Abrupt and Gradual Sound Change in an Expanding Lexicon*

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Abstract

The sound structure of language changes over time, but the process of change is not well understood. Sound change appears to occur abruptly as well as gradually, but it is not clear why, and it is not clear how the different rates of change affect the sound structures that emerge. This paper advances two hypotheses to answer these questions: (1) The Rate Hypothesis suggests that change occurs abruptly or gradually depending on how much an existing system is destabilized by social and cultural forces. (2) The Variation Hypothesis suggests that a greater diversity of sound structures emerge from abrupt change than gradual change because selection occurs on larger amounts of variation in more destabilized systems. These two hypotheses were tested in a computational model of sound change. The simulation results confirmed the hypotheses, and further suggested that abrupt change initially results in functionally suboptimal structure, whereas gradual change preserves good functionality. Overall, the study explains different rates of change in terms of a single framework and resolves a paradox in historical linguistics in which abrupt and gradual change are seen as incompatible, yet both exist.

1 INTRODUCTION

The pronunciation of words in a given language changes over time. This process, known as sound change, begins when speakers start pronouncing words with similar sound structures differently. Over time, several pronunciations coexist; eventually a single new pronunciation becomes the standard for a particular word class in a lexicon, completing the change. A well-known example of sound change is Grimm's Law, which formalizes the First Germanic Consonant Shift (Hock, 1991). As part of this shift, most instances of Proto-Indo-European voiceless stops were changed into Germanic voiceless fricatives. Accordingly, Germanic words differ predictably from their Romance language counterparts, which did not undergo the same sound change. For instance, compare the Latin words *piscis, pater, tres* with the English equivalents *fish, father, three*. This example also demonstrates why sound change is important—it is one of the major ways in which languages differentiate over time. In order to understand how different sound systems emerge, it is important to understand the process of sound change.

Sound change appears to be systematic, in that a particular change affects all eligible words in a lexicon (McMahon, 1994). It is not known, however, how this process takes place. A group of 19th century German linguists, called the Neogrammarians, originally proposed that sound change occurs abruptly across the lexicon. This view is still accepted by many linguists (e.g. Hock, 1991; Labov, 1994). In contrast, others have argued that sound change spreads gradually across the lexicon (e.g. Chen & Wang, 1975; Krishnamurti, 1978). The same language data is sometimes used to support each hypothesis. For instance, the English Great Vowel Shift, which brought about a series of vowel changes in Early Modern English, is used as an example of gradual change (Ogura, 1987; Aitchison, 1991) as well as abrupt change (Hock, 1991; Labov, 1994). So, the argument over whether sound change occurs abruptly or gradually presents a paradox: "both (views) are right, but both cannot be right (Labov, 1981: 269)."

The paradox leads to two main problems for understanding the process of sound change: (1) why does sound change proceed at different rates; and (2) what effect do the different rates have on the structure that emerges. In the present paper, we address these problems by developing a model of sound change, based on an analogy between linguistic and biological change. The model assumes that destabilizing, social and cultural pressures of variable strengths stimulate variation, and that new sound structures are selected from that variation according to the functional

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pressures of articulatory ease and perceptual distinctiveness. This model leads to two hypotheses, addressing each of the above problems: (1) Strong destabilizing pressures induce abrupt change, whereas weak pressures induce gradual change. (2) Strong destabilizing pressures induce more variation than weak pressures, giving rise to a greater diversity of structures.

The above hypotheses, identified as the Rate and Variation Hypotheses, were tested in simulations in which we manipulated the strength of a destabilizing pressure on an evolving lexicon. Simulation results supported the hypotheses. Strong and weak destabilizing pressures induced abrupt and gradual change, respectively. The changed lexicons differed in structure depending on whether they emerged abruptly or gradually. In addition, the results suggested that abrupt sound changes are initially suboptimal (under the functional pressures), whereas gradual changes maintain good functionality. Overall, these results support a new model of sound change—one that explains why sound change occurs at different rates, and how abrupt and gradual change can be distinguished. In the next two sections, we develop the model in detail, followed by simulations, results, and comparisons to other theories of sound change.

2 SOUND CHANGE

Explanations of language change have often been inspired by evolutionary theory (McMahon, 1994; Croft, 2000). In biological evolution, morphological or behavioral traits such as height or eating habits vary in a population of organisms. Changes in environmental or social (sexual) factors may favor a less well represented variant of a trait over a more highly represented one. For instance, if the environment suddenly changed so that the only food source available was tree foliage, the tallest individuals in a population would be favored over individuals of average height. Change occurs over generations as the new variant of a trait becomes highly represented and the mean character of the population shifts. Thus, the process of biological change can be understood as selection operating on variation.

Sound change can also be explained this way; however, since language is a cultural organism, variation and selection must be defined in social terms (Croft, 2000). In sound change, the way a sound sequence is produced varies from speaker to speaker. Changes in social or cultural factors may encourage a community of speakers and listeners to favor a new variant in production over a standard one. Sound change occurs when the new variant replaces the standard pronunciation, thereby shifting the sound structure of the lexicon. In this way, the process of sound change is analogous to evolution by natural selection.

Below, we develop this view of language change further to address the problems raised by the paradox of sound change. We look more closely at how language change is initiated and how structure emerges, aiming to explain why sound change proceeds at different rates and what effects, if any, rate of change has on the structure of a sound system.

2.1 Initiating Change: Variable Pressures

The main reason for language change is analogous to the reason for biological change: the social environment is constantly changing. Such a dynamic environment creates instability, which provides the impetus for language change (Steels & Kaplan, 1998; Nettle, 1999; Dircks & Stoness, 1999).

Linguists have identified a number of forces that create instability (for an overview, see Aitchison, 1991). We call these forces variable pressures and categorize them into two main types: sociolinguistic and expansion pressures. Sociolinguistic pressures destabilize language when the social structure of a society undergoes change, for instance, when group identity is forged or changed. Expansion pressures create new lexicons and occur with cultural change, for instance, with technological innovation or word borrowing. Either pressure will force language into disequilibrium, initiating language change.

2.2 Emergent Structure: Constant Pressures

A new sound structure emerges as equilibrium is restored through social selection, which can be influenced by many factors including prestige, identity, or language contact (Fasold, 1984; Edwards, 1985). The most fundamental factor influencing social selection arises from the function of language, that is, the need to communicate effectively (Martinet, 1955; Lindblom, MacNeilage, Studdert-Kennedy, 1984; Steels, 1997): (1) sounds must be easy to articulate; and (2) they must be perceptually distinctive. Functional pressures apply in the same way for all speakers of all languages, and do not change over time.

Models of emergent sound structure have shown that cross-language regularities can be explained in terms of either articulatory ease or perceptual distinctiveness or both (e.g., Liljencrants & Lindblom, 1972; Joanisse & Seidenberg, 1997; de Boer, 1999, Oudeyer, 2001; Redford, Chen, Miikkulainen, 2001). Language differences are also consistent with these functional pressures. This is because articulatory ease and perceptual distinctiveness often conflict with one another and so define a complex optimization problem that different sound structures may solve equally well (Redford, Chen, Miikkulainen, 2001). In other words, different languages arise as equally good solutions to the same optimization problem.

2.3 The Process of Change: Selection on Variation

The variable and constant pressures on a system are independent, but linked through variation. Variable pressures amplify normal (accidental) variation and introduce new variation, affecting both the rate and structure of sound change. The effect on the rate is proposed as the Rate Hypothesis. The effect on the structure is proposed as the Variation Hypothesis.

2.3.1 Rate Hypothesis

The Rate Hypothesis suggests that the rate of sound change depends on the strength of the variable pressure that destabilizes the sound system. In a destabilized system, structure is less evident than variation. Depending on the strength of the pressure, the system is destabilized to a greater or lesser extent. In the extreme, a strong variable pressure will cause the existing structure to be obscured by variation. Under these conditions, new structure emerges de novo with few constraints, and sound change is abrupt. In the other extreme, a weak pressure will allow the existing structure to remain evident despite variation. Emergent structure is additionally constrained by the pre-existing structure, and sound change is gradual, as new forms are slowly selected over old ones. This way sound change occurs either abruptly or gradually through the same process.

2.3.2 Variation Hypothesis

The Variation Hypothesis suggests that a greater diversity of sound structures emerge from an abrupt change than from a gradual change. This is because variable pressures affect the amount of variation available for selection, which in turn affects the number and types of structures that can emerge. For example, a strong pressure for upward social mobility causes lower-middle and upper-working class British English speakers to hypercorrect their speech and introduce new variants into their language. Lower-working class speakers are unaffected by such a pressure (they are not socially mobile) and do not introduce these types of variants (McMahon, 1994: 244). A larger amount of variation allows a greater diversity of sound structures to emerge because more different variants are available for selection, and many different structures will satisfy the functional constraints equally well (Redford, Chen, Miikkulainen, 2001). So, abrupt change can be distinguished from gradual change on the basis of the diversity of structures that emerge.

In this paper, we test the Rate and Variation Hypotheses in a computational model of sound change, called the Lexicon Expansion Model (LEM). A single lexicon is evolved according to constant and variable pressures, thereby simulating the conditions of language change over time, as will be described in the next section.

3 LEXICON EXPANSION MODEL (LEM)

The Lexicon Expansion Model (LEM) first evolves a population of syllables according to the constant pressure for articulatory ease. Once a syllable population is established, syllables are randomly selected and concatenated to form words of differing lengths. A number of words are combined to form an initial lexicon, which is evolved according to the constant pressure for perceptual distinctiveness.

Sound change occurs when the lexicon is destabilized by a pressure for new words, which can be weak or strong. Word generation introduces variation into the lexicon in the form of new syllable combinations. Selection according to perceptual distinctiveness then occurs on new and old variants, causing the structure of the lexicon to change over time. This process of selection on variation will be referred to as *sound system evolution* in this paper.

The structure of the model is outlined in Figure 1, and described in more detail in the following subsections.

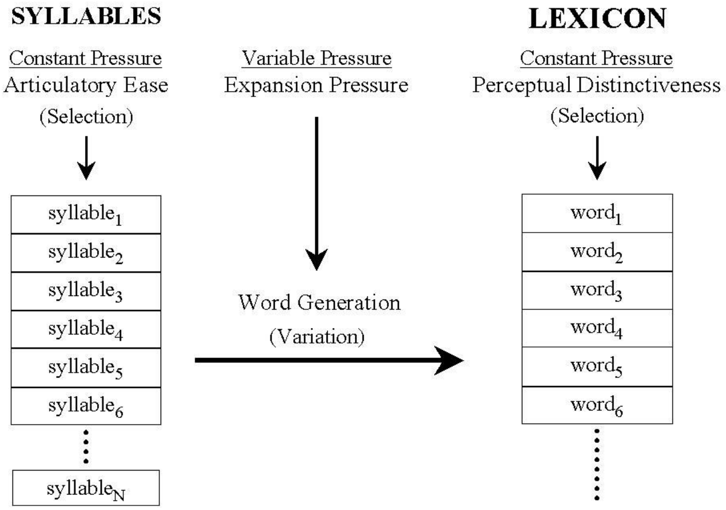

Figure 1: The Lexicon Expansion Model (LEM) first evolves a stable syllable population according to the constant pressure for articulatory ease. An initial lexicon is then evolved according to the constant pressure for perceptual distinctiveness. Sound change occurs when the lexicon is destabilized by a variable pressure for new words.

3.1 Syllable Population

In LEM, individual syllables are generated according to a detailed articulatory program. This ensures that the syllables are natural, i.e., they could have been produced by a human speaker. A number of syllables are created randomly to form an initial syllable population. The population is then evolved according to the constant pressure for articulatory ease, which is realized as a set of articulatory costs.

3.1.1 Syllable Generation

Syllables are generated as sound sequences produced by speech articulators. The model encodes the movements of five articulators: the glottis, the jaw, the tongue body, the tongue tip, and the lips. With the exception of the jaw, the movements of all the articulators are represented categorically in an end state. The opening and closing movements of the jaw are continuous, but discretized as a series of time steps.

A syllable is defined by a single jaw cycle, that is, by the movement from a rest (closed) position to an open position and back (MacNeilage, 1998; Redford, 1999). The co-occurring movements of the articulators are defined as consonant, sonorant, or vowel articulations depending on jaw height. Once described as sequences of segments, the syllables are included into the syllable population and evaluated according to how costly they are to articulate.

3.1.2 Articulatory Costs

Articulatory ease is determined by two costs: a production cost motivated by the biomechanical factors involved in sound generation and a motor-routine storage cost motivated by psychological factors that depend on the entire population of sounds.

1. Production cost $C_{P,x}$ is determined as the sum of the number of movements executed by the articulators during production of syllable x. Specifically,

$$C_{P,x} = \sum_a \sum_t M_{at}, \tag{1}$$

where a is an articulator, and t is a time step, and

$$M_{at} = \begin{cases} 1 & \text{if articulator } a \text{ moved at time } t, \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

This way, more complex syllable articulations are more costly than simpler articulations.

Syllables are generated randomly and those with the smallest production costs are selected to form the initial syllable population. A second articulatory cost is then applied to measure the efficiency of the syllable as a part of the entire population.

2. Storage cost $C_{G,x}$: Syllables that diverge more from others in the population receive higher costs than those that diverge less. The onset and offset of syllable x are compared with other types of onsets and offsets in the population, and the differences between the evaluated syllable and the population are summed:

$$C_{G,x} = \sum_s (N_s + F_s), \tag{3}$$

where s is a syllable in the population,

$$N_s = \begin{cases} 1 & \text{if } s \text{ has a different onset than } x, \\ 0 & \text{otherwise,} \end{cases} \tag{4}$$

$$F_s = \begin{cases} 1 & \text{if } s \text{ has a different offset than } x, \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

This way, a syllable population that is more uniform in structure is less costly than one that is less uniform. The rationale is that a more uniform system has a simpler representation in memory (Lindblom, 2000).

The two articulatory costs are multiplied to obtain the total cost of the syllable. Syllables are then sorted according to the total cost. The most costly syllables are replaced by new, randomly-generated syllables with smaller initial costs and the evaluation and selection process is repeated. In this way, after many iterations, an efficient syllable population emerges. This population provides the basis for word generation.

3.2 Lexicon

In LEM, words are composed of one or more syllables and combined to form a lexicon. The lexicon is evolved according to the constant pressure for perceptual distinctiveness, which is realized as a set of perceptual costs.

3.2.1 Word Formation

Words are generated by randomly selecting one to four syllables from the syllable population. If more than one syllable is selected, they are concatenated in the order selected to form multisyllabic words.

The words are tagged to indicate when they were generated relative to the other words in the system. In this way, the number of variants generated during the evolution of a single lexicon is tracked. The tag also allows us to determine the age of a word in a lexicon at any given point during evolution.

The first few words generated are combined to form an initial lexicon. The lexicon is then evolved to make the words perceptually more distinctive.

3.2.2 Perceptual Costs

Perceptual distinctiveness is determined by three perceptual costs: structural, distinctiveness, and intelligibility. These costs are motivated by perceptual and cognitive factors, as outlined below.

1. Structural cost $C_{T,y}$ evaluates the perceptibility of the component syllables of word y. Different syllable forms have different perceptual costs because consonants are more or less perceptible, depending on their position in a word. In the present version of the model, the costs for the different types of onsets and offsets (with C a consonant and S a sonorant) were as follows: C/S onset = 1, C/S offset = 2, CS onset = 3, SC offset and CC onset = 4, CC offset = 5, CCS onset = 6, SCC offset and CCC onset = 7, and CCC offset = 8. The values indicate that onsets are more perceptible than offsets, single consonants are more perceptible than consonant clusters, clusters with two consonants are more perceptible than clusters of three consonants, and consonant-sonorant combinations are more perceptible than consonant-consonant combinations (Redford & Diehl, 1999; Redford, 1999). The initial perceptual cost of a word is the sum of the syllable onset and offset costs:

$$C_{T,y} = \sum_{x} (n_x + f_x), \tag{6}$$

where x is a syllable in a word y, n_x is its onset cost, and f_x is its offset cost.

2. Distinctiveness cost $C_{D,y}$ evaluates how distinctive word y is compared to other words in a lexicon. Each of its constituent syllables is compared to all the other syllables in all the other words. The number of identical onset and offset types (e.g., C, CC) are counted, but only if they are made up of different phonemes (e.g., /b/, /br-/). The cost for a word is then calculated as the sum of identical onset or offset types that occur in the lexicon:

$$C_{D,y} = \sum_{s} \sum_{y \neq w} \sum_{x \neq s} (K_{yxws} + L_{yxws}), \tag{7}$$

where x is a syllable in word y, and s is a syllable in word w, and

$$K_{yxws} = \begin{cases} 1 & \text{if the onset of syllable } x \text{ in word } y \text{ has the same type,} \\ & \text{but different phoneme than onset of syllable } s \text{ in word } w, \\ 0 & \text{otherwise,} \end{cases} \tag{8}$$

[L_{yxws} similarly for offsets]

The rationale for this cost is that sounds of a word are less distinctive if they participate in a structure that is highly common throughout the lexicon. For example, if multiple different sounds can occur in syllable offset position, any single sound is likely to be confused with the other sounds that can occur in that position and the perceptual cost is high. If, however, only one sound can occur in a syllable-offset position, then all syllable offsets will be safely perceived as that sound and the perceptual cost is low.

3. Intelligibility cost $C_{I,y}$ evaluates the intelligibility of word y in the lexicon by calculating the number of different instances of the same word in the lexicon. The more instances there are, the less intelligible the word is, and therefore the greater its cost:

$$C_{I,y} = \sum_{w} I_w, \tag{9}$$

where w is a word in the lexicon, and

$$L_W = \begin{cases} 1 & \text{if word } w \text{ is identical to } y, \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

The rationale for this cost is that in an ideal lexicon, each word corresponds to exactly one meaning (Vennemann, 1978). We take multiple instances of the same word in a lexicon to indicate that the word has multiple meanings.

The perceptual costs are multiplied to obtain a total cost for each word. Words are then sorted according to this total cost and a percentage of high-cost words are replaced by new randomly-generated words. Several versions of the lexicon are created in this way, and the perceptual costs of the words are re-evaluated in each version. Each version is assigned an overall cost, determined as a sum of the total costs associated with the individual words. The version with the lowest overall cost provides the basis for the next iteration of evolution.

The sound structure of a lexicon becomes progressively more distinctive according to the evolution process described above. At some point, no further gains are made and the sound structure remains stable, despite the continuing replacement of a portion of the lexicon with new words. Once stability emerges, the sound structure will only change if the system is destabilized.

3.3 Variable Pressure

Stability is disrupted by a pressure to expand the size of the lexicon. This pressure is implemented as a growth rate parameter. At every iteration of evolution, a continuous lexicon size variable is multiplied by the growth rate parameter. If the size increases over an integer value, a word is added to the lexicon. This way, under very low expansion rates, the lexicon is not necessarily augmented at each generation. The growth rate parameter also ensures that the number of new words added to a lexicon is proportional to the size of the lexicon, i.e., the lexicon expands exponentially. Exponential growth is more realistic than linear growth in modeling, for example, lexical borrowing. Borrowing is likely to begin slowly and build on itself over time (Aitchison, 1991).

In the present study, we manipulated the growth rate parameter to study the effect of a variable pressure on sound change. Lexicons were expanded at a fast and slow rate to model a strong and weak variable pressure on a system.

3.4 Predictions

The model allows us to make several specific predictions derived from the Rate and Variation Hypotheses, that is, (1) the strength of a variable pressure determines the rate of change, such that a stronger pressure induces abrupt change and a weaker pressure induces gradual change; and (2) abrupt change is associated with a greater diversity of structures than gradual change.

More specifically, to test the Rate Hypothesis, we examined changes in the sound structure during different rates of expansion. We focused on changes in the percentage of two types of word onsets: single consonants and vowels. These were chosen as indices of sound structure for two reasons. First, we could predict the direction of change based on an interaction between lexicon size and the constant pressure for perceptual distinctiveness. Consonant onsets were predicted to decrease and vowel onsets to increase over the course of lexicon expansion because consonant onsets are more basic and therefore less distinctive than vowel onsets (Bell & Hooper, 1978; Hock, 1991). Second, the abruptly and gradually changed lexicons were expected to have comparable structures because the onset types were highly constrained by the structure of the underlying syllable population. Therefore, any changes in these indices would be due to lexicon size, not to differences in the amount of variation.

Third, the Rate Hypothesis implies that structure emerges de novo in lexicons destabilized by strong variable pressures, but that new forms are adopted slowly in lexicons destabilized by weak pressures. To test this idea, we examined the age of words in the final lexicons of the two conditions. If the structure emerged de novo, all the words should be roughly the same age, whereas if new forms were adopted slowly, the words should be of many different ages.

To test the Variation Hypothesis, we measured changes in the percentage of monosyllabic and multisyllabic words. We expected that the larger amount of variation in the fast condition would lead to greater diversity in word length. Specifically, we expected that lexicons that expanded slowly would continue to be composed mostly of monosyllables, whereas there would be more long words in lexicons that underwent fast expansion.

Second, we compared the sound structures that emerged on different runs of the model with the same expansion rate. Variance across the runs was expected to differ in the fast versus slow expansion conditions if the underlying variation differed. For example, variance in word onsets would be equal in the two conditions because they were constrained by the same syllable population. On the other hand, variance in word length was expected to be greater in the fast condition because word length was randomly determined during word generation. Since more words were generated during fast expansion, a larger number of variants would be available for selection, and a greater diversity of structures could emerge on different runs of the model. Such a result would demonstrate that there are indeed many equally good solutions to the optimization problem, and therefore the diversity of structure in the final lexicon is due to the amount of variation generated during the evolutionary process.

Third, we examined the overall perceptual costs associated with the changing lexicons in the two conditions. Costs were predicted to converge in the two conditions, even if structure differed. This prediction was based on the idea, central to the Variation Hypothesis, that many different sound structures are possible under the constraints imposed by the constant pressures, and the structures are equally good.

Below, the simulations are described and the results are presented and discussed in detail.

4 SIMULATIONS

Lexicons were expanded at a fast and slow rate, as shown in Figure 2. Fast expansion was preceded by slow expansion and followed by no expansion. Slow expansion was also followed by a period of no expansion so that, the lexicon was evolved over the same number of iterations in both simulations. This way, the final lexicons had the same size, and the only difference was the rate at which it was achieved. Below, the exact parameter values are specified and the results reviewed.

4.1 Parameter Values

Lexicons in the two expansion conditions were formed from the same underlying syllable population of 100 syllables, developed in 500 iterations of evolution, as described in the previous section. Twenty-five percent of the population was replaced during each iteration. Initial lexicons were composed of 5 words each, obtained through 50 iterations of evolution.

Fast and slow lexicon expansion were achieved in the following way. The growth rate parameter was set to 1.01 in both conditions until the 150th iteration, when the lexicon had 22 words. At this point in the fast condition, the growth rate parameter was set to 1.10 and the lexicon began to expand rapidly. When it reached its final size of 226 words at the 177th iteration, the parameter was set to 1.0 (i.e., no expansion) and evolution continued until the 399th iteration. In the slow condition, the growth rate parameter was changed only once—when the final lexicon size of 226 words was reached at the 383rd iteration. At this point, the parameter was set to 1.0 and evolution continued until the 399th iteration.

Throughout the simulation, 10 percent of the word population was replaced during selection, and 250 new versions of the lexicon were created each time. The version with the lowest overall cost was then used as the basis for the next iteration of evolution. Twenty-two simulations were run in each condition.

4.2 Results

As described in section 3.4, to test the Rate Hypothesis, we examined (1) the direction and (2) rate of change in the percentage of consonant and vowel onsets during lexicon evolution, and (3) the average age of words in the final lexicons of the two conditions. To test the Variation Hypothesis, we compared (1) the percentage of monosyllabic

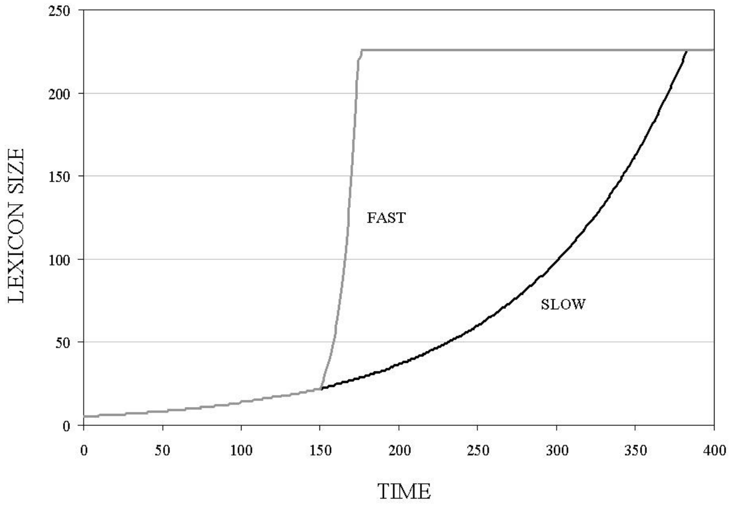

Figure 2: Lexicons were expanded at a fast and a slow rate over the same number of iterations by manipulating a growth rate parameter. Different expansion rates modeled different strengths of the same variable pressure on the system. Fast expansion modeled a strong pressure, and slow expansion a weak one.

and multisyllabic words during fast and slow lexicon expansion, (2) the variance across the different runs of the two conditions, and (3) the changes in the overall costs during evolution.

In short, we found that a strong (fast) expansion pressure induced abrupt change, and a weak (slow) one induced gradual change. The word histories showed that structure emerged de novo in the fast condition and a few words at a time in the slow condition. Together, these results confirmed the Rate Hypothesis.

Lexicons with fewer monosyllables and more multisyllables emerged in the fast condition than in the slow one, resulting in a greater diversity of word lengths. In addition, there was more variance across the fast expansion runs, even in word onsets. Third, overall perceptual costs converged in the two conditions, in spite of persistent differences in structure. Together, these results confirmed the Variation Hypothesis.

Examination of the perceptual costs also led to an interesting insight about the evolution process. The perceptual costs increased dramatically during fast expansion, but not during slow expansion. Costs were rapidly minimized in the fast condition once the expansion pressure subsided. This result suggests that under a strong variable pressure emergent structure is functionally suboptimal because selection is overwhelmed by large amounts of variation.

The results are presented in more detail below.

4.2.1 Rate Hypothesis

To test the Rate Hypothesis, we examined how the percentage of consonant and vowel onsets in the lexicons changed during fast and slow expansion. These percentages are shown in Figure 3.

The changes occurred in the predicted manner. Consonant onsets decreased during lexicon expansion from an average of 47.27% to 37.06% and vowel onsets increased from 20.91% to 28.79%. Change was abrupt in the fast condition and gradual in the slow condition. To quantify the difference, we compared the percentages at 11 points during lexicon evolution, specifically at iterations 25, 75, 125, 150, 175, 200, 225, 275, 325, 375, and 399. The two conditions differed in consonant onsets only at iteration 175 [$F(1, 42) = 13.45$; $p < .01$], which was just before the end of expansion in the fast condition. The vowel onsets were different at iterations 150 [$F(1, 42) = 5.83$, $p < .01$], 175 [$F(1, 42) = 13.00$, $p < .01$], and 200 [$F(1, 42) = 5.92$, $p < .01$], in other words during and after the fast expansion. The fact that sound structures differed during evolution, but not at the beginning or end, confirms that the lexicons

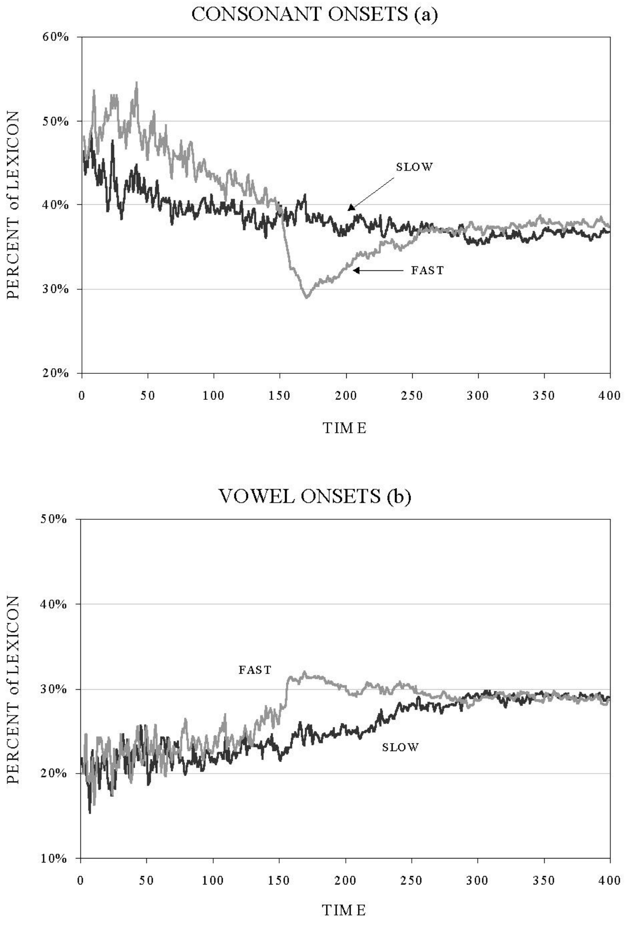

Figure 3: The percentage of single consonant onsets (a) and vowel onsets (b) are displayed for the fast and slow condition, averaged over 22 runs of the model. The proportion of consonant onsets decreased, whereas that of vowel onsets increased. The changes were abrupt in the lexicons of the fast condition and gradual in the lexicons of the slow condition, confirming the Rate Hypothesis.

underwent the same sound change differently.

Figure 3a shows an additional difference between the two cases. In the fast condition, the decreases in consonant onsets that occurred during fast expansion were not stable. Once the expansion pressure subsided at iteration 177, the percentage of these onsets increased again. In contrast, the decreases reached an asymptote in the slow condition before the expansion pressure subsided at iteration 383. This instability in the fast condition suggests that selection during expansion does not optimize the structure of the lexicon.

To determine whether the different rates of change affected how structure emerged, we examined the age of participating words in the final lexicons. The age of each word was determined with respect to the newest word in each lexicon. The results, averaged over all the simulations, are shown in Figure 4.

As is evident from the figure, words in the final lexicons of the fast expansion condition were roughly the same age, indicating that structure emerged de novo. Words of the final lexicon in the slow condition were of different ages, indicating that new variants were adopted slowly in this case.

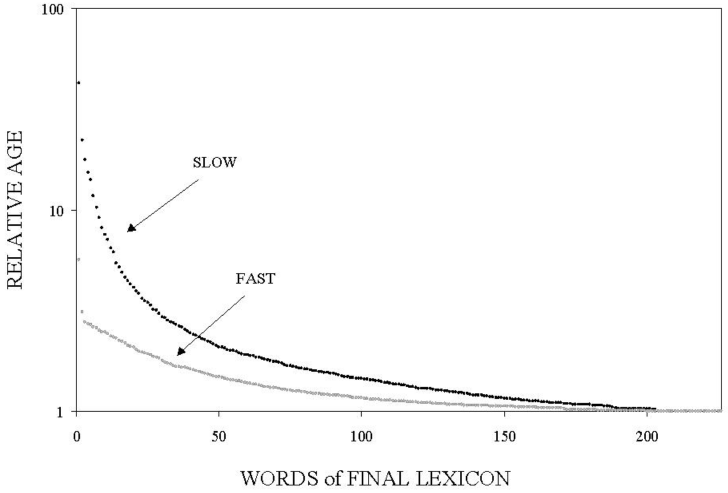

Figure 4: The average age of each of the 226 words are shown for the 22 final lexicons of the fast and slow conditions on a logarithmic scale. Overall, the words in the fast condition are more homogeneous in age than those in the slow condition, indicating that structure emerged de novo.

4.2.2 Variation Hypothesis

To test the Variation Hypothesis, we measured the percentage of monosyllabic and multisyllabic words during lexicon expansion.

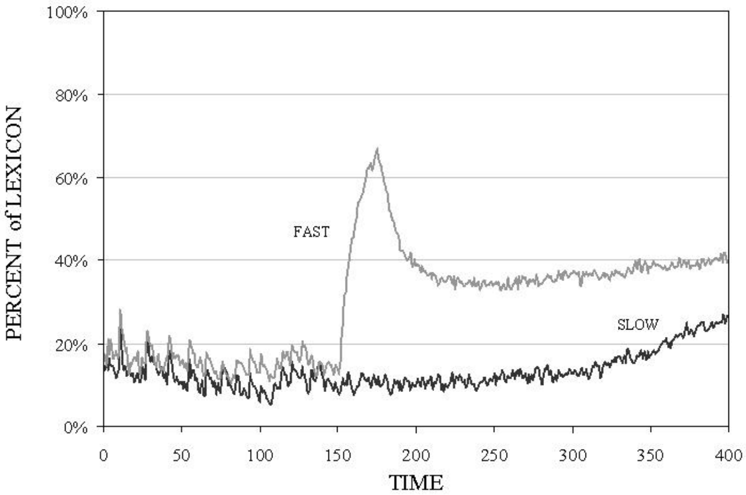

Figure 5: The percentage of multisyllabic words is shown for the fast and slow condition, averaged over 22 runs of the model. The proportion of multisyllables increased under the constant pressure for perceptual distinctiveness. The change was greater in the fast condition than in the slow one, supporting the first prediction of the Variation Hypothesis.

As seen in Figure 5, the proportion of multisyllabic words increased in both conditions, which is to be expected because longer words are more distinctive than shorter words (Hock, 1991). As predicted, the change was greater in the fast condition than in the slow condition. As before, we compared the lexicons at 11 points during evolution, specifically at iterations 25, 75, 125, 150, 175, 200, 225, 275, 325, 375, and 399. The differences were significant ($p < .001$) from iteration 175 to 399. This result is obvious from Figure 5, where the percentages diverge in the two conditions after iteration 150. Such persistent differences in structure confirm the first prediction of the Variation Hypothesis: larger amounts of variation in the fast condition leads to more diversity in word length.

As described in section 3.4, the Variation Hypothesis also predicted that variance across the runs of the model would differ in the two conditions if the variation also differed, that is, we expected variances to be equal for onsets and different for word length. However, in all cases variance was greater in the fast condition than in the slow one: 1.55 times greater for consonant onsets, 1.43 times greater for vowel onsets, 2.35 times greater for monosyllabic words, and 4.61 times greater for disyllabic words. This result suggests that a large amount of variation during expansion is not the only factor that contributes to the rise of a greater diversity of structures in the fast condition, as will be discussed in more detail in section 5.2.3.

To test the prediction that the lexicons of the fast and slow condition are equally well optimized under the constant pressure, we measured their overall perceptual costs throughout evolution. Figure 6 shows that the average costs differed in the two conditions during lexicon expansion. In the slow condition, costs remained low, whereas costs increased dramatically in the fast condition. This result suggests that selection, which discards only a few variants at each iteration of evolution, was overwhelmed by the number of new words added to the lexicon during fast expansion. Once the expansion pressure subsided and no new words were added, selection was effective and perceptual costs were minimized. Costs converged in the two conditions when the lexicons reached their final sized of 226 words. This latter result confirms the third prediction of the Variation Hypothesis.

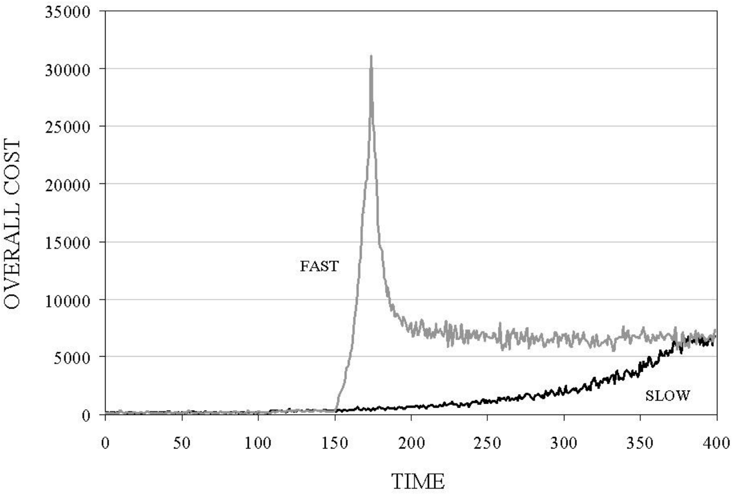

Figure 6: The overall perceptual costs are displayed for the fast and slow condition, averaged over 22 runs of the model. The costs increase abruptly during fast expansion and are quickly minimized once the pressure subsides. The overall costs converge when the slowly expanded lexicon reaches its final size, showing that the final lexicons are equally distinctive despite their differences in structure.

5 DISCUSSION

So far, we have shown that the simulation results support the Rate Hypothesis, which suggests that the rate of sound change is determined by different strengths of a variable pressure. The results also support the predictions of the Variation Hypothesis in that a greater diversity of structures emerge from abrupt than from gradual sound change. Further, the results indicate that costs were not optimized during fast expansion, which suggests that selection does not operate effectively on large amounts of variation.

In this section, we will return to the paradox of sound change and the two problems that arise from it, and show how these new insights help resolve them. Specifically, we show how abrupt and gradual change are compatible with a single mechanism of change. Second, we consider how the strength of a variable pressure affects the amount of variation and how different amounts of variation affect social selection, resulting in different emergent structures. In addition, we compare the types of sound changes in LEM with those that occur in natural language and identify future directions of research in computational modeling of sound change.

5.1 One Mechanism, Two Rates of Change

In the sound change paradox, the terms abrupt and gradual refer not only to different rates of change, but also to different linguistic theories. Abrupt change is associated with the Neogrammarian theory, which suggests that change takes place at the phonetic level. All sounds in the same context are affected simultaneously, and independently of any other factor, such as word meaning (Hock, 1991; Labov, 1994). Gradual change, on the other hand, is associated with the Lexical Diffusion theory. According to this theory, change is transmitted from word to word within a lexicon (Chen & Wang, 1975). The rate at which the transmission occurs is sensitive to nonphonetic factors (such as word meaning) that influence whether or not a change is adopted.

The two theories imbue the terms abrupt and gradual with special meaning. Abrupt change refers to a discontinuous shift from one sound structure to another. In contrast, gradual change refers to a continuous change in a sound system. The paradox of sound change cannot be resolved by either theory because abrupt and gradual change are thought to denote two separate mechanisms of change.

In the present paper, a third mechanism of change was proposed: selection on variation according to constant functional pressures. Importantly, in a dynamic system, this mechanism gives rise to qualitatively different types of change. When the system is disrupted by a strong variable pressure, structure emerges de novo, and the transition from one structure to another is discontinuous. In contrast, under a weak variable pressure, the emerging new structure is highly constrained by existing structure. New and old variants co-exist, with the new ones gradually replacing the old. In the simulations, these two different modes of change were evident in the discontinuous versus gradual shifts in sound structure (Figures 3 and 5) as well as in the different age distribution of words in the final lexicons (Figure 4). Interestingly, these descriptions of change match those given in the Neogrammarian and Lexical Diffusion theory.

In conclusion, LEM shows that both abrupt and gradual change are consistent with a single mechanism, thereby resolving the first problem of sound change.

5.2 The Effect of Variable Pressures on Emergent Structure

The second problem of sound change is how the different rates of change affect the structure that emerges. Below, the insights from LEM are reviewed and compared to natural language: we discuss how a variable pressure affects the amount of variation, how the amount of variation affects social selection, and how differences in selection affect emergent structure, resolving the second problem.

5.2.1 How Variable Pressures Affect Variation

In LEM, the variable pressure was the need to expand the lexicon. Depending on the strength of the pressure, different numbers of new words were added to the lexicon during each iteration of evolution. More words were added under a strong pressure than under a weak one. Since variation was introduced during word formation as new combinations of syllables, a stronger expansion pressure also introduced more variation than a weak pressure.

An expansion pressure can be satisfied in natural language in a number ways. One way is through borrowing, which introduces new variation into a lexicon in the form of foreign words. Since the foreign words often have different sound patterns than the native words, a large amount of borrowing can lead to change in the native sound system (McMahon, 1994).

Strong social and cultural pressures will induce more borrowing than weaker ones. Specifically, when different language communities come into contact, one language (A) is often more dominant than the other (B) for economic or political reasons. In cases where the dominant language is also the prestige language, the speakers of language B will borrow freely from language A, whereas the reverse will not happen (e.g. German vs. Hungarian in Oberwart; Fasold, 1984: 222). However, language A may not be always be prestigious. In these cases, borrowing will be diminished (e.g. English vs. French in Quebec; Edwards, 1985: 28-29). So, the extent of borrowing depends on the (perceived) prestige of the loan language. Greater prestige induces more borrowing, which results in more new variation in the language.

Thus, in natural language, as in LEM, strong variable pressures induce a large amount of variation. In the following subsection, we consider how the amount of variation in turn affects social selection.

5.2.2 How Variation Affects Social Selection

In LEM, variation was subject to selection according to the same constant pressure at each iteration of evolution. As was discussed in section 4.2.2., selection was effective on the small amount of variation introduced during slow expansion, but ineffective on the larger amount of variation introduced during fast expansion (Figure 6). This difference explains why gradual change was stable, but abrupt change was not (Figure 3a and 5).

Selection in LEM models a tacit agreement between speakers to use one form instead of another. The results suggest that this process breaks down under a strong variable pressure that introduces larger amounts of variation and abrupt change. Interestingly, Ogura and Wang (1996) make a similar suggestion based on their two-dimensional model of sound change.

The two dimensions in Ogura and Wang's (1996) model are word (W) and speaker (S). Sound change is characterized as W- and S-diffusion, that is, diffusion of a sound change from word to word in a single speaker, and from speaker to speaker in the language community. Change can proceed quickly or slowly along either dimension. They argue that fast W-diffusion and slow S-diffusion describe abrupt change, whereas slow W-diffusion and fast S-diffusion describe gradual change. Changes can be distinguished because variation is greater for an incomplete change than for a complete one. So, greater variation between speakers in the pronunciation of a particular class of words signifies abrupt change, whereas gradual change is signaled by greater variation in an individual's pronunciation of the same class of words.

The prediction of more variation in the S-dimension during abrupt change is novel and supported by Ogura and Wang with specific language examples. However, they do not provide a reason for this prediction. In our view, variation between speakers signifies a problem in selection, implying that speakers have not yet come to a tacit agreement on what should be the standard pronunciation. LEM suggests that such variation occurs because the selection process is swamped by the large numbers of new forms induced by a strong variable pressure for change.

5.2.3 How Differences in Social Selection Affect Emergent Structure

Let us now turn to the third component of our answer to the second problem of sound change: how a greater diversity of structures emerge from abrupt change than from gradual change.

Our original hypothesis was that more variation would give rise to a greater diversity of structure because there are many equally good ways to solve the optimization problem defined by the functional pressure. This hypothesis was tested by measuring variance of sound structures across different runs of the model, with and without differences in underlying variation. Contrary to our expectations, variance was always greater in the fast condition, suggesting that the amount of variation was not the only factor affecting what structures emerge.

The other factor is selection. Effective selection under a weak expansion pressure minimized the perceptual costs of the lexicon, but also minimized the variety of word forms available for selection. Consequently, gradual change was conservative. In contrast, ineffective selection under a strong pressure allowed many different forms to enter the lexicon. Once the expansion pressure subsided and selection became effective, this variety gave rise to a greater diversity of structures that were equal under the functional pressures, and to changes that were more extreme.

The simulation results lead to two further predictions about change in natural language. First, LEM predicts that if a strong variable pressure does not subside, a language may become too inefficient for use and language death could result. This prediction is supported by cases of language death where two languages are in prolonged contact and one of them is more prestigious than the other. For example, consider the (near) death of Irish due to 400 years of contact with English (Edwards, 1985). Second, LEM predicts that if the pressure eventually subsides, the new, stable sound structure will diverge more from old structure than it would have through gradual change. This prediction can be tested by measuring the correlation between the size of change in a language with the strength of the variable pressure.

In conclusion, LEM suggests that a stronger variable pressure introduces more variation than a weak one, and that social selection does not operate effectively on large amounts of variation. Consequently, abrupt change results in a greater diversity of structure than gradual change. Together these results resolve the second problem of sound change.

5.3 Modeling Known Sound Change

So far, the simulation results have been discussed in the context of the different theories of sound change. We found that LEM unifies many hypotheses in a coherent and principled way, and makes novel predictions. We turn now to comparing the simulation results to known sound changes in natural language.

At an abstract level, the sound changes in LEM are consistent with known tendencies in language. In LEM, change increased structural complexity. The basic forms—consonant onsets and monosyllables—were replaced over time by more derived forms, such as vowel onsets and multisyllables. This overall direction of change matches that of natural language (Hock, 1991). In addition, the basic and derived forms in LEM are also basic and derived forms in languages (Bell and Hooper, 1978; Hock, 1991).

At a more concrete level, though, the particular sound changes in LEM are quite different from those described for natural language. In LEM, we observed changes in the relative frequency of sound structures already present in the lexicon. In contrast, sound changes in the literature are often described as categorical changes to a sound system. For instance, McMahon (1994: 210) explains that the sounds /d g/ were introduced into Spanish through lexical borrowing. Since LEM also introduced new words into a lexicon, why did categorical changes of this type not occur in the simulations?

The answer is that the present version of LEM did not include a component for generating phonetic variation. Instead, variation was introduced into the lexicon as new syllable combinations. The syllables were drawn from a fixed population, which had been previously evolved according to articulatory ease. Such a two-layered architecture allowed us to test one of the assumptions of the Variation Hypothesis by constraining the potential variation in structure (i.e., onsets), but not in word length. The limitation that this architecture imposes is easily remedied in LEM by having the speech articulators produce words directly, and then evolving lexicons according to the conflicting pressures for articulatory ease and perceptual distinctiveness. Such a modification would allow LEM to model categorical change as it occurs through borrowing, and constitutes a most interesting direction of future research.

6 CONCLUSION

The Rate and Variation Hypotheses proposed in the present paper resolve two problems stemming from the paradox of sound change. Abrupt and gradual change result from strong and weak variable pressures on the sound system, and can be distinguished on the basis of emergent diversity in structure. The hypotheses were tested in a model of sound change, where variable pressures affect variation and new structure emerges through selection according to functional pressures. This model grounds an evolutionary approach to understanding sound change on precise computational terms, and is the first approach to explain abrupt and gradual change according to a single mechanism.

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