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Brief article

The basic reproductive ratio as a link between acquisition and change in phonotactics

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ABSTRACT

Language acquisition and change are thought to be causally connected. We demonstrate a method for quantifying the strength of this connection in terms of the 'basic reproductive ratio' of linguistic constituents. It represents a standardized measure of reproductive success, which can be derived both from diachronic and from acquisition data. By analyzing phonotactic English data, we show that the results of both types of derivation correlate, so that phonotactic acquisition indeed predicts phonotactic change, and *vice versa*. After drawing that general conclusion, we discuss the role of utterance frequency and show that the latter exhibits destabilizing effects only on late acquired items, which belong to phonotactic periphery. We conclude that – at least in the evolution of English phonotactics – acquisition serves conservation, while innovation is more likely to occur in adult speech and affects items that are less entrenched but comparably frequent.

1. Introduction

Languages are systems of mental instructions that are shared by their speakers. They are instantiated in the mind-brains of many individuals and transmitted across generations through communicative interaction and language acquisition. For a constituent of linguistic knowledge to be successfully transmitted across generations, it needs to be used and expressed by adult speakers in such a way that new generations can acquire it successfully. Thus, the history of language constituents depends on language use and language acquisition and is likely to reflect constraints on both of them. This paper focusses on the relation between history and acquisition.

That language acquisition is crucial for language history is trivially true and generally acknowledged (Briscoe, 2008; Smith & Kirby, 2008). After all, constituents that are not acquired cannot survive. However, the matter is both more complex and more interesting than that. On the one hand, there is considerable disagreement about how much language acquisition contributes to linguistic change, and on the other hand, some correlations between acquisition and diachronic stability appear to be quite specific. For instance, Monaghan (2014), demonstrates that the age at which a lexical item is acquired predicts the diachronic stability of its phonological form. The finding has inspired various attempts to account for it, but no consensus has been reached. On one interpretation, early acquisition is thought to cause diachronic stability: early acquired items become strongly entrenched, get to be used frequently, and are therefore more likely to be historically stable than items that are acquired later (MacNeilage & Davis, 2000; Monaghan, 2014). On another view, early acquisition and diachronic stability are thought to have common causes: items will both be acquired early and remain diachronically stable if they are easily produced, perceived, or memorized, for example.

This paper explores the relation between the diachronic stability of linguistic constituents and the age at which they are acquired. To determine how systematic that relation is, we introduce and test a rigorous quantitative model that relates patterns attested in historical language development to patterns attested in language acquisition. More specifically, we show how age-of-acquisition and diachronic stability can be related to each other in terms of a standardized measure of reproductive success, namely their 'basic reproductive ratio' (henceforth R_0) (Dietz, 1993; Heffernan, Smith, & Wahl, 2005). That measure (more on it below, see Section 2.1) has proved useful in the study of population dynamics. We use a population dynamic model[1] that has already been applied to explain linguistic phenomena (Nowak, 2000; Nowak, Plotkin, & Jansen, 2000) and show how estimates of R_0 can be derived for linguistic constituents. Crucially, they can be derived both from age-of-acquisition data and from diachronic corpus evidence. By comparing the two estimates, one can then put numbers on the relation between language acquisition and language history. Thus, the model

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[1] That model we use is similar to mathematical models of cultural and linguistic change (Cavalli-Sforza and Feldman (1981), Wang and Minett (2005), Niyogi (2006)) and equivalent to basic epidemiological models (Anderson and May (1991); see also Sperber (1985)).

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provides a method for relating data of different origins in a principled way.

Empirically, our discussion is based on English word-final CC diphones (i.e. consonant clusters containing two segments). They are short, yet clearly structured linguistic constituents (Kuperman, Ernestus, & Baayen, 2008), and have had long and diverse histories. For instance, the word final cluster /nd/ as in English *land* is likely to have existed already > 5000 years ago in Indo-European, the ancestor of English. It still thrives today. Many others, however, such as /gz/ or /vz/ as in English *legs* or *loves*, emerged much more recently, i.e. about 800 ago in the Middle English period. There are also considerable differences among the histories of individual clusters as far as their frequencies are concerned. Some of them, such as /xt/ – orthographically still reflected in words like *knight* or *laughed* – have disappeared altogether.

Since (a) there is considerable diversity among the historical developments of final consonant clusters, and since (b) the ages at which they are acquired are similarly diverse, English consonant clusters are highly suitable for our purpose. They allow us to see clearly whether the reproductive ratios that population dynamic models derive from historical evidence and acquisition data actually correlate or not. We show that they do and interpret this as proof of the concept that models which derive R_0 for linguistic constituents are capable of rigorously relating language acquisition and language history.

Thus – and although we are interested in the specific phenomena we investigate – our primary concern is in fact more general. In the context of testing the usefulness of population dynamic models for linguistic purposes, we address questions such as the following: (a) Does the age at which consonant clusters are acquired correlate with their historical stability? (b) Is there a single measure that relates these two properties? (c) What can be learnt from such measurements about causal relations between language acquisition and language history?

For (a) and (b), our study suggests positive answers: models developed in the study of evolutionary dynamics do indeed provide systematic and quantifiable correlations between the historical development of final clusters and the age at which are acquired. With regard to (c), we ask if the correlation between acquisition and diachronic stability differs between morpheme internal clusters (such as /mp/ in *lamp*) and morphologically produced ones (such as /gz/ in *eggs*), and whether the correlation between age-of-acquisition and historical stability is affected by utterance frequency. We show that the morphological status of clusters does not seem to matter much, but that the correlation between age-of-acquisition and historical stability is tighter among frequent than among rare clusters. Our results corroborate the view that phonological change may be more strongly driven by frequent use in adult speech (Bybee, 2007), and that early acquired core items are more resistant against frequency-driven effects like reduction, assimilation, or deletion. Thereby, our study contributes to the debate on the role which language acquisition plays in language change.

In terms of its general approach, our paper relates to a growing body of research that views culturally transmitted knowledge in evolutionary terms and models it accordingly (Cavalli-Sforza & Feldman, 1981; Dawkins, 1976; Henrich & Boyd, 2002; Newberry, Ahern, Clark, & Plotkin, 2017). It is also based on the view that the repeated learning events involved in cultural history can amplify and make visible cognitive biases that are too weak to be traceable in the behavior of individuals (Reali & Griffiths, 2009; Smith & Wonnacott, 2010; Smith et al., 2017).

We describe our modeling approach together with both ways of estimating the basic reproductive ratio in Section 2. After that, we introduce the statistical tools (3) which are used to test our model empirically against data from phonotactic acquisition and diachrony. The results of our analysis (4) are finally discussed in Sections 5 and 6, where we focus particularly on the effect of utterance frequency.

2. Data and methods

2.1. Standardizing reproductive success: basic reproductive ratio

Our analysis employs a modified version of the population dynamical model of linguistic spread proposed by Nowak and colleagues (Nowak, 2000; Nowak et al., 2000; Solé, 2011). For each linguistic constituent, i.e. in our case for each cluster, the model consists of two differential equations that track the growth of the number of 'users' U (speakers that know and use the cluster), and the number of 'learners' L that do not (yet) know or use it.

When users and learners meet, learners acquire the cluster at a rate $\alpha > 0$, whereby they become users (i.e. switch from class L to class U). Conversely, at a rate $\gamma = 1/G$, where $G > 0$ is linguistic generation time, users 'die' (i.e. are removed from class U) and learners are 'born' (i.e. added to class L). The respective rates of change thus read

$$\begin{aligned} \dot{L} &= -\alpha LU + \gamma U \\ \dot{U} &= \alpha LU - \gamma U \end{aligned}$$

where we set $L + U = 1$.[2]

The expected number of learners that acquire a cluster from a single user introduced into a population of learners is $R_0 = \alpha/\gamma$ (Hethcote, 1989). R_0 represents what has been labelled 'basic reproductive ratio' (Anderson & May, 1991; Nowak, 2000). It figures centrally in epidemiological research due to its straightforward properties: whenever it holds for a population (e.g. a subpopulation of infected individuals) that $R_0 > 1$, that population increases in size and spreads.

In our model, $R_0 > 1$ entails that the population of users approaches a stable equilibrium $\hat{U} = 1 - \gamma/\alpha = 1 - 1/R_0$, so that $\hat{L} = 1/R_0$. If, on the other hand, $R_0 < 1$, the fraction of users approaches 0. The linguistic item vanishes.

R_0 represents a standardized measure of reproductive success that reflects the diachronic stability of linguistic items. Its greatest asset is that it can be derived from different types of data and that all derived estimates are situated on the same scale. Thus, estimates derived from different data types can be compared directly and without further transformation. In our paper, we exploit this for comparing the R_0 derived from diachronic frequency data to the R_0 derived from language-acquisition data. We show that such a comparison yields interesting perspectives on the relation between age of acquisition and historical stability.

2.2. Estimating reproductive success from diachronic growth

The model of linguistic spread outlined in the previous section can be reformulated in terms of a logistic equation (Hethcote, 1989; Solé, Corominas-Murtra, & Fortuny, 2010) with an intrinsic (potentially negative) growth rate $\rho = \alpha - \gamma$. Thus, if the linguistic generation time G: $=1/\gamma$ and the growth rate ρ are known, α and $\alpha/\gamma = 1 + \rho G =: R_0^{\mathrm{GR}}$ can be determined. We approximate G, i.e. the average time it takes for new language learners to enter the population, by biological generation time, so that $G \cong 30$ years (Worden, 2008). This leaves the intrinsic growth rate ρ to be determined.

In order to estimate the intrinsic growth rates ρ of final CC clusters, we use logistic growth rates r_{lg} obtained from diachronic frequency data as a proxy (see also the discussion in Section 5). For that purpose, we determine a trajectory of normalized token frequencies f from 1150 to 2012 for each word-final CC cluster. The token frequencies were retrieved from various historical and contemporary language databases and corpora (see Table 1, which also indicates who carried out the phonological interpretation). The collected data were divided into

[2] For $\gamma = 1$, the above system is exactly the model of word dynamics in Nowak (2000). In his model, α depends on the utterance frequency and learnability of a word, as well as on the number of informants a learner is exposed to (network density).