Bilingual beginnings as a lens for theory development: PRIMIR in focus

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Abstract

PRIMIR (Processing Rich Information from Multidimensional Interactive Representations; Werker & Curtin, 2005; Curtin & Werker, 2007) is a framework that encompasses the bidirectional relations between infant speech perception and the emergence of the lexicon. Here, we expand its mandate by considering infants growing up bilingual. We argue that, just like monolinguals, bilingual infants have access to rich information in the speech stream and by the end of their first year, they establish not only language-specific phonetic category representations, but also encode and represent both sub-phonetic and indexical detail. Perceptual biases, developmental level, and task demands work together to influence the level of detail used in any particular situation. In considering bilingual acquisition, we more fully elucidate what is meant by task demands, now understood both in terms of external demands imposed by the language situation, and internal demands imposed by the infant (e.g. different approaches to the same apparent task taken by infants from different backgrounds). In addition to the statistical learning mechanism previously described in PRIMIR, the necessity of a comparison-contrast mechanism is discussed. This refocusing of PRIMIR in the light of bilinguals more fully explicates the relationship between speech perception and word learning in all infants.

Keywords: bilingualism, theoretical framework, infant speech development, word learning

1. Introduction

Upon viewing a work of art, many different aspects of a painting might draw the viewer's eye: the artist's use of color and light, the particular scene depicted, or the historical context of the painting. What the viewer attends to in any given moment is likely influenced by whether the goal is enjoyment or critical analysis, the viewer's background knowledge of art, and even the range of colors perceptible by the human eye. A striking parallel can be seen when that same person listens to a conversation, and how that person attends to the speech sounds that comprise the words. The listener can glean information from many levels, including acoustic, phonetic, and phonemic. Whether information at a particular level is attended to depends on the demands of the task, the developmental level of the listener, and perceptual biases brought by the human perceptual system.

These two observations - that rich information is available in the speech stream and that the listener dynamically filters that information – provide our starting point for exploring how speech perception develops prior to and after the emergence of the lexicon. Previously, Werker & Curtin (2005) proposed the theoretical framework PRIMIR (Processing Rich Information from Multidimensional Interactive Representations), to explain the relation between speech perception and early lexical development. For a speech processing framework to be of theoretical and practical use, it should be general enough to apply to children developing in a variety of different language environments. A growing number of children worldwide are brought up with two languages from birth. These bilinguals receive input from two languages simultaneously, and each of these languages is

characterized by a different inventory of sounds, sometimes overlapping and sometimes not. There is a growing interest in and research about how bilingual infants navigate this complex phonetic space, develop phonetic and phonological categories, and ultimately use their sound categories to learn words in each of their languages (e.g. Werker & Byers-Heinlein, 2008). In this paper we draw on recent research with bilingual infants to elaborate PRIMIR, and more fully explicate the relationship between speech perception and word learning in all infants. Consistent with the goals of the original PRIMIR framework (Werker & Curtin, 2005), this broadening of PRIMIR to encompass bilingual acquisition aims to unify and organize the myriad of sometimes divergent findings in the areas of speech perception and word learning by bilingual infants.

1.1 Theoretical foundations

The language-learning situation for infants is ripe with complexity ranging from different voices, accents, and dialects to multiple languages in the input (see Schmale & Seidl, 2009; Schmale, Cristià, Seidl & Johnson, 2010 for a discussion of these issues). Numerous models of speech perception and word recognition have contributed to our understanding of how infants negotiate their early language environments, and these in turn have offered a springboard for developing PRIMIR (Werker & Curtin, 2005). The Perceptual Assimilation Model (PAM; Best, 1994; Best & McRoberts, 2003; Tyler, Best, Goldstein, & Antoniou, submitted), and the Native Language Magnet model (NLM; Kuhl, 1993; Kuhl et al., 2008), provide a basis for understanding how experience shapes phonetic categories, while the Word

Recognition and Phonetic Structure Acquisition model (WRAPSA; Jusczyk, 1993; 1997) offers an explanation of how words are recognized. Missing from these models is an explanation as to why some, rather than other, information available in the speech signal, is selected for attention in different processing situations. PRIMIR was thus proposed to provide a more comprehensive framework, pulling together the processing and the storage of information, which fundamentally depend on the age of the infant, the nature of the task, and the infant's perceptual biases.

Infants begin life with shared perceptual biases that constrain and guide information pick-up. That is, the perceptual system detects certain auditory configurations in an automatic and efficient way, similar to visual Gestalts (Kanizsa, 1955). Newborns demonstrate preferences for speech (Vouloumanos & Werker, 2004; Vouloumanos, Hauser, Werker, & Martin, 2007), proper syllable form (Bertoncini & Mehler, 1981), point vowels (Polka & Bohn, 2003), infant-directed speech (Cooper & Aslin, 1990), and an ability to process rhythm (Mehler et al., 1988; Ramus, Hauser, Miller, Morris, & Mehler, 2000). These perceptual biases, which are available from birth, can be employed by the linguistic system for language acquisition.

Ultimately, infants must establish the appropriate linguistic categories of their native language. PRIMIR posits that infants use domain-general learning mechanisms to establish these native categories. These learning mechanisms may initially be influenced by perceptual biases, but over time, shifting and growing knowledge about the language or languages being acquired will help to direct information uptake. The learning mechanisms not only detect information in the

input, but also operate over stored information. Many empirical studies have shown that infants indeed have powerful statistical learning mechanisms available for language learning (see Saffran, 2003 for a review). Further, infant-directed speech contains distributional cues that are consistent with adult phonetic categories (Werker et al., 2007). Even without a-priori specification of the number of phonetic categories in the input, neural network models can determine the number and boundaries of phonetic categories from infant-directed speech (de Boer & Kuhl, 2003; McMurray, Aslin, & Toscano, 2009; Vallabha, McClelland, Pons, Werker, & Amano, 2007). Research has shown that infants can track both absolute frequencies (Anderson, Morgan, & White, 2003) and relative, distributional frequency information (Maye, Werker, & Gerken, 2002; Maye, Weiss, & Aslin, 2008; Yoshida, Pons, & Werker, 2010) to support phonetic category learning. These findings suggest that infants use mechanisms sensitive to an array of statistical patterns to pick up information from the linguistic environment. Organization of stored information based on statistical patterns can been seen in connectionist models of lexical development (Li & Farkas, 2002) and in Bayesian approaches to learning (see Griffiths, Kemp, & Tenenbaum, 2008).

2. PRIMIR described

PRIMIR is a theoretical framework of early speech perception and word learning. As such, there are numerous other related aspects of language development that PRIMIR does not address, for example phonological development beyond the emergence of phonemes. The PRIMIR framework includes representational spaces for storing information, learning mechanisms for altering

extant representations and building new ones, and dynamic filters that direct information processing. The original framework referred to the representational spaces as planes (Werker & Curtin, 2005; Curtin & Werker, 2007), but here we rename them spaces to emphasize their multidimensional nature. The representational spaces are highly interactive, and include a General Perceptual space, a Word Form space, and a Phoneme space. From birth, the General Perceptual space has some initial organization that results from the discontinuities that the human perceptual systems impose on incoming speech. The General Perceptual space stores phonetic (articulatory/acoustic features and cues) and indexical (including visual, affect, voice quality, etc.) information. Statistical learning allows the formation of similarity clusters that coalesce over time into native phonetic and indexical categories. Although the native language influences the organization of these phonetic categories, they are not yet considered true phonemes, as they do not serve to contrast meaning (Trubetskoy, 1969).

The Word Form space stores sound-sequence exemplars that have been extracted from the speech signal. Initially stored word forms do not have an associated meaning, but rather meaning later becomes linked to appropriate word forms as the conceptual system develops. At first these are simple associations between words and objects that are driven by the statistics in the input. As full referential understanding develops, so too do meaningful words.

With increasing numbers of word form-meaning linkages, the Phoneme space begins to emerge. Phonemes emerge from generalizations across information stored within the Word Forms space and from the phonetic categories within the

General Perceptual space. Phonemes serve to summarize across context-sensitive variation, and are important in guiding subsequent learning. Phonemes in PRIMIR are initially positionally sensitive (e.g. there are separate representations for word-initial /d/ and word-final /d/) and emerge in a staggered fashion.

Integral to PRIMIR is the relationship between representations and processing. Three dynamic filters direct processing: perceptual biases, task demands, and developmental level. As described above, the perceptual biases include preferences for speech, proper syllable form, point vowels, infant-directed speech, and an ability to process rhythm. These biases also direct attention to the critical cues that distinguish most possible phonetic contrasts (see also Polka & Bohn, in press). The contribution of the perceptual biases gradually becomes less important across development with growing native language knowledge. Concurrently, the two other dynamic filters, task demands and developmental level, become increasingly important over the course of development as the infant gains native language knowledge and becomes adept at adjusting to varying demands. Task demands influence what information is given processing priority at a given moment. Straightforward discrimination tasks access all available phonetic and indexical information in the General Perceptual space. Categorization tasks access language-general, and later language-specific information over the course of development. What information is accessed in more demanding tasks, such as forming new word-object associations, depends on the developmental level of the infant. Developmental level is a function of the current state of the infant's knowledge. Age can serve as a proxy for developmental level, but it should be noted

that the developmental level of two infants of the same age will differ when their knowledge differs. As an infant's knowledge grows, the state and organization of the overall system changes, and this in turn affects in-the-moment information uptake. It is in this sense that developmental level acts as a dynamic filter.

Perhaps the most unique aspect of PRIMIR is that the system is interactive, allowing information to be accessed from any space at any time. Further, the representational spaces do not develop or emerge in a hierarchical fashion. That is, the General Perceptual space does not fully develop before the Word Form space, and both of these are not fully established before the emergence of phonemes within the Phoneme space. The first space to store information is likely the General Perceptual space, which at first operates in conjunction with the perceptual biases. As soon as infants begin to segment the speech stream and recognize some highly frequent words, the Word Form space begins to develop. At this point the system's interactive nature is truly apparent. The General Perceptual space informs the Word Form space and supports its development and the Word Form space informs the General Perceptual space and supports its development. Learning mechanisms and dynamic filters direct online processing of incoming information, with reference to information already stored within one or more representational spaces. Offline, the learning mechanisms continue to organize information within the representational spaces. As categories and neighborhoods form within these representational spaces, phonemes begin to emerge within the Phoneme space. Phoneme-like categories that are positionally tied emerge in a staggered fashion. That is, allophones, at least in the initial stage of lexical development, might be characterized in the system as

separate entities from their appropriate phonemes. True abstraction to a phoneme category within the Phoneme space occurs over time via the statistical regularities (see White, Peperkamp, Kirk, & Morgan, 2008, for evidence that infants can learn a phonological alternation through statistics in the input) and also once orthography is introduced to the system.

With the development of the Phoneme space, interaction occurs between all of the spaces and helps the infant to process and store information. As spaces emerge and stored information becomes increasingly organized, access to information at any level is possible. Whether information within a particular space is accessed depends on the dynamic filters. Early on, information uptake is strongly influenced by perceptual biases, but over time representations become more robust. As the infant learns, perceptual biases play a lesser role, and task demands together with the infant's developmental level are primary in determining what information the infant uses.

To summarize, PRIMIR draws on the observation that information in the speech stream is abundant. The ability to perceive and process this information in a meaningful way is in part made possible by general learning mechanisms that tracks statistical patterns. The dynamic filters work with the statistical learning mechanisms to detect and organize information within multidimensional interactive spaces. The dynamic filters can enhance or diminish the raw saliency of the input and this can affect what information is tracked by the learning mechanisms. The dynamic filters and learning mechanisms work together to ensure that only linguistically plausible combinations are learned. Emergent representations within

the various spaces allow information uptake to be directed. That is, the interactive nature of the system allows for emergent categories to influence the processing of incoming information just as incoming information can influence the emergence of representations.

3. Refocusing PRIMIR: bilingualism

The goal of this paper is to refocus the PRIMIR framework by extending PRIMIR to infants and children growing up in bilingual environments. Although we use the umbrella term *bilingual*, it is important to recognize the diversity of the experience and of the challenges faced by bilingual and multilingual infants. For example, the two languages being acquired might vary in their similarity, from highly dissimilar language pairs such as English and Mandarin, to historically close languages with many cognates such as Spanish and Catalan, to learning two dialects of the same language such as Canadian and British English (which might be considered bidialectism rather than bilingualism). Other sources of variation amongst bilingual infants include the contexts of exposure (one-parent-one-language versus bilingual caregivers), the amount of exposure to each language (balanced versus unbalanced), and whether some input is accented (for a more detailed discussion of these issues, see Werker & Byers-Heinlein, 2008). Throughout this extension of the PRIMIR framework to bilinguals, we will consider such variation in experience where possible, while focusing on the common challenges faced by all bilinguals.

In extending PRIMIR to bilingual and multilingual development, we begin with five starting assumptions. Three of these reflect the belief that monolinguals and bilinguals come equipped in fundamentally the same way:

1) Monolingual and bilingual infants possess the same representational spaces.

2) The same dynamic filters - perceptual biases, task demands, and developmental level - all operate in bilinguals just as they do in monolinguals.

3) The same learning mechanisms support monolingual and bilingual acquisition.

Two other assumptions recognize the uniqueness of the bilingual language environment, and the particular ways it must be negotiated by bilingual infants:

4) The nature of the learning mechanisms, the way these mechanisms operate over the input, and the structure of the representations within the spaces enable language separation by bilingual infants.

5) Even in the same apparent experimental situation, bilinguals may experience different task demands, which may change the way any particular situation is negotiated.

On the basis of our review and interpretation of the recent empirical findings with bilinguals, we adhere to the above assumptions, and further make two additions to the PRIMIR framework. We suggest:

1) Because input to bilinguals is divided between two languages, the developmental level of a bilingual infant in a particular task is a product of both the learning that has taken place vis-à-vis the particular language used

in the task, as well as more general aspects of cognitive and linguistic development. This has particular implications at the intersection of the Word Form and Phonemic spaces.

2) In addition to the general statistical learning mechanisms, PRIMIR must also include a mechanism that aids in comparing and contrasting information. Thus we introduce a type of learning mechanism that is sensitive to an array of relationships. This mechanism operates alongside statistical learning to organize information within the representational spaces.

3.1 Tracking the bilingual input

PRIMIR is based on the observation that languages are replete with statistical patterns and regularities, and that infants possesses powerful statistical learning mechanisms. But, take two languages and mix their statistics: the result would likely be one big bowl of language mush. To effectively acquire two languages simultaneously, the learner needs to be able to put each language in a separate bowl, metaphorically speaking. Statistics should be tracked within each language, rather than collapsing across the entire input. Adults are able to track two sets of statistics independently, if given an indexical cue such as speaker gender that differs across the two sets (Weiss, Gerfen, & Mitchel, 2009). Similarly, adults succeed if exposed to two different artificial languages in concert with two different speakers lip-synching the speech stream (Mitchel & Weiss, 2010). Parallel infant work is ongoing, and although results are not yet available, infants may similarly be able to track two sets of statistics if given a cue that allows them to separate their two languages.

Moreover, as reviewed below, perceptual biases could provide a foundation by which bilingual infants begin to separate their languages, and thus compute useful rather than useless statistics.

3.1.1 Auditory language discrimination

Infants begin life with perceptual biases that allow them to tell apart different languages. Initial studies using a head-turn procedure showed that monolingual infants aged 2 months will turn their heads more rapidly to the direction from which the native language is played than they will to an unfamiliar language (Mehler et al., 1988). Follow-up studies using low-pass filtered speech revealed that discrimination is based on the rhythmical properties of the languages. At birth, infants are only able to discriminate languages from different rhythmical classes, e.g. syllable-timed languages (such as French and Spanish) from stress-timed (such as English and German) or mora-timed languages (such as Japanese). It is not until after 4-months that infants begin to discriminate two languages from within the same rhythmical class, and even then only do so if one of the languages is familiar (for a review, see Nazzi & Ramus, 2003). Bilingual Spanish-Catalan infants can also discriminate either of their native languages from an unfamiliar language, but opposite to monolinguals, show this discrimination ability by turning their head more *slowly* to the native language (Bosch & Sebastián-Gallés, 1997). This reveals that although the perceptual biases and underlying learning mechanisms are the same in bilingual and monolingual infants, the application of these biases is different in a bilingual setting. Bosch and Sebastián-Gallés suggest this is because the

monolingual infants simply orient upon detection of the native language, whereas bilingual infants identify which of the two native languages is being spoken before orienting. It is plausible that across a wide variety of language situations, bilinguals first attempt to determine which language is being used, in order to appropriately direct processing, a possibility we will return to again later in this paper. Thus, task demands may be different in bilinguals even when the same experimental procedure is used.

The critical task for bilingual infants is not only to discriminate their native languages from an unfamiliar language, but also to discriminate the two familiar languages from one another. Here too, bilingual infants are remarkably successful. The first demonstration of this ability was with bilingual Spanish-Catalan infants aged 4 months, tested in a visual habituation looking task (Bosch & Sebastián-Gallés, 2001). The bilinguals showed a robust ability to discriminate these two familiar and rhythmically similar languages. Thus, with appropriate listening experience, bilingual infants can tune into subtle differences between native languages from within a single rhythmical class.

More recently, researchers have found that newborns with prenatal bilingual experience can discriminate their two languages even at birth (Byers-Heinlein, Burns, & Werker, 2010). This finding is of particular importance because related work has shown that these newborns have already learned something about the properties of the native languages. In this research, Byers-Heinlein and colleagues undertook a series of studies with infants born to mothers who spoke two rhythmically distinct languages regularly throughout their pregnancy: English

(which is stress-timed) and Filipino (which is syllable-timed). Newborn infants were tested using a high amplitude sucking procedure, wherein each time an infant sucked strongly on a rubber nipple, a sound was played. Previous work has demonstrated that monolingual newborns prefer their native language at birth (Moon, Cooper, & Fifer, 1993), and so it was predicted that if bilingual infants can learn about two languages prenatally, they should show similar preference for each of these languages, as both are familiar. Indeed, when the bilingual newborns were played alternating minutes of filtered English and Filipino sentences, they sucked similarly to each language, suggesting equal preference. Monolingual English-exposed infants replicated the pattern of a preference for English. One interpretation of the preference results could be that bilingual newborns, through their prenatal experience with two languages, simply lump both native languages together as familiar, irrespective of rhythmical properties. If so, early bilingual experience could interfere with language discrimination. Thus, in a second study, discrimination was tested directly. Both monolingual English-exposed and bilingual English-Filipino-exposed infants were habituated to either filtered English or filtered Filipino sentences. At test, infants heard sentences from the other language. Both monolingual and bilingual newborns increased their sucking at test, while infants in a control condition showed no change in their sucking. These results reveal that even with prenatal bilingual experience, the perceptual biases that support language discrimination continue to operate (Byers-Heinlein et al., 2010). This work with newborn infants provides an example of how perceptual biases and

learning work together to lay the foundation for either monolingual or bilingual acquisition, depending upon the input encountered.

3.1.2 Visual language discrimination

The auditory modality is not the only source of information available to young bilinguals to support language acquisition. Visual information present on the mouth and face can also be distinct for different languages. Adults are able to discriminate video clips of a silent talking face speaking sentences from a familiar language from a face speaking sentences from an unfamiliar one, and bilingual adults are especially adept at visually discriminating their two languages (Soto-Faraco et al., 2007).

Bilingual infants also show particular sensitivity to visual information that distinguishes their languages. Weikum and colleagues (2007) used a habituation paradigm to compare visual language discrimination abilities in English monolingual and French-English bilingual infants. They showed infants images of several individuals silently speaking either French or English. Once infants' interest in the videos began to wane, they tested infants by showing them either new sentences from the same language as before, or by showing them sentences from the other language. At 4 and 6 months, both monolingual and bilingual infants showed increased interest when sentences from a new language were presented, suggesting that they had discriminated the languages visually. However, at 8 months, only the bilingual infants noticed the change in language, revealing maintenance in bilinguals' ability at the same age when monolinguals show a decline in sensitivity.

Infants' sensitivity to visual and rhythmic information that discriminates languages is useful for organizing information in the bilingual (and monolingual) environment. When languages are discriminated, the system might track patterns separately for the different languages. PRIMIR posits that infants use domain-general statistical learning mechanisms to reorganize their perceptual biases into language-specific phonetic categories. Statistical coherence within each language might lead to language-specific clustering within the representational spaces, thus yielding representations that are appropriate to each language. The question remains as to whether tracking statistical patterns is the only mechanism by which monolingual infants establish native categories, and if it is a sufficient mechanism for bilingual infants who are faced with multiple patterns that may or may not overlap across the various languages being learned.

3.2 Mechanisms for organizing information

All infants, monolingual and bilingual, likely require and use other forms of information beyond the statistical patterns of speech in order to form categories and to organize information in the multidimensional interactive spaces. On the basis of recent research (Yeung & Werker, 2009), we suggest that infants have available to them a mechanism that compares and contrasts information, which was not considered in previous discussions of the PRIMIR framework. This mechanism can identify categories using multiple sources of information, track information coming from different sources, and determine similarities and differences along multiple parameters.

Learning mechanisms whose functions are to detect differences and similarities have been proposed for perceptual learning across numerous domains (e.g. vision, taste, audition) and for human and non-human animals (Hall, 1991). Traditionally, acquired distinctiveness and acquired equivalence (Lawrence, 1949) refer to whether similar cues are associated with separate outcomes to enhance discrimination (acquired distinctiveness) or whether distinct cues are associated with the same outcome to reduce discrimination (acquired equivalence; Bonardi, Graham, Hall, & Mitchell, 2005). Comparison, contrast, and analogy mechanisms have been shown to operate over numerous levels in language learning (Gentner & Namy, 2006; Waxman, 2009), for example in structural alignment theory accounts of category formation (Falkenhainer, Forbus, & Gentner, 1989; Gentner & Markman, 1994). This type of mechanism could facilitate the formation of phonetic categories within the General Perceptual space, the development of neighborhoods within the Word Form space, and the emergence of phonemes within the Phoneme space.

As they establish native phonetic categories, infants might consider not only acoustic information but also correlated visual information. In one study, 6-month-old monolingual infants were exposed to a unimodal distribution of sounds on a [ba]-[da] continuum (Teinonen, Aslin, Alku, & Csibra, 2008). Synchronously with the audio, infants saw a face articulating one of the sounds, either [ba] or [da]. Half of the infants were assigned to the one-category group, and always saw the face producing the same sound. The other half of the infants were assigned to the two-category group, and saw the face producing [ba] when auditory tokens were from the [ba] end of the continuum, and [da] when tokens were from the [da] end of the

continuum. At test, infants in the two-category group showed evidence of discriminating auditory endpoints [ba] and [da] while those in the one-category group did not, suggesting that redundant visual phonetic information can also support phonetic category learning, even when auditory cues are insufficient.

More recently, it has been shown that contrasting visual information need not encode redundant phonetic information to help support phonetic category learning. Yeung and Werker (2009) showed that objects also serve as cues for monolingual infants in establishing phonetic categories. In their study, infants aged 9-months were trained on a consistent pairing of a dental [da] syllable with object A, and a retroflex [da] syllable with object B. These infants were subsequently able to make the difficult phonetic distinction between the dental and retroflex [d] sounds, that English infants this same age can typically no longer make (Werker & Tees, 1984). In a control study that presented infants with inconsistent pairings such that both [d] sounds were presented with both objects, infants did not discriminate between the two sounds.

The above study shows that infants can use contrasting visual information that co-occurs with phonetic distinctiveness to better delimit phonetic categories. This reveals the functioning of mechanisms beyond distributional learning that likely play an important role in phonetic category development. Indeed, the fact that a co-occurrence between words and objects can drive phonetic categorization, shows that infants keep track of statistics across domains. Yeung and Werker (2009) propose that this is an example of the broader notion of acquired distinctiveness (Lawrence, 1949). In most previous work, comparison-contrast

mechanisms have been assumed to operate at an explicit level, but in the Yeung and Werker study there is no evidence that the infants have actually learned the association between syllable and object. Hence, although acquired distinctiveness is typically considered to rest on explicit associative learning, infants may possess an implicit mechanism that uses the principles of acquired distinctiveness and acquired equivalence and expands them beyond perceptual learning to incorporate higher order learning.

A comparison-contrast mechanism would be particularly useful for bilingual development, by allowing bilinguals to bootstrap their language learning through making comparisons across their native languages. The use of such strategies could help solve the mystery of how bilinguals keep pace with their monolingual peers, even though their input is divided between two languages (Werker & Byers-Heinlein, 2008). Specifically, comparison across their languages on the basis of rhythm (Byers-Heinlein et al., 2010), visual speech information (Weikum et al., 2007), or other salient dimensions, could help bilingual infants discriminate and separate their languages. For example, if one set of distributional statistics occurs with a particular language rhythm, and a different set occurs with a second rhythm, PRIMIR predicts that bilingual infants will use this information to keep track of the two sets of distributional statistics, for example to establish phonetic categories in each of their languages (see also Sundara & Scutellaro, submitted). Conversely, input that hinders the operation of a comparison-contrast mechanism could pose an impediment to learning. For example, there is preliminary evidence that bilingual 1- and 2-year olds who hear frequent language mixing (a bilingual parent reporting

frequently mixing words from different languages in the same sentence) show smaller vocabularies than bilinguals exposed to less language mixing (Byers-Heinlein, 2009). It is also theoretically possible that a comparison-contrast mechanism enables infants to keep track of nested statistics, tracking phonetic properties and rhythm as a function of one another in a simultaneous, rather than sequential fashion. We posit that such an ability is available to both monolingual and bilingual infants, but given the properties of the input that each group receives, is implemented differently in each group.

In sum, we propose that in addition to the general statistical learning mechanisms, all infants have available to them a comparison and contrast mechanism. Comparisons group similar types of information, while contrasts separate information that is dissimilar along one or more dimensions. The representational spaces become warped, and neighborhoods, natural classes, and categories take shape. As information is stored, relationships between stored knowledge both across spaces (e.g. linkages between word forms and meaning) and within spaces (e.g. neighborhoods) emerge. These links and connections between the spaces in turn help to inform information uptake. In the next section, we turn to a more explicit discussion of PRIMIR's multidimensional spaces and their operation in a bilingual context.

3.3 Organizing multidimensional spaces

3.3.1 General perceptual space

The reorganization of perception from language-general sensitivities to language-specific ones has been an area of particular interest in phonetic development (Werker & Tees, 2005), and such reorganization tends to occur before the end of the first year of life in monolingual infants. Much less work has been done examining bilingual phonetic development, but findings in this area are growing. Recent studies have suggested that, like monolinguals, bilinguals show brain responses consistent with discrimination of contrasts in their two languages by age 10-12 months, although brain responses to the contrasts native to a particular language may vary with amount of exposure to that language (Garcia-Sierra et al., submitted). These findings are consistent with the behavioral studies described below, showing that bilinguals maintain the ability to discriminate phonetic contrasts that occur in each of their languages, as well as sensitivity to contrasts that occur across their languages.

Burns, Yoshida, Hill, and Werker (2007) studied a case where French-English bilingual infants encounter a category boundary that is realized differently in each of their two languages, the case of bilabial stops /p/ and /b/. Both French and English have these phonemes, but the boundary occurs at a shorter voice-onset-time (VOT) in French than in English (Caramazza, Yeni-Komshian, Zurif, & Carbone, 1973). Hence, there is a circumscribed region on the VOT continuum that is categorized as /b/ for English-speaking adults, and /p/ for French-speaking adults.

Burns and colleagues habituated infants to tokens in this ambiguous region, and at test played infants tokens from either the unambiguous /b/ or the unambiguous /p/ regions. At 6-8 months of age, monolingual English-learning infants and bilingual French-English infants showed the same patterns of discrimination, indicating that discrimination was not yet language-specific for either group. However, at 10-12 and 14-20 months of age, both groups showed experience-specific patterns of response. English monolinguals discriminated only across the English boundary, while French-English bilinguals discriminated across both the English and the French boundaries.

Sundara, Polka, and Molnar (2008) also explored phonetic development in French-English bilinguals, this time examining a single phoneme which has a different realization in the two languages, /d/. In English /d/ is alveolar, while in French it is dental. At 6-8 months of age, monolingual English, monolingual French, and French-English bilingual infants were all able to discriminate the two realizations of this phoneme. However, a few months later, at 10-12 months, only monolingual English and bilingual English-French infants continued to show evidence of discrimination. Bilinguals' sensitivity to the differences in the realization of the same phoneme across their two languages could assist in language separation, and in the building of distinct representations in each language.

Vowel perception is also of interest in bilingual infants, as there are cases where a certain vowel contrast is present in one of the bilingual's languages but not the other. This is the case for Spanish-Catalan bilingual infants for the open and closed 'e' sounds, /e/ and /ɛ/, a contrast which is meaningful in Catalan but not in

Spanish. Monolinguals show characteristic developmental patterns with respect to this contrast. Monolingual Spanish-learners can discriminate the contrast at younger ages, for example 4 months, but not at 8 months of age, while Catalan-learners continue to discriminate the contrast throughout the first year of life (Bosch & Sebastián-Gallés, 2003). However, bilingual Catalan-Spanish infants show a unique pattern of successful discrimination at 4 and 12-months-of-age, but an apparent failure to discriminate the contrast at 8 months of age (Bosch & Sebastián-Gallés, 2003). Spanish-Catalan bilinguals have also shown a failure at 8 months to discriminate at least one other phonemically close contrast, /o/-/u/, which monolingual Spanish and Catalan-learners are able to discriminate at the same age (Sebastián-Gallés & Bosch, 2009). It does not appear that bilinguals of this age have a more general problem with vowel discrimination, as Spanish-Catalan bilingual 8-month-olds successfully discriminate the more distinct /e/-/u/ contrast, which monolinguals can also discriminate (Sebastián-Gallés & Bosch, 2009). It may be that because the Spanish and Catalan vowels overlap, distributional learning leads to a temporary collapse of perceptual distinctiveness at 8 months, before further input allows the two categories to separate again (Bosch & Sebastián-Gallés, 2003). Another possibility is that bilinguals' failure to discriminate certain contrasts is an artifact of the experimental task used. Albareda-Castellot, Pons and Sebastián-Gallés (2010) showed that 8-month-old bilinguals can discriminate the difficult /e/ - /ɛ/ contrast when tested in an anticipatory eye movement paradigm rather than in a traditional habituation paradigm. Research is ongoing to understand the origin of

this pattern of results, and possible candidates include the frequency of the different sounds, acoustic similarity, and a role for cognate words.

The evidence reviewed above indicates that at least by the end of the first year of life, bilingual infants can discriminate contrasts within and between their languages. This would allow for the formation of clusters on the basis of language. For example, in the case of a French-English bilingual, French /d/'s are primarily dental, while English ones are alveolar. The discrimination results of Sundara and colleagues (2008) indicate that bilingual infants do not have a single /d/ category but rather have separate clusters that correspond to each language. Similar support is provided by the finding that French-English bilingual infants can make a three-way distinction in terms of a bilabial VOT contrast (Burns et al., 2007). A comparison-contrast mechanism, together with the multidimensional, multi-space organization in PRIMIR, could build on this statistical clustering, allowing further tracking and differentiation of the properties of each of the two native languages.

3.3.2 Word Form space

Infants can extract and learn word forms from the speech stream independently from linking that word form to meaning. The Word Form space in PRIMIR stores exemplars of such word forms. To study infants' recognition of word forms from the ambient language environment, one method is to play infants familiar (e.g. common in the input), and rare words without prefamilarization. Results from these studies suggest that monolingual infants pay more attention to familiar word forms than to rare words matched in phonotactic properties by 11-12

months of age. This finding has been replicated across numerous languages including English (Vihman, Nakai, DePaolis, & Hallé, 2004; Vihman, Thierry, Lum, Keren-Portnoy, & Martin, 2007), French (Halle & Boysson-Bardies, 1994), and Welsh (Vihman et al., 2004). Welsh-English bilinguals of 11 months also attend more to familiar words than to rare words when tested in a similar paradigm, and do so in both of their languages (Vihman et al., 2007). Further, bilinguals' difference in response to familiar versus rare words has been replicated in an electrophysiological paradigm using event related potentials (ERPs) measured on the scalp (Vihman et al., 2007). These convergent results suggests that the Word Form space develops on a similar timeframe in monolingual and bilingual infants.

However, there is some evidence for differences between monolinguals and bilinguals in word form recognition later in the second year of life. In one study, English-Spanish bilinguals of 19-22 months were played known (based on parental report) and unknown words while ERPs were recorded (Conboy & Mills, 2006). Differences in responses to known vs. unknown words occurred earlier in time for words in the dominant language than words in the non-dominant language. The authors interpreted this finding as indicating that non-identical brain systems within the bilingual process the two languages. However, an alternate possibility is that these differences stem from how frequent words from the dominant language versus the non-dominant language are in the input, rather than differences in the system(s) that underlie each language. Under the PRIMIR framework, exemplars of word forms cluster together on the Word Form space. If the dominant language is heard more frequently than the non-dominant language, then there may be more

exemplars for words in this language. Even if parents report that an infant "knows" that word, the representation in the dominant language might be stronger, leading to differences in ERPs that are an artefact of word frequency.

The interpretation of potential processing differences in early bilingual word recognition raises the larger question of how word forms are organized within the Word Form space of bilingual infants. A major debate in the area of bilingualism is whether bilinguals have a single lexical system or two lexical systems. The nature of PRIMIR's multidimensional spaces allows for organization along different dimensions based on characteristics of the input, without the need for separate systems. For example, exemplars of the same word will tend to cluster together. Recently, a self-organizing connectionist model of bilingualism has demonstrated a similar principle (Li & Farkas, 2002). Words from the same language tend to be adjacent to each other in the speech stream more frequently than words from different languages, as an utterance is typically produced in either one language or the other. Consequently, word forms from each language may eventually cluster separately. PRIMIR supports this notion, thus reframing the question of whether bilinguals have one or two lexicons to characterizing how word forms are clustered within their respective languages at any point in development. Clustering by language could allow bilinguals to preferentially access words from one language or the other. PRIMIR thus predicts that bilingual infants should have an emerging ability to distinguish between words in their two languages at the lexical level, because as words are learned, each language forms a distinct cluster within the Word Form space. At the same time, eventual links to meaning may result in

semantically related words from different languages also clustering together. The simultaneous operation of a comparison-contrast mechanism could add enormous power to a statistical clustering algorithm.

3.3.3 Meaningful words: word-object linkages

Surprising findings in a number of studies of word learning have given impetus to the development of the PRIMIR framework. In particular, PRIMIR helps to explain striking failures in minimal pair word learning, first demonstrated in monolingual infants and then replicated in bilinguals. As discussed above, it has been frequently demonstrated that by the end of the first year of life, infant speech perception has narrowed from the broad-based phonetic discrimination apparent in early infancy, to selective and enhanced sensitivity to just those phonetic contrasts used in the native language (for a review see Gervain & Werker, 2008). On the basis of this robust developmental pattern, it was originally predicted that infants would be able to use the perceptually-established categories to drive word learning. Specifically, once they reach an age when word learning is possible, infants should treat any two discriminably different labels as two possible words, and be able to associate them with two different objects.

To test this prediction, the "Switch" task, initially developed by Cohen and colleagues for testing visual categorization in infants (Younger & Cohen, 1986), was adapted to test word-object associative learning (Werker, Cohen, Lloyd, Casasola, & Stager, 1998). In the Switch task, infants are habituated to two word-object pairings (Word A-Object A, Word B-Object B), and then tested on a pairing that maintains the

habituated word-object link (a *Same* trial) in comparison to a pairing that violates the habituated word-object link, such that Word A is paired with Object B (a *Switch* trial). Infants of 14 months can learn to associate two phonetically dissimilar words with two different objects (Byers-Heinlein, Fennell, & Werker, under review; Werker et al., 1998). Surprisingly, however, at this same age monolingual infants fail to associate two phonetically similar words, such as *bih* and *dih* with two different objects (Stager & Werker, 1997). This was unexpected given infants can discriminate the words in a standard phonetic discrimination task (Stager & Werker, 1997), and that, further, they can distinguish an already known word from a phonetically similar mispronunciation (e.g. Swingley & Aslin, 2000). The difficulty learning minimally different words has now been replicated a number of times with monolingual infants, using a variety of different stimuli in a number of different labs using both behavioral (Pater, Stager, & Werker, 2004; Rost & McMurray, 2009; Thiessen, 2007; Werker, Fennell, Corcoran, & Stager, 2002) and event related potential recording tasks (ERPs; Mills et al., 2004). Indeed, infants of 14 months even fail if taught only a single word object pairing (rather than two pairings), and then tested with a Switch trial that involves a change to a phonetically similar word (Stager & Werker, 1997).

Bilinguals also sometimes fail to apply their phonetic sensitivities to word learning. Just like monolingual infants, bilinguals can associate phonetically dissimilar words *lif* and *neem* with two different objects in the Switch task by 14 months (Byers-Heinlein et al., in prep.). However, when minimal pair words are presented with the same two objects, 14-month-old bilinguals fail to learn the

words (Fennell, Byers-Heinlein, & Werker, 2007), while succeeding at a simple discrimination task (Fennell, 2005). Further, bilinguals sometimes fail even at an age at which monolinguals succeed. As described above, monolinguals can associate *bih* and *dih* with two different object successfully at 17 months. But Fennell and colleagues (2007) tested three groups of 17-month-old bilingual infants that failed at the same task: a French-English group, a Chinese-English group, and a group of mixed bilinguals. Success was shown by bilinguals only at 20 months, and in some groups only girls showed above-chance performance.

A set of studies by Mattock and colleagues has shown that bilinguals do not always show a disadvantage for minimal pair word learning relative to monolinguals (Mattock, Polka, Rvachew, & Krehm, 2010). Using the same procedure and objects as Fennell and colleagues (2007), 17-month-old monolinguals and bilinguals were taught the words *bos* and *gos* paired with two distinct objects. Three different types of tokens were used: tokens that were typical of an English pronunciation, tokens that were typical of a French pronunciation, and mixed tokens that were selected to be intermediate between French and English. The results showed that infants succeeded when the tokens matched their language-learning environment: English monolinguals succeeded with English tokens, French monolinguals succeeded with French tokens, and bilinguals succeeded with mixed tokens. However, infants did not succeed with mismatched tokens: French-monolinguals failed both with mixed tokens, and with English-only tokens. Intriguingly, the differences between the tokens were very subtle: monolingual English and monolingual French adults reported that French-pronounced, English-

pronounced tokens, and mixed tokens were equally native-like for their own native language. The results indicate that, at 17 months, success in the Switch task may not generalize across tokens that adults find highly similar. The authors suggested that the variability in the mixed tokens matches the phonetic variability regularly encountered by bilingual infants, leading to their success in this condition, and that difficulty processing non-native variability could have contributed to the French monolingual infants' failure to learn when tokens were mixed or English-pronounced. Results from several monolingual and bilingual studies using the Switch task are shown in Table 1.

Insert Table 1 about here

Across these studies with both monolinguals and bilinguals, infants consistently have difficulty with the conjunction of two abilities: associative word learning and accessing fine phonetic detail. For novice word learners, each of these two tasks likely requires a fair amount of computational resources. Accordingly, the *resource limitation hypothesis* has suggested that infants fail at learning minimal pair words in the Switch task not because they are unable to perceive the phonetic difference, but rather because the resource requirements of word learning make them unable to attend to and/or use the phonetic detail. In other words, at the initial stages of word learning, the task of linking a word to an object is computationally demanding for a young infant, making it challenging to simultaneously pay attention

to both the object and the phonetic detail in the word (Stager & Werker, 1997). Another factor is that infants not only perceive and represent the phonetic detail, but like adults (e.g. Nygaard & Pisoni, 1998) also perceive and represent the indexical detail in words (e.g. Singh, Morgan, & White, 2004; Singh, 2008). Unlike adults who pinpoint phonetic differences as being criterial for contrasting word meaning, novice word learners may pay equal attention to indexical as to phonetic differences in words. For younger infants, successful word learning may only be possible with external cues to help focus attention on the phonetic detail.

The resource limitation hypothesis has also been invoked for bilingual infants (Fennell, Byers-Heinlein, & Werker, 2007). As computationally demanding as minimal pair word learning is for monolinguals, it may be even more so for young bilinguals. Bilinguals simultaneously learn and use two sets of phonetic categories (Fennell, Byers-Heinlein, & Werker, 2007; Werker, Byers-Heinlein, & Fennell, 2009), potentially resulting in a crowded and complicated General Perceptual space. The Word Form space might also be more complex in bilinguals than in monolinguals, as bilinguals must represent words from two languages. Another challenge specific to bilingual infants might be to ascertain the language of the stimuli (Fennell & Byers-Heinlein, 2009; Fennell, Byers-Heinlein, & Werker, 2007). Unlike real life where most words occur in the context of sentences and conversations, the classic version of the Switch task contains no explicit cues as to which language is being uttered. Without explicit cues indicating which of their two languages is being spoken, bilinguals might find it difficult to interpret the fine phonetic detail that is crucial for success in the minimal pair Switch task.

PRIMIR incorporates the resource limitation hypothesis by arguing that dynamic filters, such as task demands and developmental level, affect infants' ability to access the relevant information in any language task, including the Switch task. The rich representational detail is stored in the word forms and is available, but due to task demands and infants' developmental level, infants cannot always access the criterial information. Described within the PRIMIR framework, differences between monolinguals and bilinguals in the minimal pair Switch task stem from two sources: (1) the two groups face different task demands even in outwardly identical tasks (e.g. bilinguals first ascertain which of their languages is being spoken), and (2) the two groups differ in their developmental level vis-à-vis the task language because bilinguals' knowledge and experience is divided between two languages. PRIMIR further argues that until infants have larger vocabularies (a proxy for developmental level), they do yet have the information which could direct attention to relevant, criterial information. Essentially, with difficult task demands, and no summary representations such as phonemes available, young infants do not succeed in the Switch task.

3.3.4 Phoneme space

Consideration has been given above as to why, under many circumstances, infants of 14 months fail to learn phonetically similar words in the Switch task, and how the circumstances can be changed to allow them to succeed. But it is equally important to explain why infants aged 17-months and older to succeed even in the basic Switch minimal pair word learning task. One possibility is that phonemes begin to emerge by 17-18 months, at least in monolingual infants, providing a stable

abstract representation that allows infants to summarize across context-sensitive variation.

There is increasing evidence that sound categories function qualitatively differently in monolinguals by 17-19 months, hinting at the emergence of phonemes. In one recent study, Best and colleagues (Best, Tyler, Gooding, Orlando, & Quann, 2009) showed that at 19-, but not at 15-months, infants can recognize familiar words across variations in accent. Infants were presented with lists of very common (and thus likely familiar) words in toddler expressive vocabularies and/or toddler reading books versus lists of very uncommon words in adult speech. Nineteen-month-old infants growing up in Connecticut showed a robust preference for the common over the uncommon words regardless of whether the words were spoken in American or Jamaican English. However earlier, at 15 months, the infants only showed a preference for the common words spoken by the American English speaker. The recognition of familiar words even in an unfamiliar accent is taken as evidence that phonemes have begun to emerge by 19 months of age. Yet even though they are beginning to emerge, it is unlikely that phonemes are fully developed by this age. Indeed, infants of 19-months sometimes have difficulty identifying words produced in a non-native dialect (Mulak, Best, Tyler, Kitamura, & Bundgaard-Nielsen, 2010a, 2010b, submitted).

As argued above, once phonemes begin to emerge, they should drive information pick-up in the minimal pair Switch task. Evidence that emerging phonemes guide word learning in monolinguals by 18-months was provided in a recent study in which English- and Dutch-learning infants were tested in the Switch

task. Both Dutch and English use vowel color to distinguish meaning, but vowel length is contrastive only in Dutch. When presented with word-object pairings in which the words differed only by vowel length (e.g. *tam* vs *taam*), Dutch-learning infants, but not English-learning infants succeeded, whereas both English- and Dutch-infants succeeded in the identical task when tested on a vowel color difference that is phonemic in both languages (e.g. *tam* vs. *tem*). These studies show that by 18-months, infants not only use native phonological categories to guide word learning, but will ignore discriminable phonetic detail if it is not phonemic (does not contrast meaning) in their native language (Dietrich, Swingley, & Werker, 2007). Thus, by 18-months of life, abstract phonological representations seem well enough established in monolingual infants to direct learning words that are otherwise similar phonetically, directing attention to only those acoustic/phonetic differences that play a role in the formal, contrastive structure of the lexicon.

In PRIMIR, phonemes are understood as summary representations of native language sounds, and their emergence can be tracked by infants' abilities to use sound contrasts in word learning and recognition tasks. Can it be said that phonemes emerge in bilinguals at the same age as they do for monolinguals? Some results have suggested maybe not. Fennell et al.'s (2007) demonstration of a later age of success in the minimal pair Switch task suggests that phonemes may be later to emerge in bilinguals than in monolinguals, perhaps not coalescing before 20 months.

This position is further supported by one study on bilingual infants' perception of word mispronunciations (Ramon-Casas, Swingley, Sebastián-Gallés, &

Bosch, 2009). In mispronunciation tasks, infants are typically presented with side-by-side pictures of two familiar objects, like a car and a baby. On some trials they hear a correctly pronounced word naming one of the objects (e.g. "Look at the *baby*!") while on other trials they hear a mispronounced version (e.g. "Look at the *vaby*!"). In monolingual infants spanning a broad range of ages, from 14-24 months, there is an important effect of mispronunciation, characterized by a shorter duration of looking towards the target and/or a slower latency to respond compared to when the word is correctly pronounced (e.g. Ballem & Plunkett, 2005; Swingley & Aslin, 2000; White & Morgan, 2008).

To examine how bilinguals' detection of mispronunciations compares to that of monolinguals', Spanish-Catalan bilingual, Spanish monolingual, and Catalan monolingual infants were tested on words with a mispronounced vowel (Ramon-Casas et al., 2009). Mispronunciations involved a substitution of /e/ for /ɛ/ or vice-versa, which is a contrast of interest because it is meaningful in Catalan but not in Spanish. As discussed in a previous section, this contrast is discriminable by Catalan monolinguals and by Catalan-Spanish bilinguals by 12 months of age, but not by Spanish monolinguals at this age (Bosch & Sebastián-Gallés, 2003). Monolinguals showed the expected pattern: Catalan-learning infants responded differently to the mispronounced words than to the correctly pronounced version, while Spanish-learning infants did not. Thus, as expected, only infants for whom the contrast was phonemic, and thus a potential signifier of a change in meaning (Catalan-learners) were affected by the mispronunciation. However, bilingual infants showed a more complicated pattern. As a group, bilinguals did not show an effect of the

mispronunciation, behaving like Spanish monolinguals even though the /e/-/ɛ/ distinction is phonemic in one of their languages. However, there was some evidence that the subset of the bilingual group that had the greatest exposure to Catalan did show an effect of the mispronunciation, a pattern which was replicated in an older group of bilingual toddlers. A control study tested 18-month-old monolinguals and bilinguals on a mispronunciation that changed /e/ or /ɛ/ to /i/, a contrast common to both Spanish and Catalan. This time, both groups showed an effect of the mispronunciation, indicating that bilinguals can detect some, although not all, vowel mispronunciations. A possible interpretation of this pattern is that bilinguals, particularly those dominant in Spanish, do not have well-solidified phonemes for /e/ and /ɛ/. Thus, it appears that at least some phonemes in some contexts of bilingual exposure are later to emerge in bilingual infants than in monolinguals.

If phonemes do emerge at different times in monolinguals and bilinguals, then it is all the more important to consider what contributes to their emergence, and how that could explain apparent differences between the two groups. PRIMIR suggests that phonemes begin to emerge when the infant has acquired enough word-object linkages in their everyday lives to pull out their phonetic regularities. Further, as shown by Rost and McMurray (2009), repetition over tokens that have indexical variability may be particularly helpful. Across enough word learning situations, and crucially, with a substantial enough vocabulary, contrasts across different words allow stable phoneme-like categories to develop. Once they begin to emerge, phonemes may not only help infants recognize familiar words across

different accents, but may also help direct attention to the phonetic over the indexical detail in word learning situations. Although it is not yet known whether emerging phonemes are simply statistical summaries of regularities in input speech, or whether their emergence also signals the establishment of a more abstract linguistic representation, once phonemes begin to emerge, the process of language acquisition, word recognition, and language use is qualitatively different.

If the learning of a sufficient number of word-object linkages allows the establishment of phoneme-like units, then we must predict the following: vocabulary size and performance in minimal pair word learning tasks will be positively correlated at the very beginning of word learning. Once word learning is firmly established, it is likely that the majority of children have a sizeable enough vocabulary to have many stable phoneme categories. However, at the younger ages the likelihood of stable categories being in place is tied directly to vocabulary size. Indeed, our research indicates that 14- and 17-month-olds with larger vocabularies show greater success on the minimal pair word learning task at 14- and 17- months of age, while no relationship between performance and vocabulary size is found at 20-months (Werker & Tees, 2005; see also Bernhardt, Kemp, & Werker, 2007). A similar relationship between performance and vocabulary size is also seen in other tasks that tap into infants' developing phonemes. In a study where 15- and 19-month-old infants heard familiar words pronounced in a non-native dialect, their orientation towards a target picture was correlated with vocabulary size (Mulak et al., 2010a, 2010b, submitted).

Differences in the learning situations of bilinguals as compared to monolinguals could explain why some phonemes might emerge at different times between the two groups. PRIMIR posits that phonemes emerge when links are made between word forms and their meanings. Although monolinguals and bilinguals have similar sized vocabularies when words from both languages are pooled (De Houwer, Bornstein, & De Coster, 2006; Pearson, Fernandez, & Oller, 1993), bilinguals tend to have a smaller vocabulary in each language than a monolingual (for a discussion of this point, see Bialystok, 2009). If phonemes emerge separately for the two languages, it may take bilinguals longer than monolinguals to accrue enough word form-concept links for a phoneme to emerge. Thus, PRIMIR predicts that for bilingual infants, the emergence of a phoneme in one particular language will be tied to vocabulary size in that language.

As reviewed above, PRIMIR's prediction of a later emergence of phonemes in bilinguals is supported by findings by both Fennell et al. (2007) and Ramon-Casas et al. (2009) showing a later age of success in bilinguals as compared to monolinguals in two tasks that are thought to tap into phonemic development. However, the findings of Mattock et al. (2010) with regards to minimal pair word learning hint at a more complicated story. As discussed in their paper, it is likely that infants who are growing up in a bilingual environment experience more variability in the input than do infants growing up monolingual. For instance, they often encounter accented speech, as bilingual infants often have one or more parents who are themselves bilingual, and these parents might show unequal proficiency in the two languages. Laboratory studies confirm that at the word form level, the degree of

variability in the input directly influences the amount of variability represented (Singh, 2008). Further, there is some evidence from a language discrimination task than 10-month-old bilinguals are more adept than monolinguals at handling talker variability (Polka, Valji, & Mattock, 2009). This suggests that further theoretical and empirical investigations are warranted to understand the characteristics of the variability in the stimuli, and the extent to which this may or may not coincide the variability encompassed in monolingual and bilingual infants' representations.

Future research is needed to address the many open questions with respect to the emergence of phonemes in bilinguals. Monolinguals' processing of accented speech (e.g. Best et al., 2009) has provided converging evidence as to when phonemes emerge in monolinguals. Investigating how bilinguals cope with unfamiliar accents could also provide a window into their phonemic development. A second area for research that could be investigated is whether the same types of manipulations that facilitate monolinguals' learning of minimal pair words (e.g. increased variability of tokens, sentence context, pre-familiarization with the target object; see Fennell & Byers-Heinlein, 2009, for such an approach) also facilitate minimal pair word learning in bilinguals. Whether such manipulations allow bilinguals to achieve minimal pair word learning at the same age as monolinguals, or whether they instead give bilinguals the same temporal advantage (e.g. bilinguals might succeed 3 months earlier than without the manipulation, but still not at the same age as monolinguals succeed) will begin to answer deep questions about the development of phonemes in bilinguals.

3.4 The influence of early bilingualism on learning mechanisms and cognitive abilities

As reviewed above, bilinguals have very early capacities that could help them to set up discrete representations for each of their two languages. Yet, successful acquisition and use of two languages also requires attention to and activation of the relevant language in a particular situation, while ignoring or inhibiting information from the irrelevant language. At other times, bilinguals must switch rapidly between their two languages, as in the case of code mixing or borrowing. There is some evidence that this constant mental gymnastics leads to early advantages in attention and cognitive control for bilinguals. It is important to review these cognitive differences in order to consider what their implications might be for language acquisition. As one example of differences in cognitive control, preschool-aged bilingual children have been show to have enhanced inhibitory and executive function skills (e.g. Bialystok & Martin, 2004; Carlson & Meltzoff, 2008). A bilingual advantage has also been found for theory of mind tasks using false-belief situations (Goetz, 2003; Kovács & Mehler, 2009ab).

Only recently have procedures been developed to examine whether bilinguals might entertain an even earlier advantage. In one study 12-month-olds were taught two rules: when words of the form ABA (e.g. lo-vu-lo) were heard, a toy appeared on the right side of the screen, and when words of the form AAB (e.g. lo-lo-vu) were heard, a toy appeared on the left side of the screen (Kovács & Mehler, 2009b). Bilingual infants were able to learn both rules, correctly anticipating which side the toy would appear based on the structure of the word. However,

monolinguals were only able to learn a single structure, correctly anticipating the toy only the AAB word was played.

In a study with even younger infants, 7-month-old bilinguals demonstrated better inhibition and cognitive flexibility than same-aged monolinguals (Kovács & Mehler, 2009a). In this study, infants were first taught a single contingency: that a toy would appear on one side of the screen when a particular auditory stimulus was heard. Monolinguals and bilinguals were equally able to learn the contingency. However, midway through the study the contingency changed, whereby the toy began to appear on the other side of the screen contingent on the same auditory stimulus. While bilinguals were able to adapt to this change in contingency, monolinguals perseverated on the originally taught contingency, even after many trials.

The results suggest that, very early on, bilinguals may be able to access adaptive strategies that allow them to process bilingual input, including enhanced attention to different speech structures (Kovács & Mehler, 2009b), and inhibition of non-adaptive responses (Kovács & Mehler, 2009a). The early development of these skills may give bilinguals a boost as they navigate the more complex bilingual environment, and further may allow them to selectively attend to the phonetic repertoires of each of their languages in order to build language-specific representations.

4. Discussion and conclusions

The current paper reasserts basic tenets of PRIMIR, while further refining the

framework in light of new research with monolingual, and especially with bilingual infants. These refinements not only help to account for an array of findings, but also help to advance the PRIMIR framework so that predictions and explanations across a range of language learning situations are possible. We maintain that the same dynamic filters (perceptual biases, task demands, developmental level), representational spaces (General Perceptual, Word Form, Phoneme), and a general statistical learning mechanism are available to and are used by infants across all learning situations.

However, we have refocused our understanding of task demands and developmental level upon consideration of the bilingual learning situation. In particular, while the task may be the same for all infants from an external perspective, different approaches to the same apparent task are likely engendered by factors internal to the infant. That is, bilingual infants need to determine which language is relevant in the context of the specific task at hand. Better inhibitory control and executive functioning in bilingual infants will help with this challenge. Similarly, careful thought must be given to what is meant by developmental level in the context of bilingual development. While some aspects of cognitive development appear to be advanced in bilinguals relative to monolinguals, the more complex nature of the bilingual development may result in the bilingual having insufficient resources in a particular language for some tasks. Specifically, in tasks where vocabulary size is criterial for describing an infants' developmental level, even though bilinguals might know a similar total number of words, they crucially may know fewer words in each individual language than a monolingual knows in the

single native language. This impacts the formation of summary representations and relationships between stored information within and across representational spaces. Thus, we expect to see advanced development in some domains for bilingual infants, but delays relative to monolinguals in other domains. As noted above, while experimental data from bilingual infants have contributed to a more nuanced description of PRIMIR's dynamic filters and learning mechanisms, the contribution to our understanding of phonemes is not as straightforward. Ultimately bilingual infants will need to have distinct phoneme representations in each of their languages. Thus it is essential that future studies be designed to probe for possible summary representations used across both languages as well as for phoneme representations that are specific to each language.

New data from monolingual infants learning non-native contrasts (Yeung & Werker, 2009) suggest that a mechanism akin to acquired distinctiveness is useful in learning phonetic contrasts. This finding, in conjunction with consideration of the challenge of bilingual acquisition, has motivated us to include in PRIMIR a mechanism capable of comparing and contrasting information across an array of representations, which operates in addition to a general statistical learning mechanism. A compare/contrast mechanism can help monolinguals establish and further refine relationships between similar sources of information which in turn helps to separate contrasting information. Bilingual infants will reap the same benefits, and in addition this mechanism can help them to separate the linguistic input so that the appropriate calculation of statistics occurs for each language.

One specific area for further research is to determine whether bilingual infants have an advantage in comparing and contrasting certain types of information. If we are correct, and a comparison-contrast mechanism allows bilingual infants to use, for example, the rhythmical properties of Language A vs. Language B to establish native phonetic categories in each language, then this should be demonstrable empirically. This could be tested either by using the familiar rhythms of the two native languages, or by using an artificial language learning paradigm wherein new rhythms and new phonetic category boundaries are taught. It is reasonable to predict that bilingual infants will perform better than monolinguals, or perhaps succeed at a younger age, in the syllable-object co-occurrence task that facilitates phonetic category formation in monolingual infants (as in Yeung & Werker, 2009). Indeed, one could even hypothesize that bilinguals are able to simultaneously keep track of multiple sets of co-occurrences, and hence, for example, are able to take advantage of two different sets of word-object co-occurrences to pull apart phonetic categories in each of their two languages.

Research into bilingual phonetic, phonological, and lexical development is, as one might say, still in its infancy. Yet, the examination of extant data from bilinguals has brought into focus numerous aspects of the relation between speech perception and word learning. These data have helped inform a further elaboration of PRIMIR, while simultaneously pointing to a number of directions for further research, for example a reconsideration of task demands from the infants' perspective, and the inclusion of a comparison/contrast mechanism that supports learning in all infants. Careful empirical work testing theoretically-motivated predictions and studying

infants from both monolingual and multilingual backgrounds, will help to further refine the PRIMIR framework, and will lead to future insights into the development of speech perception and word learning.

Table 1

		Monolinguals		Bilinguals		
Contrast	**Token type**	**14m**	**17m**	**14m**	**17m**	**20m**
/lif/-/neem/	English	√		√		
/bih/-/dih/	English	X	√	X	X	√
/bos/-/gos/	Mixed		X		√	
/bos/-/gos/	English		√ (English-learners) X (French-learners)			
/bos/-/gos/	French		√ (French-learners)			

Table caption: Monolingual and bilingual infants' performance on the Switch task as reported in Byers-Heinlein et al. (in prep.), Fennell et al. (2007), Mattock et al. (2010). Checkmarks represent success in the task as measured by statistically significant longer looking to the Switch trial than the Same trial, while exes represent no evidence of success.

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