding the important distinctions between the two views of these time windows. To underline the distinction and to ensure that we are referring to a window that is more variable in onset and offset than a classic CP, in this article we will employ the term ''optimal period'' (OP).

An OP, like an SP, differs from a CP in assuming that neither the onset nor the offset of the period is ''absolute'' (or invariant). Tees (2001) suggested the description of an optimal period as a biologically (and experientially) determined period, usually early in ontogeny, during which some aspect of an organism's neural and behavioral functioning is especially sensitive to a particular environmental factor. Environmentally induced modifiability (albeit less effective) outside this ''best'' time period is acknowledged as a real and testable possibility. Additional possibilities involve shifts in the beginning and the end of the best period depending on the organism's stimulation history prior to and during the optimum time period (see Cancedda et al., 2004). As was implicit in the case of the original characterization of the CP, it is recognized that there also are logically or empirically derived limitations on the nature of the stimulus input that can influence the organism during the time window in question. This is graphically illustrated in Figure 2.

The theoretical and practical advantages of allowing openness throughout the life span in comparison to assuming fixed onsets and offsets will be elaborated as the article unfolds. Moreover, at the end of the article we will introduce a new concept to the OP notion by suggesting that part of what makes a particular window in development optimal is the contribution of already-established

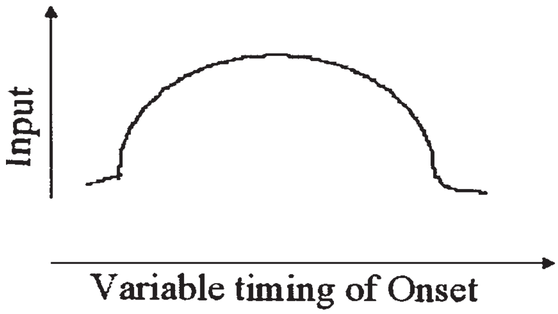

FIGURE 2 Schematic illustration of a conception of an optimal period in perceptual development with a peak period in sensitivity and reduced, but real, openness to experiential influences outside of that window of enhanced plasticity.

sensitivities to the emergence of the new organization in question, and the foundation that new organization will provide for subsequent advances. We will refer to this as ‘‘cascading influences.’’

Mechanisms

In theorizing about perceptual development and its neural substrate, Hebb (1949) proposed that mammals inherit basic neurocircuitry underlying certain fundamental discriminative abilities whereas circuitry underlying others (e.g., perception of shape) require further elaboration, gradually emerging as a result of maturation as well as learning and experience. Others (Aslin, 1981; Gottlieb, 1976; Tees, 1976, 1990a) delineated the different roles experience might and does play in specific instances. Experimental evidence has shown that experience may maintain or sustain some abilities. In other cases, appropriate sensory experience may facilitate or sharpen an emerging ability. A normal albeit limited exposure might prune more broadly based perceptual competences to match those of the subsequently expected (and experienced) environment. Changes in early stimulation history also can induce a qualitative shift in the ontogeny of a certain aspect of perceptual behavior. When these various roles of experience maximally impact the developing biobehavioral system at key intervals in development, they can be said to be operating within an OP.

There are additional matters to be accounted for beyond what initial abilities are and what (if any) the general role of subsequent experience might play. These include (a) how best to characterize the windows of time (their onset, length, and offset, the invariance of the period) during which experience might influence the ontogeny of a specific perceptual ability; (b) the degree of reversibility of any experience-induced plasticity; (c) the specification as to what aspect of stimulation can affect, or is advantaged to affect, the outcome; and (d) if there are any enabling factors (e.g., arousal, ‘‘active use,’’ emerging memory substrates) not directly related to the nature of the sensory stimuli themselves which might contribute to the impact. These issues will be considered vis-à-vis the development of speech perception.

The descriptive nature of any OP results from a number of developmental processes that are manifest at different levels in different parts of the underlying neural system. One could imagine the proposed mechanism for an apparent beginning or end of a language-related OP being related, for example, to changes in synaptic receptor N-methyl-D-aspartate subunits, GABAergic inhibition, a neurotrophic factor, or a specific immediate gene in neurons in a particular region of brain (Berardi, Pizzorusso, & Maffei, 2000; Erisir & Harris, 2003; Hensch, 2003). One could characterize the mechanism in terms of stimulus-induced and/or maturational changes in synaptic events, local or regional neuronal circuitry, a large integrated neural system, or in terms of specific perceptual/cognitive competences (e.g., Pulvermüller, 2002). If one views the language-related competences (as we do) as reflecting different related underlying circuitries, then each of these competences might be expected to have staggered OPs which could well depend on one another.

Critical Periods in Language Acquisition

In his influential book, *Biological Foundations of Language*, Lenneberg (1967) proposed that language is a system that is deeply constrained by biology. He proposed that language can be acquired only during a critical period in development which lasts from birth until the onset of puberty. He argued that both maturational and experiential forces lead to a gradual specialization of the left hemisphere for language, which is completed by puberty whether or not language acquisition is complete. As such, after puberty, language can no longer be learned through specialized neural systems but only via general-purpose learning mechanisms. Lenneberg offered further support for this hypothesis with data from aphasia patients. Functional recovery from damage to the language areas in the left hemisphere is often possible if the injury occurs prior to puberty, but similar damage after puberty results in permanent loss. Similarly, Lenneberg pointed to data on second-language acquisition showing accent-free acquisition up to the age of puberty, but rarely beyond. At the same time that Lenneberg was advancing his proposals, Chomsky (1965) was arguing for a specialized, hard-wired language-acquisition device, and his views also were becoming increasingly influential. Although there are important theoretical distinctions between the strong nativist stance of Chomsky and the more epigenetic approach offered by Lenneberg, their theorizing converged to lead to a general consensus that biology and maturation constrain language acquisition.

The ontogenetic roots for the specialization for the perception of speech by humans (and of biologically significant communicative signals by other animals) involve the probabilistic outcome of both endogenous and environmental factors (Werker & Tees, 1992). Just as many animals begin life with a perceptual preference for species-specific calls (e.g., Gottlieb, 1985), human infants begin life with a preference for listening to speech over other complex sounds (Vouloumanos & Werker, 2004a, 2004b). Human infants also show privileged processing of speech in other ways, for example, with a preference for good syllable form (Bertoncini, Bijeljac-Babic, Jusczyk, & Kennedy, 1988) and categorical discrimination of content versus function words (Shi, Werker, & Morgan, 1999). These initial biases, which may themselves reflect a prenatal epigenetic history (see Gottlieb, 1998), impose direction and facilitation of subsequent perceptual learning of linguistic information (see Jusczyk & Bertoncini, 1988, for a discussion of innately guided learning). The focus of the current review is whether perceptual input impacts those, and later emerging perceptual abilities, differentially at key windows in development.

There is overwhelming support for the hypothesis of one or several OPs in language acquisition. In study after study, a strong relationship between age of acquisition and ultimate proficiency has been established (for a review, see Newport, Bavelier, & Neville, 2001). This is seen both in studies of children acquiring a second language at different ages (e.g., see Johnson & Newport, 1989, with Chinese immigrants to the United States) as well as in studies of adults who have been using a second language for decades, but acquired it relatively late in childhood (Mayberry & Fischer, 1989). The interpretation of behavioral studies is corroborated by the results of neuroimaging studies, which reveal more overlap in the brain regions activated to first and second language in bilinguals who acquired their second language in early childhood than in individuals who acquired their second language after puberty (Kim, Relkin, Lee, & Hirsch, 1997; Perani et al., 1996).

There are differences in the impact of age of acquisition across domains within language. Some aspects of language, such as syntax and phonology, seem to show strict onset and offset to experiential influences whereas other aspects, such as acquisition of new lexical items, show relative openness to experiential input across the life span (see Johnson & Newport, 1989). Electrophysiological studies confirm differential age effects for different aspects of language. Late L2 (second-language) learners show unique event related potential (ERP) responses to violations of grammaticality (more bilateral, distributed responses in comparison to the anterior, left-hemisphere responses seen in monolinguals and early bilinguals), but they show similar ERP responses to word meaning violations irrespective of the age of acquisition (Weber-Fox & Neville, 1996).

The pattern of OPs seen in perception of spoken language is also seen in perception of signed languages. Exposure, even in infancy, can have a lasting impact on level of attainment and neural organization (Petitto et al., 2000). Moreover, the same kinds of age-of-learning differences across domains of language are seen, with earlier appearing OPs for acquisition of syntax and morphology but continuing openness for acquisition of new lexical items (e.g., Mayberry & Lock, 2003). The most striking example of how experience and maturation collaborate to organize neural processing is seen in the comparison of signed versus spoken language. In deaf individuals who acquired American Sign Language (ASL) as their first language from infancy, ASL activates not only the visual cortex but also the classic language areas in the left-hemisphere temporal lobe (Neville et al., 1997).

PHONOLOGY AND OPTIMAL PERIODS

Language involves many different subsystems including semantics, syntax, morphology, and phonology—each likely with its own OP or interrelated set of OPs. In spoken languages, phonology refers to the rules governing language usage at the level of the phone, or the sound. There are many levels even within phonology. The phonemes of a language are those phonetic segments that are used to contrast meaning. For example, /b/ and /p/ are different phonemes, as illustrated by the words ‘‘bit’’ and ‘‘pit.’’ There are subphonemic regularities as well. The same /p/ phoneme is acoustically different in the words ‘‘pit’’ ([p^h]) and ‘‘spit’’ ([p]), for example, because allophonic rules condition different phonetic instantiations of the phoneme depending on the phonological context in which the phoneme occurs. In addition to phonemic and allophonic rules, there are phonological rules for the sequences of phones that can occur in a language. Such ‘‘phonotactic’’ rules specify, for example, that the sequence ‘‘str’’ can occur in English, but only in word-initial position and ‘‘rst’’ only in word final position (e.g., ‘‘string’’ and ‘‘worst’’). There would be a phonotactic violation if ‘‘rst’’ were to occur word-initially as well as if ‘‘str’’ were to occur word-finally. Phonology determines how adjacent and nonadjacent phones condition one another. Phonology also encompasses the rules for syllable form in a language and the metrical rules for stress and timing. As such, phonology determines the rhythmical structure of a language as well. It is likely that there are different OPs for the acquisition not only of phonology in comparison to other subsystems of language but for the different realms within phonology as well.

Our characterization of OPs rests on the premise that complex biobehavioral systems involve distributed, multi-tiered networks that have multiple, ‘‘nested’’ OPs. The degree of openness to experience of the various parts of the system varies from level to level as a function of the changing demands. For example, a young, prelinguistic infant being bathed in a sea of language sounds may have one OP for tuning to the acoustic/phonetic properties of the sounds of the native language. A slightly older infant who is now listening to the sounds of words to figure out their meaning may be constrained in part by the tuning that took place in prelinguistic perception, but may be open to a different level of variation in the signal. As will be reviewed later in this article, the language-specific perceptual categories established in infancy do indeed play a role in guiding word learning, providing evidence of nested influence. We envision that the opening and closing of OPs varies from level to level within the larger realm of phonology. As will be elaborated later, this allows, for example, for tuning to acoustic phonetic properties of sounds in early infancy, and the theoretical possibility of a second OP when the infant begins to map sounds onto words, and yet another when he or she begins to understand rhyming, and so on.

Phonology: Phonetic Perception

One well-known phenomenon within speech perception is that there are discontinuities in the way humans perceive speechlike sounds. In many experimental situations, adults are best able to discriminate those differences among phones that they can label as instances of different phonemes. For example, although there are many gradations within the /b/ category, adult English speakers tend to label all of those as ‘‘b,’’ and are less able to discriminate similar-sized acoustic differences from within the /b/ phoneme category than they are an equal-sized acoustic difference that spans the /b/ to /p/ boundary (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967).

Although languages differ in the number of phoneme categories they utilize and in the precise specification of those categories, there are regularities across the languages of the world in the regions in which a phonemic boundary might be placed (see Williams, 1980). Infants are sensitive to these natural boundaries. Without specific listening experience to a language, infants in the first 6 months of life show sharper discrimination peaks in consonant boundary regions than they do in regions where there are not (known) phonemic category boundaries (Aslin, Pisoni, Hennessy, & Perey, 1981; Eimas & Miller, 1992; Eimas, Siqueland, Jusczyk, & Vigorito, 1971; Werker & Lalonde, 1988). Similarly, infants show an internal structure to their vowel categories (e.g., Kuhl, 2000) that also may be language universal, giving favored status to those vowels that are most distinct acoustically and produced most far apart in the oral cavity (Bohn & Polka, 2001).

Phonetic perception appears to involve specialized networks in the left temporal lobe in both adults and infants. Left-hemisphere advantage (LHA) was first noted in dichotic listening studies (e.g., with infants: Bertoncini et al., 1989; with adults: Studdert-Kennedy & Shankweiler, 1970). More recent studies have confirmed this effect using ERP (see Dehaene-Lambertz & Gliga, 2004), magnetoencephalography (Phillips, Pellathy, & Marantz, 1999), and neuroimaging functional magnetic resonance imaging (fMRI) techniques (Binder et al., 2000; Zatorre, Evans, Meyer, & Gjedde, 1992). Moreover, in some studies, the LHA is even seen with very young infants (e.g., Dehaene-Lambertz & Baillet, 1998; also see Dehaene-Lamberts, Dehaene, & Hertz-Pannier, 2002, and Peña et al., 2003, for recent neuroimaging studies showing an LHA for other aspects of language processing).

THE EFFECTS OF EXPERIENCE: MAINTENANCE

Languages differ in many properties, including their phoneme inventories. English, for example, contains a contrast between /r/ and /l/ which is lacking in Japanese, but English lacks the retroflex /D/ versus dental /d/ distinction that is used in Hindi and other South Asian languages. Adults have difficulty discriminating acoustically similar phonetic contrasts that are not used in their native language (e.g., Lisker & Abramson, 1971; Strange & Jenkins, 1978) whereas young infants discriminate phonetic contrasts even if they are not used in the language they are learning (Aslin et al., 1981; Lasky, Syrdal-Lasky, & Klein, 1975; Streeter, 1976; Trehub, 1976).

In our early research, we confirmed that listening experience (or the lack of such) is necessary to maintain sensitivity to a speech contrast by comparing infants and adults on their ability to discriminate native and nonnative phonetic contrasts (Werker, Gilbert, Humphrey, & Tees, 1981). We compared English infants aged 6 to 8 months, English adults, and Hindi adults on their ability to discriminate both a common contrast found in English and Hindi and two (non-English) Hindi consonant contrasts. We used precisely the same methodology, the conditioned head-turn procedure, with the three groups. English infants, English adults, and Hindi adults all discriminated the common ba-da contrast, but only the Hindi adults and the English infants discriminated the two Hindi distinctions (ta-Ta), thus showing support for the maintenance pattern of perceptual learning. In a series of follow-up studies, we showed that the reorganization in phonetic perception occurs during the first year of life. At 6 to 8 months of age, English-learning infants successfully

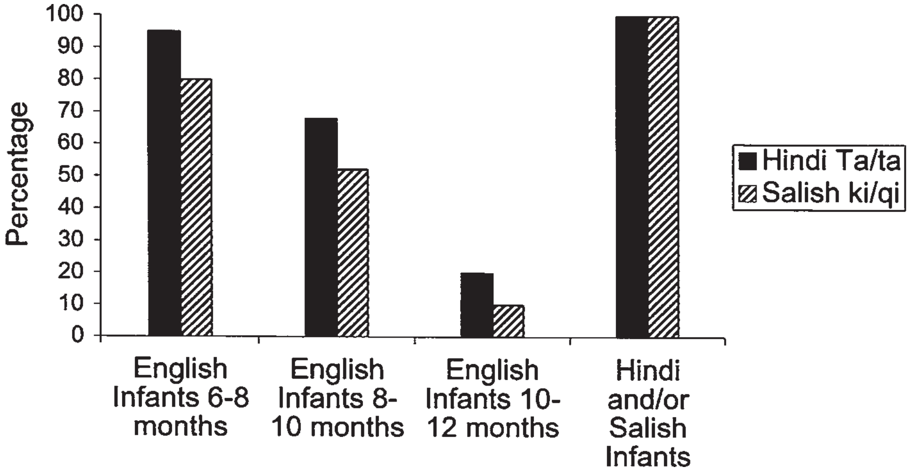

FIGURE 3 The effects of age and experience on infants' ability to discriminate two non-English contrasts. The proportion of infants at each age reaching discrimination criterion on the Hindi and Salish (non-English) contrasts. From ''Cross-language speech perception: Evidence for perceptual reorganization during the first year of life,'' by J. F. Werker & R. C. Tees, 1984a, *Infant Behavior and Development*, 7, 49–63. Adapted with permission of the authors.

discriminate the Hindi retroflex-dental distinction and another non-English (Interior Salish, Nthlakampx glottalized velar vs. uvular distinction), but by 10 to 12 months of age, the English infants no longer discriminate the non-English distinctions (Werker & Tees, 1984a). In confirmation that the age-related change was one of maintenance, Werker and Tees (1984a) showed that infants aged 10 to 12 months exposed to either Hindi or Nthlakampx in the first year did—unlike the English-only infants—successfully discriminate whichever contrast they had been hearing. These results are illustrated in Figure 3.

The finding of a maintenance-related decline in performance on nonnative contrasts has now been replicated in a number of behavioral (e.g., Best, McRoberts, LaFleur, & Silver-Isenstadt, 1995; Bosch & Sebastián-Gallés, 2003; Burns, Werker, & McVie, 2003; Pegg & Werker, 1997; Tsao, Liu, Kuhl, & Tseng, 2000; Tsushima et al., 1994; Werker & Lalonde, 1988) and ERP studies (Cheour et al., 1998; Kuhl & Coffey-Corina, 2001; Rivera-Gaxiola, Silva-Pereyra, Garcia-Sierra, Klarman, & Kuhl, 2003).

There are several ''enabling'' factors that influence the age at which the effect of experience might be seen. The effect of auditory exposure may be apparent at an earlier age for vowels than for consonants (Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992; Polka & Werker, 1994), perhaps because vowels are more acoustically salient. Even among consonants, environmental influences of different types may titrate the precise time period at which the reorganization takes place. Extremely common native phonetic categories are reorganized at a slightly earlier age than the phonetic categories representing less frequent ones (Anderson, Morgan, & White, 2003), and the age of reorganization appears to be delayed by several months in infants growing up in a bilingual environment—again perhaps because of the overall frequency of input given that there are two input languages (Bosch & Sebastián-Gallés, 2003; Burns et al., 2003). Moreover, dietary factors—specifically essential fatty acids—may even impact the age at which a phonetic reorganization takes place (Innis, Gilley, & Werker, 2001). It is theoretically important to consider whether these enabling factors which lead to small differences in age of tuning have an impact on later emerging phonological skills, such as word learning, that build on the initial establishment of language-specific phonetic categories.

The Effect of Experience Might Not Only Reflect Maintenance

Evidence is accumulating from a number of studies that maintenance alone is insufficient to capture the dynamics of the experientially induced changes in infant speech perception. For example, it is now known that experience listening to speech in the first year of life not only maintains but also sharpens initial phonetic categories (Polka, Colantonio, & Sundara, 2001). This is seen in improvements in childhood in discrimination of native distinctions among children with different types of listening experience in infancy. Moreover, exposure to a distribution of sounds that either fall into one or two categories can lead to changes in category structure, at least in infants 6 to 8 months of age (Maye, Werker, & Gerken, 2002).

In this work, infants were presented with stimuli from an eight-step continuum from one type of /t/ to another. All infants heard all eight steps, but one group of infants heard more instances of Stimuli 2 and 7 than any other, simulating a bimodal distribution of input, whereas the other group of infants heard more instances of the middle Stimuli 4 and 5. After 2.4 min of exposure, infants in the bimodal condition were better able to discriminate the endpoints, Stimulus 1 versus Stimulus 8, than were infants in the unimodal condition. This mimics the natural cross-language learning situation in which infants growing up in a language with two categories (such as the Hindi dental /d/ vs. retroflex /D/) hear a bimodal distribution in comparison to infants growing up in a language such as English where /d/ is pronounced differently in different contexts, but all varying around a single, central tendency. Although this type of distributional learning is evident at 6 to 8 months when the infants' phonetic categories are still relatively plastic and open to input, there is no evidence to date that it is equally effective in older infants. Indeed, recent research suggests that perceptual tuning toward the end of the first year of life is most successful when the nonnative speech contrasts are presented in a social, interactive context than when presented in a noninteractive fashion via a video display (Kuhl, Tsao, & Liu, 2003).

Even in our original work, we had found that the declines in performance on nonnative contrasts were not absolute. Subsequent studies using more sensitive behavioral testing procedures (e.g., Tees & Werker, 1984; Werker & Logan, 1985; Werker & Tees, 1984b) showed that a latent sensitivity to nonnative distinctions, although not at the level of that shown by native speakers (see Polka, 1992), continues to exist. That led us to argue that the experiential ''maintenance'' in this instance should be conceptualized as resulting in a reorganization rather than a ''loss'' of initial perceptual sensitivities (Werker, 1995). More recent studies using ERPs provide further support for the notion that the decline in nonnative speech perception is one of reorganization rather than loss. Indeed, there are now a number of ERP studies which reveal neural responses to both native and nonnative distinctions (Aaltonen, Niemi, Nyrke, & Tuhkanen, 1987; Tsui, Shi, Werker, & Stapells, 2004). However, the ERP to the nonnative contrast may be slower and/or be over different recording sites than is the ERP to native phonetic distinctions (Dehaene-Lambertz, 1997; Rivera-Gaxiola, Csibra, Johnson, & Karmiloff-Smith, 2000; Sharma & Dorman, 2000). This evidence for the involvement of different brain systems is consistent with the argument that the change seen in the first year of life involves a reorganization rather than a loss of initial sensitivities.

Finally, listening experience also impacts perception of many other properties of language. By birth, infants show a preference for listening to speech with the rhythmical properties of the native language (Moon, Cooper, & Fifer, 1993) and become increasing able to discriminate rhythmically similar languages over the first 4 months of life (Nazzi & Ramus, 2003). At 6 months of age, infants listen equally to lists of words that either conform to or violate the phonotactic constraints (acceptable sequences of sounds, e.g., ''str'' is acceptable, ''srt'' is not), but by 9 to 10 months of age, infants prefer listening to words that conform to common, acceptable phonotactic patterns in the native language (Jusczyk, Friederici, & Wessels, 1993; Jusczyk, Luce, & Charles-Luce, 1994). A similar change is seen between 7 and 10 months for preference for the strong–weak dominant stress pattern of English words (Jusczyk, Cutler, & Redanz, 1993).

Temporal Characteristics of the OP: Onset Versus Offset

The research reviewed in the previous section would suggest that tuning to the phonetic categories of the native language, and many other properties of the phonology, begins in the first year of life. This suggests that at least for these aspects of language acquisition, the onset of the OP begins early in life, with possibly some differences in age of onset for different aspects of phonology.

In many perceptual systems, the onset of the CP/OP is delayed if relevant experience is withheld. The classic demonstration of this is the work showing that depriving the organism of visual input leaves the CP/OP for binocular vision and its related neural substrate in the visual cortex open for a much longer period of time (2 years) than was originally thought (Cynader et al., 1980; Mitchell et al., 1994). Similarly, the CP/OP for learning birdsong can be extended. Numerous studies have revealed that there is a CP in early development during which the young bird needs exposure to the adult song to set irreversibly the perceptual template used in later song production (Marler, 1990); however, this period can be extended if all relevant experience is withheld. For example, zebra finches raised in complete isolation have been shown to remain ''open'' to learning new songs even in adulthood (see Slater, Eales, & Clayton, 1988).

It is not known whether the onset of the language-related CP/OP would be extended in humans if relevant experience was in some way withheld. Two ''model'' systems exist which might address this question: (a) work with children with cochlear implants and (b) studies of perception of ''click'' contrasts (sounds that fall outside the language system in most languages of the world, but inside in a few).

Infants born deaf and then fitted with cochlear implants at different ages exemplify the first model system (Eggermont & Ponton, 2003; Kral, Hartmann, Tillein, Heid, & Klinke, 2002). Although children fitted with cochlear implants likely never regain normal hearing, cochlear implant studies reveal that earlier implantation does lead to a better outcome than does later implantation. For example, Sharma, Dorman, and Spahr (2002) showed that if children are implanted before age $3\frac{1}{2}$, the latency of a particular ERP component (P1) to sound becomes normal within 6 to 8 months following implantation; however, if they are implanted after this age, the outcome is more variable, and there is uniformly poor outcome in children implanted after 7 years of age.

Houston, Ying, Pisoni, and Kirk (2003) examined actual phonetic perception. They found that children implanted up to age 2 were able to discriminate basic speech-sound distinctions when tested 6 to 9 months after implantation. Thus, the OP for speech-sound discrimination seems to have remained open. Of interest, however, there seemed to be an earlier onset for the OP of the more integrative ability of associating sounds with objects. For this more difficult task, infants implanted prior to 14 months of age performed better than infants implanted between 15 and 24 months (Houston et al., 2003). This is one of the many examples that motivates the cascade model we will propose at the end of the article. Perhaps it is necessary to have language-specific phonetic categories in place to help kick-start the word learning process, and without this, word learning itself is compromised.

To the best of our knowledge, however, there have not been studies comparing perception of native and nonnative phonetic contrasts in cochlear-implant individuals in the weeks and months following implant. This would be of interest because it would allow a direct test of whether a lack of relevant input preserves initial sensitivities; i.e., extends the OP.

Although there is no human speech-perception work directly analogous to the animal work revealing an extension of the CP/OP in the complete absence of experience, a potential direction for answering this question can be found in the work of Best comparing infants, children, and adults from different languages on their ability to discriminate contrasts from click languages. These sounds, which may be used extralinguistically (e.g., ‘‘tsk, tsk’’), fall outside the language space for infants growing up in most languages of the world (see Best, 1999); however, for speakers of languages such as Zulu, the clicks are an integral part of the phonology of the language, just as vowels and consonants are for English. In a series of studies, Best and colleagues (Best, 1985; Best, McRoberts, & Sithole, 1988) showed that English infants, children, and adults continue to discriminate many click contrasts throughout their lives, even though they have not had the experience thought necessary to maintain discrimination of other types of phones. This suggests that the early onset of the CP/OP is specific to only those types of sounds which are heard as part of the linguistic input. Indeed, speakers of other click languages (who thus do treat clicks as linguistic) have difficulty discriminating nonnative clicks (Best & McRoberts, 2003; Best, McRoberts, & Goodell, 2001), just as English adults have difficulty discriminating the Hindi, retroflex-dental distinction.

Experience listening to click sounds impacts brain organization. In adult speakers of click languages, the left hemisphere is differentially activated in response to clicks; however, when adults from nonclick languages are tested on their perception of click contrasts, both the left and right hemispheres are equally involved. This left-hemisphere specialization for the processing of clicks in speakers of click languages and bilateral processing in speakers of nonclick languages has been shown both in dichotic listening studies (Best & Avery, 1999) and in fMRI work (Best & Faber, 2000).

Similar, but importantly different, types of results are found in behavioral and imaging studies of speakers of tone languages in comparison to speakers of nontone languages. Experience learning a tone language is necessary for categorical perception of tone distinctions (Gandour, Wong, & Hutchins, 1998; Van Lancker & Fromkin, 1973; Wang, Jongman, & Sereno, 2001). Moreover, experience learning a tone language results in left-hemisphere lateralization for perception of tone contrasts. In tones (unlike clicks), however, privileged left-hemisphere processing is restricted to only those tone distinctions that are used in the native language. Nonnative tone contrasts fail to reveal specialized left-hemisphere processing (see Gandour et al., 2000; Wang et al., 2001).

What is not known from the existing studies of click and tone perception is precisely what kind of effect listening experience has. It is possible that experience listening to click and/or tonal languages is necessary to induce left-hemisphere specialization and the concomitant categorical perception. It also is possible that such organization was there in early infancy and failed to be maintained by lack of relevant listening experience.

Interlude

It is useful to consider the various implications of the finding that some sounds (in the earlier case, Zulu clicks) which are seldom experienced, and never in a language context, remain discriminable to English speakers across the life span. One unlikely, albeit possible, interpretation is that it is arbitrary which type(s) of sounds can be treated as linguistic, and that the critical variable is simply whether the sound is used in a language context. This stance would suggest that the effect of experience in speech perception is to induce perceptual organization, and privileged perceptual processing of any and all sounds. CP/OP models typically assume, and a great deal of evidence confirms (e.g., see Tees, 1990a, 1990b) that there may be a genetically specified range of acceptable input that fulfills basic requirements for influencing the specialized parts of a developing organism's nervous system. Stimuli outside of this range will simply not activate the relevant cells, and thus will not influence postsynaptic activity.

Earlier in the article, we reviewed evidence showing privileged processing of speech and speechlike stimuli by human neonates (Vouloumanos & Werker, 2004b). We believe this evidence confirms that there are restrictions on the kinds of stimuli that can be incorporated into a linguistic system. We would suggest that those stimuli are sounds that can be produced by a human vocal tract in a rapidly, coarticulated fashion (see also Liberman & Mattingly, 1985). Tonal or click stimuli fall within this category, but apparently only when they are employed linguistically. Other auditory stimuli typically heard (noises made by toys, keys, etc.) neither are appropriate nor could "engage" the language-processing system of the child even if they were used in a linguistic context (beyond the occasional sound or two incorporated into a play game). Thus we would argue, and we think few would disagree, that the range of sounds which can invoke linguistic processing is restricted, and that click and tone contrasts fall within that range.

Does Presence of Listening Experience Necessarily Have an Impact?

Just as lack of specific listening experience does not necessarily lead to the loss of or decline in the ability to discriminate nonnative contrasts, the simple presence of specific listening experience does not always produce maintenance or facilitation in a simple fashion. Infants exposed to two languages from birth may show dominance for the phonetic system of one language. In their work, Bosch and Sebastián-Gallés (2003) found that although 4-month-old infants from Spanish and Catalan (and bilingual) environments can discriminate the Catalan (non-Spanish) distinction between /e/ and /ae/, at 8 months of age, Spanish–Catalan bilingual infants fail. In this case, the dominance of one phonological system (Spanish) is temporary. By 12 months of age, Spanish–Catalan bilinguals can again discriminate the Catalan /e/–/ae/ contrast. Evidence of continued dominance is seen in another study testing bilingual learning, French–English infants on their sensitivity to the French versus the English boundary along the voicing continuum. In this study, Burns et al. (2003) tested English, French, and bilingual English–French infants on their sensitivity to the French and the English boundaries between /b/ and /p/. By the end of the first year of life, the monolingual infants showed the expected pattern and better discriminated the stimuli in their native boundary region. The pattern for bilingual French–English infants was different. Approximately 40% of the bilingual infants maintained sensitivity to both the English and French boundary regions. The other 60% of the bilingual-exposed infants seemed to perform as either English or French monolinguals. Some infants better discriminated the /b/–/p/ stimuli at the English boundary, and the remainder better discriminated the /b/–/p/ stimuli at the French boundary.

How Lasting Is the Effect of Early Exposure?

Only a few studies have examined the permanency of the effects of listening experience in infancy. In one study, Tees and Werker (1984) tested adults who had been exposed to Hindi as a language in the home in the first 2 years of life, but not subsequently on their ability to discriminate the Hindi retroflex-dental distinction. The results revealed that although these adults were unable to discriminate the Hindi contrast upon first exposure, only a small amount of familiarization and training was needed for discrimination to return to native-like levels. This suggests a lasting effect of early experience. Although this work shows that early experience can lead to some lasting maintenance of an initial sensitivity, two sets of recent studies with Korean adoptees provide counterexamples. One series of articles reports on adults whose first language was Korean and who were adopted into French families between 4 and 9 years of age. Because the families were scattered in small villages throughout France, following adoption, these individuals had no further exposure to Korean (except the 8–10 words their adoptive families had been taught). When subsequently tested as adults on their ability to discriminate Korean (non-French) consonant contrasts (specifically, a voiceless consonant distinction), they performed no better than native French speakers and significantly worse than Korean speakers (Ventureyra, Pallier, & Yoo, 2004). Neuroimaging studies using event-related fMRI revealed the same pattern as that seen in French speakers: activation of the specialized language areas in the left hemisphere only to French, with Korean activating the same general auditory analysis areas as another unfamiliar language did (Pallier, Colome, & Sebastián-Gallés, 2003). The only difference between the two groups was a slightly larger area of activation to French in the Korean adoptees. These studies suggest, then, that early experience does not have a lasting effect—which is at odds with the interpretation of results reported by us (Tees & Werker, 1984). A potential criticism of our study, however, is that the sample tested by Tees and Werker (1984) may have had continued exposure to Hindi-accented English. Thus, although not exposed to speech with the retroflex/dental distinction, per se, they may have heard English /d/ and /t/ sounds produced with more retroflexion than is heard in typical English.

There are other examples of systems for which early experience has a lasting effect only if there is occasional reexposure throughout development (Campbell & Jaynes, 1966; Hartshorn, 2003; Rovee-Collier, Hartshorn, & DiRubbo, 1999). One example with human infants can be found in the work of Pascalis, de Haan, and Nelson (2002) showing that human infants younger than 6 months can discriminate among individual chimpanzee faces, but that after 9 months of age they cannot. This shows the same kind of decline seen in speech-perception performance in the first year of life (Werker & Tees, 1984a). Of interest, however, is the fact that if human infants have occasional exposure to primate faces in the first several months of life, the ability to discriminate individual faces is maintained (Shannon et al., 2004).

Perhaps the continued experience with Hindi-accented English acted to reinforce the early experiential influences shown by Tees and Werker (1984) of success by early exposed adult students of Hindi. Support for this possibility is provided by a study in which childhood Korean adoptees were placed in English-speaking families in California. Unlike the children adopted to various small villages in France, the children adopted into American families were primarily in larger metropolitan areas where they had the opportunity to be exposed to other Korean speakers. Using self- and family-report, Oh, Jun, Knightly, and Au (2003) divided the participants (now adults) into groups based on the amount of reexposure to Korean they had following adoption. Their results suggested that their perception of Korean was impacted by the amount of further exposure to Korean. As expected, lack of any reexposure resulted in difficulty discriminating the Korean (non-English) contrasts. Those who had but limited reexposure (as little as a few hours per month) after age 6 years were able to maintain the same phonetic sensitivities as the native (L1) Korean speakers whereas those without that minimal reexposure were no better able to discriminate Korean phonetic distinctions than were other English-only speakers (for similar work with Spanish L1 adoptees into English homes, see Au, Knightly, Jun, & Oh, 2002). Taken together, these studies suggest that although the CP/OP may begin in early infancy, some reexposure during development may be necessary to sustain the early experiential influence. If that is the case, it obviously underlines the need to think more flexibly about the characteristics of these periods and about the nature of their openness. It strengthens the argument that describes them as OPs rather than CPs.

More on the Timing of the Offset of OPs

Several studies point to the possibility that under normal listening conditions, the offset of the OP for phonetic perception occurs sometime between 4 and 8 years of age. For example, bilinguals who acquired their second language after infancy but by 4 to 8 years of age have difficulty discriminating the phones of the L2 still do so even as adults after continuing to use both of their languages effectively throughout their lives. This was first shown by Mack in her dissertation research (Mack & Blumstein, 1983). Similar findings have been reported by Flege (1991), showing the difficulty bilingual Spanish–English children who acquired English by age 5 to 6 have in perceiving and producing the English /t/–/d/contrast and by Pallier, Bosch, and Sebastián-Gallés (1997) in the difficulty Spanish–Catalan bilinguals who acquired Catalan only at the ages of 3 and 4 have in perceiving the Catalan /e/–/ae/ distinction (see also Bosch, Costa, & Sebastián-Gallés, 2000).

These kinds of findings support the idea that the offset of the CP/OP for phonetic perception occurs in early childhood. Undoubtedly, there are advantages to the developing system from an early closing OP. This facilitates selection of and attention to just that information that will be required to master the language being spoken around the child. However, the natural ecology of human existence, such as migration, adoption, and so on, also involves situations in which a new language must be acquired after early childhood. What remains to be addressed in this article is just how irreversible the offset of the CP/OP is for human speech perception. Is change possible after native-language categories are in place? And if so, does this involve reactivation of initial capabilities or the learning of new ones?

The Effect of Training after the Offset of the OP

There is virtually no system for which some mechanism, at some level, cannot be found to allow further change beyond the point in time at which input would typically have the greatest influence. This can be seen at every level of analysis from the behavioral through the molecular (e.g., for reactivation of ocular dominance plasticity in adult rats, see Pizzorusso et al., 2002; for environmentally induced effects on methylation and subsequent gene expression which may be reversible, see Weaver et al., 2004).

In the field of speech perception, the focus of most research on recovery following the offset of the OP involves behavioral training studies. This work is often within the context of second-language instruction, as L2 learning can be impeded by difficulties in perception of the individual sounds. Highly fluent L2 speakers do show superior discrimination of L2 contrasts over less proficient speakers (Tees & Werker, 1984). Moreover, laboratory training in adulthood, long after the purported offset of the CP/OP, can lead to improvements in nonnative speech perception (see Logan & Pruitt, 1995).

However, neither naturalistic nor laboratory training necessarily guarantees the levels of accuracy shown by native speakers (Polka, 1992; Takagi, 2002). Factors that influence training success will be discussed later. These include the specific nonnative contrasts in question and their relation to the native phonology, the type of training regimen used, and the depth at which training has an impact (e.g., training on discrimination may not necessarily facilitate use of that nonnative distinction in word recognition).

Differences in difficulty versus ease of retraining specific nonnative contrasts can be predicted, in part, by the similarity/dissimilarity between the nonnative contrasts and the phonological categories used in the native language (Best, 1994; Flege, Bohn, & Jang, 1997). Best (1994), for example, describes the similarity/dissimilarity in terms of how the nonnative contrasts assimilate to those used in the native language. The Hindi retroflex-dental /Da/–/da/ distinction is an example of one of the most difficult nonnative contrasts, as English listeners assimilate both of the nonnative "d" phones to the single intermediate alveolar /d/ in English. Category goodness assimilations (e.g., a velar /k/ vs. a postvelar, uvular /q/ are good vs. poor instances of English /k/) have been shown to be easier to relearn than the single-category assimilations illustrated by the retroflex-dental contrast. Two-category assimilation has been shown to be easier (Best et al., 1995). In these instances, two nonnative phones can be assimilated to two distinctive phones in the native language. Perhaps surprisingly, the easiest nonnative assimilations are for those contrasts, such as the Zulu clicks, which fall completely outside of the phonological system used in the native language (Best et al., 1995), but as discussed earlier, this is likely because the sounds are not assimilated to the linguistic system at all and thus remain beyond its influence.

Most of the other adult speech-perception training studies have focused on just which type of training leads to the most improvement (Jamieson & Morosan, 1986; Strange & Dittmann, 1984) and the most lasting change (e.g., Lively, Logan, & Pisoni, 1993). Repetition, feedback, and occasional reactivation all turn out to be important variables in ensuring success (Tees & Werker, 1984). However, gradual training—moving category boundaries bit by bit—seems to lead to the most improvement (McCandliss, Fiez, Protopapas, Conway, & McClelland, 2002). This is directly comparable to the work with barn owls showing that although the capacity of the optic tectum to acquire new representations of auditory space is typically closed early in life (Knudsen & Knudsen, 1985), incremental training can uncover plasticity even in adulthood (Linkenhoker & Knudsen, 2002). Similar findings have been reported for many aspects of visual perception (e.g., Mitchell et al., 1994). The relative advantage of incremental training may prove to be one of the most generalizable facts across perceptual domains about recovery following the apparent end of OPs.

A second conclusion is that it is not simply repeated exposure to the precise physical characteristics of the stimuli used in the training regimen that leads to their subsequent discriminability; rather, it is the relative frequency of exposure to the distributional characteristics that is important. An illustration of this comes from the distributional learning studies of Maye and Gerken (2000). As in the Maye et al. (2002) infant studies reviewed earlier, participants—in this case English adults—were exposed to stimuli from an eight-step continuum of syllables all within the English /ta/ category. Prior to training, the English adults confused the endpoints of this continuum. Training consisted of simply exposing adults to all eight stimuli from along the continuum in random order. The only difference was in the distribution of exposure. One group of adults—those with "bimodal" exposure—heard relatively more instances of Stimuli 2 and 7, and a second group of adults—those with "unimodal" exposure—heard relatively more instances of Stimuli 4 and 5. Following massed exposure, adults in Group 1 were better able to discriminate Stimulus 1 versus Stimulus 8, the endpoints of the continuum, than were adults from Group 2, although adults in both groups had heard equal numbers of Stimuli 1 and 8 during the training regimen. This work reveals that whatever the neurophysiological and molecular events are that allow some plasticity in the OP, they operate in a relational fashion.

As described earlier, this same type of monomodal versus bimodal distributional exposure in the laboratory setting also can change consonant category structure in infancy as well (Maye et al., 2002). We view this as a form of statistical learning whereby the perceptual system tracks the independent and joint frequencies of relevant information in the input. This type of learning mechanism, which may very well be available across the life span, could thus account—at least in part—both for changes in phonetic category structure in infancy and for recalibration in adulthood.

What is not known from the training studies is where and how the training has had its effect. It could restore functional use of initial neural connectivity, and it might do so at many different levels or parts of the overall underlying circuitry (see Werker & Tees, 1999). It could lead to the creation of new circuitry that is not activated during linguistic tasks. As such, the training studies might allow for recovery only at the most peripheral levels of use. For example, training may lead to changes in phonetic discrimination, but not in use of phonetic information for higher level phonological tasks. For example, although highly fluent bilinguals may be able to learn to discriminate the individual phones of their L2, they still may have difficulty using those L2 phones in word recognition or other types of lexical decision tasks (Pallier et al., 1997; Yoshida, 2004).

The training studies reviewed previously involve samples of listeners who continue to have exposure to their first language. As such, they may reveal more about ‘‘interference’’ than they do OPs. In each case, the phonological categories used in the L1 likely impact on perception of information in the L2. In many ways, this creates a much more complicated learning situation than that supplied by a situation in which an adult no longer has any opportunity to use the L1. The previously cited research on Korean adoptees into French-only speaking families uncovers the potentially massive effect that interference from the first language can have on acquisition of the phonological system of a second language. Indeed, as cited earlier (Pallier et al., 2003), Korean-speaking children who were adopted into French-speaking homes and subsequently not again exposed to Korean performed like French speakers on perception of Korean phonetic contrasts (Ventureyra et al., 2004). Unfortunately, explicit comparisons of perception of French-specific phonetic distinctions were not conducted. However, a number of tests approximating phonetic discrimination were used. Here, the Korean adoptees (L2 French speakers) without early French experience were as proficient as the native French speakers. This work does imply that with incremental training, and without interference, full recovery of phonetic perceptual flexibility is possible.

DISCUSSION

A Cascade of Events Leads to the OP

We have argued throughout this article that language involves a number of interrelated, hierarchically organized subsystems. Most complex biobehavioral systems, vision being one, share this quality. In the visual system, aspects of the information about each event are processed relatively independently by interconnected cortical regions (Van Essen & Deyoe, 1995). Processing some aspects of the visual world is more affected by manipulations of experience than others. Their ontogeny also is dependent on what has gone before: how other early developing modules have been shaped by previous sensory input (Tees, 1990a, 1990b). Those modules that are apparently involved in competences or operations that rest on more basic information, or require more information integration, appear to be later developing and logically would be more vulnerable to manipulations of early stimulation history. An excellent example of this is provided in the work showing that deprivation of visual input early in life impacts differently on the second order configural aspects of face processing than it does on basic featural perception. Infants with corrected cataracts can later acquire the ability to perceive facial features, and to distinguish individuals on the basis of those features. However, there is no evidence that they can acquire the normally developing ability to use cues such as the relative distances between facial features to distinguish one person from another (Le Grand, Mondloch, Maurer, & Brent, 2003).

The different subsystems involved in the acquisition of language also likely have different OPs. Babies begin life with a number of perceptual biases which guide acquisition of phonology. Some of these early biases are independent of prenatal experience, and some are shaped by experience listening to speech in utero. As reviewed earlier, babies begin life showing a preference for speech over nonspeech that is not easily explained by prenatal experience (Vouloumanos & Werker, 2004b), and are able to discriminate language from different rhythmical classes (Mehler et al., 1988)—but only if the speech is played forwards (Ramus, Nespor, & Mehler, 1999). Experience listening to speech in utero leads to a preference for listening to speech with the rhythmical properties of the native language (Moon et al., 1993). This early processing of the rhythmical properties of the native language is later seen in a preference for words that conform to the SW (strong/weak) stress pattern of the native language (Jusczyk, Cutler, & Redanz, 1993), and to an ability to use this pattern to segment words from continuous speech (Jusczyk, 1997). During the first year of life, infants also tune perceptually to the phonotactic properties of the native language, and by 9 to 10 months show a preference for listening to acceptable and common sequences of phones (e.g., words that start with ‘‘str’’ vs. words that end in ‘‘str’’). The tuning which takes place to each of these properties of the native language has, as revealed earlier, its own developmental time frame and likely its own time window (CP/OP) and selectivity. Moreover, and of central importance, tuning to each aspect of the native language impacts the processing of other phonological information, and ultimately, it impacts the acquisition of language. For example, it may be this tuning to the rhythmical properties of the native language that ultimately allows infants to segment words and to learn the position-specific (e.g., syllable initial vs. syllable final) properties of the phonetic segments of the native language. And indeed, there is evidence that word segmentation even in adulthood is influenced by the rhythmical characteristics of the dominant language heard in infancy (Cutler, Mehler, Norris, & Segui, 2002).

Continuing to use phonetic categories as our example, during the first year of life infants tune to the consonant and vowel categories of the native language, and show enhanced discrimination of native phonetic contrasts and impaired discrimination of nonnative phonetic contrasts. By the middle of the second year of life, infants use their native phonetic categories to represent words and guide word learning. In illustration, Werker, Ladhar, and Corcoran (2005) showed that an English-learning infant will not only fail to discriminate the Hindi retroflex /Da/ versus dental /da/, but he or she also will treat the label "dog," whether pronounced with a retroflex or a dental /d/, as the same word, and will search for only a single referent when hearing that word. These language-specific phonetic categories will subsequently be the phonological categories that guide rhyming and alliteration in the preschool years and that are essential for mapping the sounds of language onto the orthography when learning to read, write, and spell (Castles & Coltheart, 2004). Indeed, these are the categories we use to segment, remember, and compare words throughout our lives. This is graphically illustrated in Figure 4.

We suggest that each step in the progression of sensitivity to, and use of, phonological categories serves—by the very fact of usage at another level—to strengthen and solidify the perceptual tuning that has taken place in infancy. The utilization of phonetic categories to direct word learning results in lexical (word-level) representations that are based on the phonetic categories established in infancy. These become self-perpetuating as they direct uptake of phonetic detail in new word-learning situations, and simultaneously serve as the basis for later emerging rhyming and alliteration which in turn serve as the foundation for literacy acquisition. The task of learning a new phonetic category after all the layers of use are already in place should be harder for the simple reason of continued reinforcement of the L1 categories by so many higher order linguistic uses. This in itself may, at least in the realm of phonology, be part of the operational definition of an OP. Latent sensitivity to nonnative phonetic contrasts as seen in ERP tasks, and as revealed in training studies, may continue to be available throughout the life span for the basic perceptual discriminations, but there may be a CP/OP that typically operates early in life for application of phonetic categories to higher areas of language use.

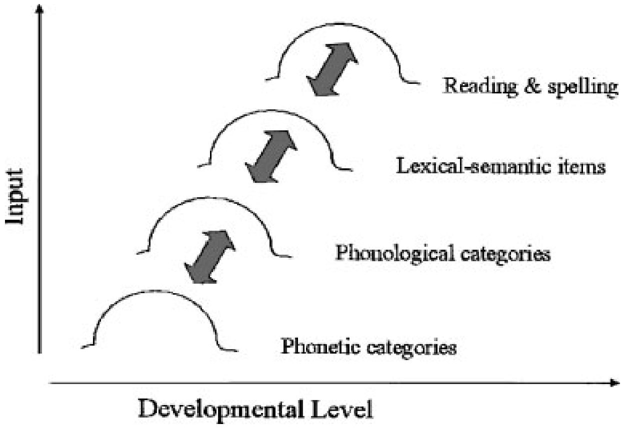

FIGURE 4 A cartoon illustrating the cascade of influences involving different components of the overall speech-processing system. Each component has a different optimal period and a different pattern of selectivity. Moreover, experientially induced changes in each component influence both later emerging and previously developed components.

This possibility receives some support from the work on bilingual acquisition. There is increasing evidence that even children who learn an L2 in early childhood and use both of their languages throughout their lives show a dominance for one of their languages, typically the L1. The L1 dominance is most pronounced at the higher levels of language use. When tested in simple perceptual discrimination tasks, fluent bilinguals may be able to show evidence of having learned to discriminate the L2 phonetic categories. Yet, when tested in tasks which require functional use of those L2 phonetic distinctions to contrast meaningful words, a deficit is apparent—even after 2 to 3 decades of speaking the L2 (Pallier, Colome, & Sebastián-Gallés, 2001; Sebastián-Gallés & Soto-Faraco, 1999; Yoshida, 2004).

Another example comes from the studies of individuals who had repeated middle-ear infections (otitis media) during infancy. One of the characteristics of otitis media is fluid in the ear, and this fluid can remain for weeks after the ear infection itself has gone away. The fluid interferes with sound transmission and, as such, dampens experiential input. Although the literature is by no means consistent, numerous studies indicate that children who had recurrent middle-ear infections in infancy may have less sharp phonetic categories than expected even in childhood (Clarkson, Eimas, & Marean, 1989), and that they also are at risk for reading and spelling difficulties (Gravel, Wallace, Ellis, Lee, & Mody, 1997). This is consistent with the notion proposed here of cascading OPs, each constraining and directing the following and preceding sensitivities.

We have described the OPs for speech processing at a psychological level of explanation, but undoubtedly explanations are possible at other levels of analysis as well. ERP studies have shown that different neural systems are activated for the same processing tasks at different points in development. For example, at 13 months of age, when infants are presented with known words, higher amplitude bilateral activation over temporal and parietal lobes is recorded in ERP studies whereas at 20 months of age, the higher amplitude ERP activation to known words is restricted to the left-hemisphere temporal and parietal recording sites (Mills, Coffey-Corina, & Neville, 1997). Infants begin to use their native phonetic categories to direct word learning by 17 to 20 months of age (Werker, Fennell, Corcoran, & Stager, 2002). It may not be a coincidence that there is a concordance between the consolidation of specialized neural-processing systems for representing words and the utilization of native-language phonetic categories in representing those words (see Mills et al., 2004). This may reveal, at the level of the underlying neural system, a cascade of psychological, neurophysiological, and neurochemical events—all of which serve to create enormous resistance to subsequent change. Yet, under the right conditions, recovery or relearning—at least to some degree—should still be possible.

We propose that similar examples should be possible to find at other levels of analysis. A challenge for future work in speech processing will be to operationalize the questions precisely enough to pursue the kinds of multitiered levels of analysis that have been pursued, for example, in certain aspects of visuospatial processing.

SUMMARY

In summary, in the past few decades our knowledge of age- and experience-related changes in speech perception has advanced considerably. In this article, we have reviewed this research, promoting the value of using the concept of an OP as a means of understanding the ways in which experience can impact perceptual development. This review has served to highlight two main themes. First, within any complex biobehavioral system, and certainly within speech processing, there are many contributing subsystems, each with its own developmental progression and OP. The utilization of one set of skills or perceptual sensitivities in the service of a higher order linguistic function serves to solidify the perceptual organization that has been established, making it even more resistant to change. These interlinked parts of the system and their OPs thus contribute, in a cascading fashion, to the coherence and stability of the overall system. Second, we have tried to stress that there is added value in examining the nature of each OP at different levels of analysis, from the behavioral through the neurophysiological and molecular. At each level of analysis, different rules and mechanisms for stability and change operate, yet each is linked in their contribution to the overall system. We have argued that even though it may be extremely difficult at some levels of analysis for some levels of organization to bring about plasticity before the onset or after the offset of an OP, such plasticity is nonetheless theoretically possible. Such plasticity needs to be considered and explicitly tested. Wherever possible, we have tried to highlight what the conditions and underlying mechanisms are that bring about commitment and, conversely, which allow continuing plasticity. In the case of speech perception, knowing the mechanisms that can bring about change is not only of scientific interest but also crucial for full recovery of language functioning, for example, in children born deaf and later fitted with cochlear implants or in individuals moving into a new language community.

NOTES

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