Perceptual narrowing in the context of increased variation:

Insights from bilingual infants

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Abstract

Human infants become native-language listeners through a process of perceptual narrowing. Monolingual infants are initially sensitive to a wide range of language-relevant contrasts. However, as they mature and gain native-language experience, their sensitivity to non-native contrasts declines. Here, we consider the case of infants growing up bilingual as a window into how increased variation affects early perceptual development. These infants encounter different meaningful contrasts in each of their languages, and must also attend to contrasts that occur between their languages. Bilingual infants share many classic developmental patterns with monolinguals. However, they also show unique developmental patterns in the perception of native distinctions such as U-shaped trajectories and dose-response relationships, and show some enhanced sensitivity to non-native distinctions. Analogous developmental patterns can be observed in individuals exposed to two non-linguistic systems in domains such as music and face perception. Some preliminary evidence suggests that bilingual individuals might retain more sensitivity to non-native contrasts, reaching a less narrow end state than monolinguals. Nevertheless, bilingual infants do become perceptually-specialized native listeners to both of their languages, despite increased variation and differing patterns of perceptual development in comparison to monolinguals.

Keywords: Bilingualism, Infant, Language Acquisition,

Early Experience, Speech Perception

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The human perceptual system embodies the amazing interplay of nature and nurture in development. Infants are born with perceptual proclivities and biases that initially direct attention and perception. Over the first weeks and months of life, infants' perceptual systems are altered by the experiences that they encounter. In the case of speech and language perception, infants are initially sensitive to wide variety of language-relevant perceptual distinctions, for example the phonetic distinction between [b] and [d] that gives different meanings to the English words "big" and "dig" (Bertoncini, Bijeljac-Babic, Blumstein, & Mehler, 1987; Byers-Heinlein, Burns, & Werker, 2010; Eimas, Siqueland, Jusczyk, & Vigorito, 1971; Mehler et al., 1988; Nazzi, Bertoncini, & Mehler, 1998). These initial sensitivities are modified through experience; by the end of the first year of life, sensitivity to native-language distinctions is maintained or sharpened (Kuhl et al., 2006), while sensitivity to non-native language distinctions declines (for a recent review, see Werker, Yeung, & Yoshida, 2012). This change from a broad-based sensitivity to many perceptual distinctions, to specific sensitivities to a subset of distinctions that are environmentally relevant is often called perceptual narrowing.

The phenomenon of experience-driven perceptual narrowing has been well documented in speech perception (e.g., Aslin & Pisoni, 1980; Burnham, 1986) and to a lesser degree in sign language perception (e.g., Palmer, Fais, Golinkoff, & Werker, 2012). Further, although it has seldom been discussed in the context of perceptual narrowing, infants also become increasingly specialized in other language-relevant perceptual tasks such as language discrimination (Nazzi, Jusczyk, & Johnson, 2000). Yet, the particulars of how experience shapes language perception remain unclear. For example, how much and what type of exposure is necessary to maintain sensitivity to a distinction? Among monolinguals, some experiments demonstrate that massed auditory exposure in a short time period can modify sensitivities to speech sounds (Maye, Werker, & Gerken, 2002), whereas in other studies infants require longer-term audio-visual exposure to live models (Kuhl, Tsao, & Liu, 2003). A related question is how linguistic variability affects perceptual narrowing. Maye et al. (2002) demonstrated that simple distributional variability alters perception of non-native linguistic categories in infancy: distributions with a central mode collapse categories, whereas two peripheral modes pull categories apart. However, the degree of perceptual alignment between languages can affect perception of non-native linguistic categories. For example, Best, McRoberts, and Sithole (1988) postulated that perceptual narrowing is dependent of the degree on overlap between the specific non-native linguistic input being heard and one's native language.

To gain traction on the above questions, our approach is to examine perceptual development in a population with a unique type of language experience: infants raised in bilingual environments from birth. Here, we use the term "bilingual infant" to refer to any infant with regular exposure to two languages simultaneously from birth, and the term "monolingual infant" to refer to an infant with regular exposure to a single language from birth. It is important to note that monolingual and bilingual infants share many similarities. Recent theoretical accounts of early bilingualism have noted that monolinguals and bilinguals are born with the same perceptual biases and the same mechanisms for language acquisition, and have therefore argued that both groups organize language information within the same types of representational spaces (Curtin, Byers-Heinlein, & Werker, 2011). Further, monolingual and simultaneous bilingual infants do not differ in their timing of exposure to their languages, as in all cases full exposure to the native language or languages begins perinatally (see Byers-Heinlein et al., 2010, for evidence that prenatal bilingual exposure can effect language preferences at birth). While it is important to recognize these important similarities between monolinguals and bilinguals, the focus of the current paper will be on how the *experiential differences* between the two groups affect early perceptual development.

Our paper will thus begin by summarizing four properties of early bilingual experience that are likely to affect the development of language perception in infancy. Next, we organize our review around two complementary processes inherent to perceptual narrowing: maintaining or increasing perceptual sensitivity to environmentally relevant distinctions, and decreasing sensitivity to environmentally absent distinctions. We will first discuss the developmental patterns seen in bilingual infants' perception of language contrasts that are native in one or both of their languages. Then, we will examine bilingual infants' non-native speech perception, which has received considerably less empirical attention. When possible, our discussion will consider the unique properties of early bilingual experience raised in the first section. Finally, we will examine how acquiring two systems in other domains (faces, music) parallels bilingual first language acquisition. Throughout this paper, we use the term "perceptual narrowing" to refer in general to experience-based tuning of the perceptual system, but at the end of the paper will consider whether the term "perceptual narrowing" is appropriate to describe the developmental patterns observed in young bilinguals. We believe that examining the development of speech and language perception in bilingual infants can provide new insights into how early experience shapes perception.

Four properties of early bilingual environments

Below, we highlight four properties of simultaneous bilingualism that we believe have particular bearing on the question of how experience modifies perception. These properties result in the increased variation that is inherent to early bilingual environments.

1. **Bilingual infants have less exposure to each language than monolinguals.**

   Language exposure can be roughly quantified by the number of words that a child hears per day. This in turn is tightly coupled with their exposure to different perceptual features of the native language. Language exposure varies widely in monolingual populations (Hart & Risley, 1995), and this is likely the case for bilinguals as well. However, all other factors being equal, it is probable that bilingual infants have similar *overall* exposure to speech and language as monolinguals. This means that, as their time is divided between two languages, they likely have less exposure to any particular language (Curtin et al., 2011; Hoff et al., 2012; Kuhl et al., 2008; Werker, 2012). Thus, studies of bilingual infants can identify more precisely how much experience is necessary to maintain and enhance native language distinctions.

2. **Bilingual infants must simultaneously represent two different languages.**

   Each language carves up the perceptual space in a different way. With their two languages taken together, bilingual infants have more native categories than monolinguals learning these languages do. For example bilingual English-

Japanese acquiring infants must learn that in English /r/ and /l/ are two separate categories, but that in Japanese they form a single category (Miyakawaki et al., 1975). This could have implications for how phonetic categories are perceived.

3. **Bilingual exposure is "noisy".** Input to the perceptual system is typically noisy, and perceptual learning entails determining which dimensions are relevant and what dimensions are not. We argue that bilingual infants encounter a *particularly* noisy perceptual environment due to the presence of two languages. This noise comes from multiple sources.

Although it is often assumed that the two languages are neatly divided in the environment (e.g. one-parent-one-language), empirical studies suggest that most bilingual infants regularly encounter two languages from the same person, in the same environment, and/or within the same sentence (Byers-Heinlein, 2013). The latter behavior is known as code switching (see Poplack, 1980, for a more complete discussion of this phenomenon). To the degree that infants use patterns of co-occurrence and frequency to drive perceptual development, exposure to code switching could make extracting such patterns more difficult. Further, bilingual adults produce and perceive some speech sounds in different ways from monolingual speakers (MacLeod, Stoel-Gammon, & Wassink, 2009; Sundara, Polka, & Baum, 2006; Sundara & Polka, 2008). Bilingual infants could therefore hear more variability than a monolingual even within a particular language, with bilingual adults in their environment producing slightly different realizations of language sounds than monolingual adults (Bosch & Ramon-Casas, 2011). Thus, bilingual infants provide a test case for how added noise in the system impacts perceptual development.

4. **Bilingual infants must separate and differentiate their languages.** To become proficient adult speakers, bilingual infants must tune their perception to each language separately, rather than to an amalgam of the two languages (Bosch & Sebastián-Gallés, 1997; Curtin et al., 2011; Werker, 2012). There is evidence that bilingual adults can use language-specific information, akin to language mode (Grosjean, 2001), to alter their in-the-moment perception of speech sounds (Gonzales & Lotto, in press), for example interpreting the same acoustic signal differently depending on language context (for reviews of adult work, see Best, 1995; Flege, 2007). It is currently unknown at what age and under what circumstances bilingual infants can engage in this type of language-specific processing. Yet, bilingual infants' ability to do so will have important implications for their perceptual development.

    Further, it has been proposed that the necessity of separating and differentiating their languages could lead to cognitive and perceptual advantages (Sebastián-Gallés et al., 2012; although see Bialystok, for a different account of bilingual cognitive advantages). This in turn could engender greater perceptual sensitivity amongst bilingual infants (Kuhl et al., 2008; Petitto et al., 2012; Sebastián-Gallés, Albareda-Castellot, Weikum, & Werker, 2012).

To examine how early bilingual experience shapes perception, this paper draws on data from a range of language-relevant perceptual contrasts across both auditory and visual modalities. We have taken this inclusive approach due to the limited amount of empirical data on many aspects of speech processing in bilingual infants, while acknowledging that different mechanisms could underlie perceptual development across the broad range of phenomena considered here.

Discrimination of native contrasts

In any particular language, only some sound differences signal a change in meaning. One example is native-language speech sound contrasts (e.g. /b/ and /d/ in English), which are known as phonemes. Another example is lexical stress, which is a perceptual pattern carried over syllables (see Cutler, 1986, for a discussion of the multiple acoustic correlates of lexical stress). In English, COMbine (an agricultural machine) and comBINE (to join or merge) consist of identical sounds in the identical order, but a change in lexical stress (i.e. the position of the stressed syllable) changes the meaning. Other languages such as French do not signal a difference of meaning in this way. Although the majority of research thus far has focused on the perceptual narrowing of phoneme perception, a proficient language user needs to discriminate all of the perceptual contrasts that are used to signal meaning in a language and learn which sound variability is irrelevant to word meaning (e.g. lexical stress changes are important in English as they indicate meaning changes, but such changes carry no meaning in French).

The developmental course for phoneme perception depends in part on whether the contrast is discriminable very early in life, which in turn depends on the acoustic salience of the phonetic distinction (Narayan, Werker, & Beddor, 2010). Salient native-language contrasts that are discriminated early in life should show a general pattern of maintenance, with possible sharpening or realignment to modify initial sensitivities to better match the native language. Discrimination of these contrasts is expected at all points in development. Low-salience native distinctions that are not initially discriminated must be induced from experience (Aslin & Pisoni, 1980; Burnham, 1986; Narayan et al., 2010). Finally, distinctions that are not present in the linguistic environment of the infant should be perceptually attenuated, although acoustically salient non-native distinctions may remain perceptible (Best et al., 1988).

The next section will examine in what circumstances bilingual infants show the first two of these well-described developmental patterns: those of maintenance and induction. However, we also identify two developmental patterns in native speech perception that thus far appear unique to bilingual infants. The first is a U-shaped pattern of discrimination: a decline in sensitivity to native contrasts and a later return of sensitivity to those contrasts. The second is a dose-response pattern, where discrimination of a particular native contrast is related to the amount that a bilingual infant is exposed to a particular language. After a discussion of these developmental patterns, we review the literature that has investigated how these native language sensitivities are applied to tasks such as word learning and recognition.

Maintenance

At birth, infants are sensitive to a wide variety of linguistically important distinctions, only some of which will be relevant in the native language. With respect to phonemes, very young infants show an ability to discriminate both native and non-native consonant and vowel distinctions (e.g. Bertoncini et al., 1987; Eimas et al., 1971). Newborn infants successfully discriminate passages from different languages, if the languages differ rhythmically (Mehler et al., 1988, Nazzi et al., 1998; Byers-Heinlein et al., 2010). Further, neonates can discriminate stress patterns of multisyllabic words (Sansavini, Bertoncini, & Giovanelli, 1997), which is a relevant distinction in some (e.g., English), but not all (e.g. French), languages. They can also discriminate different pitch contours (Nazzi, Floccia, & Bertoncini, 1998), which are relevant to tone distinctions in languages such as Mandarin.

Amongst these initially wide-ranging sensitivities, infants must maintain, with some sharpening and realignment, the native language contrastive information to which they are exposed. Indeed, this is the predominant pattern of development seen amongst monolingual infants for native-language sounds (Werker & Tees, 2005). However, bilingual infants have reduced exposure to each of their two languages. As frequency of exposure has been highlighted as an important foundation for phonetic development (Anderson, Morgan, & White, 2003), bilingual infants might not show the same pattern of maintenance as seen in monolingual infants. Specifically, bilinguals might show delays in their refinement of native language categories. Further, bilinguals must deal with a greater variety of speech sounds than their monolingual peers. Not only do languages differ in their phonemic inventories, in that they possess differing sounds, they also differ in how speech sounds are realized. For example, an English /p/ is not pronounced identically to a French /p/. Additionally, as discussed earlier, bilingual adult caregivers may produce phonemes in a different manner than monolinguals. Bilinguals' crowded perceptual space might lead to a pattern of development that deviates from monolinguals (e.g., later refinement).

Despite the potential challenges outlined above, there is evidence from a number of studies that bilingual infants robustly maintain some native contrasts.

Electrophysiological work has begun to examine the question of native language speech perception in bilinguals. Two studies have thus far examined Spanish-English bilingual infants' neural discrimination of an English vowel contrast that is not made in Spanish. Infants ranging in age from 3-36 months were tested. The results suggest that these bilingual infants show equivalent discrimination of this contrast in comparison to English monolinguals of the same ages, and that younger bilinguals (6-month-olds) have increased attention to the contrast compared to their monolingual peers. Further, bilinguals' brain responses mature over time just as monolinguals' do, with the 2- to 3-year old monolinguals and bilinguals in this research showing very similar brain responses to the stimuli (Shafer, Yu, & Datta, 2011; Shafer, Yu, & Garrido-Nag, 2012).

Are these neural sensitivities also demonstrated in behavior? French-English bilingual infants of 10 to 12 months of age maintain both English-specific and French-specific /p/ - /b/ distinctions, while monolingual-English learners maintain only the English-specific distinction at this age (Burns, Yoshida, Hill, & Werker, 2007). Similarly, bilingual speech-sign learning infants maintain sensitivity to a sign language phonetic category, while sensitivity declines amongst monolingual speech-learning infants. In one study, infants (with a mean age of 15 months) learning English and American Sign Language (ASL) successfully discriminated a linguistically significant hand shape distinction from ASL (analogous to a spoken-language phoneme distinction). Infants acquiring only English did not discriminate the same distinction at 14 months, despite being able to do so at 4 months of age (Palmer et al., 2012). Thus, there is convergent evidence from electrophysiological and behavioural studies across different groups of bilingual infants. Bilinguals are able to maintain many native phonetic categories even given their reduced input.

Interestingly, bilingual infants also maintain some speech sound contrasts that are not meaningful in either of their languages, but instead occur across the two languages. These are known as latent contrasts. For example, English and French both possess a /d/ sound, but the two languages differ on where the tongue is placed in the mouth to produce it. This leads to small differences in the nature of the respective /d/ sounds, which, while not a meaningful difference in either language, could serve to tell the two languages apart. Research suggests that French-English bilingual infants are able to discriminate between English and French pronunciations of the /d/ sound at age 10-12 months (Sundara, Polka, & Molnar, 2008; see also Sundara & Polka, 2008; Sundara et al., 2006, for related work with bilingual preschoolers and adults). Monolingual French-learning infants do not show discrimination of the same contrast. Yet, in a pattern consistent with English-speaking adults, monolingual English-learning infants can discriminate this contrast at the same age even though it is not meaningful in English (see Sundara et al., 2008, for a further discussion of this pattern). It is unclear whether bilingual infants' maintenance of this distinction is due to their bilingual experience, or whether it simply stemmed from their exposure to English. Nonetheless, sensitivity to this distinction could be important for bilinguals as a marker for each language as they navigate their dual-language environments.

Dose-response

While the results reviewed above suggest that bilingual infants' reduced exposure does not impair the maintenance of native speech sound contrasts, other work that quantified language exposure as a continuous variable (rather than only making a categorical distinction between monolinguals and bilinguals) suggests that there are limits to this interpretation. In one study, monolingual and bilingual infants were tested on their ability to discriminate lexical stress patterns (e.g. strong-weak as in COMbine versus weak-strong as in comBINE; Bijeljac-Babic, Serres, Höhle, & Nazzi, 2012). Ten-month-old monolingual infants acquiring French, a language where stress is not contrastive, were not able to discriminate words that differed only in stress. French-learning bilingual infants with exposure to a stress language (e.g. English, Spanish, Urdu, Swedish, amongst others) 70-80% of the time were able to discriminate the stress contrast. However, bilinguals with less exposure to a stress language, between 40-60% of the time, failed to show discrimination. These results suggest that maintaining sensitivity to lexical stress requires a criterial amount of exposure to a language in which stress is contrastive. These results are consistent other studies that found early effects of language dominance on bilingual infant speech perception (Sebastián-Gallés & Bosch, 2002). It is currently unclear, however, whether such patterns hinge on the relative exposure to each language, the absolute amount of experience with a particular language, or both (see also Martínez, Rodríguez, Marchman, Hurtado, & Fernald, 2013).

This research with bilingual infants is consistent with studies of adult second language learners, who show persistent insensitivity to lexical stress even after acquiring a language in which stress is contrastive (Dupoux, Sebastián-Gallés, Navarrete, & Peperkamp, 2008). Even adults who learned both languages early in life sometimes show patterns of speech processing consistent with monolinguals of their dominant language but not their non-dominant language (Cutler, Mehler, Norris, & Segui, 1989; Dupoux, Peperkamp, & Sebastián-Gallés, 2010). Thus, at least for some native categories, there may be a threshold of exposure necessary to maintain certain native language contrasts, and this exposure is most influential early in life. More research is needed to determine whether dose-response patterns are shown in other groups of bilingual infants, and for other language contrasts.

Induction

Induction, the development of a perceptual sensitivity not present at birth, would on the surface appear to be a developmental pattern that requires extensive experience. Thus, it might be predicted that bilinguals would fail to show this pattern during infancy. However, several studies have suggested that bilingual infants are able to induce the discrimination of perceptual contrasts not made at birth. Narayan et al. (2010) tested infants' discrimination of a difficult nasal contrast that is meaningful in Filipino, but not in English. Infants aged 4-5 months from both English and Filipino language backgrounds were unable to discriminate the contrast. This is different from young infants' performance on most other consonant contrasts, which are typically easily discriminated. However, by 10-12 months, the Filipino-learning infants, most of whom were bilingual in English, successfully discriminated the target contrasts, while monolingual English-learners did not show discrimination. It is unknown whether the pattern of induction demonstrated by the Filipino-English bilinguals would be the same in monolingual Filipino infants, as this latter group was not tested. Thus, the possibility remains that monolingual Filipino-learning infants would show even earlier discrimination of this contrast than the bilinguals. While several previous studies have also shown induction or facilitation patterns in monolinguals[1] (Tsao, Liu, & Kuhl, 2006; Polka, Colantonio, & Sundara, 2001), these results suggest that even bilinguals' reduced exposure to the language with the relevant contrast is sufficient for its induction.

A recent electrophysiological study also showed a pattern of induction in bilingual infants. Neural discrimination of language sounds is indicated by a component in the electroencephalogram (EEG) signal called a mismatch response (MMR). The MMR is generated in response to a *deviant* phoneme produced in a string of *standard* phonemes (e.g., two deviant "da" sounds randomly embedded in a string of 18 standard "ba" syllables). Using a double-oddball task, Garcia-Sierra et al. (2011) presented infants learning Spanish and English with three consonants: an English /t/, a Spanish /d/, and a common consonant that is heard as /d/ in English and /t/ in Spanish. The common consonant was the standard stimulus and the language-specific consonants were the deviants. As bilingual infants must eventually learn the relevant distinctions in both their languages, they must represent three phonemes in this acoustic-perceptual space in order to discriminate both deviants. Monolingual English learners face an easier task: they must learn to discriminate the consonant considered /d/ in English from the English /t/, but not from the Spanish /d/, thus only representing two phonemes in the same space. English monolinguals demonstrated the standard maintenance and narrowing patterns. They generated an MMR to both English and Spanish deviants at 7 months, but that neural response was limited to only the English deviants at 11 months (Rivera-Gaxiola, Silva-Pereyra, & Kuhl, 2005). Younger bilinguals (6-9 months) did not generate a MMR to

[1] Tsao et al. (2006) reported that some of their Mandarin-learning infants came from multilingual households, but that Mandarin was the dominant language within the home.

either deviant; however, older (10-12 months) infants showed a MMR to both native-language deviants (Garcia-Sierra et al., 2011). Once again, it appears that the bilingual infants required sufficient experience with their native languages to successfully discriminate these consonant contrasts. Bilinguals' reduced experience in each language in comparison to monolinguals might explain the slightly later age at which they demonstrated refined neural discrimination of native contrasts. However, it should also be noted that the bilingual group was of a lower socioeconomic status than monolingual infants in previous studies. Thus, it is difficult to conclude whether differences in the younger infants' performance reflect language experience, SES, or an interaction of the two.

Garcia-Sierra et al. (2011) attempted to address the question of whether some criterial amount of experience with a language leads to induction for close contrasts in that language. They compared the neural responses to the English deviant in bilingual infants who had high versus low English exposure. A similar analysis was conducted examining the neural response to the Spanish deviant in bilingual infants who had high versus low Spanish exposure. For the 10-12 month-old infants, only infants with high exposure to English showed the MMR to the English deviant and only infants with high exposure to Spanish produced a MMR to the Spanish deviant. These results support the supposition that a criterial amount of exposure to a particular contrast leads to phoneme induction in bilingual infants, similar to the dose-response pattern of phoneme maintenance discussed above.

The discrimination of passages from different languages also improves significantly from birth, showing a pattern consistent with induction via experience.

Language experience does not begin at birth: fetuses learn about and recognize their mother's voice in the womb (Kisilevsky et al., 2003) and newborns can recognize passages repeatedly heard in the late fetal period (DeCasper & Spence, 1986). Fetuses also learn the rhythm of their maternal language. Kisilevsky et al. (2009) demonstrated that fetuses of 33-41 weeks gestational age successfully discriminate their maternal language (English) from a rhythmically distinct language (Mandarin). At birth, monolingual infants continue to discriminate languages that have different rhythmic properties, such as French and English, but not languages that are rhythmically similar such as French and Spanish (Mehler et al., 1988, Nazzi et al., 1998). In monolingual infants, experience serves to induce the discrimination of rhythmically similar languages by age 4-5 months (Nazzi et al., 2000). But, do infants with prenatal, perinatal, and postnatal bilingual exposure demonstrate that same pattern of induction?

Similar to monolingual newborns' abilities, infants who had prenatal bilingual exposure are able to discriminate their two native languages at birth if the two languages are rhythmically distinct (Byers-Heinlein et al., 2010). Bilingual infants also begin showing sensitivity to more fine-grained differences between languages a few months after birth. Spanish-Catalan bilingual infants are able to discriminate their two native languages, which are rhythmically similar, by age 4 months (Bosch & Sebastián-Gallés, 2001). Further, they are also able to discriminate between their native languages and other rhythmically similar languages (e.g., Italian; Bosch & Sebastián-Gallés, 1997). Thus, even though bilingual infants have less exposure to each language, the development of this rhythmic discrimination ability occurs on the same time frame as monolingual infants. It is possible that the need to acquire two languages simultaneously, and indeed to continuously discriminate and differentiate these languages, allows infants to overcome the challenges related to reduced exposure to each language by augmenting their attention to cues that distinguish their languages.

U-shaped developmental patterns

There is one striking pattern in bilingual native phonetic discrimination that has not yet been observed amongst monolinguals: a U-shaped developmental pattern (see Rakison & Yermolayeva, 2011, for a review of U-shaped patterns seen in other domains). This pattern was first observed in a study of Spanish-Catalan bilingual infants' perception of a vowel contrast, /e/ versus /ɛ/, that exists in Catalan but not Spanish. Results from monolingual infants showed a classic pattern of perceptual narrowing. Monolinguals followed a developmental trajectory of maintenance when the contrast was native (Catalan monolingual infants), and decline when the contrast was non-native (Spanish monolingual infants). At 4 months, both Spanish and Catalan monolingual infants discriminated the contrast. At 8 and 12 months, only Catalan monolinguals maintained the vowel distinction, while Spanish monolinguals no longer discriminated the contrast. However, bilingual Spanish-Catalan infants showed the aforementioned unusual U-shaped pattern. They successfully discriminated the contrast at 4 months, failed at 8 months, and again successfully discriminated the contrast at 12 months (Bosch & Sebastián-Gallés, 2003a; see also Bosch & Sebastián-Gallés, 2003b, for a U-shaped developmental pattern observed for the /s/-/z/ contrast).

Several explanations have been proposed for this surprising finding. The distributional explanation posits that the decline in sensitivity to a native-language perceptual category is due to high overlap between the single, and frequent, /e/ vowel category that exists in Spanish, and the infrequent Catalan /e/ and /ɛ/ categories (Bosch & Sebastián-Gallés, 2003a). Training studies have shown that differing distributions of sound tokens can alter infants' ability to make a speech sound discrimination in experimental tasks (Maye et al., 2002). If bilingual infants represent speech sounds for both languages in a common distributional space (e.g. Curtin et al., 2011), then the frequency of the Catalan and Spanish vowels might initially give infants evidence for a single vowel category (the infrequent Catalan vowels subsumed into the central frequent Spanish category) rather than three (Catalan /e/, Spanish /e/ and Catalan /ɛ/). Perhaps only with increased exposure to the target phonemes can infants pull the infrequent categories apart from the frequent category around age 12 months.

Other research has suggested that, with supporting cues, bilingual infants can discriminate even these highly overlapping contrasts. At 8 months of age, English-Spanish acquiring infants succeed in discriminating the same /e/ versus /ɛ/ contrast that bilingual Catalan-Spanish learners of 8 months failed to discriminate (Sundara & Scutellaro, 2011). The target contrast exists in English (e.g., *bait* versus *bet*) but not Spanish, which again only possesses the /e/ sound. So, the English-Spanish bilinguals faced the same overlapping categories as Catalan-Spanish bilinguals. The authors proposed that the key difference is that English and Spanish are rhythmically distinct, while Spanish and Catalan are rhythmically similar, and that this rhythmic difference supported infants in overcoming overlapping vowel distributions by associating rhythmic cues with the differing distributions. Curtin et al. (2011) have proposed more generally that comparison and contrast mechanisms can help bilingual infants use cues such as rhythmicity to separate and differentiate their languages. This language differentiation might then allow infants to refine speech sounds according to the distributions unique to each of their languages. However, another possibility is that slight differences in procedure or stimuli, rather than the nature of the particular language pair being learned, were responsible for the aforementioned English-Spanish bilinguals' success at 8 months.

A second argument against the distributional account is that the discrimination of acoustically close contrasts that occur frequently in both languages can also follow a U-shaped developmental pattern. Sebastián-Gallés & Bosch (2009) tested Spanish-Catalan bilingual infants on a contrast that is prevalent in both Spanish and Catalan, /o/ versus /u/. Again, bilingual infants showed the U-shaped developmental pattern of discrimination: success at 4- and 12-months, but failure at 8-months. The authors also tested 8-month-old bilinguals on /e/ versus /u/, another contrast that is frequent in both languages, but is farther apart in acoustic-perceptual space than the previously tested vowel contrasts. Infants successfully discriminated this more distinct contrast, suggesting that the U-shaped pattern is not the result of an inability to discriminate all contrasts at this age. Instead, bilinguals' difficulties might stem from the acoustic-perceptual closeness of the target phonemes.

Another possible source of this U-shaped pattern might be the highly variable input, in comparison to monolinguals, that bilingual children receive. Not only are bilingual children themselves acquiring two languages, they are often raised by parents who are themselves bilingual. Bosch & Ramon-Casas (2011) studied the production of the Catalan /e/ – /ɛ/ distinction in Spanish-Catalan bilingual mothers who had learned both languages early in life. A subset of mothers made frequent pronunciation errors in words that involved these vowels, and these mothers generally showed large variability in their productions. Thus, it might be that even if bilingual infants are getting regular exposure to both of their languages, the microstructure of the input in each language could be different and indeed noisier than what monolinguals receive. Other research examining language mixing by bilingual parents – the use of words from more than one language in the same sentence – has hinted that this unique type of input might make some aspects of acquisition more difficult for infants who encounter frequent mixing (Byers-Heinlein, 2013). Thus, bilingual infants might show later stabilization of phonetic categories not due to bilingualism per se, but because of differences between monolinguals and bilinguals in the microstructure of the input.

A final possible explanation for the U-shaped developmental pattern is the lexical similarity between Spanish and Catalan. In particular, the two languages have many cognate words (i.e. words that share form and meaning across languages) that differ only in their vowels (e.g. ship is /barku/ in Catalan and /barko/ in Spanish). Eight-month-old Spanish-Catalan bilinguals may have simply learned to ignore some close vowel variability, particularly where a vowel difference does not signal a difference in meaning (see also Yeung & Werker, 2009). In other words, their language environment might promote a greater acceptance of acoustic variation in phonemes – small changes are normal and therefore unsurprising. Most studies of phonetic discrimination in bilingual infants have used variants of a habituation paradigm, whereby infants hear repeated tokens of one phoneme, and are expected to show dishabituation or "surprise" when a different phoneme is played. Could it be that Spanish-Catalan bilinguals do detect the change in phoneme, but simply fail to show the classic dishabituation response? This explanation is supported by one study that showed that Spanish-Catalan infants of 8 months are able to discriminate a close phonemic contrast when tested in a task that does not require a surprise response (Albareda-Castellot, Pons, & Sebastián-Gallés, 2011). In this task, infants were trained to look at different areas of a screen depending on the phoneme heard, so no surprise reaction was required. Spanish-Catalan bilingual infants looked to the appropriate side when hearing each member of the Catalan /e/ – /ɛ/ distinction, thus revealing maintenance of their perceptual sensitivity to these vowels. Thus, some suggest that the U-shaped function seen in bilingual infants might be illusory (Albareda-Castellot, et al., 2011) – perceptual ability is constant, but differences in performance arise due to extraneous factors such as bilingual infants' construal of the experimental task at this age, and the particular stimuli used (Vouloumanos, 2011; Curtin et al., 2011; Werker, Byers-Heinlein & Fennell, 2009). On the other hand, even if 8-month-old bilinguals can demonstrate sensitivity to the /e/ - /ɛ/ contrast under certain experimental conditions, their failure in the original study in comparison to the success of both younger and older infants (Bosch & Sebastián-Gallés, 2003a) nonetheless suggests a temporary decline in discrimination ability at this age.

Native contrasts in word learning and recognition

The refinement of perception to environmentally relevant stimuli reflects a progression toward greater efficiency in information processing. While bilingual infants show a variety of developmental trajectories in their perception of native language contrasts, by age 12 months these abilities appear to stabilize. By this age, bilinguals successfully discriminate every native sound contrast tested to date. However, while simple discrimination is an important ability, ultimately the function of such perceptual sensitivity is to be used in more complicated speech tasks, for example word learning and recognition.

Several studies have begun to examine how bilingual infants apply phonetic sensitivities to word-related tasks (Werker et al., 2009; Werker, 2012). In one study, infants learning English and another language were taught the minimal pair *bih – dih* produced by a native English speaker (Fennell, Byers-Heinlein, & Werker, 2007). Monolingual infants succeed by age 17 months (Werker, Fennell, Corcoran, & Stager, 2002), but bilingual infants did not succeed until 20 months. This finding was replicated in several groups of bilingual infants, including English-Chinese bilinguals (Cantonese and Mandarin), and English-French bilinguals.

However, in a similar study, 17-month-old French-English bilinguals succeeded at learning the minimal pair *bos – gos* (Mattock, Polka, Rvachew, & Krehm, 2009) in a condition where monolinguals failed. An important difference of this study as compared to Fennell et al. (2007) is that the stimuli were pronounced by a bilingual English-French speaker, and they differed in subtle ways from stimuli produced by a monolingual speaker. Mattock et al. (2009) argued that bilingual infants can succeed at the same age as monolinguals when the task matches their language learning environment. This argument is reminiscent of the microstructure argument discussed earlier. The specific realizations of phonemes heard by bilingual infants from their bilingual models (e.g., their parents and siblings) can differ from the speech of monolinguals. It may be that bilinguals' perceptually narrowed categories may be demarcated differently from those of monolinguals and only stimuli that falls within those boundaries will be efficiently processed by these infants. Further, the use of monolingual stimuli and approaches may sometimes underestimate bilinguals' early capacities.

Two studies to date have examined how bilingual infants apply their phonetic sensitivities to the task of word recognition. Spanish-Catalan bilingual infants aged 17-24 months were tested on their ability to recognize mispronounced words (Ramon-Casas, Swingley, Sebastián-Gallés, & Bosch, 2009). Infants were shown pictures of two familiar objects side-by-side while simultaneously hearing the label for one of the objects. To investigate how infants use their perceptually narrowed sound categories to recognize words, infants heard either a correct label or a mispronunciation of that label. Typically, monolingual infants are slower (they show a longer latency to orient to the labeled object) and less accurate (they look less at the labeled object) when responding to mispronounced words compared to correctly pronounced words (Swingley & Aslin, 2000; Swingley, 2007). Mispronunciations in the bilingual study involved the aforementioned Catalan /e/ – /ɛ/ distinction. As discussed earlier, perceptual discrimination of this distinction in isolated syllables may follow a U-shaped trajectory, however bilinguals can succeed in simple discrimination tasks by age 12 months. The results of two different studies suggested that infants treat cognate (e.g. Catalan *abella* and Spanish *abeja,* both meaning bee) and non-cognate (e.g. Catalan *pitet* and Spanish *peto*, both meaning bib) words differently. When words were cognates, bilingual children between 19 and 28 months of age did not show a mispronunciation effect as a group for the Catalan distinction, treating mispronunciations and correct pronunciations of familiar words as the same. Only those who were Catalan-dominant appeared to detect the mispronunciation. Spanish-dominant bilingual toddlers again accepted Catalan mispronunciations as the same as correct pronunciations (Ramon-Casas et al., 2009). However, when the words were not cognates, all toddlers showed a robust ability to detect the mispronunciation (Ramon-Casas & Bosch, 2010).

Although bilingual infants successfully discriminate many native speech contrasts by the end of the first year, they do not always apply these perceptual abilities to more advanced language tasks. This developmental pattern is reminiscent of findings from studies with monolinguals. Stager & Werker (1997) found that 14-month-old monolingual infants failed at learning the minimal pair *bih* and *dih* even though infants succeeded at simple discrimination of these sounds, and could learn dissimilar-sounding words in the same task (Werker, Cohen, Lloyd, Casasola, & Stager, 1998). It has been argued that infants' performance in these tasks is supported by the emergence of phonemes, abstract speech-sound representations that generalize over words, which are distinct from the phonetic categories that can support simple discrimination (Curtin et al., 2011; Yoshida, Fennell, Swingley, & Werker, 2009; Werker et al., 2009; Werker & Curtin, 2005). Abstract phonemes might develop later for bilingual infants because of the reduced frequency of input in each language, and the more complicated perceptual space that they must build.

Discrimination of non-native contrasts

While the previous section discussed the development of bilingual infants' perception of native contrasts, we now turn to their perception of non-native contrasts. Although patterns such as maintenance and induction are key aspects of perceptual refinement, the development of non-native perception represents the classical "narrowing" aspect of perceptual narrowing. Decades of research with monolinguals have shown that non-native speech perception declines in the first year of life (Werker & Tees, 1984). As discussed above, at birth infants are sensitive to many of the contrasts present in the world's languages. While infants must maintain and refine those that are relevant to their native language, they also show loss of sensitivity to contrasts that are not native (although see Best, 1994; Best & McRoberts 2003; for a discussion of English-learning infants' continuing sensitivity to some distant non-native sounds such as Zulu clicks).

If experience is important for the decline in non-native sensitivity, then non-native speech perception is where the largest differences between monolinguals and bilinguals might be seen. An extended period of non-native sensitivity might be predicted on several different grounds, each related to the key differences between monolingual and bilingual experience we have previously laid out.

First, to the degree that experience with the native language contributes to the decline in sensitivity of non-native perception, bilinguals' less frequent exposure to each language might delay the decline of sensitivity (Anderson et al., 2003; Curtin et al., 2011; see also Kuhl et al., 2008). In this case, the maintenance of sensitivity to native contrasts and the decline of sensitivity to non-native contrasts would be tightly coupled.

Second, as bilinguals are acquiring two languages, each with its own repertoire, more contrasts will be native for bilinguals than for monolinguals. The presence of extra phonetic categories across the two languages could enable discrimination of latent contrasts that are not native to either language, but instead occur across the two languages (Sundara, Polka, & Molnar, 2008). This is consistent with the Perceptual Assimilation

Model (Best, 1994), which predicts that non-native phonemic contrasts that are perceptually close to contrasts in one's native language(s) will remain discriminable.

Third, we have argued that early bilingual experience constitutes a more variable linguistic environment, where infants face extra challenges in extracting patterns and meaning from the speech signal due to the presence of the two different languages. Rats exposed to white noise show an extended period of neural plasticity in the primary auditory cortex (Chang & Merzenich, 2003). While the type of structured "noise" encountered by bilingual infants is very different from the white noise used in these animal experiments, this finding raises the possibility the increased variability encountered by bilinguals might also extend neural plasticity.

Finally, bilinguals' cognitive advantages might support enhanced perceptual sensitivities. This could lead to superior non-native speech perception, an ability that could be beneficial in some contexts (e.g. acquiring a new language) although possibly problematic in others (e.g. efficient native language processing). Studies have shown that bilinguals, including those as young as 7 months old (Kovács & Mehler, 2009), have better attentional control than their monolingual peers (for a review see Bialystok, 2009). This could result in bilinguals attending to subtler linguistic distinctions, including those not meaningful in their native languages. Conversely, the particular demands of successfully navigating a bilingual environment might yield extra sensitivity to non-native contrasts, which might contribute to cognitive advantages.

There are many different reasons to predict that bilingual infants will show an extended period of sensitivity to non-native contrasts, but it is also possible bilinguals might not show any differences from monolinguals in non-native speech perception.

Another explanation for the decline in sensitivity to non-native contrasts is simply a lack of evidence that these contrasts are important in the native language. In this case, bilinguals would show a decline of sensitivity on the same time frame as monolinguals, as the two groups are similar in their lack of relevant experience.

Visual speech

The first investigation of infants' perception of a non-native distinction was not in the domain of auditory speech discrimination, but rather in the domain of visual speech discrimination. Visual speech discrimination is the ability to tell two languages apart from a silent talking face. Young English-learning infants can discriminate visual English from visual French, but lose this discrimination capacity by age 8 months presumably because French is not in their environment. This is perhaps unsurprising considering the vast literature demonstrating perceptual narrowing over the first year of life for face perception (e.g., Pascalis, de Haan, & Nelson, 2002; Kelly et al., 2007). French-English bilingual infants continue to visually discriminate French from English at 8 months (Weikum et al., 2007), thus demonstrating a pattern of perceptual maintenance to environmentally relevant distinctions even in the visual language domain.

Recent follow-up work has investigated whether bilingual infants' sensitivity is limited to their native languages, or whether bilingual infants might maintain an ability to make a non-native distinction between two unfamiliar languages. Sebastián-Gallés et al. (2012) argued that bilinguals possess enhanced attention to their own languages due to their need to separate the two linguistic streams and that this perceptual attentiveness may transfer to other languages. Indeed, they found that 8-month-old Spanish-Catalan bilingual infants were able to discriminate visual English from visual French, even though neither language was native. Catalan and Spanish monolingual infants failed to discriminate the stimuli. Work with adults has shown that the ability to visually discriminate languages is maintained by bilingual adults fluent in both languages, and is induced in monolingual adults, but only if they are familiar with one of the languages (Soto-Faraco et al., 2007). Thus, bilingual infants remain particularly sensitive to non-native contrasts in the domain of visual speech discrimination. Their perceptual attentiveness to non-native language input may be indicative of the general cognitive advantages attributed to bilingualism (Sebastián-Gallés et al., 2012).

Phonetic contrasts

Researchers have only just begun to examine whether bilingual infants also have greater sensitivity to non-native contrasts in phonetic perception. In one study, infants were tested using fNIRS, a non-invasive brain imaging technique (Petitto et al., 2012). Monolingual English-learning and bilingual infants learning English and another language were tested on a native and a non-native contrast. A younger group (aged 4-6 months) and an older group (aged 10-12 months) were tested in an oddball paradigm. The results showed a trend towards a significant age by language interaction in probes thought to be measuring activation in the left inferior frontal cortex. The differences between the two groups were especially pronounced for the native contrast, where monolinguals showed an increase in activation with age, while for bilinguals activation appeared to decrease with age. The authors interpreted their results as evidence for enhanced perceptual sensitivity by bilingual infants, emphasizing that bilinguals showed similar developmental patterns for the native and non-native contrasts, while monolinguals showed dissimilar patterns for the two types of contrasts. However, in all groups, for all contrasts, and in both brain regions studied, infants showed a significant brain response to the change, indicating discrimination of the contrasts. This finding makes it difficult to determine whether bilingual infants truly show enhanced sensitivity to these non-native phonetic contrasts.

A very recent study has investigated bilingual infants' discrimination of a non-native tone contrast. Tones are prosodic cues over syllables and are contrastive in languages such as Mandarin. For example, the syllable /ma/ with a steady high tone means "mother", but the same syllable with a falling tone means "to scold". Tone perception in monolingual infants follows the classic perceptual narrowing pattern: young infants discriminate tone regardless of their linguistic environment, but amongst monolinguals perception of tone is only maintained if an infant is learning a tone language (Mattock & Burnham, 2006; Yeung, Chen, & Werker, 2013). Liu and Kager (2013) tested two groups of infants on tone perception: monolingual Dutch-learning infants and bilingual infants learning Dutch and another language. Crucially, none of the infants were exposed to a tone language. All infants were able to discriminate a highly salient tone contrast throughout infancy. For a more difficult tone contrast, monolingual infants showed perceptual narrowing at 8-9 months, replicating previous findings (Mattock & Burnham, 2006; Mattock, Molnar, Polka, & Burnham, 2008; Yeung et al., 2013), although there was evidence that sensitivity was regained at a later age. For bilinguals, this decline in sensitivity was much less pronounced, and appeared to last for a shorter duration. It is unknown whether this U-shaped pattern in *non-native* tone discrimination for monolinguals and bilinguals is related to the U-shaped pattern shown by bilinguals in *native* language vowel perception discussed above. Nonetheless, these results still point to an overall advantage for bilingual infants in the discrimination of non-native tone contrasts.

Work with adults can provide insights about the developmental endpoint of non-native language perception amongst bilinguals. Following seminal work on the decline of sensitivity to non-native sound contrasts by monolingual infants (Werker & Tees, 1984), Werker (1986) investigated whether bilingual and multilingual adults not exposed to a particular contrast might nevertheless maintain extra perceptual sensitivity to the contrast. Bilingual and multilingual adults were tested on non-native contrasts from unfamiliar languages. Like monolingual English-speaking adults, they showed no capacity to discriminate the non-native contrasts, suggesting no bilingual advantage. However, other work has indicated that multilinguals might have enhanced ability to *learn* non-native distinctions. Tremblay and Sabourin (2012) found that while monolinguals and bilinguals did not differ in their ability to discriminate a non-native contrast at pre-test, bi/multilinguals outperformed monolinguals on perceiving the non-native distinction after training on the contrast, and were better able to transfer their learning to a different non-native contrast. This suggests that bilinguals have enhanced perceptual sensitivity to non-native contrasts into adulthood. However, it should be noted that most studies on adult bilinguals group together a variety of bilinguals with different ages of acquisition, and thus are distinct from individuals who acquire both languages during the classical period of perceptual narrowing in infancy. More work will be needed to determine whether enhanced perceptual sensitivity is limited only to those with very early bilingual experience.

In sum, the work investigating bilingual infants' perception of non-native contrasts has been extremely limited, and more work is needed, especially studies of non-native speech contrast perception in bilingual infants. However, results to date suggest that bilinguals could have prolonged sensitivity to non-native contrasts. As discussed above, there could be many explanations for this phenomenon, and these can only be teased apart by future research. However, regardless of the particular explanation, the bilingual data to date suggest that experience with the native languages, rather than lack of experience with the target non-native language tested, plays a key role in driving the decline in sensitivity to non-native contrasts (see also Kuhl et al., 2008).

Acquisition of two non-linguistic systems

As illustrated by the other papers in this issue, perceptual narrowing does not occur solely in the domain of language perception. Striking parallels in development are observed in multisensory integration, face perception, and music perception, amongst others (Lewkowicz & Ghazanfar, 2009; Scott, Pascalis, & Nelson, 2007). In this section, we consider cases where these domains might parallel the case of bilingualism in language acquisition.

In the domain of face perception, a well-known example of perceptual narrowing is the other-race effect. Early in life, infants show sensitivity to distinctions across a wide variety of faces. Within the first year of life, perception narrows such that faces from the own race are easier to discriminate than those from an unfamiliar race. What happens if infants' experience with faces is analogous to bilinguals' experience with language, in the sense of having regular exposure to faces from two different races? Like bilingual infants, these infants have less experience with faces from each race, but a more diverse experience overall. This case was tested in a group of 14-week-old African Ethiopian infants raised in Israel, where the majority of residents are Caucasian. Unlike infants exposed primarily to a single race, these infants did not show race-based preferences, and instead showed equal preference for both types of faces (Bar-Haim, Ziv, Lamy, & Hodes, 2006). These results are parallel to results of language preference studies with bilingual infants, whereby bilingual infants show similar preference for their two native languages (Byers-Heinlein et al., 2010). Further data come from a recent study investigating Caucasian, Asian and biracial (Caucasian-Asian) 3-month-olds' recognition of Caucasian and Asian faces. The monoracial and biracial groups showed different responses in both their preferences for, and the manner in which they scanned faces (Gaither, Pauker, & Johnson, 2012). However, it should be noted that both of these studies tested infants at an age younger than race-related perceptual narrowing is typically seen, around 6-9 months (Kelly et al., 2007). Future studies of older infants will be informative.

These latter findings are reminiscent of the processing differences between monolingual and bilinguals in phoneme discrimination and detection of phoneme changes in words. The above results open the door to future studies that could examine perceptual narrowing to faces in infants exposed to multiple categories of faces. How does their exposure to a wider variety of faces affect their discrimination? Does perceptual narrowing proceed on the same schedule in these infants as in infants exposed primarily to faces from a single race? Will future studies reveal U-shaped developmental trajectories, similar to those observed in bilingual infants' perception of several native speech sound contrasts? What about dose-response effects for face processing in infancy? This final possibility seems particularly likely, given that some studies have provided evidence for dose-response effects in other-race face processing in adulthood (e.g. Chiroro & Valentine, 2007).

Parallels with bilingual language acquisition can also be considered in the context of music perception. For example, North American music is characterized by a simple metrical structure, while music from numerous other cultures shows a more complex metrical structure. Infants raised in North America are initially sensitive to both simple and complex metrical structure, but sensitivity to non-native structure begins declining over the latter half of the first year (Hannon & Trehub, 2005a). In this study, infants were familiarized to a piece of music, and tested on their interest in an alternation that either preserved or violated the music's metrical structure. At 6 months, whether the music characterized a simple or complex metrical structure, infants showed greater interest in the test stimulus that violated the previously-heard structure, suggesting that they were sensitive to both types of structures. However, by 12 months infants showed sensitivity to non-native musical structure only if they had been pre-exposed to that type of music (Hannon & Trehub, 2005b).

By adulthood, perception has narrowed even further. In a related adult paradigm, North American adults showed better perception of the simple structure, and had difficulty detecting violations of foreign metrical structure even with some exposure (Hannon & Trehub, 2005a,b). However, adults of Bulgarian or Macedonian origin living in North America, who have extensive experience with both simple and complex structures, showed perceptual sensitivity to both types of structures. Further, the performance of the Bulgarian/Macedonian origin adults hinted at a dose-response effect, as performance on both types of stimuli was predicted by years of musical training in metrical and non-metrical music respectively. Thus, while there is more research to be done in this area, the perception of music by individuals with exposure to multiple types of music shows some similarities to speech perception by bilingual infants.

In sum, research on individuals exposed to more than one non-linguistic system is thus far limited. Yet, such research should be of interest to the field given that perceptual narrowing occurs across multiple modalities at similar developmental times (Lewkowicz & Ghazanfar, 2009; Scott et al., 2007). This observation has led to domain-general explanations for perceptual narrowing, such as synaptic pruning (e.g., Scott et al., 2007), although others have argued against synaptic pruning as being responsible for these parallel developmental patterns (Lewkowicz & Ghazanfar, 2009). If the underlying mechanisms responsible for perceptual narrowing are truly domain general, then systematic variation in any domain (e.g., linguistic, facial, or musical) should produce similar effects on the perceptual maintenance and induction of stimuli present in the infant's environment, and on the perceptual decline of environmentally absent stimuli. However, it is also possible that the demands of processing multiple languages are very different from the demands of processing faces from different races or music of different metrical structures, and that the same developmental patterns will not be observed. With more research, it will be possible to further investigate whether the striking parallels in perceptual narrowing across domains also hold in situations in other domains analogous to bilingualism, which will further inform debates about the mechanisms underlying perceptual narrowing.

Conclusions

In this paper, we have reviewed developmental patterns of speech and language perception in infants raised bilingual from birth. We have highlighted four aspects of bilingual infants' early experience that we believe play an important role in perceptual development 1) bilinguals have reduced exposure in each language, 2) bilinguals must represent two languages, 3) bilingual exposure is noisy, and 4) bilingual infants must separate and differentiate their languages.

The reduced exposure to each language is a difference that is particularly relevant for the maintenance and tuning of native language contrasts. On one hand, bilinguals show similar patterns of maintenance as monolingual infants for some linguistic stimuli, even given reduced input. On the other hand, we have identified two unique patterns of phonetic development shown by bilingual infants. These patterns provide insight into the mechanisms that underlie early perceptual development, and raise interesting questions for future research.

In the dose-response pattern, increased exposure to a language leads to better maintenance of a native contrast in that language. This finding supports the notion that frequency plays a key role in the maintenance of native contrasts. An important research question will be to determine whether this function is continuous or discontinuous. For example, is an infant who is exposed to another language 5% of the time "slightly bilingual", or is this small amount of another language ignored by the perceptual system? What is the minimum amount of exposure required to maintain a contrast? The answer will likely depend on the particular aspect of perception that is being assessed, and thus is an area ripe for future research.

The second unique pattern shown by bilinguals is a U-shaped pattern in phonetic perception of native contrasts. Here bilingual infants show a temporary period during which their sensitivity to a native contrast declines. This pattern has been replicated several times amongst Catalan-Spanish bilingual infants, but has not yet been observed in other bilingual groups. Explanations for this finding include overlapping distributions of input between the two languages, variability in the productions of parents, the high frequency of cognates across the languages, and the lack of a cue such as rhythm that could easily distinguish Spanish and Catalan. Continued research with bilingual infants learning different language pairs, perhaps varying in their perceptual distinctiveness, will help to investigate the specific cases in which this U-shaped pattern is observed, and will serve to constrain potential explanations.

Although considerable progress has been made in understanding the perception of native contrasts amongst bilinguals, much less work has investigated bilinguals' perception of non-native contrasts. What research has been undertaken to date has hinted that bilinguals might show a prolonged period of sensitivity to non-native contrasts. We have outlined how several differences between monolingual and bilingual experience might predict this developmental pattern. Sensitivity to non-native contrast could stem from high-level cognitive advantages amongst bilinguals, but might equally have a low-level explanation such as reduced frequency of input or increased variation. In either case, research with bilinguals supports the position that some aspect of experience with the native languages, rather than a lack of experience with non-native languages, is at the root of the decline in perceptual sensitivity (see also Best, 1994; Kuhl et al., 2008; Werker & Curtin, 2005, for related arguments concerning monolingual development).

Future work directed at testing bilingual infants on non-native contrasts, and further refining these explanations, could significantly add to our understanding of the underlying mechanisms.

Throughout this paper, we have used the term "bilingual" to refer to any infant hearing two languages regularly from birth, and have discussed such infants as a homogeneous group. Yet, it is important to note that there is variability amongst this group that remains poorly understood (see also Werker & Byers-Heinlein, 2008, for further discussion). For example, little is known about how the particular language pair being learned by a bilingual infant affects perceptual development. Similarly, some bilinguals do grow up in an environment more akin to "one-person-one-language" while others interact largely with bilingual adults. This might also have systematic effects on perception. Further, many children growing up bilingual are not exposed to both languages from birth, but instead begin to learn a second language several months or years later, for example upon entering daycare. It is not known how these very early second language learners differ from simultaneous bilinguals. Finally, bilingualism is often confounded with other factors. For example, bilinguals may be of a systematically different socioeconomic status than monolinguals in the same community (see Morton & Harper, 2007, for a review of this issue). Further, bilingual infants might be more likely to be exposed to accented speech. None of these factors is inherent to bilingualism per se, but must be considered when interpreting findings from studies that compare bilinguals and monolinguals. It will be very important for future studies of perception test groups of bilingual infants that vary systematically in terms of the aforementioned aspects of language environment.

In reflecting on these findings, it is pertinent to ask whether perceptual development in bilingual infants should be described as “perceptual narrowing”. In some ways, this terminology does not match well with the bilingual data. Although bilingual infants show the steady maintenance of some native distinctions, other native distinctions show a unique U-shaped pattern, inconsistent with the monotonic developmental function suggested by the term “perceptual narrowing”. Further, studies to date on non-native language perception suggest that the developmental endpoint for bilinguals might be substantially less narrow than for monolinguals, although considerably more data is needed on this topic. On the other hand, like monolinguals, bilinguals do become native listeners who are specialized in their perception, albeit attuned to their unique bilingual environments. As the demands of a bilingual environment are different from those of a monolingual environment, this could result in somewhat different perceptual outcomes. Certainly, the unique developmental patterns seen in young bilinguals points to the plasticity of the perceptual system in adapting to diverse types of early experience. Continued research with bilingual infants, particularly on their perception of non-native contrasts, is likely to generate further insights about the interplay of nature and nurture in perceptual development.

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