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Semantic Network Structure in Bilingual and Monolingual First Language Acquisition

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Abstract

Infants learning words in a bilingual language environment face a number of difficulties that may alter the number and kinds of words learned early in life. The research described here investigates several aspects of word learning that may differ between bilinguals and monolinguals. Using a dataset of 353 infants between the ages of 6 months and 7 years old, approximately half of which are bilingual, we examined three aspects of early word learning: 1) the rate of word learning, 2) the comparative structure of the English semantic network for monolingual and bilingual language learners and 3) how word acquisition in one language is affected by the other in bilingual children. Our results suggest that bilingual language learning follows the same pattern of acquisition as monolingual language learning in almost every respect but one. Though a model of language acquisition for monolingual children is a good predictor of bilingual acquisition, simulations based on this model under-predicts bilingual translational equivalents for many bilingual children. This suggests that learning a word in one language may facilitate its acquisition in a second language.

Keywords: Networks; Bilingual; Language Acquisition

Introduction

Children around the world commonly learn more than one language at birth. Unfortunately, we have a limited understanding of how bilingual first language acquisition (BF) and monolingual first language acquisition differ because the dominant share of research on early language acquisition has focused on monolinguals. Though various theoretical positions have suggested that bilingual first language acquisition is akin to learning two languages independently or to learning a single undifferentiated language (Genesee, 2009), investigations of the statistical structure of learned words as well as the application of formal models of word learning have yet to be applied. Here, we investigate the statistical structure of word semantics in the early lexicon of 353 monolingual and bilingual children and ask to what extent the order of word acquisition among these two populations fits a recently developed model of early word learning. Thus, we aim to answer the following question: Do the associative relations between words in English first language acquisition differ if children simultaneously learn a second language?

Numerous comparative studies between bilingual and monolingual first language learners have pointed to both similarities and differences in the way these two populations learn language. With respect to vocabulary size, bilinguals and monolinguals appear to learn new concepts at approximately the same rate (Hoff et al., 2012; De Houwer, Bornstein, & Putnick, 2013) and they also show similar capacities for mapping words to objects in the learning environment (Byers-Heinlein & Werker, 2013; Werker, Byers-Heinlein, & Fennell, 2009). However, bilinguals and monolinguals differ in the way they perceive words (Ramon-Casas, Swingley, Sebastián-Gallés, & Bosch, 2009; Byers-Heinlein & Werker, 2013) and in their usage of mutual exclusivity to disambiguate word referents (Byers-Heinlein & Werker, 2009; Houston-Price, Caloghris, & Raviglione, 2010). In particular, bilingual infants tend to show either less reliance on mutual exclusivity or slower development of its use during early word learning. Furthermore, these differences in the language environment appear to induce more general cognitive differences (Kovács & Mehler, 2009), which may persist across the lifespan (Bialystok, Craik, Klein, & Viswanathan, 2004).

The above findings suggest that though concept learning rates may be similar among bilinguals and monolinguals, the patterns of word acquisition may be unique, with the simultaneous learning of two languages influencing the relative order in which words across languages are learned. There are several specific reasons why this may be true. Firstly, via the mutual exclusivity principle (Markman & Wachtel, 1988) (see also the principle of contrast (Clark, 2009)), whereby words acquire their meaning via their relationship with other words in the language environment (Hills, 2012; Mather & Plunkett, 2010). However, bilingual children appear to relax this principle in order to acquire multiple words for the same object (Byers-Heinlein & Werker, 2009) and this may make learning new, semantically different words more difficult when a few words are already known. Secondly, two sets of labels for objects in the world provides the infant with a plausible alternative to learning two names—since producing one name is potentially sufficient to communicate the object of reference.

Indeed, bilingual infants code-mix, producing words from a non-target language when they do not know the appropriate word in the target language (Genesee, Nicoladis, & Paradis, 1995; Deuchar & Quay, 1999) and this may inhibit the learning of translational equivalents. Thirdly, since only one language can be spoken at a time, early language learning may be situation specific (we take a bath in English and eat breakfast in Spanish), and thus limit the infants ability to learn one languages referents across situations. Finally, though we do not yet understand the causal pathway, late talkers show a different pattern of word learning than typical talkers, one that is marked not only by slower acquisition but also by different semantic relationships between words (Beckage, Smith, & Hills, 2011). Within a language, bilinguals show a similar slower acquisition rate and this may similarly be related to preferences for learning certain words over others.

In the current article we use network analyses to understand how the semantic knowledge of two languages may influence the order of early word learning. Network analyses have been used successfully to understand semantic relationships in monolingual language acquisition (Hills, 2012; Beckage et al., 2011) as well as within languages more generally (Serrano, Flammini, & Menczer, 2009; Arbesman, Strogatz, & Vitevitch, 2010). A network can be constructed from language by allowing words to be nodes and connections between words (i.e., edges) to be based on specific relationship between words (e.g., features (Hills, Maouene, Maouene, Sheya, & Smith, 2009a), co-occurrences in text (Hills, Maouene, Riordan, & Smith, 2010), phonological neighbors (Vitevitch, 2008) or free association norms (Steyvers & Tenenbaum, 2005)). These relationships allow one to formally describe a statistical relationship between words and to use these as predictors for when and how words will be added into a child's lexicon. As an example, (Hills et al., 2010), showed the statistical structure of child-directed speech could predict how children's early semantic networks grew over a period of approximately 10 months between 15 and 25 months of age. Moreover, the formal description of this model (called preferential acquisition) was a better predictor of word learning than a model based on the structure of known words (the more commonly known preferential attachment).

How might such an approach be applied to bilingual first language acquisition? If learning one lexicon influences the capacity to learn a second lexicon, then three potential outcomes are possible. Learning the first lexicon may facilitate the learning of the second; for example, having the concept dog in English facilitates the acquisition of the word perro in Spanish. Here semantic words facilitate the learning of related words across languages. The second possibility is that learning one lexicon inhibits the learning of a second lexicon. This is possible if a child uses mutual exclusivity across languages and thus fails to map perro onto dog after learning the word dog. This failure to map should have noticeable repercussions, because it allows semantically similar words

in Spanish to be learned (via mutual exclusion), but inhibits semantically similar words in English. The result is that the languages should show language specific semantic clustering if there is inhibition. Recent evidence indicates that children as young as 18 months show semantic priming, indicating that children's earliest lexicons could show a semantic influence between words (Arias-Trejo & Plunkett, 2013; Willits, Wojcik, Seidenberg, & Saffran, 2013). The final possibility is that no such influence between languages exists, or that the first and second possibilities cancel in such a way that there is no discernible effect.

If either of the two former cases is an appropriate description of the processes underlying bilingual language acquisition, then the semantic network structure of bilingual infants earliest words should differ from those in the monolingual population. In particular, if the two languages influence one another, then the properties of translational equivalents should differ between bilinguals and corresponding translational equivalents (that is concepts that are in the productive vocabulary of both languages) taken from random pairings of appropriate control lexicons. Second, because English is a language common to all of our participants, we can compare the associative structure of the English network among monolinguals and bilinguals to ask if these networks show greater or lesser semantic similarity—indicating an influence of exposure to two languages.

Method

The words that a child can produce by a specific age were taken from the MacArthur-Bates Communicative Development Inventory (MCDI) (Dale & Fenson, 1996). The data consists of 606 children across 10 separate spoken languages, with 888 recorded entries (since some children were recorded more than once at different ages). Of these entries, 486 were monolingual children (that is children whose parents speak the same language), 331 were bilingual children (that is children whose parents speak different languages), and the rest were trilingual children or not recorded. After removing incomplete data, we were left with 467 monolingual entries (of which 205 are English speakers) and 246 bilingual entries (of which 148 have English as one of their languages). Parents were provided with a checklist of words (two separate checklists in the case of bilinguals) and asked how many of those words the child produces. The vocabulary checklists correlate positively and significantly with laboratory observations of vocabulary and have been shown to reflect bilingual language acquisition (Marchman, 2002). The English checklist included 429 words sub-categorized into nouns, verbs, adjectives etc. Also of importance for this work are the 240 words whose concept translation appears in all 10 separate language checklists. These words provide the nodes in our child semantic networks. The edges are provided by a measure of semantic connectivity, namely the University of South Florida Free Association Norms (FAN) (Nelson, McEvoy, & Schreiber, 2004).

The free associations were collected by saying a word (the cue) and asking an adult to provide a word in response (the target). From this process, one can establish cue-target pairs. For example, if the cue is ‘dog’, a participant might respond with ‘cat’ (the target). This constructs the associative pair dog-cat. The FAN (Nelson et al., 2004) consists of 5044 word cues. The FAN is used to construct an adjacency matrix F_{ij} such that

$$F_{ij} = \begin{cases} 1 & \text{Word } j \text{ is the target of word } i \\ 0 & \text{Otherwise.} \end{cases}$$

Throughout the rest of this work we define the associative indegree of word i , as $k_i = \sum_{j=1}^n F_{ji}$, and the average degree as $\langle k \rangle = \sum_{i=1}^n k_i/n$.

Results

Do bilinguals and monolinguals learn concepts at different rates?

Much previous work has established that bilinguals learn words in one language more slowly than monolinguals learning words in that language. This presents difficulties for early detection of language impairment in bilinguals, whose may be over or under-diagnosed with language impairment based on factors unrelated to their abilities. Thus, before we analyze the network structure of the monolingual/bilingual children, we first consider the growth of their respective lexicons over time. To model the acquisition of unique words or concepts, $x(t)$, produced by a monolingual or bilingual child by month t , we make use of a simple statistical model of language acquisition which treats all words equally—i.e., the binomial distribution. Let x be the number of words or concepts a child knows, integer valued in the range $[0, N]$. Children started to produce words in our data at $t = 6$ months. Thus we assume $x(6) = 0$ and $\frac{dx}{dt}|_{t=6} = 0$. We also note that there is an upper bound $x \leq N$ due to the checklist being a subset of the actual number of words/concepts produced by the child. Thus our model should show asymptotic behavior $\lim_{t \rightarrow \infty} x(t) = N$. We consider a one parameter binomial distribution showing such behavior, $x|t \sim B(q(t, \alpha), N)$, where

$$q(t, \alpha) = 1 - \exp(-\alpha(t - 6)^2), \quad \alpha > 0 \quad (1)$$

We can construct the likelihood function $\mathcal{L}(\alpha) = p(x|t, \alpha)$ given data $(x, t) = \{(x_i, t_i)\}_{i=1}^n$ as follows:

$$\mathcal{L}(\alpha) = \prod_{i=1}^n \binom{N}{x_i} q(t_i, \alpha)^{x_i} (1 - q(t_i, \alpha))^{N-x_i} \quad (2)$$

By the usual technique of maximising the log-likelihood for both the monolingual and bilingual datasets, we can find the maximum likelihood estimators (MLEs) $\hat{\alpha}_M$ and $\hat{\alpha}_B$. The resulting best fits and MLEs are given in figure 1. It is clear that monolingual English children learn words at a faster rate, R , with maximum $R_M^{max} = 14.6 \pm 0.2$ words/month than bilingual children ($R_B^{max} = 10.3 \pm 0.2$ words/month). However, when considering the growth in the number of *concepts* from either

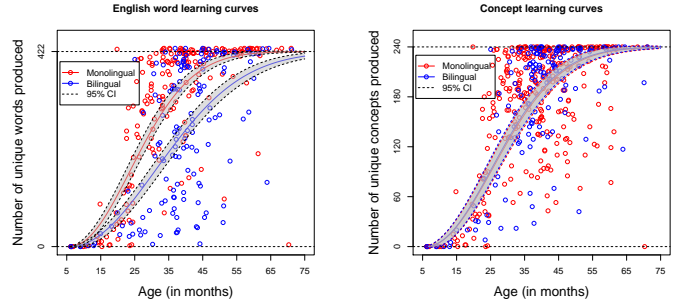


Figure 1: Left: $\hat{\alpha}_M = (1.58 \pm 0.04) \times 10^{-3}$ and $\hat{\alpha}_B = (7.88 \pm 0.38) \times 10^{-4}$. Right: $\hat{\alpha}_M = (1.29 \pm 0.03) \times 10^{-3}$ and $\hat{\alpha}_B = (1.33 \pm 0.04) \times 10^{-3}$

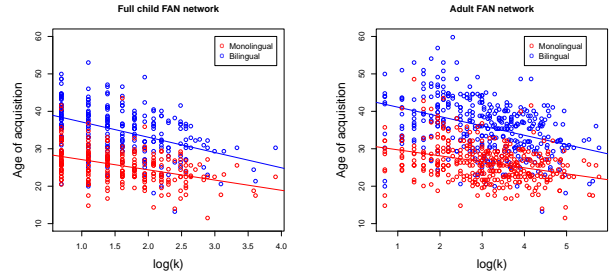


Figure 2: The AoA for monolinguals and bilinguals in relation to indegree.

language, there is little difference between the monolingual and bilingual learning curves where $R_M^{max} = 7.40 \pm 0.08$ and $R_B^{max} = 7.51 \pm 0.12$ words/month. This is consistent with the idea that even though the frequency of words in the learning environment is different, the frequency in the number of *concepts* is similar.

Properties of earliest learned English words

In previous work we found that age of acquisition was correlated with associative indegree (Hills, Maouene, Maouene, Sheya, & Smith, 2009b). If bilingual children show the same pattern of learning, then their earliest learned words should also show a bias for higher associative indegree. Figure 2 shows two measures of indegree in relation to age of acquisition (AoA) of English words for both monolingual and bilingual children. The age of acquisition is defined via logistic regression as the age at which 50% of children know the word. For the indegree we consider two network sizes of the final size child FAN network (395 words) and the full adult FAN network (5044 words). From simple regression analysis, we see in both cases that monolinguals and bilinguals show a negative correlation between AoA and k : (Monolinguals: $\beta = -0.347$ & -0.037 , $p < 0.001$) (Bilinguals: $\beta = -0.510$ & -0.0567 , $p < 0.001$).

Modeling growth of semantic networks

It is clear from Figure 2 that words are acquired in relation to their indegree, with larger indegree nodes being acquired earlier in the growth of the network. This is suggestive of learning orders of words based on the value of their indegree. Previous work has investigated several learning rules associated with the growth of semantic networks (Hills et al., 2009b). In this section, we examine two versions of these learning rules: preferential acquisition and preferential attachment.

We consider two¹ simplistic one-parameter models which show such behavior. Both models select a unique word (node i) from the subset \mathbb{W} of the English MCDI word list that is present in the FAN data (395 words in total). It is then added to the existing network according to a probability distribution $P(i)$ dependent on the indegree K_i^{in} of that word (or a combination of the indegrees k_j in the child network given that word i was added). Here we define the in-degree K_i^{in} to be the number of unique cue words for which that word is a target in the entire adult FAN dataset of 5044 words. A realisation of these models is constructed as follows: A word $i \in \mathbb{W}$ is sampled without replacement, and added to the child network according to the following discrete probability distributions

$$P(i) = \begin{cases} \frac{(K_i + 1)^\beta}{\sum_{i \in \mathbb{W}} (K_i + 1)^\beta} & : \text{Acquisition} \\ \frac{\prod_{j|i} (k_j + 1)^\beta}{\sum_{i \in \mathbb{W}} \prod_{j|i} (k_j + 1)^\beta} & : \text{Attachment} \end{cases} \quad (3)$$

with $\beta > 0$ in both cases. The next word is then sampled via equation (3) from the remaining word list. This process is repeated until no words remain. For every $N \in \{1, 2, \dots, N_{max}\}$, a network was formed using the words selected by equation 3 and with the FAN edge structure. This gives one realisation of our network growth model. We then averaged over 500 realisations, calculating the mean growth curves $\langle k \rangle(N, \beta)$. Our best-fit value $\hat{\beta}$ was then calculated for each model by minimising the MSE (mean squared error) between our model and the dataset $\{\langle k \rangle_j, N_j\}_{j=1}^n$, i.e.

$$\hat{\beta} = \arg \min_{\beta} \frac{1}{n} \sum_{j=1}^n (\langle k \rangle(N_j, \beta) - \langle k \rangle_j)^2 \quad (4)$$

The results are given in Table 1. We see that preferential acquisition performs considerably better, and the similarity in $\hat{\beta}$ suggests this.

However, to see if there is any bias in word acquisition, we also include a simulation of random word learning that samples from a uniform distribution of the word list in the same way as described above. Plots of $\langle k \rangle$ along with $\pm 2\sigma$ prediction intervals are included in figure 3 for each N , where σ is the standard deviation from 500 realisations. The plots show a clear difference between random word learning and the data for monolinguals and bilinguals, and favors models

¹Other models of preferential attachment and acquisition were considered, with similar results.

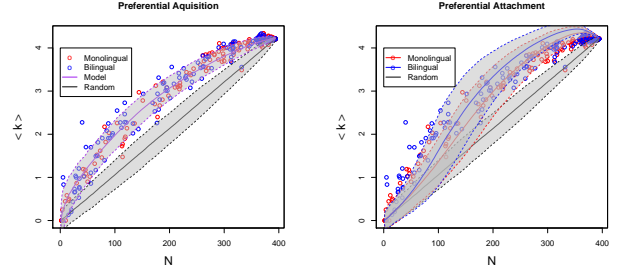


Figure 3: Best-fit models of network growth using preferential acquisition, preferential attachment and random learning.

Table 1: Comparing models

	Acquisition	Attachment
MSE-Monolingual	0.0209	0.0644
MSE-Bilingual	0.0585	0.1754
$\hat{\beta}$ -Monolingual	0.018 ± 0.001	0.30 ± 0.01
$\hat{\beta}$ -Bilingual	0.018 ± 0.001	0.46 ± 0.01

which show preferential acquisition of words with high indegree.

These results from our dataset suggest that the general order in which monolinguals and bilinguals learn English words is very similar, driven by the contextual diversity of the English learning environment, with little influence from the alternate language on word acquisition. However, this tells us little about how the learning of a word in one language influences the learning of its translational equivalent, or its influence on clustering. The next sections address such questions.

Is semantic network structure altered by bilingual first language acquisition?

Figure 4 presents a typical English language network with edges defined by the free association norms. There are numerous network metrics for analysis of network structure. Here we chose four measures often associated with network analysis and indicative of general connectivity. These are the number of nodes (words), the clustering coefficient, the diameter of the network, and the density of the network. These network measures allow us to evaluate how the semantic structure of learned words changes as a result of learning two languages. Table 2 presents the results of this analysis. The results show that, after controlling for the number of words in the network (which is larger for monolinguals), bilingual children have similar clustering coefficients and similar density, but possibly smaller diameter networks. This supports the hypothesis that bilinguals are largely learning similar sets of words as monolinguals, though subtle differences may exist.

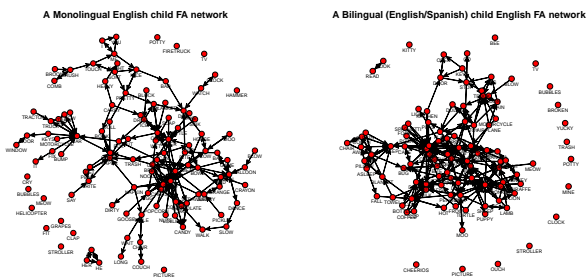


Figure 4: Representative English networks for a monolingual and Spanish-English bilingual

Table 2: Statistical properties of English networks from monolingual and bilingual children. N = number of words, C = clustering coefficient, D = diameter, ρ = density. p = results of significance test after partialling out effect of the number of words.

	Monolinguals	Bilinguals	p =
N	290.1 ± 125.5	232.6 ± 133.1	$< .001$
C	0.179 ± 0.003	0.182 ± 0.005	.47
D	11.96 ± 3.59	11.64 ± 3.90	.05
ρ	0.014 ± 0.008	0.019 ± 0.024	.23

Associative properties of translational equivalents

Translational equivalents represent words that children can produce in both languages. If the two languages are learned as if the speaker were simply two monolinguals, then the earliest translational equivalents should have features that are consistent with those words that are learned earliest among monolinguals. Indeed, the properties of translational equivalents should be predictable from examining duplicate word learning among randomly chosen pairs of control (monolingual) learners. If translational equivalents follow a similar process of acquisition as to words for monolinguals, then these words should be words that have high associative indegree. To investigate this, we examined the translational equivalents in the bilingual lexicons for their associative indegree, and compared these with the remaining English words that were not translational equivalents. As shown in Figure 5, bilingual children’s translational equivalents have a much higher associative indegree than those words which are not known in both languages ($t(311.68) = -19.53, p < 0.001$).

Though the above evidence suggests that translational equivalents may be acquired with similar precedence for both languages in a bilingual lexicon, it does not provide a basis for determining whether or not one language is influencing the acquisition of another. As noted in the introduction, we may see semantic facilitation or inhibition. The network measures above suggest potential changes, but are difficult to interpret in relation to translational equivalents. To investigate this further, we compared the growth in the fraction of translational equivalents in bilingual children to independent growth of monolingual lexicons as modelled by preferential

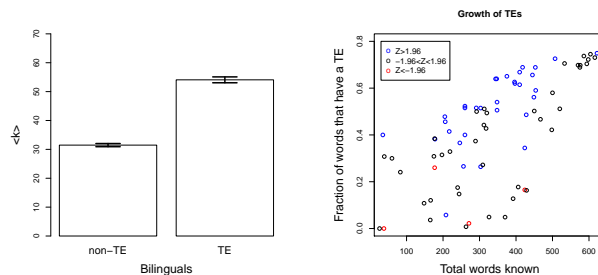


Figure 5: Properties of TEs

acquisition. We achieve this by finding a value of $\hat{\beta}$ for non-English word acquisition in the same way as for English words ($\hat{\beta} = 0.018 \pm 0.001$), and using the best-fit models to simulate the acquisition of English and non-English words independently. This was repeated 10^3 times to find the mean fraction of translational equivalents and the standard deviation for the lexicon sizes of the bilingual dataset. A Z-score was then calculated for each bilingual child and results are presented in Figure 5. With a mean Z-score of 1.44 and $p = 0.075$, the bilingual children tend to overproduce translational equivalents compared with an independent growth hypothesis, suggesting facilitation.

Discussion

This research asks how bilingual children acquire words in an early learning environment. Motivated by similar research of monolingual children, answers to this question were advanced based on combining language acquisition models with semantic networks derived from free association data. Initial analysis of word learning curves showed a smaller rate in the number of English words learned by bilingual children as compared to monolingual children. Similar analysis on the number of unique concepts learned showed no such difference. This is consistent with the claim that exposure to English words in a bilingual learning environment correlates with the rate at which the child learns those words.

By considering adult free association norms and their relation with age of acquisition, we constructed semantic networks for both monolinguals and bilinguals. From analyses of their respective English word network properties, we found a high degree of similarity in how both networks grow. Bilinguals and monolingual data both supported a model based on preferential acquisition by associative indegree, consistent with the amplified associative structure in child-directed speech (Hills, 2012). Moreover, the models’ parameter values were identical for monolingual and bilingual children. This suggests that the general order in which bilinguals learn English words is largely independent of the other language, and that this order is different from random word learning. However, bilingual children do show a potential for language facilitation—with words in one language facilitating the learning of the translational equivalent in the second language. This was indicated by bilinguals overproducing trans-

lational equivalents in comparison to simulated growth networks based on preferential acquisition, reflecting a potential for facilitation of word acquisition during early bilingual language acquisition.

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