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The role of phonological similarity in constructing a developing lexicon

Lin Li

Abstract

The implicational hierarchy of phonological feature development has proposed that children acquire native phonemic inventory in a systematic way, from the least articulatory-effort-required phonemes to most demanding ones. On the phonemic inventory level, the hierarchy suggests that perceptual features bearing by oral stops /p/, /b/, /t/, /d/, /k/, /g/ would appear ahead of perceptual features bearing by fricatives, affricatives and liquids /f/, /v/, /θ/, /ð/, /s/, /z/,/ʃ/, /ʒ/, /h/,/ʧ/,/ʤ/, /l/ and /r/ ,while nasals stops /m/, /n/ and /ŋ/ would emerge in the middle. With the help of age-of-acquisition index and a phonemic change schema, the distributions of 489 phonological neighbors have been examined against the data from MacArthur Communicative Development Inventory to test the predicted sequence of early phonemic and lexical acquisition. The results didn't support a strict stage-like interpretation of the implicational hierarchy, but a general trend sketched by it has been observed again from both sparse and dense phonological neighborhoods. A connectionist model with a phonological self-organizing map has been proposed conceptually to integrate the results and claims from the phonemic implicational feature hierarchy.

I certify that I have read this thesis and find that, in scope and quality, it satisfies the requirements for the degree of Master of Arts.

Signature

Dr. Ping Li, Committee Chair

Signature

Dr. Cindy Bukach, Committee Member

Signature

Dr. Jane Berry, Committee Member

THE ROLE OF PHONOLOGICAL SIMILARITY IN CONSTRUCTING A DEVELOPING LEXICON

By

Lin Li

B.A., Northwest University, Xi'an, China, 1994

M.A., Shaanxi Normal University, Xi'an, China, 2001

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Continuous sound sequences of speech seem to be perceived as discrete phonemes by normal adults, which often facilitate comparisons of language input with entries in a mental lexicon and results in successful spoken word recognition (McClelland & Elman, 1986; Norris, 1994; Luce, 1986; Luce & Pisoni, 1998). Word boundaries, perceptual similarities and dissimilarities are pre-lexical consequences of such a recognition process (Luce & Pisoni, 1998). The sense of perceptual similarities can be attributed to several sources, such as surface phonetic distributions of a specific vocabulary or a phonological structure of mental lexicon (Luce, 1986; Luce & Pisoni, 1998). For example, the surface similarity of /dɔg/ and /blɔg/ may be attributed to English etymology; but a sensitivity to detect such a perceptual similarity also depends on the development of a specific phonological structure of input lexicon to facilitate its perception (Li, Farkas & MacWhinney, 2004). That is to say, an adult may easily detect the similarity because he or she has acquired a specialized input lexicon to detect it. Such a facilitory or inhabitory effect often biases adults to respond to language input in one way or another, which can be shown by contrasting lexical performance of different age groups (Charles-Luce & Luce, 1990, 1995).

A widely used metric to measure similarity structure of entries is phonological neighborhood, which is commonly defined by substituting, deleting or adding one phoneme in any word position (Luce, 1986). For example, words "dupe, coop, hoop, loop" can be considered as neighbors of "soup" by substituting, deleting or adding one phoneme. Words are said to reside in sparse neighborhoods if they are phonologically similar with only a few other entries by substituting, deleting or adding only one phoneme, whereas words similar to many other items are said to reside in dense neighborhoods. The micro-structures of phonological neighborhoods can further be revealed by type of similarity and position of similarity overlap. Type of similarity refers to possible sources of phonological similarity, i.e. articulation manner similarity, phoneme similarity and articulation position similarity. For example, words 'vat' and 'fat' have a similar articulation manner of [fricative] at word beginnings (see Venezky, 1999 for details). Position of similarity overlap refers to word initial overlap, nucleus overlap and word final overlap, or different combinations of these overlap positions (Venezky, 1999). The manner similarity of 'hat' and 'ham' can be said to locate at the initial+nucleus position. Other developmental phonological variables may also include variables coming from lexical, phonemic, and phonotactic probability levels.

Processing similar sounding words may pose a perceptual challenge to an underdeveloped phonological system or to a deviated phonological one, such as foreign language learners' perceptual system, but after having acquired 50 first words, children often show a rapid increase in rate of word learning and don't suffer too much phonetic confusion as much as late adult foreign language learners would do. It seems that even with constraints of children's underdeveloped oral-motor systems, the interaction between early word learning and phonological development somehow achieves a balance to speed up overall language development. How does acquiring a native phonemic inventory facilitate early lexical development? What kind of cognitive models can capture such a phonemic-lexical interaction for children in their first two and a half years?

Research on biological constraints of vocal tract, jaw, lips and tongue movements has shown that early attempts at target phonemes result in some predictable error patterns congruent with the range of movements available to the biologically underdeveloped system (Stokes, Klee, Carson & Carson, 2005). Children worldwide are predicted to learn phonological segments--- both consonants and vowels, which require the least articulatory precision first, regardless of the language they speak (Stokes, 2006). These are the most basic of segments, described by the distinctive features [sonorant], [consonant] and [syllabic]. An implicational hierarchy of feature development has also been constructed to describe the rate and route of phonological development in typically developed children across languages (Dinnsen, Chin, Elbert & Powell, 1990). The hierarchy suggests that children acquire native phonemic inventory in a systematic way, from the least articulatory effort required phonemes to most demanding ones (Stokes, 2006).

This thesis further tested the predictions from the phonemic implicational feature hierarchy against data from MacArthur Communicative Development Inventory and tried to integrate early lexical and phonemic development results by applying a cognitive connectionist framework to the phonemic-lexical interface of early word learning.

The thesis is organized to first provide a background to phonological similarity neighborhood, phonemic implicational feature hierarchy and lexical reconstruction model, which all describe early lexical and phonemic interactions from their unique perspectives. Converging positions and controversies between these claims will lead hypotheses of the current study. The order of English phonemic development predicted by the phonemic implicational feature hierarchy is then checked with observational data from MacArthur Communicative Development Inventory, especially across words from dense and sparse phonological neighborhoods. By introducing an inner phonological self-organizing map, a modified two-representation model will provide a means of integrating early word and phonemic acquisition. The phonological neighborhood density effects will be further illustrated by such a model. Finally a discussion of limitations and implications of the current study will conclude the thesis.

Literature Review

It was only after corpus-based computations were introduced into spoken word recognition research that quantitative measures of phonological similarity could be realized by algorithms. The construct of phonological neighborhood was first introduced by Luce (1986) in his Ph.D. thesis. Since then, it has always been a central concept for both computational and behavioral research of various phonological similarity effects on lexical tasks.

The Psychological Reality of Phonological Similarity Neighborhoods

The purpose of Luce's (1986) original research was to quantify the effects of phonological similarity structure on perceptual identification of words under a noisy background. To calibrate the performance of a human "word recognizer" working under a distorted situation, Luce proposed a construct to integrate stimulus word intelligibility, stimulus word frequency, neighborhood confusability, and neighborhood frequency simultaneously altogether. The general form of the construct can be described as "the probability of identifying the stimulus word is equal to the probability of the stimulus word divided by the probability of the stimulus word plus the sum of the probabilities of identifying the neighbors" (Luce & Pisoni, 1998), which has been shown in Equation (1).

$$P(ID) = \frac{p(S)}{p(S) + \sum_{j=1}^{n} p(N_j)} \qquad (1)$$

Where P (ID) refers to the probability of correctly identifying the stimulus word, p(S) to the probability of the stimulus word, and $p(N_j)$ to the probability of the jth neighbor. A word perceptual identification task was then carried out to test the validity of the metric. Ninety subjects were instructed to type out 918 targets words with a signal/noise ratio at +15dB, +5dB and -5dB separately. The results clearly indicated that words with high frequency and low neighborhood similarity were responded to with the highest level of accuracy; words with low frequency and high neighborhood similarity were responded with the lowest accuracy (Luce, 1986).

In order to more closely examine the effects of neighborhood structure and frequency on lexical tasks, a frequency-weighted means of determining phonological neighborhood membership was also devised, which has been shown in Equation (2).

$$P(ID) = \frac{\prod_{i=1}^{n} P(PS_i|PS_i)*Freq_s}{[\prod_{i=1}^{n} P(PS_i|PS_i)]*Freq_s + \sum_{j=1}^{nn}[[\prod_{i=1}^{n} P(PN_{ij}|PS_i)]*Freq_{Nj}]} \quad (2)$$

Where PS_i refers to the probability of the *i*th phoneme of the stimulus word, PN_{ij} to the probability of the *i*th phoneme of the *j*th neighbor, n to the number of the phonemes in the stimulus word and neighbor, $Freq_s$ to the frequency of the stimulus word, $Freq_{Nj}$ to the frequency of the *j*th neighbor, and *nn* to the number of neighbors.

An auditory lexical decision and a word naming task were further employed to examine the reliability of this frequency weighted phonological similarity metric. In the lexical decision task, analysis of percentage correct indicated that words in high density neighborhoods were responded to 3.38% more accurately than words in low density neighborhood. And, words residing in low-frequency neighborhoods were responded to 1.39% more accurately than words in high-frequency neighborhoods. Analysis of reaction time also indicated words residing in high density neighborhoods were responded to 13.5 msec slower than words in low-density neighborhoods. In the word naming task, the results indicated words from high density neighborhoods were responded to 0.28% worse than words from low density neighborhoods. Words from dense neighborhoods were responded to approximately 102 msec slower than words from low density neighborhoods. It demonstrated that words with many neighborhoods were named more slowly than words with few neighborhoods.

Neighborhood density was shown twice as a sensitive index of human auditory lexical classification and word identification performance. The density effect was also consistent across word frequency and neighborhood frequency in most cases.

In summary, Luce (1986) first devised and demonstrated the validity of neighborhood similarity measures in predicting the performance of identifying words. He also found that items in dense and/or high frequency neighborhoods tended to be processed slower and/or less accurately than items from more sparsely populated, low frequency neighborhoods.

Since then, the construct of phonological neighborhood has been widely used in how children acquire sounds (Gierut, Morrisette & Champion, 1999), in how children acquire the words (Charles-Luce & Luce, 1990, 1995; Coady & Aslin, 2003; Storkel, 2004; Garlock, Walley & Metsala, 2001), in studying spoken word recognition in children who stutter (Arnold, Conture & Ohde, 2005), and in young adults with fluent speech in English and in Spanish (Vitevitch, 1997; Vitevitch & Stamer, 2006). The phonological neighborhood variable that I used for this study will also be calculated in this way.

Similar sounding words and their perceptual similarities may pose a challenge of discrimination to children and less proficient foreign language learners. The word "thin", "sin" and "tin" may not equally discernable to a developing phonology system until the degree of phonetic sophistication increases to the extent more and more like adult speech (Stokes, 2006). How does phonemic development facilitate such a process? How does phonemic and lexical development interact with each other? Phonemic implicational feature hierarchy, lexical reconstruction model all provided explanations for these questions.

Background and Predictions of Phonological Implicational Hierarchy

Stokes, Klee, Carson and Carson (2005) summarized Dinnsen's (1990) phonemic implicational feature hierarchy to describe early phonological development. For example, similar sounding speech sequences are proposed to be first contrasted between [consonant] feature, distinguishing between consonants and vowels; and the next division is at [syllabic], which divides vowels and glides; and the next is at [sonorant], which facilitates contrasts between /b/ and /m/. Further divisions can be tracked along a non-sonorant subclass or a sonorant subclass. Within the non-sonorant class, there are further divisions for [voice], distinguishing between /b/ and /p/; [continuant] for contrasting /b/ and /f/; [delayed release] for /ʧ/ and /p/. Within sonorant class, there are subdivisions, with [nasal] distinguishing /n/ and /l/ and [lateral] distinguishing /l/ and /r/, finally is the division by articulation places, such as [coronal] and [anterior] employed in English. Such a system came from research of (nonorganic) functional speech language pathology (Dinnsen, 1990).

To address whether or not functional speech disorders are simply the result of delays in the normal acquisition process, Dinnsen, Chin, Elbert and Powell (1990) examined 40 functional misarticulators aged from 40 to 80 months. Some principles governing disordered phonological systems were found parallel with the principles governing normal first language acquisition. A hierarchy was derived from the principles and the hierarchy was proposed to be used to determine a sequence of phonological development in a given language.

The principles have been summarized as (a) the presence of [strident] and/or [lateral] implies the presence of [nasal]; (b) the presence of [nasal] implies the presence of [continuant] and/or [delayed release]; (c) the presence of [continuant] implies the presence of [voice]; (d) the presence of [voice] implies the presence of [syllabic], [consonant] ,and [sonorant] ; and (e) obstruents of level A are anterior. Beginning from the preliminary structure of a phonological system to its fully developed form, these implicational constraints have been interpreted as developmental levels by Stokes (2005). The levels from A to E have suggested a typical route of normal phonological development, from a basic phonological system at level A to a complex one at level E.

On the phonemic inventory level, the implicational hierarchy suggested that perceptual features bearing by plosives /p/, /b/, /t/, /d/, /k/, /g/ would appear ahead of perceptual features bearing by fricatives, affricatives and liquids /f/, /v/, /θ/, /ð/, /s/, /z/,/ʃ/, /ʒ/, /h/,/ʧ/,/ʤ/, /l/ and /r/ ,while nasals /m/, /n/ and /ŋ/ would emerge in the middle. If such a phonemic development inventory is valid, it should lend its support to early word learning and show its influence on early lexical development. Besides such an implicational hierarchy, dynamic and static lexical development hypotheses have also been proposed to address early phonemic and lexical acquisition.

Two Competing Hypotheses on Lexical Development

Different from Luce's (1986) research on the density effect of spoken language processing, computational and behavioral structural analyses of a developing lexicon try to answer how children organize entries in their mental lexicons and how these items will change along with early phonological development.

The dynamic hypothesis (Storkel, 2002) proposed that children may first code words in a less specific way or only at onset position, which makes few items distinct enough for children to discriminate first words compared with adult lexicons. During childhood, both type of similarity and position of overlap for phonological neighborhood may go through some changes because lexicon increases in size. The previous loosely packed neighborhoods may become denser by incorporating more specific phoneme similarity or discriminating phonemes at rhyme position, so some new neighbors will join in and some will move out of formerly sparse neighborhoods. Both dense and sparse neighborhoods are expected to transit in a similar manner and only the dense one will change more quickly because of a greater potential for decreasing confusion among similar entries. Charles-Luce and Luce's (1990, 1995) computational research supported such a perspective, as well as Garlock, Walley & Metsala's (2001) and Storkel's (2002) behavioral results.

The static hypothesis (Storkel, 2002) proposed that phonological neighborhoods are stable, but children's focus shifts as different aspects of words become salient as lexicon increases in size. What changes across development is the salience of particular similarity relationships at different overlap positions. During childhood, the increased salience of phoneme similarity and increased salience to rhyme position causes some neighbors to move in and some to move out a former sparse neighborhood. Both dense and sparse neighborhoods would change as children's focus of salience changes. The dense neighborhood will change in an accelerated manner because more similar words easily cause greater confusion. Coady and Aslin's (2003) computational research was support this position as well as Werker, Fennell, Corcoran & Stager's (2002) behavioral results.

Evidence That Supports the Dynamic Hypothesis

Charles-Luce and Luce (1990) conducted a computational research to examine phonological neighborhood distributions across 5 year olds, 7 year olds and adults. Lexicons with 679, 943 and 20,000 words were used to calculate the phonological neighborhoods for 3-phonemes, 4-phonemes and 5-phonemes words. The results indicated that 36% of 3-phoneme words have less than 2 neighbors and over 45% have more than 3 neighbors for 5-year-olds.It has been suggested that 3-phoneme words in 5-and 7-year old lexicons have sparsely populated neighborhoods compared with adult ones.

For the 5-year-old lexicon, 81% of their 4-phoneme and all 5-phoneme words have 0 or 1 neighbor; for the 7-year-old lexicon, 68% of their 4-phoneme and 95% of 5-phoneme words have 0 or 1 neighbor. Finally, the 7-year-old lexicon tends to be denser than the 5-year-old one. Compared with adults' results, such a result has been interpreted to suggest that words in the children's lexicons are theoretically more discriminable when they are younger, and similarity neighborhoods tend to grow denser as children grow up. The authors argued that phonological neighborhoods became more and more densely packed over lexical development and the size of an increasing lexicon is not a direct effect of accumulating vocabulary size. The size of expanding lexicon and its associated demand for more differentiated phonological neighborhoods were thus considered as an indirect evidence for the possible emergence of mature segmental representations from primary holistic representations.

The same analysis strategy has also been used to study verbal interactions of three mother-child dyads by Charles-Luce and Luce (1995). The children aged from 1;1 to 1;9. The results replicated the above neighborhood statistics computed for young children's lexicons. At each phoneme length, neighborhood density was more evenly distributed in the adults' lexicons compared with children's lexicons. For young children, phonological neighborhood density was shown to be skewed toward sparse neighborhood (Charles-Luce & Luce, 1995). A developmental change of phonological structure has been clearly shown again in this study.

A two alternative forced-choice classification game was chosen to ask preschool children (M=4;8; range 3;7-5;11) to categorize words (Storkel, 2002). If a word was identified as similar to a standard word, a chip was supposed to be put into a character bank; if not, a chip was supposed to be put into a small toy garbage can. By collecting data of children's judgments of phonological similarity, the effects of neighborhood density, type of similarity and position of phonological overlap were analyzed by repeated measures ANOVAs. The results demonstrated that dense neighborhoods were largely organized by phoneme similarity at onset+nucleus or rhyme overlap position, which paralleled the patterns found in adults' lexicon. On the contrary, the structure of sparse neighborhood appeared to include phoneme or manner similarity at the rhythm position. From this membership classification task, the neighborhood structural difference at rhyme position has been considered as a direct evidence of pre-school children's holistic phonological representation.

The above evidence suggested that word acquisition is influenced by vocabulary growth, as lexical representations become more fine-grained and/or segmental; the ability to acquire new words from a dense neighborhood will increase. For children at different developmental stage, what kinds of word will be acquired first may be determined by what kinds of phonological representations have been segmentalized, and may not totally be dependent on mapping competitions induced by word exposures, because the children may not recognize and repeat them in the first place if their phonological representations have not been fully developed.

Evidence That Supports the Static Hypothesis

Dollaghan (1994) criticized Charles-Luce and Luce's (1990) study and pointed out three limitations. 1) The size of children's vocabulary had been underestimated. Since Carey (1981) inferred that a typical 6-year-old has approximately 8,000 root form word entries, while Charles-Luce and Luce's (1990) study only analyzed 679 words for 5-year-olds and 943 for 7-year olds; 2) Other known factors, such as word familiarity and word frequency had not been included into analysis; 3) children's phonological neighbors and adults' neighbors were not calculated on a similar order of magnitude. One was calculated against hundreds of words, the other against tens of thousands words.

Coady and Aslin (2003) also noticed these points and conducted four computational studies by using mother-children interaction data, by using a frequency-weighted neighborhood density and by calculating a ratio to normalize children and adults' lexicon. Their results suggested that children actually acquire words with more frequent sounds and sound combinations before those containing the less frequent sounds. This meant that children must possess considerable sensitivity to acoustic-phonetic details to be able to differentiate these similar sounds. Their normalized lexicon ratio showed that neighborhood density of children's lexicon actually was higher than that of adults. This totally contradicted previous results based on simple counts. Such a result suggested children may be more sensible to differentiate similar sounds than adults, so they suggested there may be other mechanism to account for children's early sensitivity to similar words in both dense and sparse neighborhoods.

A word-object associative-learning task and classic switch task was combined by Werker and Tees (1984) to test children' ability to detect a switch in a pairing after they have habituated to two word-objects pairs. They assumed if children have associated a new sound sequence with an object, he or she should spend more looking time at a violation of that link when a switch is presented. Their results indicated children become rapidly attuned to many properties of their native language, including the language-specific phonemic categories across the first year of life, but sometimes children do not appear to be able to immediately use all the "knowledge" gained from perception when acquiring new words. Since children of 14 months were shown not to be able to use all of the details in the language-specific phonetic categories they have established during infancy to discriminate possible words in a word learning task, they don't think the result reflected phonological representation changes. Instead they proposed the difficulties are more likely to reflect attentional-processing limitations than a holistic-to-specific phonological representation explanation.

Taken the above evidence together, how children construct their phonological neighborhoods is still unclear and in controversy. The dynamic view suggests that children start with sparser neighborhoods, in which a holistic, coarse phonological representation is sufficient to discriminate few early words. With addition of more and more similar words, a more mature phoneme identification strategy will emerge to facilitate contrasting similar sounds at all possible positions. With neighbors moving in and out, adult-like denser neighborhoods will be gradually built up.

In contrast, the static view holds that specific phonological representations have already been established during the first year of development. It is attentional-processing limitation and infant's focus shifts that determine how they would perceive new words and construct a phonological neighborhood; it is not because they don't possess specific phonological representations.

From the perspective of implicational hierarchy, holistic lexical representations of early words may reflect those phonemic combinations, that have not been fully mastered by early phonological systems, such as acquiring words with more complex fricatives /f/, /v/, /θ/, /ð/, /s/, /z/,/ʃ/, /ʒ/, /h/, and words can't be analyzed at the phonemic level, they are all taken as a whole. On the other hand, the specific lexical representations of early words may reflect the other phonemic combinations, which have already acquired in the acquired phonemic inventory, such as acquiring words comprised with plosives /p/, /b/, /t/, /d/, /k/, /g/ with vowels. These words can be processed at both a lexical and a phonemic level.

The dynamic view of phonological neighborhood seems to conform to phonological implicational hierarchy, which requires a prolonged period of time for acquiring a fully developed phonological system. During that period of time, some early words may be acquired wholly without intentionally discriminating them at underlying phonemic level. On the other hand, the static view of phonological neighborhood seems to suggest that a complete phonemic inventory has already been acquired after first 50 words, it is the task requirement that determines whether lexical or phonemic level will be attended to and provide behavioral evidence. These issues will later be further discussed with a two level representation connectionist model of early words.

Computational neighborhood analyses can only provide some meaningful results on static lexical organization. They didn't tap on the phonological structure of lexical items, nor on children' phonological implicational hierarchy. The cited studies are based on a snapshot of the lexicon at a static point in time while the lexicon in early childhood is a dynamic entity (Coady & Aslin, 2003). To address these limitations, further confirmatory examinations of early phonological development on early word learning are needed because they will further test the applicability of implicational hierarchy and its predictions about the route of early phonemic development for a larger population and across different tasks.

To dynamically study the interaction between early phonological and lexical development, parents' reported age of acquisition (AoA) index has been computed for each early word. Phonological neighbors derived from changing oral stops /p/, /b/, /t/, /d/, /k/and /g/, changing nasal stops /m/, /n/, /ŋ/, changing fricatives /f/, /v/, /θ/, /ð/,/s/, /z/, /ʃ/, /ʒ/ and /h/, changing affricative /ʧ/, /ʤ/ and changing liquids /l/, /r/ have been coded accordingly. The early words have also been divided into groups according to how many phonological neighbors they have. Words that have 1 to 4 neighbors have been grouped as sparse phonological neighborhoods; while words that have 5 to 8 neighbors have been grouped as dense phonological neighborhoods. With an AoA index and a phonemic change schema, the distribution of phonological neighbors for a dense or sparse neighborhood can be checked comparatively. If the implicational hierarchy is valid, phonological neighbors derived from changing oral stops /p/, /b/, /t/, /d/, /k/and /g/, nasal stops /m/, /n/, /ŋ/ should appear earlier than ones derived from changing fricatives /f/, /v/, /θ/, /ð/,/s/, /z/, /ʃ/, /ʒ/ and /h/, affricatives /ʧ/, /ʤ/ and liquids /l/, /r/ across both dense and sparse neighborhoods. If it is not, other patterns may be observed to describe the interaction between early phonemic and lexical interactions.

Methods

Materials

Early words and derived phonological neighborhoods were taken from MacArthur communicative development inventories (CDI). The CDI consists of an extensive list of words from approximately 1,800 children (see http://www.sci.sdsu.edu/cdi/, Dale and Fenson, 1996). The infant inventory consists of 384 words being reported by parents of their children age 8-16 months. Parents were asked to report both the words their child comprehends as well as the words their children produce. The toddler inventory consists of 652 words of children aged 16-30 months. Normed data from 652 words have been used to calculate AoA indexes to tag words in relation to a dense or sparse phonological neighborhood.

Procedures

Data preparation

Before generating phonological neighbors and categorizing them according to the implicational hierarchy's schema. Six hundred and fifty two raw words were screened according to the following criteria: 1) have semantic meanings or serve a specific grammatical function; 2) homophones will be excluded; 3) word phrases will be excluded; 4) non-words will be deleted; 5) if multiple words appear, only the earliest acquired word has been included; 6) compound words will be deleted; 7) must have at least one phonological neighbor. These criteria was to set to ensure that further analyses would be carried out only on phonological level and to meet the computational requirements for deriving phonological neighbors, so 12 sound words, 11 multiple words, 43 contractions and phrases were first excluded. There were 61 words at the end of the 30th month, which had not met the acquisition threshold of more than 50% parents reported having acquired them, so the words were also excluded. After pre-screening, 525 words were submitted to derive phonological neighborhoods. Two hundred thirty seven early words have yielded 489 phonological neighbors for further analyses.

As per Luce (1986) and Coady & Aslin (2003), neighbors were defined as words that differ from a target word by the addition, substitution, or deletion of a single phoneme in any position. Phonological neighbors derived from changing nasal stops /m/, /n/, /ŋ/, changing oral stops /p/, /b/, /t/, /d/, /k/and /g/, changing fricatives /f/, /v/, /θ/, /ð/,/s/, /z/, /ʃ/, /ʒ/ and /h/, changing affricative /ʧ/, /ʤ/ and changing liquids /l/, /r/ and others have been coded accordingly. The early words were also divided into groups according to how many phonological neighbors they had. Words that had 1 to 4 neighbors were grouped as sparse phonological neighborhoods, while words that had 5 to 8 neighbors were grouped as dense phonological neighborhoods.

The construction of an age of acquisition index

The first point of acquisition a specific word was defined as the first month with over 50% caregivers reported their children can understand or produce the word. Based on this measurement, words were listed on a timeline according to the acquisition order from the 17th month to 30th month. To reflect the differences between words reported as acquired at the same month, a second part have been calculated and added to the acquisition months based on Equation (3).

$$AoA_i = \%_M - \%_{prior} \qquad (3)$$

Where $\%_M$ refers to the actual percentage first reported by caregivers over the threshold 50%, $\%_{prior}$ to the percentage reported by caregivers immediately prior to the threshold month. Such a difference for each word has been added as the second part after decimal point to form a unique word AoA tag. For example, The AoA index of 18.03 has been assigned to the word "cat", since in the 18th month over 50% caregivers have reported their children can produce the word "cat", and the actual percentage in the threshold month is 51.2%, the percentage reported by caregivers immediately prior to the threshold month is 48.5%, so $AoA_i = \%_M - \%_{prior} = 51.2\% - 48.5\% = 2.7\%$, which has been rounded to 0.03.

Data analysis

Since AoA indexes of phonological neighbors were only ordinal data, Loglinear models were used to examine observed frequencies and expected frequencies of 489 phonological neighbors across dense and sparse neighborhoods. Five observation periods have been created to reflect which kinds of phonological neighbors have joined neighborhoods earlier. Observation period 1 would cover the interval from the 16^{th} to the 18^{th} month of CDI investigation, observation period 2 from the 19^{th} to the 21^{st} month, observation period 3 from the 22^{nd} to the 24^{th} month, observation period 4 from the 25^{th} to the 27^{th} month and observation period 5 from the 28^{th} to the 30^{th} month.

A loglinear model was chosen to examine the difference of the observation frequencies and expected frequencies of phonological neighbors by the factors of the phonological change level and density. Because a loginear model tests the possible associations between variables of a designed model, and because words and phonemes may not conform to a normal distribution, the observed sample distribution was submitted to check against a multinomial distribution. Observed and expected frequencies from the above 5 observational periods were submitted to the loglinear model to examine possible significant results.

Results

Descriptive statistics have been reported according to phonological density and phonological change levels, and then the results from a loglinear model has been be reported to show the differences between expected frequencies and observed frequencies for phonological neighbors crosstabulated by the factors of phonological change levels and density.

Figure 1 shows a general picture of phonological neighborhood acquired from the 16th to the 30th month. Most phonological neighbors were acquired from the 19th month to the 27th month. Phonological neighbors have been shown to grow in parallel with early lexical acquisition, which can be illustrated by that phonological neighbors have been acquired across all observation periods. There was no observation period which had no phonological neighbors acquired.

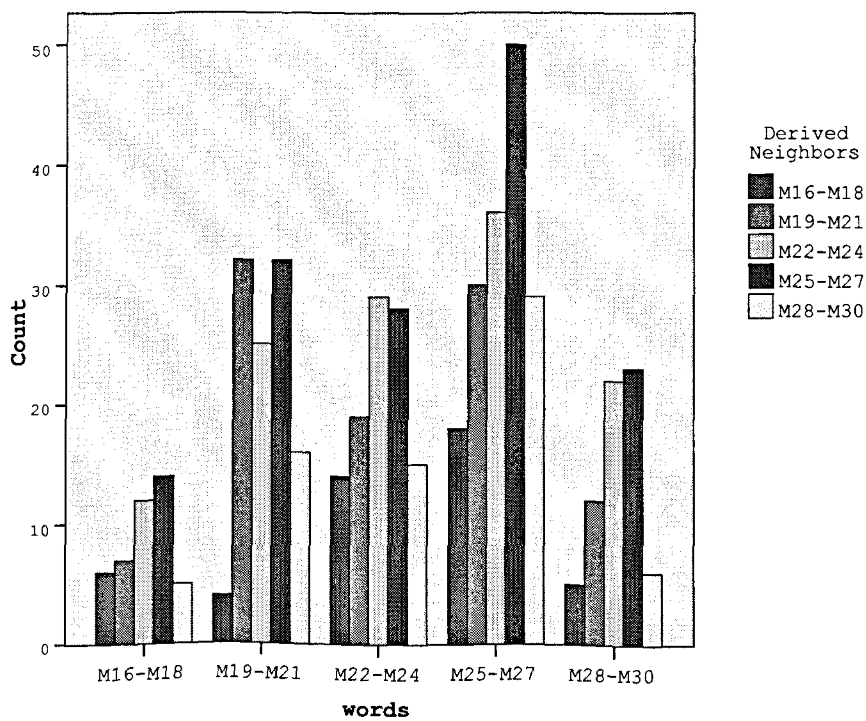

Figure 1. Words and their derived phonological neighbors summarized over observation periods.

Four hundred and eighty nine phonological neighbors have been further crosstabulated by phonological change position, phonological density and have been contrasted by phonological change levels in Figure 2. Although a similar neighborhood development pattern can be identified again, the surface dense phonological neighborhoods comparatively actually acquired fewer neighbors across all observation periods than sparse neighborhoods, especially for phonological neighbors derived from fricatives, affricatives and liquids located at word final position for dense neighborhoods. Such a pattern prompts a further loglinear examination.

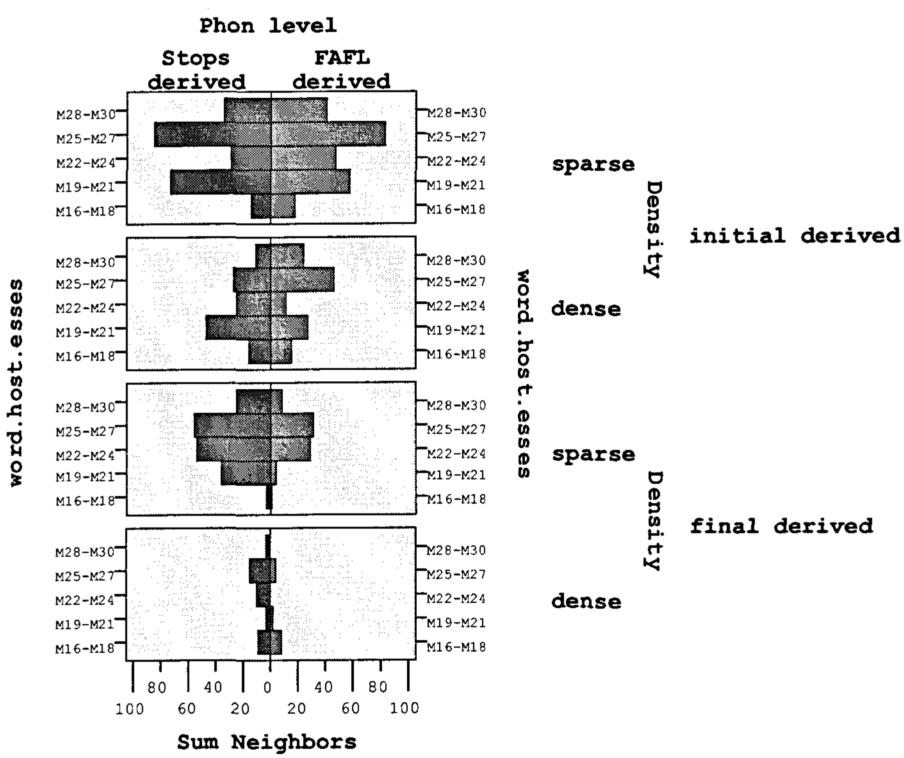

Figure 2. The sum of phonological neighbors derived from oral and nasal stops, fricatives, affricatives and liquids for early words crosstabulated by phonological change position and density.

Within the observation periods from the 19th to the 27th month, there were 189 phonological neighbors acquired for this period for the sparse ones and 82 for the dense ones. (See Table 1 for details). If checked by density and phonemic development levels, sparse phonological neighborhoods had acquired 348 neighbors. Within these 348 neighbors, the vowels derived phonological neighbors formed the largest subset, which amounted to a total of 112 early words. The second was the set of oral stops with a total of 96. The third was the set of fricatives with a total of 73.

On the other hand, dense neighborhoods had acquired 141 early words. Within these 141 neighbors, the vowels derived phonological neighbors formed the largest subset, which amounted to a total of 46 early words. The second was also the set of oral stops with a total of 45. The third was the set of fricatives with a total of 39. Only for dense neighborhoods, no affricative-derived neighbors have been acquired across the whole observation periods.

Table1 *The observed sum of phonological neighbors crosstabulated by phonological change level and density*

Count

Density			Neighbors M16-M18	M19-M21	M22-M24	M25-M27	M28-M30	Total
sparse	pnlevel	vowel derived neighbors	10	24	28	38	12	112
		nasal stops derived neighbors	5	7	10	8	7	37
		oral stops derived neighbors	8	21	26	28	13	96
		frivative derived neighbor	9	12	17	19	16	73
		affricative derived neighbors	1	4	1	4	2	12
		liquid derived neighbors	1	6	7	3	1	18
	Total		34	74	89	100	51	348
dense	pnlevel	vowel derived neighbors	5	8	12	12	9	46
		nasal stops derived neighbors	0	2	0	4	2	8
		oral stops derived neighbors	6	6	13	16	4	45
		frivative derived neighbor	2	10	9	14	4	39
		liquid derived neighbors	0	0	1	1	1	3
	Total		13	26	35	47	20	141

Figure 3 and Figure 4 contrast the phonological neighbors derived from each change level for sparse and dense neighborhoods across the 16th month to 30th month. For sparse neighborhoods, phonological neighbors, which derived from all change levels, can be found for each observation period, though the fricative-derived, affricative-derived and liquid-derived neighbors were always less than vowel-derived, oral stop-derived and nasal stop-derived phonological neighbors. For dense neighborhoods, nasal-derived phonological neighbors were missing from the 16th to the 18th month, and the 22nd and the 24th month. Liquid-derived neighbors were missing from the 16th to the 21st month. The distribution of dense phonological neighbors was much more complicated than that of sparse phonological neighborhoods.

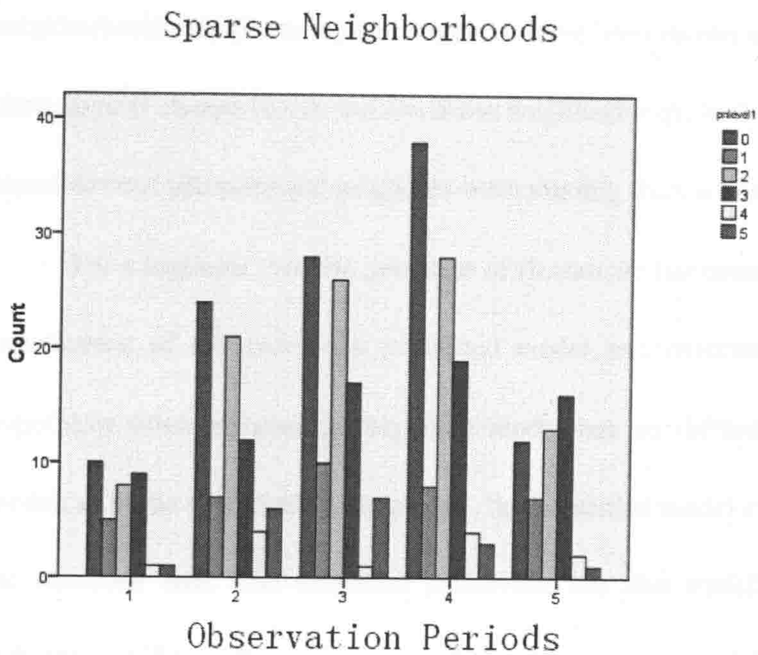

Figure 3 Phonlogical neighbors in sparse neighborhoods across observation periods

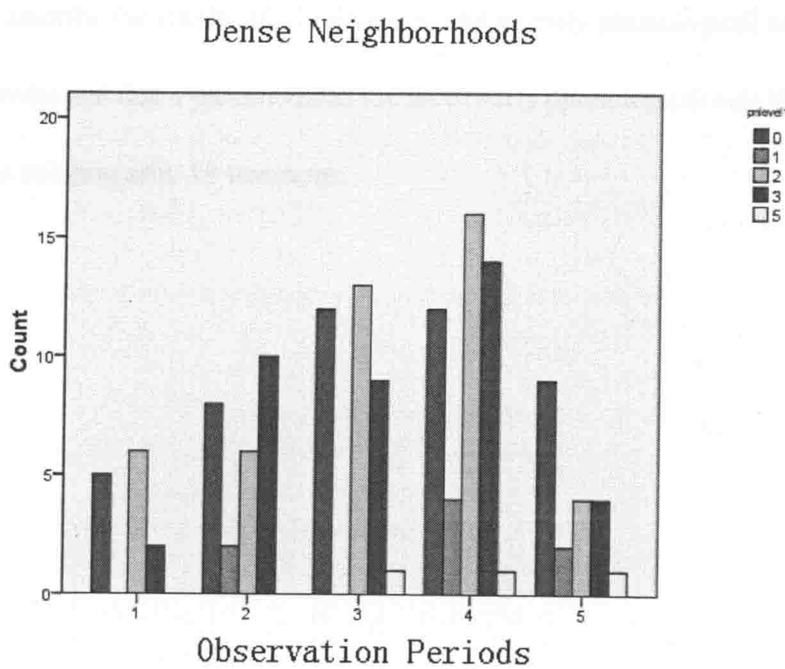

Figure 4 Phonlogical neighbors in dense neighborhoods across observation periods

In summary, the above statistics revealed an unbalanced distribution across phonological change levels for sparse and dense neighborhoods. For sparse neighborhoods, the phonological neighbors have been shown to be acquired across all phonological change levels, but for dense neighborhoods, both nasal stop-derived and liquid-derived phonological neighbors were missing from several observation periods.

For a loglinear test, the goodness of fit statistic has been designed to reflect the significance of deviance of a submitted model and observed pattern, so the null hypothesis often assumes an expected model has no difference with an observed model, so at the significant level $p > .05$, the submitted model can adequately describe the observed data. The estimated parameters are also transformed to Z scores to indicate significant factors of a possible parsimonious model. Tables 2 to Table 4 describe the results of a loglinear model of early phonological neighborhoods. Table 2 indicates that a parsimonious model of early phonological neighbors had been reached a solution after 19 iterations.

Table 2 *The number of iterations of the multinomial logit model*

Convergence Information[a,b]

Maximum Number of Iterations	20
Converge Tolerence	.00100
Final Maximum Absolute Difference	1.0E-010[c]
Final Maximum Relative Difference	2969.848
Number of Iterations	19

a. Model: Multinomial Logit

b. Design: Constant + neighbors + neighbors * density * pnlevel * position

c. The iteration converged because the maximum absolute changes of parameter estimates is less than the specified convergence criterion.

Table 3 shows that likelihood ratio was only marginally significant (L2 = 156.60, df=128, p>.01); while another goodness-of-fit index Pearson $\chi 2$ = 138.62 (*p* >.05). Since the indexes reflect how well a parsimonious model differs from a saturated one, the non-significant results indicated an acceptable parsimonious model. The non-significant Pearson $\chi 2$ indicated dependence among testing factors, which meant one or more significant interactions had been identified by the loglinear model.

Table 3 *The Goodness-of-Fit tests of the multinomial logit model*

Goodness-of-Fit Tests[a,b]

	Value	df	Sig.
Likelihood Ratio	156.598	128	.044
Pearson Chi-Square	138.616	128	.246

a. Model: Multinomial Logit

b. Design: Constant + neighbors + neighbors * density * pnlevel * position

Table 4 shows the parameters calculated after 19 iterations. Since significant interactions had been identified, the main effects of phonological levels, phonological change position and density may be misleading and has been skipped over. Seven significant 4-way interactions had been identified by the loglinear model, which may reveal the significant differences between expected frequencies and observed frequencies. They are the sparse neighbors, which had been derived by changing *stops* at word *initial* position during the 16th and 18th month, had been identified as significantly different (Z =18.82, $p < .001$); the sparse neighbors, which had been derived by changing *stops* at word *final* position during the 16th and 18th month, had been identified as significantly different (Z =15.81, $p < .001$); the sparse neighbors, which had been derived by changing *fricatives, affricatives and liquids* at word *initial* position during the 16th and 18th month, had been identified as significantly different (Z =18.27, $p < .001$); the sparse neighbors, which had been derived by changing *stops* at word *final* position during the 16th and 18th month, had been identified as significantly different (Z =15.65, $p < .001$);the *dense* neighbors, which had been derived by changing *stops* at word *initial* position during the 16th and 18th month, had been identified as significantly different (Z=17.12, $p < .001$); the *dense* neighbors, which had been derived by changing *stops* at word *final* position during *the 22nd and 24th* month, had been identified as significantly different (Z=18.30, $p < .001$); the *dense* neighbors, which had been derived by changing *stops* at word *final* position during the 22nd and 24th month, had been identified as significantly different (Z=18.82,

$p < .001$). All other 2-way, 3-way and 4-way interactions were found as non significant.

Table 4 *Parameter Estimates for the multinomial logit model*

Parameter Estimates[c,d,e]

Parameter		Estimate	Std. Error	Z	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Constant	[ds = 1] * [lv = 2] * [ps = 1] * [hos = 1]	-.026[a]					
	[ds = 2] * [lv = 2] * [ps = 3] * [hos = 5]	.000[a]					
[nbs = 1]		-18.360	.866	-21.200	.000	-20.057	-16.663
[nbs = 2]		2.29E-008	1.414	.000	1.000	-2.772	2.772
[nbs = 3]		2.29E-008	1.414	.000	1.000	-2.772	2.772
[nbs = 4]		3.51E-008	1.414	.000	1.000	-2.772	2.772
[nbs = 1] * [ds = 1] * [lv = 1] * [ps = 1]		18.178	.966	18.816	.000	16.284	20.071
[nbs = 1] * [ds = 1] * [lv = 1] * [ps= 3]		17.379	1.099	15.810	.000	15.225	19.534
[nbs = 1] * [ds = 1] * [lv = 2] * [ps= 1]		17.731	.970	18.272	.000	15.829	19.633
[nbs = 1] * [ds = 1] * [lv = 2] * [ps= 3]		18.072	1.155	15.651	.000	15.809	20.336
[nbs = 1] * [ds = 2] * [lv =1] * [ps= 1]		18.360	1.072	17.121	.000	16.258	20.462
[nbs = 1] * [ds = 2] * [lv =1] * [ps= 3]		36.580	2.000	18.290	.000	32.660	40.500
[nbs = 3] * [ds = 2] * [lv =1] * [ps= 3]		19.829	1.565	12.668	.000	16.761	22.897

a. Constants are not parameters under the multinomial assumption. Therefore, their standard errors are not calculated.

c. Model: Multinomial Logit

d. Design: Constant + neighbors + neighbors * density * pnlevel * position

e. Some of the parameter estimates are estimated to be zeros because the Hessian matrix is singular and cannot be inverted. Therefore a generalized inverse of the Hessian matrix is computed instead.

Discussion

The predicted sequence from Phonological Implicational Hierarchy

The phonemic implicational hierarchy suggests that perceptual features bearing by plosives /p/, /b/, /t/, /d/, /k/, /g/ would appear ahead of features bearing by fricatives, affricatives and liquids /f/, /v/, /θ/, /ð/, /s/, /z/,/ʃ/, /ʒ/, /h/,/ʧ/,/ʤ/, /l/ and /r/, while nasals /m/, /n/ and /ŋ/ emerge in the middle. The descriptive results of MacArthur Communicative Development Inventory didn't support a strict stage-like interpretation of such a claim. For sparse phonological neighborhoods all kinds of phonemes did appear from the 16th month to 30th month, although the fricative-derived, affricative-derived and liquid-derived neighbors were always less than vowel-derived, oral stop-derived and nasal stop-derived phonological neighbors. For dense neighborhoods, nasal stops-derived phonological neighbors were missing from the 16th to the 18th month, and the 22nd and the 24th month. Liquid-derived neighbors were missing from the 16th to the 21st month, but a possible reason is that the phonemes of nasal stops and liquids are relatively small and word neighbors in dense neighborhoods are also less than words in sparse neighborhoods.

Significant 4-way interactions identified by the loglinear model also didn't support the claims from phonological implicational hierarchy. The results may suggest other possible routes and mechanisms existed for both sparse and dense neighbors.

On the other hand, a general trend predicted by the phonemic implicational hierarchy has been observed again from the data of MacArthur Communicative Development Inventory. Regardless of sparse or dense neighborhoods, vowel-derived, oral stop-derived and nasal stop-derived phonological neighbors are always acquired more than other neighbors derived from fricatives, affricatives and liquids. Such an unbalanced acquisition distribution lent partial support to the claims that children acquire native phonemic inventory in a systematic way, from the least-articulatory-effort- required phonemes to most demanding ones.

In summary, the results yielded from MacArthur Communicative Development Inventory didn't fully support a strict stage-like interpretation of the phonemic implicational hierarchy, but a general trend sketched by such a implicational hierarchy, which implies first acquiring the least-articulatory- effort- required phonemes, have been observed from both sparse and dense phonological neighborhoods.

Dynamic vs. Static Phonemic and Lexical Development

Charles-Luce and Luce (1990) have suggested a sparser lexicon of children than that of adults, which lent support a dynamic lexical development. Although Dollaghan (1994) provided a different result and interpreted it based on weighted word frequencies. The results from current study indirectly support the claim that children possess a sparser lexicon, since checking from each phonological change level, children always acquire more words for sparse phonological neighborhoods over all observation periods.

More early words residing in sparse neighborhoods, not distributed in the other direction, may also lend support to the position of dynamic phonemic and lexical development, which assumes more phonological sophistications will be needed for children's sparser neighborhoods to gradually transform into a more-adult-like denser neighborhood.

On the other hand, only 4-way significant interactions have been identified didn't support a simple interpretation of phonological density effect. It seems to reveal many surface factors deeply intertwined together during early phonemic and lexical development. Whether or not these effects can be untangled and can be tested individually calls for further effort. Another possibility is that of a simple modular explanation which is implied by the phonemic implicational hierarchy may not fit the early phonemic and lexical development research. It is unimaginable to interpret significant 4-way interactions within a serial, discrete and modular framework. One alternative is seeking explanation from interactive connectionist models.

Interactive Connectionist Model of Early Word Processing

Some researchers have applied the principles of interactive connectionist to early word learning modeling, such as a dynamic self-organizing model (Li, Zhao and MacWhinney, 2007) and a two representational model (Storkel and Morrisette, 2002). In the dynamic self-organizing early word model, an unsupervised process dynamically develops clusters of units on a self-organizing map that capture language input features; statistical patterns of early words will be gradually preserved on such a self-organizing map. The map will be attuned to language input patterns (Li, 2006). Such a model has been used for modeling Chinese character acquisition, modeling lexical category formation and bilingual language processing, with a focus mainly on early semantic acquisition.

On the other hand, Storkel and Morrisette's (2002) two-representational connectionist model of early word learning tried to capture the interactions between a phonemic representation and a lexical representation. Different from the dynamic self-organizing model, the concept of resting threshold of each node has been introduced, which reflects how much extra input activation will be needed to activate a lexical node. For frequently used words or phonemes, their resting thresholds may be higher compared with less frequent ones, so relatively less extra activation will be needed to activate the nodes. Inhibitory and facilitory connections weave a network of inhibitory and facilitory activations across all possible representations.

Lexical Representations

According to Strokel and Morrisette's (2002) the resting threshold of lexical representations of early words can be modified by language experience. Thus, words that are frequently recognized or produced presumably will have a higher resting threshold than words that are infrequently recognized or produced. As a result, these frequent words should require less external activation than infrequent words to reach the activation threshold for recognition or production and, thus, recognition or production should be facilitated.

Besides word frequency, recognition of early words is also influenced by connections between words. These connections allow both inhibitory or facilitory activation to spread between related words, blocking or amplifying the related phonological neighbors' activation. In such a way, phonological neighbors can influence the activation of a target lexical representation, which can be activated or inhibited in phonological neighborhoods, and the number of neighbors determines the degree of negative activation for a phonological neighbor. A word in a dense neighborhood may receive more inhibition from many more words than a word in a sparse neighborhood. As a result, a word from a dense neighborhood will more likely be inhibited in reaching the activation threshold for recognition or production.

Phonological Representations

On the phonological representation level, phonemes that are commonly encountered in recognition or production will be more likely to have higher resting thresholds than those that are rarely encountered. Such a difference in resting threshold may indicate that common phonemes are more activated at rest than are rare ones. Consequently, just like the situations in the lexical level, common sounds should reach the activation threshold for recognition or production more rapidly than should rare sounds.

The strength of connections between phonemes may also be altered by word learning experience. When phonemes are commonly encountered in early word processing, it is thought that the connection between these phonemes is strengthened. Since the number of phonological neighbors and their phonotactic distribution will determine how much activation will spread to the related phonemes, phones with strong facilitory connections may reach the activation threshold more rapidly than those sound sequences with weak facilitory connections.

Interactions between Lexical and Phonological Representations

Interactions between lexical and phonological representations are also described by facilitory connections between lexical and phonological representations. The implication of these lexical-phonological connections, according to Strokel and Morrisette's (2002), is that once a lexical representation is activated, it will also activate its corresponding phonological representation. Activation can also occur in the opposite direction, with a phonological representation activating corresponding lexical representations. Such an interface between lexical and phonological representations will allow for capturing interactions between lexical and phonological processing.

In summary, connectionists' models of early word learning either use an inner self-organizing map or a combination of resting threshold and inhibitory and facilitory connections to capture input word patterns. The currents results can better be interpreted from these connectionist models.

Phonological Implicational Hierarchy and Connectionist's Interpretation

Since phonemic development didn't exactly conform to the specific order as predicted by the phonological implicational hierarchy, but a similar general trend was identified again. If a contradiction had been interpreted from the perspective of training an inner phonological self-organizing map, the flexibility of phoneme acquisition can be seen as a dynamic self-organizing map tuning process. It allows individual flexibility as well as preserves a common developmental trend. Tuning a self-organizing map doesn't imply which phonological features must be acquired first, and then move on to the next stage; phonemes need not be acquired from the least-articulatory- effort- required phonemes. Turning to resting threshold and inhibitory and facilitory connections, early phoneme and lexical development also need not conform a specific implicational hierarchy. Many routes of acquiring a phonemic inventory exist after adjusting resting threshold and the strength of inhibitory and facilitory connections. The flexibility of phonological development will be preserved as long as the resting threshold and connections can be readjusted according language input.

Dynamic vs. Static lexical development and connectionist's interpretation

Dynamic and Static lexical development with their proposals of a holistic and specific representations can also be reinterpreted under an interactive connectionist framework. The holistic-to-specific representation suggested by dynamic lexical development partially overlaps with tuning a self-organizing map or adjusting resting threshold and resetting inhibitory and facilitory connections. They all suggest early phonological systems need more time to develop its sophistication; only connectionists' model would use tuning or adjusting processes to replace a hypothetical holistic-to-specific transition. On the other hand, static lexical development assumes a complete phonemic inventory had been acquired after first 50 words. It seems such a position leaves a very short period of time for the self-organizing map tuning and resting threshold. In summary, a parallel, distributed and interactive connectionist model seems to have more potential to integrate results from the complicated interaction of early phonemic and lexical development.

Compared with direct activation links, an unsupervised self-organizing map seems to be more capable of capturing early phonemic-lexical interaction, but the current self-organizing model mainly focuses on the semantic level, and semantic distances have been used to calculate the distribution of early words. A two representational model with an inner phonological Bayesian learning map may better serve to model the process from a less-accurate imitation to a more sophisticated mastery of a native phonemic inventory. Recently Shortlist B theory of speech recognition (Norris, McQueen, 2008) introduced a word model based on the Bayesian principle. The Bayesian perspective was also rooted from calibration of phoneme likelihoods and on perceptual confusion data. How to integrate such an approach with tuning phonological self-organizing map calls for further efforts.

Limitations

The current study artificially divided early words into phonological neighbors and then categorized the words on a quantative level, i.e. how many neighbors they have. If checked by phonemes at any position, the phonological neighborhoods can be connected in a direct way or in a relayed manner. That means phonological neighbors are not isolated as shown by the current study, most of them are more tightly connected together. Vitevitch (2008) recently simulated an adult lexicon with 20,000 words. The results showed that there were 10,265 "lexical hermits" in a normal adult lexicon, which had no phonological neighbors. The average path length was 6.05. Such a characteristic had made the whole lexical network easy to traverse from one word to another one. There were only 6 proxy words on average in between all neighborhoods. This meant the current study only captured a localized surface layer of phonological similarity, an overall and deeper phonological similarity and lexical hermits have all been overlooked in the current study. Although with a large sample size, only words have been analyzed at item level by a loglinear model. This may also further undermine the validity of this study.

Implications and Future Directions

Since the above claims mainly came from speech language pathologists, the current confirmatory examination of the phonemic implicational hierarchy to another population revealed its limitations. The current results can help clinicians assess treatment protocols for phonologically disorders. Foreign language learners, who possess a special subset of deviant phonology, may also benefit from the research, because it would greatly help foreign language instructors and learners make comparisons on missing or mismatched phonemic elements and to set learning priorities accordingly.

Contemporary computer simulations of early phonological development can also benefit from these kinds of research, because typical developmental datasets could provide training sets for feeding Bayesian learning algorithms, and a computer assisted transcription algorithms, which can extract and categorize both phonemic and phonetic level errors patterns will greatly improve the efficiency of clinical speech language pathology.

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