Lexical Processing and Organization in Bilingual First Language Acquisition: Guiding Future Research

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Abstract

A rich body of work in adult bilinguals documents an interconnected lexical network across languages, such that early word retrieval is language independent. This literature has yielded a number of influential models of bilingual semantic memory. However, extant models provide limited predictions about the *emergence* of lexical organization in bilingual first language acquisition (BFLA). Empirical evidence from monolingual infants suggests that lexical networks emerge early in development as children integrate phonological and semantic information. These findings tell us little about the interaction between two languages in the early bilingual memory. To date, an understanding of *when* and *how* languages interact in early bilingual development is lacking. In this literature review, we present research documenting lexical-semantic development across monolingual and bilingual infants. This is followed by a discussion of current models of bilingual language representation and organization and their ability to account for the available empirical evidence. Together, these theoretical and empirical accounts inform and highlight unexplored areas of research and guide future work on early bilingual memory.

Keywords

Bilingualism; Lexical Networks; Semantics; Vocabulary; Language Acquisition

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The period of early language acquisition provides a window into the developing cognitive system. One of the earliest developing components of language is vocabulary comprehension. Central questions in this area are concerned with the network between lexemes (i.e., single lexical units) and their respective meanings. An especially productive

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avenue of research investigates this question in bilinguals, providing insight into language exposure factors that contribute to the organization of meaning in two separate languages. Indeed, bilingualism is an invaluable model for exploring normative language development, as many children around the world are exposed to more than one language. In particular, the period of *early* bilingual first language acquisition informs our understanding of the development of the complex and interconnected linguistic system of the bilingual.

Extant research on the question of bilingual lexical processing has primarily focused on adults. Perhaps most importantly, work on adult bilinguals has generated some of the most influential models of language representation. Currently, however, a gap exists between the infant and adult literatures with regard to both theory and empirical evidence. It has been noted that a developmental perspective is lacking in our current understanding of bilingual lexical processing (e.g. Grainger, Midgley, & Holcomb 2010). A developmental perspective that includes the early preschool period can clarify a number of existing issues in the current bilingual language processing literature. We discuss three primary questions in bilingual language processing that can be informed by a developmental approach.

First, a developmental model answers the questions of *when* and *how*. For example, *when* and *how* do the lexicons of bilinguals begin to separate? Are they ever integrated? Historically, researchers debated language-selective versus language-nonselective semantic activation in bilingual language processing. Although previous findings demonstrate that language-nonselective access takes place in adulthood (e.g. Dijkstra, 2005; Kroll, Bobb & Wodniecka, 2006; Marian & Spivey, 2003) there is insufficient evidence to determine when early parallel processing begins and whether it is universal in bilingual acquisition.

Secondly, a developmental perspective offers insight into the factors that influence language processing. Unlike many of the existing models that describe the late L2 adult learner, the young child does not have a strong pre-existing L1 lexical network onto which it is possible to map a second language. Indeed, in Bilingual First Language Acquisition (BFLA), the networks for the two languages arise in concert and dependencies between languages influence processing in important ways. Relatedly, understanding how the young bilingual solves the problem of language might help us understand why and how early and late L2 learners differ. Indeed, adult bilinguals differ as a function of the age of first second language exposure, such that the brain's gray matter and functional organization is modulated by age of acquisition and second language proficiency (Fabbro, 2001; Perani et al., 1996; Klein, Mok, Chen, & Watkins, 2014; Mechelli et al. 2004; Vaid & Hull, 2002).

Thirdly, a model of bilingualism that extends from infancy through adulthood would allow us to address relations between simultaneous and sequential acquisition and their implications for lexical-semantic structure. Importantly, such a model would of necessity be based on auditory language processing. Models that explain visual word recognition in adulthood are limited in their ability to explain auditory comprehension early in the process of language acquisition. This illustrates the importance of a developmental model of acquisition that takes into account the early origins of lexical-semantic structure in audition and, ultimately, how this becomes realized in reading and writing. The focus of the present review is on the literature on early auditory language processing with the goal of

synthesizing extant research and recommending directions for future research to flesh out the early stages of a comprehensive developmental model.

The goal of the present review is twofold. The first aim is to outline our current understanding of lexical-semantic processing in the early preschool period, before children have begun to read, across monolingual and bilingual first language acquisition. The focus is on auditory comprehension of spoken language rather than production, as comprehension generally precedes production and provides an earlier window into the emerging lexical system. In addition, we focus on lexical-semantic processing as a means of exploring language co-activation in early bilingual development. That is, how and when do children connect words across lexicons based on meaning?

The second aim of this review is to discuss how this literature might inform existing models of bilingual lexical acquisition, and to suggest gaps in our understanding to guide future research. Throughout this review, we evaluate extant bilingual models in light of the available evidence with regard to lexical-semantic processing in monolingual and bilingual children. This review helps to address each of our motivating questions by covering the extant literature on the early, auditory, stages of lexical-semantic processing in BFLA. First, when and how do bilinguals build a lexical-semantic system? Second, what are the lexical-semantic learning mechanisms involved in BFLA and how do these differ from monolingual acquisition? As we discuss, there is a dearth of evidence to fully answer each of these questions. As such, we end with a discussion of gaps in our current understanding of the development of lexical-semantic processing and suggestions for future research.

Literature Search

In order to review lexical-semantic processing in early development, we first began the literature search with a small set of papers that explicitly addressed the issue of early lexical-semantic organization: Mani and Plunkett (2010), Mani, Durrant, and Floccia (2012), Arias-Trejo and Plunkett (2009; 2013), Willits, Wojcik, Seidenberg and Saffran (2013), Wojcik and Saffran (2013), Van Holzen and Mani (2012), and Singh (2013). This guided the choice of selection criteria for a more systematic electronic search. We were particularly interested in evaluating models of bilingual auditory language acquisition. Importantly for the purposes of this search, the models that we review are revisions of previous models within the last 5 years (e.g. the Self-Organizing Model of Bilingual Processing, SOMBIP, was revised in 2010 into DevLex-II; Processing Rich Information from Multidimensional Interactive Representations, PRIMIR, was revised to include bilinguals in 2011). These revisions modeled the behavioral evidence up to 2008 and 2010, respectively. Thus, the aim in the present manuscript was to review research that has emerged since 2008 to evaluate the validity of these models against new findings and to guide future work.

The electronic search included English language, peer-reviewed, empirical manuscripts in PsycNET and PubMed for the period of infancy and toddlerhood. We sought empirical research that assessed lexical processing in spoken language with the following selection criteria: a) assessed auditory language; b) language comprehension rather than production; c) included infants and/or toddlers; d) included monolinguals and/or bilinguals; and e)

studied normative populations. The search included the following keywords: (lexico-semantic OR lexical OR semantic OR networks OR language processing OR comprehension OR bilingual OR monolingual OR priming OR activation OR recognition OR implicit naming OR auditory OR lexicon OR vocabulary) AND ages 0 to 5 years. A total of 56 publications met these criteria.

Lexical-Semantic Development in Early Language Acquisition

There is a dearth of research on language co-activation in bilinguals to parallel that in monolinguals, and even less has been conducted in children prior to school entry. In what follows, we present evidence from two separate lines of research that have investigated how the early lexical-semantic system develops in monolinguals and bilinguals, respectively. We review the earliest stages of development, namely infancy and toddlerhood. Although the present discussion is mainly concerned with lexical-semantic organization, we include some findings on the interaction of phonology and grammar with semantics in language acquisition to highlight what appears to be the early development of a highly interconnected lexical-semantic network. However, it is important to note that, in the interest of characterizing the development of this network, the majority of the research reviewed focuses on word-level learning and organization. We take a chronological approach and begin with the period of early infancy, characterized by word learning in the early stages of building a lexical-semantic system. This is followed by the literature on toddlers, where we find more direct evidence of the existence of a lexical network as early as the second year of life.

Early Word Learning Mechanisms in Monolinguals and Bilinguals

Before children can begin forming lexical networks and thereby connect words based on meaning, they must first acquire the lexical items themselves. Early in infancy, children are tasked with the problem of forming the object representations onto which words are mapped. A rich word learning literature that documents the complex task of linking words onto referents over the first few months of life emerged beginning in the late 1950s (e.g., Bates, Benigni, Bretherton, Camaioni, Volterra, 1979; Brown, 1958; Nelson, 1973; Nelson, 1974; Werner & Kaplan, 1963). Rather than review this impressive literature in its entirety, we focus here on studies that provide a comparison between monolinguals and bilinguals and the word learning mechanisms they employ before age 2 to reveal the putative beginnings of lexical-semantic networks. As we discuss, the literature demonstrates similarities in the mechanisms that support early word learning and differences in relative timing across monolingual and bilingual first language acquisition.

We begin by considering evidence of differential developmental timing of word learning mechanisms. For example, 14- and 19-month-old bilingual children are able to learn syllables that differ only in their pitch contour (rising vs. falling intonation) as distinct labels for objects in a habituation paradigm, even when their native language does not use pitch contour as a cue for meaning. By 22-months, however, they no longer distinguish syllables based on pitch (Graf Estes & Hay, 2015). Monolinguals, in contrast, fail to distinguish syllables based on pitch as early as 17 months when their language does not use pitch as a

cue to meaning (Hay, Graf Estes, Wang, & Saffran, 2015). However, evidence from a preferential looking paradigm suggests that the extended sensitivity for pitch as a cue to meaning applies only to those bilinguals learning a language that uses pitch as a phonemic contrast (Singh, Hui, Chan & Golinkoff, 2014). Specifically, bilinguals and monolinguals learning languages where pitch is non-phonemic showed similar developmental trajectories. These disparate findings across studies may be explained by differences in task demands (e.g. habituation vs. preferential looking). Nevertheless, findings demonstrating a prolonged period of flexibility in bilinguals are consistent with the "resource limitation hypothesis" in phonetics that suggests that bilinguals face more challenges in word learning relative to monolinguals (Costa, & Sebastián-Gallés, 2014; Fennell, Byers-Heinlein & Werker, 2007; Fennell & Werker, 2003; Stager & Werker, 1997; Werker & Fennell, 2004; Werker, Fennell, Corcoran & Stager, 2002). Despite being exposed to greater linguistic breadth than monolinguals, bilinguals may have reduced exposure to the unique characteristics of their languages (since exposure is split across languages) resulting in a protracted trajectory with regard to the application of early word learning mechanisms.

This unique bilingual challenge has implications for the rate and order of word learning. By comparing the vocabularies of bilinguals and monolinguals as early as 6 months of age Bilson, Yoshida, Tran, Woods, and Hills (2015) assessed vocabulary development in bilinguals and monolinguals beginning at 6 months of age and demonstrated that a similar word learning model fit both the monolingual and bilingual data. However, in bilinguals there was an interaction between the first and second language such that word learning was facilitated by knowledge of the translation equivalent in the non-target language. This facilitation effect influenced the order of word learning in bilinguals. In a separate study, Bosch and Ramon-Casas (2014) investigated the nature of translation equivalent facilitation effects. Their findings demonstrated that the extent of facilitation is limited by the phonological similarity of the two languages that the child is learning, such that greater phonological overlap leads to a greater facilitation effect. These findings have implications for lexical-semantic structure across monolingual and bilingual development. When word knowledge in one language facilitates word learning in a second language, this suggests early-developing links across lexicons in the young bilingual that foster word learning within and across languages. Indeed, as we review in the following section, there is evidence from toddlers that there may be significant differences in the lexical-semantic networks of monolingual and bilingual children.

As children enter the period of toddlerhood, they begin to use more sophisticated approaches to word learning, and the interaction between acquired word knowledge and continuing word learning becomes more apparent. Sixteen to 22 month old monolingual children become increasingly skilled in using the presence of a known referent to guide the mapping of novel labels and referents (i.e., disambiguation), and this ability correlates with expressive vocabulary size (Graham, Poulin-Dubois, & Baker, 1998). However, it is not until 30-months of age that this learning strategy results in the retention of word meaning over a short delay (Bion, Borovsky, & Fernald, 2013). Thus, prior word knowledge exerts an effect on subsequent word learning in the second year of life and into the third.

This interaction of lexical knowledge with word learning is also evident in bilingual development. Recent findings suggest that the propensity to use disambiguation in word learning is related to the complexity of lexical-semantic structure. Here, complexity refers to the extent that there exist many-to-one mappings between words and referents, in addition to one-to-one mappings. This is true in bilingualism to the extent that children possess unique words specific to a single referent across their two languages as in the case of translation equivalents (e.g., *dog* and *perro*). Bilinguals who know more translation equivalents are less likely to apply disambiguation in a word learning task than bilinguals who know fewer translation equivalents (Byers-Heinlein & Werker, 2009, 2013). That is, those children that more often map two words onto a single referent across languages are likely to apply a novel label equally to a novel and known referent as opposed to using disambiguation as a strategy.

In contrast to the previous mechanisms discussed, associative learning is one way that monolingual and bilingual child may approach the task of word learning similarly. Although the extent to which associative learning is used in early language acquisition is debated, there is evidence that children can achieve word referent mappings using associative learning strategies prior to significant vocabulary growth. As early as 2 months of age, young monolingual infants map simple syllable sequences to novel objects via associative links. However, this word learning mechanism is relatively weak, as they form these syllable-object pairings only if auditory and visual information are synchronized (Gogate, Prince, & Matatyaho, 2009). By 6 months, monolinguals are able to form word-object pairings for highly frequent words in their environment (Tincoff & Jusczyk, 1999). Word-object association continues to develop, such that by approximately 14 months, infants link referents and objects after only a few minutes of exposure to the arbitrary mapping (Curtin, 2011; MacKenzie, Graham & Curtin, 2011; Schafer & Plunkett, 1998; Werker, Cohen, Lloyd, Casasola, & Stager, 1998). A bit later, between 18 and 24 months of age, toddlers similarly map words to motion events (Friend & Pace, 2011; Katerelos, Poulin-Dubois, Oshima-Takane, 2011).

The question remains, however, whether a similar developmental trajectory characterizes associative word learning in bilinguals. Using the Switch procedure (Werker, Cohen, Lloyd, Casasola, & Stager, 1998), Byers-Heinlein, Fennell, and Werker (2013) compared associative word learning in monolingual and bilingual 12- and 14-month-olds. After habituating to a word-object pair both monolingual and bilingual 14-month-olds (but not 12-month-olds) demonstrated longer looking to the named object during switch trials (when an untrained label was presented) relative to when the trained word was presented. Notably, no differences were observed between bilingual and monolingual children in their ability to detect a change in the word-object pairing.

Although the previous findings provide evidence that bilingual and monolingual children apply associative learning strategies similarly, it remains unclear whether these strategies suffice under conditions of dual language exposure. Specifically, in experimental conditions like those we have reviewed, both monolingual and bilingual toddlers receive similar exposure to a particular word-object pairing. However, as has been suggested previously, bilinguals experience fewer exposures to any single word-object mapping relative to monolinguals because these mappings occur across languages.

Important for the present discussion, differences in the frequency of word-object associations have implications for lexical-semantic processing. Even before the first birthday, at 10-months, young infants draw category boundaries based on whether objects receive consistently distinct labels, or a single label across all objects (Plunkett, Hu, & Cohen, 2008). Vouloumanos and Werker (2009) investigated 18-month-olds' word learning given reliable versus random word-object mappings. Eighteen-month-olds were sensitive to statistical regularities in word-object mappings, even in low-frequency conditions. However, the statistical strength of the word-object associations modulated auditory processing of newly learned words, such that children were faster at shifting their gaze to the referent for strong (or frequent), relative to weak (or infrequent), word-object associations. This is early evidence that the frequency of word-object mappings modulates lexical processing. One prediction that follows from these findings is that bilinguals may be slower to develop strong word-object associations by virtue of more limited exposure in any one language and, consequently, may evince slower lexical processing. However, no study to date has directly compared differences in lexical access across bilingual and monolingual infants as a function of associative frequency. Preliminary evidence, however, suggests that speed of lexical access is equivalent in monolingual and bilingual toddlers at 16 and 22 months of age, such that both groups do not differ in speed of online word processing (Legacy, Zesiger, Friend, & Poulin-Dubois, 2015). These findings suggest that early simultaneous dual language experience might not, in fact, modulate the speed of word processing.

The findings on word learning mechanisms in bilingual and monolingual children highlight two important implications for the present discussion: first, although bilinguals learn words at approximately the same rate as monolinguals (Pearson, Fernandez & Oller, 1993), and can (and do) apply similar word learning heuristics, they often differ from monolinguals in the frequency and timing of their use. Second, these findings on disambiguation provide suggestive evidence of an interconnected system across languages as early as the second year of life for young bilinguals, such that this cross-linguistic network has implications for the application of word learning strategies.

Evidence for Lexical-Semantic Organization

Monolinguals—In addition to learning individual words, bilingual and monolingual children begin organizing their existing vocabularies even before entering the period of significant vocabulary growth. In the previous section, we focused on the organization of single words. In addition to indirect evidence in the word learning literature of a lexical-semantic system developing early in the second year, neural and behavioral methods provide converging direct evidence for early lexical-semantic organization. For example, evidence from magnetoencephalography and structural magnetic resonance imaging suggests that the brain areas recruited for semantic processing between 12 and 18 months of age in the earliest stages of language acquisition continue to develop with age (Travis et al., 2014) and parallel those recruited in adults (Travis et al. 2011).

Behavioral evidence corroborates these findings. Delle Luche, Durrant, Floccia, and Plunkett (2014) presented 18-month-old monolinguals with lists of related (e.g. animals) and unrelated words (e.g. clothes and food) using a head-turn preference procedure. Infants

listened longer to the related versus the unrelated word list suggesting that, indeed, children are sensitive to the semantic relatedness of known words as early as the second year of life. In addition, 24-month-olds prioritize semanticity over visual information (such as color). Specifically, children are faster to orient to semantically-related referents for a target word rather than referents that share the same color (Mani, Johnson, McQueen, & Huettig, 2013).

In an earlier study Mani, Durrant, and Floccia (2012) examined children's sensitivity to both phonological and semantic relatedness between words. In this study, related trials consisted of primes that contained a phonological sub-prime that related semantically to the target image. For example the prime *boat* is phonologically related to *bowl,* which is semantically related to the target, *cup.* At age 2, monolinguals showed increased looking times to targets for phono-semantically related primes relative to the unrelated trials. There are two possible accounts of this finding. First, the phonological prime may recruit looking to a phono-semantically-related target (i.e., boat primes bowl which is related to cup) through subprime semantic *activation* of the target (i.e., bowl primes cup) resulting in an increment in looking time to the target in the related condition relative to the unrelated condition. Alternatively, this increment in looking time could be caused by subprime *inhibition* of semantically unrelated words (i.e., bowl inhibits shirt). In either case, the findings highlight the interaction between phonological and semantic information.

Similarly, there is evidence that grammar influences lexical activation. At age 2, monolinguals encode grammatical gender information for known nouns (Bobb & Mani, 2013). German toddlers were presented with pairs of visual objects that grammatically and semantically congruous, grammatical congruous and semantically incongruous, semantically congruous and grammatically incongruous, or did not match grammatically or semantically. When targets and distractors were semantically and grammatically congruous, children showed fewer overall looks to the target, suggesting impaired activation of the target relative to the distractor. In contrast, children were able to identify the target when it differed from the distractor either semantically or grammatically. In sum, by age 2, monolinguals exhibit lexical networks that interact at phonological, grammatical, and semantic levels to produce co-activation of related known words within their single language system.

In the following section, we review toddlers' lexical activation on the basis of purely semantic cues. In a study examining English monolinguals at 18 and 21 months of age, Arias-Trejo and Plunkett (2009) presented taxonomically *and* associatively related or unrelated word pairs using the Intermodal Preferential Looking (IPL) paradigm. Twenty-one-month-olds, but not 18-month-olds, demonstrated semantic priming between related words. That is, in the IPL, although pure phonological priming is evinced as early as 18 months of age (Mani & Plunkett, 2010), semantic priming emerges later, at 21 months. In a subsequent study, Arias-Trejo and Plunkett (2013) explored the nature of semantic priming effects by comparing priming between two types of semantic relationships in 21- and 24-month-olds: taxonomic *or* associative. This time 24-month-olds, but not 21-month-olds, evinced priming effects. How do we reconcile these seemingly disparate results? In the first study (Arias-Trejo & Plunkett, 2009), 21-month-olds were exposed to word pairs that were *both* associatively and taxonomically related. In the follow-up study, word pairs were *either* associatively *or* taxonomically related. The support of multiple semantic cues in the first

study provided a "priming boost" that allowed the 21-month-olds to detect the semantic relationship between the presented words (Arias-Trejo & Plunkett, 2013, p. 217). A similar pattern of results was reported in an earlier study: 24-month-olds, but not 18-month-olds showed evidence of semantic priming (Styles & Plunkett, 2009). Semantic priming continues to develop in the second year, such that by 24 months children can access word meaning for basic nouns even in the absence of a visual referent (Willits, Wojcik, Seidenberg, & Saffran, 2013).

Toddlers also show rich semantic knowledge for verbs, such that they predict the upcoming subject of a verb based on semantic relatedness. Specifically, by age 2, children will fixate on an edible referent after hearing a semantically related verb, such as "eat," within a sentence (Mani & Huettig, 2012). This ability to predict the upcoming referent was correlated with expressive vocabulary size, such that children with higher expressive vocabularies reliably predicted the upcoming referent. Indeed, semantic knowledge about a verb includes an understanding about the type of objects that can be taken as arguments, and children use this knowledge even when learning a new noun. Nineteen-, but not 15-month olds, can learn a novel noun by using the representations of known verbs (Ferguson, Graf, & Waxman, 2014).

The development of lexical-semantic networks that takes place over the second year of life is also evident in studies using event-related potentials (ERP). In an auditory priming paradigm in which children heard semantically-related and unrelated word pairs, 24-month-olds showed reliable N400 semantic incongruity effects for the unrelated word, whereas only 18-month-olds with high expressive vocabularies showed comparable processing, suggesting a relation between breadth of word knowledge and lexical processing and organization (Rämä, Sirri, & Serres, 2013). Similarly, in a picture-word mismatch paradigm, 20-month-olds showed N400 modulation for basic-level known words given between- and within-category semantic violations (von Koss Torkildsen et al., 2006). This ERP evidence suggests that young monolinguals can detect semantic violations even for objects within the same category and that vocabulary size is related to more mature lexical processing.

Recent evidence suggests that the ability to categorize words extends to newly learned words even for visually similar referents at age 2 (Wojcik & Saffran, 2013). Further, 2-year-olds show stronger word learning for words that form part of a well-known category relative to words that are part of lesser-known categories (Borovsky, Ellis, Evans, & Elman, in press). That is, a child who already knows many words for the animal category is more likely to learn the name of a new animal relative to a word from a category for which the child knows only a few words. These findings demonstrate that monolingual toddlers encode similarity between referents, and that this information guides word learning.

In conclusion, monolingual toddlers evince a lexical network that interacts at phonological, grammatical, and semantic levels. Further, this network modulates subsequent word learning. Lexical-semantic networks also continue to develop over the second year of life, such that by 24 months, monolinguals are sensitive to the taxonomic and associative links between words.

Bilinguals—Bilinguals, on the other hand, face a different type of lexical organization task. Do lexical-semantic connections emerge in bilinguals on the same developmental time course as monolinguals? There is reason to believe that the development of a semantic network might differ as a function of language exposure. Bilinguals must learn to connect words both *within and across* languages. Bilinguals must organize known words, and categorize newly learn words into their existing lexical system. After all, these connections between lexicons are thought to lead to parallel processing in adults. But *when* do bilinguals achieve this? Given that monolingual infants show priming for phonologically and semantically related words, the question remains whether similar relations exist *across* languages for bilinguals.

There is some evidence in the word learning literature in support of an *earlier*-emerging lexical-semantic system in bilinguals relative to monolinguals. In a word learning task, Byers-Heinlein and Werker (2013) found that 17- to 18-month-old bilinguals, in contrast to monolinguals, are more likely to accept a novel name for a previously named object. This propensity varies as a function of the number of translation equivalents known across languages: bilinguals who knew many translation equivalents were more likely to show this effect relative to bilinguals who knew fewer translation equivalents. The authors propose the *lexicon structure hypothesis,* which suggests that bilingual infants with knowledge of many translation equivalents have richer semantic organization relative to monolingual peers, as the relationship between words and concepts across two languages supports a many-to-one mapping structure. That is, bilinguals are more likely to map two separate words onto a single concept than monolinguals, and they are more likely to do so *earlier* in development as well by virtue of their dual language exposure.

Similarly, using the Computerized Comprehension Task (CCT), a touch- based response measure, Poulin-Dubois, Bialystok, Blaye, Polonia and Yott (2012) found that 24 month old bilinguals with knowledge of many translation equivalents show faster lexical access than bilinguals with fewer translation equivalents, suggesting a facilitative priming effect that follows from a many-to-one lexical organization. These findings are in-line with adult research that demonstrates faster picture naming for words with known translation equivalents (Costa & Caramazza, 1999; Gollan, Montoya, Fennema-Notestine, & Morris, 2005).

Extending previous work in monolinguals, Von Holzen and Mani (2012) examined whether bilinguals' second language primed the first language given phonologically related word pairs between 21 and 43 months of age. Remarkably, bilingual toddlers showed facilitated target recognition, even in cases where the phonological prime was mediated by a translation equivalent. For example, children showed facilitated recognition of the dominant German language target "stein" given the non-dominant English language prime of "leg" because of the phonological overlap between the target ("stein") and the L1 translation of the prime, "bein." This finding demonstrates two key points. First, German-English bilinguals activate phonological knowledge from the non-dominant language to the dominant language. Second, like monolinguals, bilinguals exhibit implicit activation of words, in this case for translation equivalents, when processing in their non-dominant language after age 2. These results parallel the findings and theoretical accounts of adult bilingual language

representation, as cross-language phono-semantic co-activation extends, at least in this case, to early toddlerhood.

In a study of 30-month-old Chinese-English bilinguals, Singh (2013) extended these prior studies to include cross-linguistic priming in the context of semantic primes (e.g. 椅子 (chair) and *table*) within and across the dominant and less-dominant language. Within-language semantic priming was observed for the dominant, but not the non-dominant, language. Further, cross-language priming was unidirectional, such that the dominant language primed the non-dominant language, but the opposite was not true. Thus, there is evidence to suggest the existence of language nonselective activation in the context of translation equivalents and semantic primes that is modulated by language dominance early in the third year of life to parallel that in adults. Similarly, Marchman, Fernald and Hurtado (2010) observed differences in speed of spoken word processing based on language dominance, such that 30-month-olds showed faster word recognition in the dominant versus the non-dominant language.

Language dominance effects are also evinced in ERP investigations of 19- to 22-month-old bilingual toddlers. Processing in the non-dominant and the dominant language shows distinct patterns of temporal and spatial neural activation (Conboy & Mills, 2006). These differences in neural processing vary as a function of total conceptual vocabulary size (a measure of the number of lexicalized concepts across languages). Although the dominant and non-dominant language elicit independent and different patterns of neural activity, the combined vocabulary across languages affects processing for both the dominant and non-dominant language, suggesting an independent but connected semantic system across languages early in bilingual development. This suggests that, like monolinguals, bilinguals are able to categorize words within and across languages based on word meaning. Indeed, even in cases in which monolinguals and bilinguals overextend word meanings, they do so within category boundaries (e.g. Holowka, Brosseau-Lapre, & Petitto, 2002; Kay & Anglin, 1982). For example, young children will extend "cow" to "horse" but never to "brush." Even though the representation for cow may be relatively weak, children already have some knowledge about its category membership.

Summary of Empirical Findings in Infants and Toddlers

Taken together, the findings across studies suggest the emergence of lexical-semantic connections early in the second year of life that are more robust by the end of the second year. Further, just like young children show comprehension of words in the absence of a referent as early as 18-months, they can also activate words that are semantically related to a target word without visual referents by 24 months (Willits, Wojcik, Seidenberg, & Saffran, 2013). That is, over the first and into the second year of life, children form semantic representations of words that are decontextualized. At the same time that word representations are becoming stronger, semantic organization is taking place within, such that it is not only evident for known words, but drives referent selection for novel words (e.g. Bion, Borovsky, & Fernald, 2013). That is, the available evidence suggests the existence of a dynamic, multidimensional process, in which individual words and lexical organization take place in tandem and are mutually interactive. For bilinguals, tasked with learning words in

both languages, similar word learning mechanisms are observed but these mechanisms are utilized over developmental periods that contrast with observations from the monolingual literature. Further, bilinguals show evidence of cross-linguistic activation to parallel that in adults as early as the third year of life. That is, toddlers exhibit knowledge of translation equivalents and semantic primes that provide evidence for an interconnected lexical-semantic system across languages (Bialystok, Blaye, Polonia, & Yott, 2012; Byers-Heinlein & Werker, 2013; Poulin-Dubois, Von Holzen & Mani, 2012; Singh, 2013).

Models of Bilingual Language Organization and Processing

We now turn our attention to a review of existing models to discuss their ability to explain the available evidence on early bilingual lexical processing. We argue that the period of early development provides important contributions to these models. Most of the early research in adult bilingualism focuses on visual word recognition or word naming as dependent measures. Several psycholinguistic models of adult bilingual language representation have been proposed. Many of these models are relatively static, and represent adult lexical processing (e.g. the Distributed Feature Model, Van Hell & De Groot, 1998; the Bilingual Interactive Activation Plus, Dijkstra & Van Heuven, 2002; the Revised Hierarchical Model, Kroll & Stewart, 1994). In the interest of space and the scope of the present review, we focus on models of auditory comprehension, rather than visual word recognition, as they are more appropriate to early language acquisition. In addition, we review models that provide a mechanism for language acquisition that can be evaluated based on the available empirical evidence. Namely, we discuss the Self-Organizing Model of Bilingual Processing (SOMBIP), DevLex-II, and the Processing Rich Information from Multidimensional Interactive Representations (PRIMIR) model, and evaluate their ability to account for the data on the development of lexical-semantic knowledge in young infants and toddlers.

SOMBIP

SOMBIP is a computational model that attempts to account for spoken word recognition in bilingual language comprehension (Li & Farkas, 2002). As its name suggests, the model presents two self-organizing maps: a semantic and phonological map (see Figure 1). These self-organizing maps are two-dimensional spaces made up of independent but interconnected units that develop representations based on the patterns derived from a training data set. These representations are distributed across the two-dimensional self-organizing map itself. Self-organizing maps like these are thought to mirror the type of topographic organization found in many sensory and motor areas in the human brain. To train the system, Li and Farkas provided conversational bilingual child input from the CHILDES corpus. English and Cantonese were presented intermittently but importantly, no explicit language tags were presented to the system. Through Hebbian learning, the model was able to categorize words appropriately into each language across the semantic and phonological maps. The representations on the phonological and semantic map were also linked through associative connections. Further, words were categorized into word class, such that nouns, verbs, and prepositions were also accurately classified within each language.

One of the notable strengths of the SOMBIP is its ability to incorporate spoken word corpus data as the training set to mirror the type of auditory input a bilingual child might encounter. In addition, the model uses learning constraints that are thought to exhibit the type of processing that might occur in the human brain. SOMBIP is able to model the way in which a bilingual child might accurately disentangle two separate language representations despite mixed input. However, important for the present discussion, it does not explain how bilinguals ultimately form associations across languages. SOMBIP shows associative links between phonological and semantic represents *within* each language, but does not model links between similar phonological and semantic representations *across* languages. In SOMBIP, both language representations are separate. As we have reviewed, the ability to associate words across languages based on meanings seems to be in place early by the second year of life, such that bilingual children show evidence of phono-semantic and semantic priming across languages (Von Holzen & Mani, 2012; Singh, 2013). In addition, these cross-language associations are modulated by language dominance, such that priming in both adults and 30-month-olds differs based on whether priming occurs from the dominant to the non-dominant language, and vice versa. Thus, although SOMBIP models how a child might arrive at separable language systems, it fails to account for the available evidence that demonstrates early parallel processing in bilingual language acquisition.

DevLex-II

The DevLex-II computational model shows many similarities to SOMBIP, but has the added benefit of incorporating a learning mechanism to explain links across languages, as well as semantic priming differences between early and late learners of a second language (Zhao & Li, 2013). Like SOMBIP, DevLex-II uses self-organizing maps to represent semantic and phonological space. It also incorporates a third map: an output layer to represent articulatory sequences necessary for production (see Figure 2). Also like SOMBIP, through Hebbian learning, DevLex-II is able to connect units across all three maps, effectively linking phonological input to word meaning and then to an articulatory phonological representation. Input to DevLex-II was provided in the form of 500-word list derived from the MacArthur Bates Communicative Development Inventories (MCDI) for English and Chinese, respectively (Fenson et al., 2006). The MCDI is a list of the most frequently used words in each language, and therefore reflects the earliest words in children's vocabularies.

One of the critiques of SOMBIP was its inability to model connections between lexicons. DevLex-II, however, incorporates lateral connections *within* each map to simulate the process of cross-language connections for translation equivalents and semantic primes. DevLex-II also captures reaction time effects elicited in priming studies, such as those measured during lexical decision tasks. To do so, changes in lexical density, or neighborhood effects, are modeled within the semantic map. Specifically, activation of one word causes residual activation to spread across related meanings. A measure of reaction time is therefore derived from this density measure, such that words with higher density exhibit stronger interference and therefore slower target recognition. This interference can also occur within and across languages in the model.

In computer simulations of DevLex-II, Zhao and Li (2010, 2013) demonstrated that the degree of overlap between two languages predicts the ease with which semantic activation occurs between related representations across semantic space. For example, translation equivalents (e.g. *perro* and *dog)* have strong lateral connections due to the large overlap in meaning, whereas semantic primes have indirect connections due to less overlap in meaning (e.g. *perro* and *cat).* This leads to larger priming effects (and faster reaction times) for translation equivalents than for semantic primes consistent with adult findings (Basnight-Brown & Altarriba, 2007; Zhao, Li, Liu, Fang, & Shu, 2011). In addition, previous simulations show that simultaneous bilinguals and early L2 learners demonstrate clear separation between L1 and L2, whereas late L2 learners show representations intermixed with the existing L1 network (Zhao & Li, 2010). The latter organization is also known as "parasitic" organization, because the L2 attaches to the existing L1 (Hernandez, Li, & MacWhinney, 2005; Zhao & Li, 2010).

How well does DevLex-II explain early bilingual first language acquisition? As is, the model provides an account of the language dominance differences observed between sequential and simultaneous bilinguals. That is, it describes how *temporal* variables associated with exposure to L1 and L2 might affect language representation. However, within simultaneous bilinguals, language dominance effects arise despite encountering language simultaneously due to differences in the *amount* of exposure to each language. The available evidence suggests that even for simultaneous bilinguals, language dominance effects emerge due to the differences in time spent hearing each language. For example, Conboy and Mills (2006) demonstrate distinct patterns of temporal and spatial neural activation in the non-dominant and the dominant language of exposure as early as 19 months of age using ERP. In addition, behavioral paradigms have elicited similar findings, such that young toddlers show faster spoken word recognition in their dominant relative to the non-dominant language (Marchman, Fernald, & Hurtado, 2010). Findings also demonstrate that cross-language priming occurs only from the dominant to the non-dominant language for semantic primes in 30-month-old bilinguals (Singh, 2013). As is, it is unclear how DevLex-II might account for such uni-directional priming effects.

Nevertheless, the reaction time simulations from DevLex-II correspond with the some of the available evidence in infants and toddlers. For example, behavioral findings demonstrate priming from the non-dominant to the dominant language for translation equivalents (Von Holzen & Mani, 2012) but not semantic primes (Singh, 2013). Although it is unclear why priming was not achieved for semantic primes, the disparity between translation equivalents and semantic primes in favor of translation equivalents is predicted by DevLex-II and in line with adult findings.

Specifically, DevLex-II predicts *faster* reaction times for words with *few* semantic neighbors. This is in contrast to recent findings documenting *faster* reaction times for children with *higher* proportions of known translation equivalents than those with knowledge of fewer translation equivalents (Poulin-Dubois, Bialystok, Blaye, Polonia & Yott, 2012). Recall that translation equivalents have the highest degree of featural overlap, therefore providing the highest level of interference within DevLex-II. According to Poulin-Dubois et al. (2012) however, the translation equivalent in the non-target language provides

a facilitative, rather than interfering, effect due to the underlying shared conceptual representation.

These disparate findings might be explained by differences in comprehension and production that are important for lexical access. In comprehension, the bilingual is tasked with retrieving meaning from word form, in which case the additional activation of related meanings from neighboring words may be facilitative. In production, one must retrieve a word form given a conceptual representation, in which case neighboring words might activate competing word forms leading to an interference effect. Adult research documents a dissociation between production and comprehension, as there is evidence of *slower* picture naming but not classification for bilinguals (Gollan, Montoya, Fennema-Notestine, & Morris, 2005). Indeed, in a word comprehension task like the one used in Poulin-Dubois et al. (2012), it is possible that knowledge of translation equivalents provides a richer conceptual representation leading to faster reaction times. Since the output layer in DevLex-II models articulatory processes, it is possible that it corresponds with production rather than comprehension.

Nevertheless, a strength of DevLex-II is that it provides a semantic architecture that can readily extend to encompass the sort of weaker semantic representations found in early development. As such, the model might predict a protracted account of semantic connections within and across languages in bilinguals, much like the "resource limitation hypothesis" that has been proposed for phonological acquisition (Costa, & Sebastián-Gallés, 2014; Fennell, Byers-Heinlein & Werker, 2007; Fennell & Werker, 2003; Stager & Werker, 1997; Werker & Fennell, 2004; Werker, Fennell, Corcoran & Stager, 2002).

According to DevLex-II, the emergence of semantic priming is a result of strengthened connections that activate words with overlapping features in semantic space. This gives rise to stronger activation for translation equivalents (in which there is a maximal amount of semantic feature overlap) than for semantic primes (in which there is some semantic feature overlap). That is, as children encounter more exemplars of *dog* and *cat*, they activate an increasing number of overlapping semantic features that leads to semantic priming effects.

The bilingual's experience with the world is split between two languages. Suppose a young bilingual infant encounters the word *chair* for the first time when sitting in a car seat, but hears *silla* for the first time in the presence of a bar stool. In this case, there would be very little, if any, overlap in meaning, as the word *chair* and *silla* would activate relatively separate sets of semantic features. As the child encounters different exemplars of each word across languages, an increasing number of overlapping semantic features would be created, linking *silla* and *chair* at the semantic level. Importantly, although we can assume that the bilingual child encounters the same number of chairs as the monolingual, bilinguals receive half as many exemplars per lexical item. If the emergence of semantic priming is brought about by the strength of semantic representations (as a function of the number of overlapping semantic features as modeled by DevLex-II), it follows that bilinguals might have a more protracted development of semantic connections relative to their monolingual peers, as there are fewer overlapping semantic features for related lexical items. This account predicts slower and later-emerging lexical-semantic priming for monolinguals

relative to bilinguals. Indeed, as we previously reviewed, empirical evidence in line with the "resource limitation hypothesis" suggests a longer period of flexibility in using phonological and pitch cues to guide word learning for bilinguals relative to monolinguals (Costa, & Sebastián-Gallés, 2014; Fennell, Byers-Heinlein & Werker, 2007; Fennell & Werker, 2003; Stager & Werker, 1997; Werker & Fennell, 2004; Werker, Fennell, Corcoran & Stager, 2002).

Currently however, there is no available empirical evidence to evaluate whether this extends to semantic development, such that bilinguals form lexical-semantic connections across languages at a slower rate than their monolingual counterparts. We discuss this as an area of future research in more detail below.

PRIMIR

A recently proposed model of early language acquisition is the Processing Rich Information from Multidimensional Interactive Representations model (PRIMIR; Curtin, Byers-Heinlein, & Werker, 2011). This model focuses on the links between phonology and lexical representations in monolingual and bilingual infants. Although rich in its description of the emergence of phono-lexical organization, the model makes very few claims about the lexical-semantic organization of the developing bilingual. Nevertheless, the predictions PRIMIR makes about lexical organization are worth noting as they follow those from DevLex-II. For example, Curtin, Byers-Heinlein and Werker contend that word forms from a single language are separate from the second language, as the languages form "clusters" in *lexical* space based on statistical learning mechanisms in PRIMIR. That is, because words from one language tend to co-occur with other words in that language, separate language clusters for word forms arise. This clustering and its mechanism are identical to those proposed by DevLex-II and SOMBIP as discussed previously. To the extent that code-switching occurs in bilingual language input, all three models lack a mechanism to account for language differentiation in the case of mixed linguistic input.

In PRIMIR, unlike in SOMBIP and DevLex-II, a second learning mechanism (a comparison-contrast strategy) accounts for the clustering of words with related word meanings across languages. Specifically, as word forms link to semantic representations, words with related meanings within and across languages cluster together. In this respect, PRIMIR is different from DevLex-II and SOMBIP in that it suggests that shared semantics across languages can operate on the organization of word forms, thus resulting in partially overlapping language representation (see Figure 3). In this way, it accounts for the type of cross-language connections demonstrated in the empirical literature.

Another important contribution of the PRIMIR model for the current discussion is its use of domain-general learning mechanisms. There is a rich literature documenting strong statistical learning skills that are in place early in development as we have previously reviewed. Indeed, languages are rich with statistical patterns and regularities that help form sound, syllable, and word categories for the monolingual infant (Saffran, Aslin, & Newport, 1996). For example, bilingual infants can discriminate their native languages from an unfamiliar language (Bosch & Sebastián-Gallés, 1997). Critically, Spanish-Catalan bilinguals can discriminate *within* their native languages as well, as early as 4 months of age

even when both languages are rhythmically similar (Bosch & Sebastián-Gallés, 2001). Newborns with prenatal bilingual exposure also show the ability to discriminate between two rhythmically distinct languages soon after birth (Byers-Heinlein, Burns, & Werker, 2010). Young infants and toddlers are able to track statistical regularities in word-object mappings and are able to draw category boundaries based on whether objects receive consistently distinct labels, or a single label across all objects (Plunkett, Hu, & Cohen, 2008; Vouloumanos & Werker, 2009).

Together, this research demonstrates that infants, even soon after birth, are able to make use of statistical patterns to aid in forming language categories. Indeed, PRIMIR suggests that this domain-general mechanism plays a role at all levels of language, allowing the young bilingual to disentangle complex input into overlapping but separable systems at the phonological, syntactic, semantic, and lexical levels. In this way, PRIMIR offers the most ecologically valid model on how children categorize language representations. It offers the most testable hypotheses about the development of a lexical-semantic system based on well-established statistical learning strategies. However, as it stands, PRIMIR makes few hypotheses that extend to semantic development, likely due to the dearth of empirical evidence for semantic, relative to phonological, bilingual acquisition.

Unanswered Questions and Directions for Future Research

As we have reviewed, the few available models of language acquisition largely map onto the available empirical evidence. Nevertheless, there are currently gaps in our understanding of the development of the early lexical-semantic system in bilinguals across the empirical and modeling literatures.

To begin, behavioral and electrophysiological evidence to delineate the time course of lexical-semantic connections within and across languages is currently lacking. For example, research in the monolingual literature indicates a very clear emerging pattern of lexical-semantic priming that begins in the early second year of life (Arias-Trejo & Plunkett, 2009, 2013). Although current findings suggest cross-language activation at 30 months of age in bilinguals (Singh, 2013; Von Holzen & Mani, 2012), it is currently unknown whether bilingual infants follow the same developmental time course exhibited in monolingual acquisition.

In addition, few studies provide a direct comparison between monolingual and bilingual infants and toddlers. Research comparing these two populations could be fruitful for understanding the implications of language co-activation for bilinguals. For example, adult research indicates *slower* lexical access for bilinguals relative to monolinguals (Ivanova & Costa, 2008). The interpretation is that bilinguals exhibit inhibition from the activation of the second language. There is some evidence that these findings may not extend to early language acquisition. Specifically, speed of online word processing did not differ at 16 and 22 months of age between monolingual and bilingual toddlers (Legacy et al., 2015). This suggests that dual language experience does not modulate word comprehension in the second year of life. Additional empirical studies and theoretical models linking the findings in toddlers to adulthood, however, are lacking.

Similarly, a model of bilingualism that extends from infancy through adulthood is needed. However, drawing parallels between the infant and adult literatures requires considering differences in task demands. Currently, research on priming in early infancy relies heavily on well-established looking-time and electrophysiological measures. Conversely, adult methods often employ lexical decision tasks or rapid naming, for example. To provide a complete account on the development of lexical access from infancy to adulthood, it is important for future research to draw clear connections between these two bodies of literature. Typically, adult methods require a volitional response in the form word production or haptic responses (i.e., button presses). Recent work in the infant literature provides support for the utility of haptic response measures within the second year of life prior to significant growth in vocabulary production (Friend & Keplinger, 2003; Friend & Keplinger, 2008; Friend, Schmidt, & Simpson, 2012; Friend & Zesiger, 2011; Hendrickson, Mitsven, Poulin-Dubois, Zesiger, & Friend, 2015; Poulin-Dubois et al., 2012). Hendrickson et al. suggest that a comparison of gaze and haptic responses in children as young as 18 months of age can provide a window into partial lexical knowledge states. Thus, a possible avenue for future research is to investigate what passive measures (such as gaze) and volitional responses (such as haptic responses) reveal about the development of lexical networks in adult and child bilinguals, and how the strength of early word representations relates to lexical-semantic organization.

Future work should also aim to disentangle the factors that affect the emergence and strength of lexical networks. As in adults, one factor that might relate to the emergence of lexical networks is language proficiency, which can be operationalized as vocabulary size in young infants and toddlers. It has been speculated that a possible dynamic relation exists between word knowledge and lexical organization. For example, the more words a child knows, the more likely it is that the child will be able to organize and categorize the words along relevant dimensions. A recent extension of TRACE, a computational model of speech perception (McClelland & Elman, 1986), to early word recognition suggests that phonological word recognition is influenced by lexical breadth and depth (e.g. vocabulary size and content; Mayor & Plunkett, 2013) and it is able to account for a number of behavioral findings using IPL tasks. An implementation of TRACE into the semantic domain would be an appropriate extension of the extant literature. Currently, however, a model or empirical evidence to extend this to semantic development is lacking. It may be the case that as more words enter the lexicon, semantic similarities and differences among words become more apparent, fostering connections and category formation within the lexicon. Indeed, children learn words faster if they have knowledge of many words of the same category (e.g. Borovsky et al., in press). However, mixed findings have been reported with respect to the relation between vocabulary size and lexical-semantic co-activation in the monolingual and bilingual literature (e.g. Arias-Trejo & Plunkett, 2009; Conboy & Mills, 2006; Friedrich & Friederici, 2004; Marchman, Fernald, & Hurtado, 2010; Singh, 2013; Willits, Wojcik, Seidenberg, & Saffran, 2013). Consequently, is not well understood how lexical breadth relates to lexical organization for bilingual and monolingual acquisition alike.

One possible reason for the mixed findings across studies has to do with the measures employed to inventory word knowledge. Developmental researchers most often rely on

parent reports of vocabulary knowledge, which does not correlate consistently with direct visual reaction time measures of lexical access (e.g. speed of word processing; Fernald, Perfors, & Marchman, 2006; cf. Marchman, et al., 2010). In a study examining speed of word processing in children between 15 and 25 months of age, Fernald et al. (2006) reported comparable processing speeds across words reported as known or unknown by parents. This suggests that online measures may index emerging word knowledge that is not captured by parent reports. Thus, the mixed findings on the question of vocabulary size and lexical organization might be explained by the variability associated with comparing direct (child behavior) and indirect (parent report) measures of lexical breadth and processing. To clarify these findings, future work must attend to the issue of method variance and take care to use comparable measures of word knowledge and lexical processing.

Future work on theoretical and computational models should also include explicit study of the stages of development. Currently missing in existing models is an account of what lexical-semantic structure looks like in cases of weak representations and sparse neural architecture, as is the case of early infancy and toddlerhood. A fruitful extension of the computational models we have reviewed would be to provide insight into the architecture of lexical-semantic representation *before* learning is completed. That is, what type of organization is observed early in learning? In addition to modeling differences between sequential and simultaneous bilinguals, computational models can vary the amount of words presented in each language to mirror the type of language exposure differences within early simultaneous bilinguals.

Conclusion

As we have reviewed, empirical evidence across monolingual and bilingual language acquisition suggests the emergence of a lexical-semantic system within the second year of life. Further, for bilinguals, there is evidence of cross-linguistic processing to parallel that found in adults, suggesting the existence of language non-selective access at the earliest stages of bilingual first language acquisition. Available models of acquisition provide a number of predictions that remain to be tested and highlight additional areas of research, but continue to be limited in their ability to link early infancy and adulthood. Finally, understanding language co-activation and its emergence will help illuminate early differences across monolingual and bilingual acquisition. An integrative goal for future research is to work toward a truly developmental model of lexical-semantic structure that extends from early acquisition through adulthood.
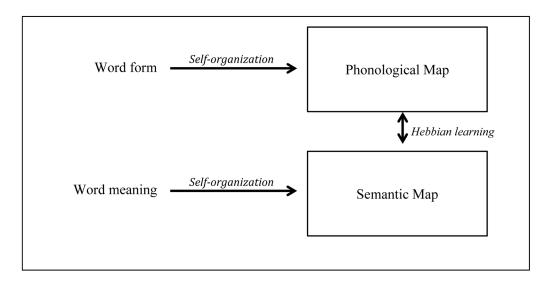
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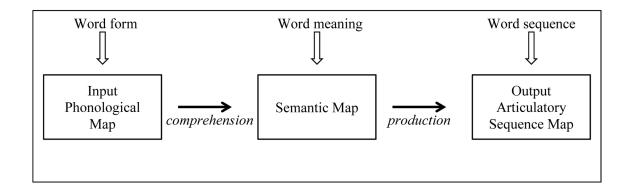
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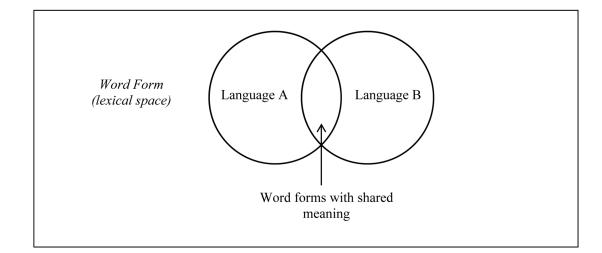
Figure 1.
A graphical representation of SOMBIP adapted from Li and Farkas (2013). The two self-organizing maps form associative connections through Hebbian learning.

Figure 2.
DevLex-II uses three self-organizing map to model auditory word comprehension and speech production that form associative connections within and across languages. Figure adapted from Zhao and Li (2010).

Figure 3.
According to PRIMIR, words from separate languages tend to co-occur, giving rise to relatively separate language clusters in lexical space. At the same time, semantics can operate on language organization, as words with shared meanings across languages may also cluster together, resulting in some overlap in word form.