Estimating historical probabilities of natural and unnatural processes *

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Abstract

This paper presents a technique for estimating the influences of channel bias on phonological typology. The technique based on statistical bootstrapping enables the estimation of Historical Probability, the probability that a synchronic alternation arises based on two diachronic factors — the number of sound changes required for an alternation to arise and their respective probabilities. We estimate Historical Probabilities of six attested and unattested alternations targeting feature [voice], compare Historical Probabilities of these alternations, perform inferential statistics on the comparison, and compare outputs of the diachronic model against the independently observed synchronic typology to evaluate the performance of the channel bias approach. The proposed technique also identifies mismatches in typological predictions of the analytic bias and channel bias approaches. By comparing these mismatches with the observed typology, this paper attempts to quantitatively evaluate the distinct contributions of the two influences on typology in a set of alternations targeting feature [voice].

1 Introduction

Typological literature in phonology has long revolved around the question of which factors influence the observed typology. Two major lines of thought emerge in this discussion: the *analytic bias* approach and the *channel bias* approach (Moreton 2008, Yu 2013).[1] The analytic bias approach argues that the observed typology results primarily from differences in the learnability of phonological processes; the channel bias approach argues that the inherent directionality of sound changes based on phonetic precursors (articulatory and perceptual) shapes typology (for further discussion, see Hyman 1975, 2001; Greenberg 1978; Ohala 1981, 1983, 1993; Kiparsky 1995, 2006, 2008; Blevins 2004, 2006, 2007, 2008a,b; Wilson 2006; Hansson 2008; Moreton 2008; Hayes et al. 2009; Becker et al. 2011; Moreton and Pater 2012a,b; Moreton 2012; de Lacy and Kingston 2013; Garrett and Johnson 2013; Yu 2013; Hayes and White 2013; Cathcart 2015; Kirby and Sonderegger 2015; Greenwood 2016; i.a.).

Empirical evidence often supports both approaches equally well. Typologically rare processes have in many cases been shown to be more difficult to learn, which supports the analytic bias approach (Kiparsky 1995, 2006, 2008; Wilson 2006; Hayes et al. 2009; Becker et al. 2011; de

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[1]Other names have been used for the two approaches, such as Evolutionary Phonology versus Amphichronic Phonology in Blevins (2004) and Kiparsky (2006, 2008).

Lacy and Kingston 2013; Hayes and White 2013; White 2017; for an overview of the experimental analytic bias literature, see Moreton and Pater 2012a,b). On the other hand, typologically frequent processes are often shown to directly result from the phonologization of underlying articulatory or perceptual phonetic precursors (e.g. sound change in progress that results in a typologically common pattern), whereas rare or unattested processes lack such precursors, which supports the channel bias approach (cf. Hyman 1975; Greenberg 1978; Ohala 1981, 1983, 1993; Lindblom 1986; Barnes 2002; Blevins 2004, 2006, 2007, 2008a,b; see also Hansson 2008 and Garrett and Johnson 2013 for an overview of the literature). This ambiguity of evidence poses the primary challenge in typological research.

The stance of this paper is that both factors influence the typology (as has been argued by a mounting body of research recently; Hyman 2001, Myers 2002, Moreton 2008, Moreton and Pater 2012a,b, de Lacy and Kingston 2013). However, the role of phonological research is to quantitatively evaluate which aspects of typology are more likely to result from one factor or the other. The question that this paper addresses is whether some observed typological distributions (e.g. those targeting feature [voice]) are influenced primarily by different degrees of the learnability of different processes or primarily by different diachronic trajectories that underlie different processes. In particular, this paper proposes a technique based on which channel bias influences on typology can be estimated.

1.1 Analytic Bias

If typologically infrequent processes are experimentally shown to be more difficult to learn than typologically frequent processes (for an overview, see Moreton and Pater 2012a,b), a reasonable conclusion would be that typological observations result precisely from these differences in learnability. A challenge that the analytic bias approach faces is that artificial grammar learning experiments testing the learnability of typologically rare or nonexistent unnatural processes frequently fail to show learnability differences compared to typologically frequent natural processes when the structural complexity of the tested alternations is controlled for. Influences of analytic bias can be subdivided into *substantive bias* and *complexity bias* (Wilson 2006, Moreton 2008, Moreton and Pater 2012a,b). *Substantive bias* states that phonetically motivated processes are easier to learn than unmotivated (or unnatural) ones. *Complexity bias* states that alternations involving more conditioning features are more difficult to learn than simpler alternations (Moreton 2008). A survey of experimental literature on Analytic Bias in Moreton and Pater (2012a,b) shows that there exist consistent differences in experimental results testing the two biases. While *complexity bias* is consistently confirmed by the majority of studies surveyed, experimental outcomes of the *substantive bias* are mixed. Several studies that test the learning of unnatural alternations as defined in Section 2 found no effect of *substantive bias* (Pycha et al. 2003, Kuo 2009, Skoruppa and Peperkamp 2011, via Moreton and Pater 2012a,b; and more recently Seidl et al. 2007, Do et al. 2016, Glewwe 2017, Glewwe et al. 2018). A comparatively smaller subset of studies, however, do report positive results (Carpenter 2006, 2010; Wilson 2006).

L1 acquisition and L2 acquisition of word-final stops by speakers of L1s that ban obstruent codas is the only place where differences between the natural and unnatural pair of alternations are observed. Learners acquire word-final voiceless stops earlier than voiced stops and devoice voiced stops more frequently than they voice voiceless stops word-finally (overview in Broselow 2018; see also Clark and Bowerman 1986, Kong et al. 2012, and literature therein). It is likely, however, that this type of experiment tests differences in the learning of more complex versus less complex articulations (Kong et al. 2012), and not the abstract phonological learning that is, for example, observed in artificial grammar learning experiments (e.g. where complex alternations are more difficult to learn than simple alternations, which is independent of articulatory factors; Moreton and Pater 2012a,b). Articulation of segments that require more articulatory effort in a given position is expected to be learned less successfully: "[c]ross-language differences in the age of children's mastery of adult-like voiced stops are typically explained in terms of the relative difficulty of the laryngeal gestures for the language's voice onset time distributions" (Kong et al. 2012: 725). The very same mechanism is in fact responsible for final voicing within the channel bias approach: even adult L1 speakers with full contrast gradiently and passively devoice final voiced stops due to their greater articulatory complexity, which can result in a typologically common sound change that operates in an adult population (cf. Labov 1994). These L1 and L2 learning differences thus likely reflect differences in articulatory effort that should be modeled as a channel bias influence. It is in fact not trivial to show how differences in L1 articulatory learning would result in phonological typology (cf. Rafferty et al. 2013), given that children reproduce their input with a high degree of faithfulness past some developmental stage (e.g. at about 2–5 years for acquisition of the voicing contrast; see Kong et al. 2012).

1.2 Channel Bias

One of the objections against the channel bias approach to typology is that it fails to explain why some processes are unattested (Kiparsky 2006, 2008; de Lacy and Kingston 2013). Kiparsky (2006), for example, lists several diachronic trajectories that would lead to final voicing, yet final voicing is arguably not attested as a productive synchronic process. More generally, combinations of sound changes could conspire to yield a number of processes that are never attested as productive synchronic alternations. In the absence of a diachronic explanation, Kiparsky (2006) invokes grammatical constraints and learnability to explain these typological gaps.

Most of the current models of typology within the channel bias approach are indeed insufficient for explaining such typological gaps because they do not quantify the probability of the occurrence of sound changes or combinations of sound changes. The default explanation within the channel bias approach has long been a qualitative observation that common processes are frequent because they are produced by frequent sound changes or because they require less sound changes to arise (Blevins 2013:485, also Greenberg 1978:75–6). Such reasoning does not provide sufficient outputs for a quantitative comparison of different influences on phonological typology.

Despite these objections, mechanisms exist within the channel bias approach to derive typology beyond the simple statement that rare sound changes produce rare alternations. Based on a typological study of an unnatural process, post-nasal devoicing, Beguš (2019) argues that unnatural processes require at least three sound changes to arise (as opposed to at least two for unmotivated processes and at least one for natural processes, the so-called Minimal Sound Change Requirement), which explains the relative rarity of processes with different degrees of naturalness. To be sure, the idea that unmotivated processes are rare because they require a complex history is not new (Bell 1970, 1971; Greenberg 1978:75–6; Cathcart 2015; Morley 2015), but the Minimal Sound Change Requirement explains why unnatural processes are the least frequent (compared to natural or unmotivated processes, see Section 2). The Minimal Sound Change Requirement on its own, however, does not explain why some unnatural processes are attested, while others are not. To quantify the channel bias influences on typology further, the concept of the Minimal Sound Change Requirement should be combined with the estimation of probabilities of individual sound changes that are required for each synchronic alternation to arise.

Two models have thus far attempted to quantify probabilities of the occurrence of various primarily static phonotactic processes and explain the relative rarity of some processes based on diachronic factors. Bell (1970, 1971) and Greenberg (1978) propose a "state-process model". Their model operates with typological states (phonological, morphological, and syntactic) that can arise from other states, depending on the number of previous states, transitional probabilities from one state to another, and the rest probabilities of each state. The model is most suitable for modeling the probabilities of various phonotactic restrictions. Modeling the probabilities of transitions (processes) in the instantiation of the model in Bell (1971) involves relative probabilities that only tangentially reflect the frequencies of the processes in the samples. The main ideas behind Bell's (1970, 1971) and Greenberg's (1978) model are similar to what will be proposed in this paper, but their proposal lacks inferential statistical tests. Crucially, by estimating uncertainty behind the distributions with bootstrapping, we can compare Historical Probabilities of alternations and perform hypothesis testing on the comparisons. Our proposal also uses substantially more elaborate historical samples.

A different model of calculating the probabilities of the combination of sound changes is offered by Cathcart (2015), who computes permutations of sound changes that lead to a certain process (in this case, final voicing) and compares that to permutations of all sound changes in a given survey to get an estimate of the probability of certain processes. Due to its design, however, Cathcart's (2015) model relies on representativeness of diachronic surveys for all sound changes, not only for the ones that are estimated (see also Section 3.2) and is computationally demanding, which makes the model difficult to implement. The models in Greenberg (1978) and Cathcart (2015) also do not take into consideration the crucial distinctions made in Beguš (2019: 744): "the subdivision of unusual rules into unnatural versus unmotivated rules, paired with the proof that the latter require at least three sound changes to arise".[2] The model proposed in this paper has a disadvantage that the trajectories of sound changes that lead to a certain alternation need to be identified manually (similar to Bell's (1971) and Greenberg's (1978) models), but this also means that samples of sound changes need to be representative only for the sound changes we are estimating.

1.3 Goals

The goal of this paper is to propose a quantitative method for estimating the influences of channel bias on phonological typology using a statistical method called bootstrapping (Efron 1979; Efron and Tibshirani 1994). The technique estimates the so-called Historical Probability, which is the probability that an alternation arises based on two diachronic factors — the number of sound changes required for an alternation to arise (the Minimal Sound Change Requirement; Section 2), and their respective probabilities, estimated from surveys of sound changes. Using the proposed technique, we can (i) estimate the Historical Probability of any alternation (Section 4), (ii) compare two alternations, attested or unattested, and perform statistical inferences on the comparison (Section 5.2), and (iii) compare outputs of the historical model with independently observed typology to evaluate the performance of the channel bias approach (Section 5.3). The assumptions of the model are discussed in Section 3.3. The paper also identifies mismatches in typological predictions between the analytic and channel bias approaches (Sections 5.3 and 6). By testing these mismatched predictions against the observed typology, we can at least partially control for one factor when testing the other and vice versa, which consequently allows for quantitative evaluation of distinct contributions of the analytic bias and channel bias factors on phonological typology (Section 6).

While the proposed method can be applied to any natural-unnatural pair of alternations, the

[2]The model of automated reconstruction in Bouchard-Côté et al. (2013) estimates the probabilities of individual sound changes, but does not deal with combinations of sound changes. Other quantitative approaches to sound change (e.g. Kirby and Sonderegger 2013, 2015; Hruschka et al. 2015) do not directly deal with estimating the probabilities of sound changes that operate in combination, but computationally model the initiation and propagation of single sound changes.

paper focuses on a subset of typology: three natural-unnatural alternation pairs that target feature [±voice]. We estimate Historical Probabilities of post-nasal voicing (e.g. /p/ → [b] / m__) and post-nasal devoicing (/b/ → [p] / m__), inter-vocalic voicing (e.g. /p/ → [b] / V__V) and inter-vocalic devoicing (/b/ → [p] / V__V); and final devoicing (/b/ → [p] / __#) and final voicing (/p/ → [b] / __#). The feature [±voice] is chosen because phonetic naturalness is probably best understood precisely for this feature (Aerodynamic Voicing Constraint; Ohala 1983, 2011; Westbury and Keating 1986; for a detailed argumentation, see Beguš 2019) and all alternations are well researched typologically. The alternations also differ in their synchronic attestedness (Figure 3) which makes good grounds for a comparison of different approaches to phonological typology.

2 Background

This paper adopts several diachronic concepts from Beguš (2019). First, this paper adopts the division of phonological processes into *natural*, *unmotivated*, and *unnatural*. Natural processes, such as final devoicing or post-nasal and intervocalic voicing, are cases of phonetically well-motivated universal phonetic tendencies. Unmotivated processes lack phonetic motivation, but do not operate against universal phonetic tendencies. An example of an unmotivated process would be Eastern Ojibwe "palatalization" of /n/ to [ʃ] before front vowels (Buckley 2000), which lacks phonetic motivation, but does not operate against universal tendencies. Unnatural processes not only lack phonetic motivation, but also operate against universal phonetic tendencies. Examples of unnatural alternations that operate against universal phonetic tendencies include post-nasal devoicing, inter-vocalic devoicing, and final voicing (discussed in this paper).

We limit modeling of sound change to a non-analogical phonetically driven sound change that targets a single feature value that becomes non-automatic and phonologized (Hyman 1976). We also assume that a single sound change is a change of a single feature or a deletion of a feature matrix (the so-called Minimality Principle; Picard 1994). We adopt featural representations from phonological theory (Hayes 2009). That a single sound change targets only one feature value is, at least in the great majority of cases (if not always), suggested by historical typology. Phonetic precursors also support the Minimality Principle: phonetic precursors that lead to sound change via phonologization are usually articulatorily and perceptually minimal. For a discussion, see Donegan and Stampe (1979), Picard (1994), and Beguš (2019).

This paper adopts two diachronic concepts for the derivation of typology within the channel bias approach that have been proposed in Beguš (2019): the Blurring Process and the Minimal Sound Change Requirement. Typological surveys of unnatural processes targeting the feature [voice] conducted in Beguš (2018, 2019) and Beguš and Nazarov (2018) identify thirteen languages in which post-nasal devoicing has been reported either as a productive synchronic alternation or as a sound change. Based on this typological survey, a hypothesis about how unnatural processes arise diachronically is proposed: the Blurring Process which states that unnatural alternations arise through a combination of a specific set of three natural (phonetically motivated) sound changes: (i) a sound change that causes complementary distribution, (ii) a sound change that targets changed or unchanged segments in the complementary distribution, and (iii) a sound change that blurs the original complementary distribution (Beguš 2019). For example, post-nasal devoicing results from three sound changes: (i) frication of voiced stops except post-nasally ([b] > [β] / [−nas]__), (ii) unconditioned devoicing of voiced stops ([b] > [p]), and (iii) occlusion of voiced fricatives ([β] > [b]) (see Tables 1 and 2).

This allows us to maintain the long-held position that sound change is limited to acoustically or perceptually motivated directions[3] (Garrett and Johnson 2013, Garrett 2014; for a discussion, see Beguš 2019). This position has recently been challenged by Blust (2005), who lists a number of unnatural sound changes. If these unnatural sound changes result from combinations of natural sound changes (as argued by Beguš 2018, 2019 and Beguš and Nazarov 2018), we can maintain the position that sound change is always phonetically motivated.

Unnatural alternations thus cannot arise from a single sound change. Beguš 2019 additionally argues that unnatural segmental alternations cannot arise from two sound changes either. If a change from value + of a given feature ϕ_1 to value − is unnatural and therefore cannot result from a single sound change, some other feature (ϕ_2) has to change first, so that the change from $+\phi_1$ to $-\phi_1$ might be natural and motivated. To get the full unnatural process, however, that other feature (ϕ_2) has to change back to its original value. No such requirement exists for unmotivated processes: they can result from two sound changes. In sum, the *Minimal Sound Change Requirement* states that a minimum of three sound changes are required for an unnatural alternation to arise, a minimum of two sound changes for an unmotivated alternation, and a minimum of one sound change for a natural alternation (see Beguš 2019).[4]

3 Bootstrapping to estimate Historical Probabilities

Our goal is to propose a model that would quantify probabilities of natural, unmotivated, and unnatural processes beyond the statement that natural processes are the most frequent, unmotivated less frequent, and unnatural the least frequent. We can combine the Minimal Sound Change Requirement with the assumption that the probabilities of sound changes influence the probabilities of synchronic alternations. The probability that an alternation arises based on diachronic factors depends on both the number of sound changes that are required for the alternation to arise and the probability of each individual sound change in the combination. Such probabilities are called *Historical Probabilities of Alternations* (P_χ).

We propose that Historical Probabilities can be estimated with bootstrapping. Bootstrapping is a statistical technique within the frequentist framework for estimating sampling distribution (and consequently standard errors and confidence intervals for a statistic of interest) from a sample by random sampling with replacement (Efron 1979; Efron and Tibshirani 1994; Davison and Hinkley 1997).

3.1 The model

3.1.1 Individual sound changes

Probabilities of individual sound changes are estimated from a sample of successes (languages in a sample with a sound change S_i) and failures (languages in a sample without the sound change S_i), according to (1). If an alternation A_k requires only one sound change to arise and invariably occurs as a result of that change (i.e. A_k is natural), then we estimate its P_χ according to (1).

[3] In some cases, multiple directions of a sound change can potentially be motivated, although such cases are rare. For a discussion, see Beguš (2019).

[4] The proposed model does not account for unnatural processes that result from morphological changes. These are, however, almost always analyzed as morphologically conditioned and can be explained by non-phonological mechanisms. The lack of modeling morphological changes is a shortcoming of the current proposal. Sound change is, however, substantially more unidirectional and sound change typology is substantially better understood compared to morphological or syntactic change, which is why a model that would include morphological sources of phonological processes would first require an elaborate typology of morphologically induced phonological processes.

(1)

$$P_\chi(S_i) = \frac{\text{number of languages with sound change S}_i}{\text{number of languages surveyed}}$$

To estimate Historical Probability of a sound change using the bootstrapping technique, we create samples from counts of languages in Tables 4 and 5. Languages with a sound change are treated as successes (coded as 1); languages without it as failures (coded as 0). The main advantage of the bootstrapping technique is that it estimates confidence intervals of a Historical Probability. To estimate confidence intervals, we sample from this distribution of successes and failures 10,000 times (with so-called sampling with replacement; Efron 1979, 1987). Each of these 10,000 samples is a probability of a success based on (1) (i.e. proportion of 1s relative to 0s in the sample). These 10,000 probabilities constitute a sampling distribution, based on which standard errors and confidence intervals are calculated.

For example, when estimating Historical Probabilities of processes targeting feature [voice], the successes and sample sizes are taken from surveys of sound changes (for exact counts, see Section 4.2 and columns *Counts* and *Surveyed* in Tables 4 and 5 for successes and sample sizes, respectively). Sample sizes in our case range from 294 to 88, depending on the sound change (see Section 4.2). This repeated sampling with replacement yields a sampling distribution of Historical Probabilities: 10,000 data points for each process. From this sampling distribution, standard error, bias, and 95% adjusted bootstrap (BC_a) confidence intervals that adjust for bias and skewness (Efron 1979, 1987) are computed.

The computation is implemented in the statistical software R (R Core Team 2016) with the *boot* package (Canty and Ripley 2016, Davison and Hinkley 1997) using the functions *boot()* and *boot.ci()*. The R code that implements the proposed technique is available in Appendix C.

3.1.2 Two or more sound changes

If an alternation A_k requires more than a single sound change, then the Historical Probability of A_k is estimated as a sum of the Historical Probabilities of each trajectory T_z that yields the alternation A_k, as shown in (2).

(2)

$$P_\chi(A_k) = P_\chi(T_1 \cup T_2 \cup \ldots \cup T_n)$$

A trajectory T_j denotes a combination of sound changes that yields an alternation A_k. In theory, there are an infinite number of trajectories that yield any given alternation, but for practical purposes, we estimate only the trajectory that involves the least number of sound changes. Historical Probabilities of trajectories that require more than three sound changes are assumed to be minor enough to be disregarded for practical purposes.

The Historical Probability of a trajectory T_j that requires more than a single sound change is estimated from the joint probability of the individual sound changes required for T_j, divided by the factorial of the number of sound changes in trajectory T_j if only one ordering results in the trajectory in question, as shown in (3).

(3)

$$P_\chi(T_j) = \frac{P_\chi(S_1 \cap S_2 \cap \ldots \cap S_n)}{n!}$$

Historical Probability is a probability that a language L features an alternation A_k, regardless of the properties of L. In other words, we do not condition Historical Probabilities on languages that feature a certain property. The Historical Probability (P_χ) of the first individual sound change S_1 is thus estimated from the number of successes (languages with S_1) and the number of failures (languages without S_1) according to (1), regardless of the phonemic inventories of languages in the sample.

For example, if the target of the first sound change S_1 in a trajectory that results in an alternation A_k is a geminate stop, we estimate the Historical Probability of S_1 from the number of languages with the sound change S_1 divided by the number of all languages surveyed, including those that do not feature geminate stops. The Historical Probability of an alternation A_k that requires S_1 is simply the probability that the alternation A_k arises in a language L, regardless of whether it features stop geminates.

Once S_1 operates, however, we know that language L necessarily has the target/result/context of the sound change S_1. For this reason, we estimate the Historical Probability of the subsequent sound changes $P_\chi(S_2)$ by dividing the number of successes (languages with S_2) by the number of languages surveyed that feature the target/result/context of S_1 if these are also the target of S_2. The same is true for any subsequent sound change. Once we condition the probability of sound changes and estimate it from samples of sound changes given that they have the target/result/context of the previous sound change, we can treat the probabilities of individual sound changes as independent events under the channel bias approach and estimate P_χ from the product of the probabilities of individual sound changes (4).

(4)

$$P_\chi(T_j) = \frac{\prod_{i=1}^{n} P_\chi(S_i)}{n!}$$

To estimate standard errors and BC_a confidence intervals for a Historical Probability of A_k that requires more than a single sound change, the proposed technique samples with replacement from n individual binomial samples (one sample for each individual sound change, constructed as described above), computes the Historical Probability of each sound change (according to (1)), and then computes the product of the Historical Probabilities of each individual sound change divided by $n!$, according to (4). This process returns 10,000 bootstrap replicates of the Historical Probability of A_k, from which the standard errors and BC_a confidence intervals are computed.

3.1.3 Comparison

The proposed technique also allows for the estimation of the difference between the Historical Probabilities of two alternations, which consequently enables inferential statements on the comparison.

(5)

$$\Delta P_\chi(A_1, A_2) = P_\chi(A_1) - P_\chi(A_2)$$

The difference between the Historical Probabilities of two alternations (ΔP_χ) is estimated with a stratified non-parametric bootstrap, where P_χ of each individual alternation A_1 and A_2 is estimated as described in Sections 3.1.1 and 3.1.2 (depending on whether A_1 and A_2 require trajectories that require one or more sound changes). To compare two Historical Probabilities, we calculate the difference between $P_\chi(A_1)$ and $P_\chi(A_2)$, which returns 10,000 bootstrap replicates, from which the standard errors and BC_a confidence intervals are computed.

The proposed technique applied on a difference between two alternations enables a comparison of the two alternations with inferential statements. If the 95% BC_a confidence intervals of the difference both fall either below or above 0, then $P_\chi(A_1)$ and $P_\chi(A_2)$ are significantly different with $\alpha = 0.05$.

3.2 Sample

Samples used for estimating Historical Probabilities are created from counts of occurrences of sound changes in typological surveys. The proposed technique is most accurate when typological surveys are large, well-balanced, and representative. Sound changes in a survey should always be evaluated with respect to the target of the change, its result, and its context. Sound change occurrences in a typological survey should be properly counted: if two or more daughter languages show the result of a sound change that operated at the proto-stage of the two languages, the sound change should be counted as a single event in the proto-language. For exact counts and a detailed description of how samples for the six alternations in this paper are created, see Section 4.2 and A.

The most elaborate survey of sound changes currently available which we use in the paper is the survey of consonantal sound changes in Kümmel (2007). One major advantage of Kümmel's (2007) survey is that it includes language families with a well-reconstructed prehistory and a well-established subgrouping. This allows for a more accurate coding of the occurrence of a sound change, compared to competing surveys (e.g. the UniDia survey; Hamed and Flavier 2009).

Sound changes are counted as single events if they operate at a proto-language stage. While it is sometimes difficult to reconstruct whether a sound change in two related languages operated at the proto-stage or independently in individual branches, especially for typologically frequent sound changes, the survey in Kümmel (2007) is the most comprehensive of all available surveys in this respect. The subgrouping in Kümmel's (2007) survey relies on historical methodology that includes information from both phonological as well as morphological and other higher level evidence.[5]

The survey in Kümmel (2007) includes approximately 294 languages and dialects of the Indo-European, Semitic, and Uralic language families. While the survey is limited to only three language families, it involves those families that have well-established subgroupings. This allows for proper coding, and at least partially compensates for the lack of representativeness. Results of the analysis can be affected by the fact that many language families are absent from the survey. However, it is likely that such effects are minor because types of sound changes do not seem to be radically different across different language families (with recurrent sound changes appearing across all families; Blevins 2007; see also Section 5.3).[6] Additionally, the author is unaware of reasons to believe that the representativeness (or bias) of a sample is unequal across different sound changes. Because we are primarily interested in the comparison between Historical Probabilities of various alternations and less so in their absolute values, the model is less prone to influence from biased samples.

3.3 Assumptions

As with any diachronic model, the proposed technique has to make some simplifying assumptions. In order to estimate the joint probability of two or more sound changes as a product of the Historical

[5]Additionally, phylogenetic tree analysis does not restrict the direction of sound change and would, for example, incorrectly analyze reported unnatural alternations as resulting from a single sound change.

[6]The only other comparable survey of sound changes known to the author is the UniDia database that surveys 10,349 sound changes from 302 languages (Hamed and Flavier 2009). The UniDia database is, however, less appropriate because it lacks elaborate diachronic subgroupings of languages.

Probabilities of each individual sound change (see (4)), the model assumes that each sound change is an independent event. The proposed model *does* account for the dependency between sound changes where one sound change alters the target or context of the following sound change. Probabilities of sound changes are estimated based on their targets, results, and contexts (Section 3.2) and, crucially, from samples conditioned on the result of the previous sound change (Section 3.1.2). Two crucial assumptions of independence remain: that sound change is (i) independent of previous sound changes when the dependence on targets, results, and contexts of the previous sound change is controlled for (Section 3.1.2) and (ii) independent of global phonemic properties of a language (those properties that do not immediately affect the conditions of sound changes in question).

The first assumption is not controversial when modeling typology within the channel bias approach. The proposed method aims to estimate only the channel bias influences on typology, which is why it has to assume that the probability of sound change is only determined by its frequency of operation evaluated on a diachronic and unconditioned level.

The second assumption of independence is more problematic: broader phonemic inventories can influence the probabilities of sound changes, especially for vocalic changes (e.g., due to the effects described in the Theory of Adaptive Dispersion, see Liljencrants and Lindblom 1972, Lindblom 1990), but also for consonantal changes. The proposed technique does not model the dependency of sound changes on those phonemic properties that do not immediately affect the targets, results, or contexts of the sound changes in question. The sample's representativeness should, however, at least partially cancel out potential dependencies. The sample of sound changes from which the Historical Probabilities are calculated includes languages with a diverse set of phonemic inventories (see Kümmel 2007). Additionally, we do not condition estimations of Historical Probabilities on any specific property of phoneme inventories, which makes the dependency between sound change and more distant phonemic properties less crucial to our proposal. Finally, we are unaware of any properties of phonemic inventories that would affect the rate of the sound changes in question (e.g. intervocalic lenition, occlusion of fricatives, devoicing of stops).[7]

As already mentioned, identification of individual trajectories leading to an alternation A_k is performed manually in the current proposal. While this task is facilitated by the Blurring Process, which describes mechanisms for unnatural processes to arise, it is nevertheless possible that some trajectories that would potentially influence the final result are missing from the estimation. If we assume that the estimated trajectory T_j is indeed the most frequent trajectory leading to A_k and that potential alternative trajectories do not crucially influence the overall Historical Probability of an alternation, we can generalize the Historical Probability of that particular trajectory to the Historical Probability of the alternation. If such an assumption is not met, however, then the proposed technique estimates only the probability that an alternation A_k arises from a trajectory T_j.[8] This paper assumes that the estimated trajectories are the most frequent ones and that potential alternative trajectories do not crucially influence the results.

The proposed model aims to estimate the channel bias influences on typology. It is possible that learnability influences the probabilities of individual sound changes: learnability can promote or demote the likelihood of a phonetic precursor being phonologized (as argued by Moreton 2008; for criticism, see Yu 2011 and Kapatsinski 2011). Even if the probabilities of individual sound changes are crucially influenced by learnability (and therefore by analytic bias) and even if learnability

[7]The dependence of sound change on broader phonemic inventories is not modeled primarily because current surveys of sound changes are not sufficiently large and representative. In principle, the proposed technique could model this dependency by estimating the probabilities of sound changes from samples conditioned on some phonemic property of the surveyed languages.

[8]When more representative surveys become available, this assumption could be weakened by using Cathcart's (2015) permutation approach to identify trajectories for each alternation estimated with the proposed technique.

causes a higher rate of operation of certain sound changes in combination, the requirement that more than one sound change needs to operate in a language for unmotivated alternations and unnatural alternations to arise has to be independent of learnability. This means that at least a portion of the estimated probabilities needs to be influenced by the channel bias.

What is not accounted for in the model are the functional load of individual phonemes (Wedel 2012, Wedel et al. 2013, Hay et al. 2015) and other factors that could potentially influence probabilities of sound changes, such as lexical diffusion or lexical/morpheme frequency during the initial stages of sound change (Bybee 2002), language contact, and sociolinguistic factors. The model makes no assumptions about how sound change is initiated or spread. These factors can mostly be disregarded because the goal is to estimate the Historical Probability of alternation A_k operating in a language L with no conditional properties.

Finally, the proposed technique does not directly model the temporal dimension. In the absence of temporal information, we have to make some simplifying assumptions. These simplifying assumptions are not unique to the present proposal and are to some degree even desirable. The proposed technique estimates Historical Probabilities within a timeframe that approximates the average timeframe of the languages in the sample. The model also assumes that in order for a resulting alternation to be productive, all sound changes need to operate within one language L. While this might be too restrictive, it is, in fact, desirable to limit the timeframe in which sound changes and corresponding processes have to operate productively for the resulting alternation to be productive. For example, the combination of sound changes (the Blurring Process) that would result in post-nasal devoicing in Yaghnobi operates over three languages and fails to result in a productive synchronic alternation. The model also assumes that once a sound change occurs in a language, it can reoccur. This is a closer approximation to reality than to assume that a sound change cannot operate in daughter languages once it has already operated in the parent language.

The Historical Probability of an unnatural alternation depends not only on sound changes that are required for the alternation to arise, but also on the probability that the opposite sound change (in our case, the natural sound change) will operate on the unnatural system and destroy the evidence for it. Currently, influences of the potential natural sound changes are not modeled because the Historical Probabilities of the natural sound changes (Table 8) are relatively similar for the processes estimated in this paper and we do not expect this additional factor to alter the results significantly.[9] For other processes not estimated in this paper, including the probability of the natural sound change in the model might alter the outcomes significantly.

4 Applications

4.1 Trajectories

The three natural alternations have obvious origins — the single natural sound changes post-nasal voicing, inter-vocalic voicing, and final devoicing, respectively.[10] For the unnatural alternations, we first identify sound changes in the Blurring Process (Section 2) that yield the alternation in question. If A > B / X is a natural sound change, then B > A / X is unnatural. Tables 1, 2, and 3 represent schematically (left column) how the unnatural B > A / X arises via the Blurring Cycle or the Blurring Chain (two subtypes of the Blurring Process; see Section 2, Beguš 2018, 2019, and Beguš and Nazarov 2018). The actual sound changes that yield the unnatural alternation are

[9] For example, the difference between Historical Probabilities of post-nasal devoicing and final devoicing is not significant ($P_\chi = 1.4\%$, BC_a CI = [−3.4%, 5.4%].

[10] T represents voiceless stops, D voiced stops, S voiceless fricatives, and Z voiced fricatives.

identified in the right columns. A combination of the following three natural and well-motivated sound changes yields post-nasal devoicing in all known cases: the fricativization of voiced stops in non-post-nasal position, the unconditioned devoicing of voiced stops, and the occlusion of voiced fricatives to stops (Table 1).[11]

Table 1: Blurring Cycle (schematic; left) yielding post-nasal devoicing (right).

	Blurring Cycle	**post-nasal devoicing**	**Schematic example**
			bamba
1.	B > C / ¬X	D > Z / [−nas]__	βamba
2.	B > A	D > T	βampa
3.	C > B	Z > D	bampa
Result	B > A / X	D > T / [+nas]__	

Beguš (2018) argues that inter-vocalic devoicing results from three sound changes. Voiced stops fricativize intervocalically, voiced fricatives devoice, and voiceless fricatives get occluded to stops (see Table 2). The result is the unnatural intervocalic devoicing (D > T / V__V).

Table 2: Blurring Chain (schematic; left) yielding inter-vocalic devoicing (right).

	Blurring Chain	**Inter-vocalic devoicing**	**Schematic example**
			baba
1.	B > C / X	D > Z / V__V	baβa
2.	C > D	Z > S	baɸa
3.	D > A	S > T	bapa
Result	B > A / X	D > T / V__V	

Final voicing is arguably unattested both as a synchronic alternation and as a sound change[12] (Kiparsky 2006, Lipp 2016, Beguš 2018, cf. Yu 2004, Rood 2016). A number of diachronic scenarios exist, however, that would yield final voicing and are identified in Kiparsky (2006). Most of the scenarios either include more than three sound changes or do not result in a phonological alternation but in a static phonotactic restriction instead (Section 4.2). One possible scenario that involves three sound changes and that would result in final voicing is Scenario 1[13] in Kiparsky (2006), which

[11]Perhaps the most intriguing of these changes is the unconditional devoicing of voiced stops that includes the post-nasal position. Both historical and phonetic evidence exist that unconditioned devoicing of stops operates in the development of post-nasal devoicing. In fact, this sound change is directly attested in Yaghnobi, one of the languages that feature post-nasal devoicing. Yaghnobi also contains evidence that this sound change operates unconditionally in voiced stops as other marginal positions (such as after a voiced fricative) also undergo devoicing. The phonetics behind unconditioned devoicing that extends to post-nasal position is straightforward: closure is always antagonistic to voicing and after some period of time, speaker need to actively adjust articulators to sustain voicing in all positions. Failure to do so results in devoicing, even post-nasally. The strongest empirical evidence in favor of this assumption comes from Davidson (2016). In English, underyling *voiced* stops are voiceless (= voicing ceases earlier than during the first 10% of closure duration) or partially voiced (= voicing ceases earlier than during the first 90% of closure duration) in 22% of measured tokens in post-nasal pre-vocalic position in Davidson (2016) (see also Beguš 2019).

[12]There is one possible case of final voicing that could count as a productive synchronic alternation — Lakota (Rood 2016). Currently, there are no acoustic studies of Lakota word-final stops. Since many reported cases of final voicing turned out to be cases of word-final unreleased or lax voiceless stops (Kiparsky 2006), I leave Lakota out of this discussion until acoustic data is available.

[13]Kiparsky's (2006) Scenario 2 also includes three sound changes, but the last sound change (apocope after a single consonant) is never attested in the UniDia database of sound changes (Hamed and Flavier 2009). Kümmel's 2007

is used here for estimating the Historical Probability of final voicing. For the sound changes in Scenario 1 to result in synchronic alternations, we need to assume that geminate simplification first operated word-finally and only later targeted other geminates. Without this assumption, the sound changes in Scenario 1 would result in a phonotactic restriction. The three sound changes operating to yield final voicing in this scenario are geminate simplification in word-final position, voicing of post-vocalic non-geminate stops, and unconditioned geminate simplification (see Table 3).

Table 3: Modified Blurring Chain (schematic; left) that would yield final voicing(right).

	Modified Blurring Cycle	**Final voicing**	**Schematic example**
			pːapːapː
1.	C > B / X	Tː > T / __#	pːapːap
2.	B > A	T > D / V__	pːapːab
3.	C > B	Tː > T	papab
Result	B > A / X	T > D / __#	

4.2 Counts

Samples of sound changes based on which estimations of Historical Probabilities are performed are constructed from counts of occurrences and languages surveyed (from Kümmel's 2007 database). Sound change occurrences are counted from the number of languages that Kümmel (2007) lists for each sound change. To reduce counting a single sound change that operates at a proto-stage and is reflected in several daughter languages as independent events, sound changes with exact same outcome in closely related languages are counted as single events (as grouped together by Kümmel 2007). While it is possible that some dependencies still exist in the data, it is currently difficult to estimate them. We assume that potential dependencies do not crucially affect the results.

If a sound change is reported to target a subset of the three major places of articulation (labial, dorsal, velar) and not the entire set, the counts for alternations that require more than one sound change are multiplied by a coefficient that proportionally penalizes the counts. For example, counts of sound changes that target only two places of articulation are multiplied by $\frac{2}{3}$ in order to reduce the possibility of final estimated probabilities being inflated: if the first sound change targets two places of articulation and the second sound change targets the third place of articulation, such a combination would, for example, not result in an unnatural process.

post-nasal voicing as a sound change is reported in approximately 28 languages in Kümmel (2007). Intervocalic voicing is reported in approximately 38 languages (including post-vocalic voicing). Final devoicing is reported in approximately 24 languages (summarized in Table 4). For raw counts, see Sections A.1, A.2, and A.3. post-nasal voicing, intervocalic voicing, and final devoicing that target a single series of stops are counted without penalization together with cases in which these sound changes target more than a single place of articulation.

survey does not include vocalic changes, which is why the UniDia database that surveys 10,349 sound changes from 302 languages is used. Because the last sound change is never attested in our surveys, I exclude Scenario 2 from the estimation of P_{χ}(final voicing).

Table 4: Counts of sound changes in Kümmel (2007) for natural alternations.

Alternation	**Sound change**	**Count**	**Surveyed**
post-nasal voicing	T > D / N__	28	294
inter-vocalic voicing	T > D / V__V	38	294
final devoicing	D > T / __#	24	294

The first sound change in the Blurring Chain that results in post-nasal devoicing, the fricativization of voiced stops, is reported in approximately 66 languages. In 32 languages, the sound change is reported to target all three major places of articulation; in 11 languages the sound change targets two places of articulation, and in 23 languages one place of articulation. The final count is thus $32+11\times\frac{2}{3}+23\times\frac{1}{3}\approx 47$. Instances of intervocalic and post-vocalic fricativization are included in the count (not only cases in which fricativization occurs in all but post-nasal position) because the result of such fricativization after the other two sound changes would be a system analyzed as post-nasal devoicing as well.[14] The probability of the first sound change in the Blurring Cycle that results in post-nasal devoicing is estimated based on the number of successes (languages in the survey with that sound change) and the total number of languages surveyed (294) without conditioning on the sample. The sample for estimating the probability of the first sound change is unconditioned because the Historical Probability of A_k is the probability that A_k arises in a language L, regardless of the properties of its phonemic inventory (see Section 3.1.2). Once the first sound change operates, however, we know that the language in question needs to have voiced stops in its inventory. The Historical Probability of the second sound change that targets voiced stops is therefore estimated from the number of successes (languages in the survey with that sound change) and the number of languages with voiced stops. The second sound change (D > T) is reported in approximately 15 ($\approx 13+1\times\frac{2}{3}+3\times\frac{1}{3}$) languages (also counting cases of devoicing that are the result of chain shifts). Approximately 31 languages lack voiced stops in the survey in Kümmel (2007),[15] which means that P_χ is estimated based on $294-31=263$ languages surveyed. After the two sound changes operate, we also know that the language L has voiced fricatives. The Historical Probability of the last sound change is estimated based on the number of languages with occlusion of voiced fricatives and the number of languages surveyed with voiced fricatives (allophonic or phonemic). Approximately 217 languages in the survey have voiced (bi)labial, alveolar/dental, or velar non-strident fricatives,[16] according to Kümmel (2007). In approximately 17 ($\approx 1+5\times\frac{2}{3}+38\times\frac{1}{3}$) languages, occlusion of fricatives is reported as a sound change. The counts for inter-vocalic devoicing are performed in the same manner as the counts for post-nasal devoicing and are given in Table 5.

The Historical Probability of final voicing is estimated based on the one scenario in Kiparsky (2006) that would result in final voicing as an alternation. The scenarios that would lead to final voicing as a static phonotactic restriction and could involve fewer than three sound changes are excluded. There are three main reasons for why it is justified to distinguish alternations from static phonotactic restrictions in a diachronic model (Beguš 2019) despite the two phenomena likely being

[14] An alternation that resulted from a combination of sound changes in which the first sound change targeted post-vocalic stops rather than non-post-nasal stops and the other two aforementioned sound changes have the same result as in the attested case of post-nasal devoicing, and would be analyzed as post-nasal devoicing with initial devoicing.

[15] One language has only /b/ in its inventory. The low number of inventories that lack voiced stops might be influenced by the areal that Kümmel (2007) surveys. Based on the PHOIBLE database (Moran et al. 2014), approximately 30% of inventories lack a phonemic labial voiced stop. For consistency purposes, we stay within Kümmel's (2007) survey with this acknowledgement.

[16] The labiodental voiced fricative /v/ is included in the count.

part of the same synchronic grammatical mechanisms (Prince and Smolensky 1993/2004, Hayes 2004, Pater and Tessier 2006). First, unnatural phonotactic restrictions provide considerably less reliable evidence for learners because the evidence is distributional rather than appearing within the same morphological unit across morphological boundaries. This means that the likelihood of a phonotactic process not being acquired by the learners is considerably greater compared to alternations. Second, alternative analyses of data are often available in the case of phonotactic restrictions. Alternative explanations are not available in the case of alternations, where evidence for a process comes from within the same morphological unit. Finally, typological surveys of phonotactic restrictions are considerably more difficult to establish (compared to typological surveys of alternations). In the absence of typological studies, it is difficult to evaluate predictions of the channel bias model for phonotactic restrictions. In fact, final voicing as a phonotactic restriction might not be as rare, with at least two potential phonological systems attested in which voiceless stops do not surface word-finally, but voiced stops do (Ho and some dialects of Spanish; see Beguš 2019).[17]

Counts of the sound changes that lead to final voicing as an alternation are as follows. In approximately three languages, word-final geminates are reported to simplify to singleton stops. (This sound change is necessary if we want the scenario to result in an unnatural alternation as opposed to a static phonotactic restriction.) Because this is the first in the series of changes and we do not condition P_χ on any property of language L, as before, the Historical Probability is estimated from the total number of languages surveyed. The second sound change, post-vocalic voicing of voiceless stops, is reported in approximately 23 languages (corrected for place of articulation). The intervocalic condition is excluded from the count, as voicing of intervocalic stops would not target final stops. Because all languages have voiceless stops, all 294 languages surveyed are included in the count for estimating the Historical Probability of the second sound change.[18] Finally, simplification of geminates is reported in 21 languages. It is difficult to estimate how many languages in Kümmel (2007) allow geminate voiceless stops. While few languages have phonologically contrastive geminates, many more must allow sequences of two identical stops at morpheme boundaries (the so-called fake geminates; Oh and Redford 2012). To estimate the number of languages that allow such sequences, Greenberg's (1965) survey of consonantal clusters and Ryan's (to appear) survey of phonemic geminates are used. At least 30% of languages in Greenberg's (1965) survey of approximately 100 languages allow stop + stop final clusters. The number of languages in our sample that allow homorganic stop-stop sequences can be approximated from the proportion of languages that allow phonemic geminates and from the proportion of languages that allow sequences of stops. Languages that allow clusters of stops at morpheme boundaries should in principle allow clusters of homorganic stops: if geminate clusters were simplified, the sound change of simplification would of course be reported in our sample. The number is thus estimated at 88 (30% of 294 languages). That this estimate is accurate is suggested by a survey of phonemic geminates: Ryan (to appear) estimates that approximately 35% of 55 genealogically diverse languages surveyed have phonemic

[17]The scenario that potentially results in final voicing in Lakota is currently also excluded: the fricativization of voiceless stops word-finally, followed by post-vocalic voicing of fricatives and occlusion of fricatives to stops, would potentially result in final voicing. A preliminary estimation of this scenario shows that its Historical Probability would be very low because the first sound change is relatively rare (reported only once for one place of articulation in Kümmel 2007).

[18]Since the survey in Kümmel (2007) does not provide the proportion of languages that feature voiceless stops postvocalically, we include all languages in the sample. Given the syllabic structure of the languages in the survey, relatively few languages are expected to lack voiceless stops post-vocalically, but this caveat has the potential to yield anti-conservative results for estimation of final voicing. On the other hand, the fact that we do not limit the counts for the T > D / V_ sound change to those that specifically mention word-final position means that the outcomes might be conservative.

Table 5: Counts of sound changes in Kümmel (2007) for natural alternations.

Alternation	Sound change	Count	Surveyed
post-nasal devoicing	D > Z / [−nas]/V__(V)	47	294
	D > T	15	263
	Z > D	17	216
inter-vocalic devoicing	D > Z / V__ (V)	42	294
	Z > S	5	216
	S > T	10	248
final voicing	T: > T / __#	3	294
	T > D / V__	23	294
	T: > T	21	≈88

Table 6: Estimated P_χ (in %) for natural and unnatural alternations with 95% BC_a confidence intervals (PNV = post-nasal voicing, PND = post-nasal devoicing, IVV = inter-vocalic voicing, IVD = inter-vocalic devoicing, FD = final devoicing, FV = final voicing). We also compute profile confidence intervals from an empty logistic regression for comparison. The highest difference between the confidence intervals is 0.5%, which suggests that the proposed model estimates CIs with high accuracy.

		95% BC_a CI		95% Profile CI	
A_k	P_χ	Lower	Upper	Lower	Upper
PNV	9.5	6.1	12.9	6.5	13.2
PND	0.01	0.006	0.02	—	
IVV	12.9	9.2	16.7	9.4	17.1
IVD	0.002	0.001	0.007	—	
FD	8.2	5.1	11.2	5.4	11.7
FV	0.003	0.001	0.01	—	

geminates.

5 Results

5.1 Individual alternations

Table 6 shows the Historical Probabilities with estimated 95% BC_a confidence intervals for the six natural and unnatural alternations discussed above. Figure 1 shows the distributions of bootstrap replicates for the Historical Probabilities (P_χ) of these natural and unnatural alternations. The results illustrate a substantial difference in Historical Probabilities between the natural and unnatural groups. The model thus predicts that the unnatural alternations will be substantially less frequent than their respective natural alternations.

5.2 Comparison of alternations

One of the advantages of the proposed model is that inferential statistics can be performed on the comparison between the Historical Probabilities of any two alternations. Significance testing is

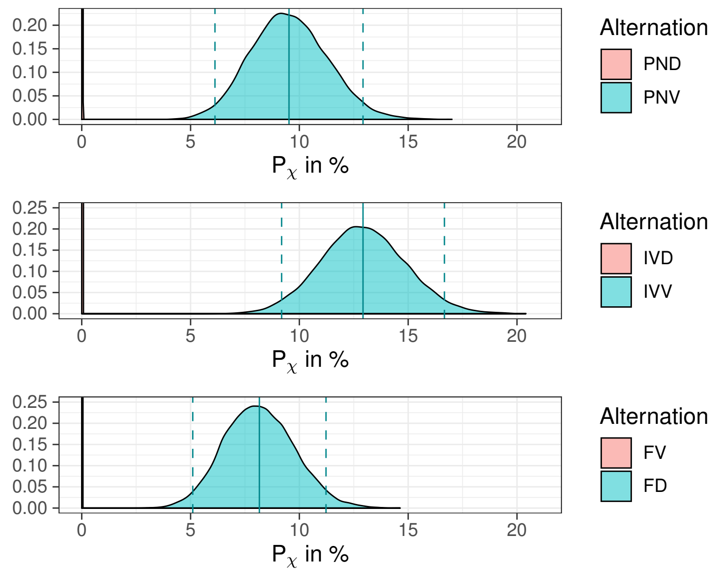

Figure 1: Bootstrap replicates for natural and unnatural alternations. The plots show the observed P_χ (solid line) and the 95% BC_a CI (dashed line) for natural alternations (PNV = post-nasal voicing, PND = post-nasal devoicing, IVV = inter-vocalic voicing, IVD = inter-vocalic devoicing, FD = final devoicing, FV = final voicing). The vast majority of bootstrap replicates for unnatural alternations fall outside the limits of the plot.

Table 7: Estimated ΔP_χ (in %) for natural-unnatural alternation pairs with 95% BC_a confidence intervals.

		95% BC_a CI		
Alternation pair	**Δ P_χ**	**Lower**	**Upper**	
PNV vs. PND	9.5	6.5	13.3	*
IVV vs. IVD	12.9	9.5	17.0	*
FD vs. FV	8.2	5.4	11.9	*

performed by estimating a difference between the Historical Probabilities of two alternations (see Section 3.1.3).

The Historical Probabilities of all three natural alternations in Figure 1 are significantly higher than the Historical Probabilities of their unnatural counterparts. Table 7 includes estimates and 95% BC_a confidence intervals of the difference in Historical Probabilities (ΔP_χ) for each natural-unnatural alternation pair.

We can also compare alternations within the unnatural group. Figure 2 shows bootstrap replicates of the individual Historical Probabilities of the three unnatural alternations. The figure shows that the Historical Probability of post-nasal devoicing is higher compared to the Historical Probabilities of the other two unnatural alternations. By estimating the difference between two alternations, we can test, for example, whether P_χ(post-nasal devoicing) and P_χ(inter-vocalic devoicing) or P_χ(post-nasal devoicing) and P_χ(final voicing) are significantly different.

(6) a. $\Delta P_\chi(\text{PND}, \text{IVD}) = P_\chi(\text{PND}) - P_\chi(\text{IVD}) = 0.010\%$ $[0.003\%, 0.02\%]$
b. $\Delta P_\chi(\text{PND}, \text{FV}) = P_\chi(\text{PND}) - P_\chi(\text{FV}) = 0.009\%$ $[0.001\%, 0.02\%]$

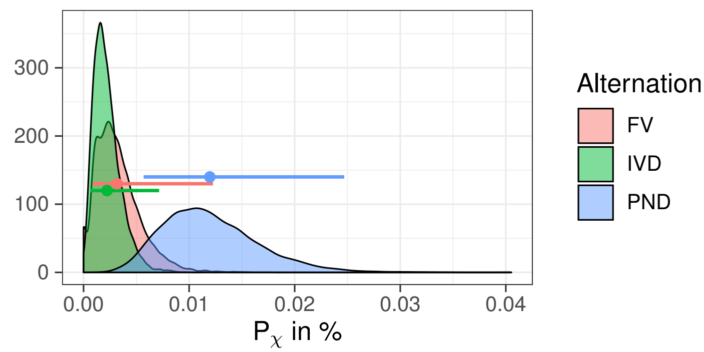

Figure 2: Bootstrap replicates for unnatural alternations with observed P_χ (colored dot) and 95% BC_a confidence intervals (colored lines).

Because the 95% BC_a CIs of the difference in Historical Probability between post-nasal devoicing and final voicing and post-nasal devoicing and inter-vocalic devoicing lie above zero, it can be concluded that the Historical Probability of post-nasal devoicing (P_χ(PND)) is significantly higher than the Historical Probabilities of final voicing (P_χ(FV)) and inter-vocalic devoicing (P_χ(IVD)) (with $\alpha = 0.05$).

Certainly, the proposed technique makes some simplifying assumptions that introduce confounds to the estimation of Historical Probabilities (see Sections 3.2, 3.3, and 4). Because differences in the Historical Probabilities between unnatural alternations are considerably smaller than differences between natural-unnatural pairs (Figure 1), estimation of these differences is substantially more prone to be influenced by these confounds and therefore less reliable. Until more comprehensive surveys are available, however, the proposed model makes, to the author's knowledge, the most accurate approximations of Historical Probabilities of alternations, both for natural-unnatural alternation pairs as well as for alternations within the unnatural group.

5.3 Comparing P_χ to observed synchronic typology

We can evaluate the model's predictions by comparing Historical Probabilities with independently observed typology of *synchronic* alternations.[19] Table 8 compares Historical and observed synchronic probabilities. Historical Probabilities (P_χ) are estimated as described above (see Section 4 and Table 6). The synchronic typology is estimated with a non-parametric bootstrap technique in the same way as described in Section 3.1.1, except that the estimation is based on the number of languages in a sample with a synchronic alternation and the number of languages in a sample without the synchronic alternation. The survey used for estimating synchronic typology is the P-base database (Mielke 2019) that surveys altogether 629 languages. Post-nasal voicing is attested in 28 languages, intervocalic voicing in 51 languages, and final devoicing in 31 languages. All three alternations are counted even if they target only one place of articulation.[20] Both the historical sample (Kümmel 2007) and the synchronic sample are not constructed specifically for the purpose of establishing typology of processes that target feature [voice], which makes them less prone to biases.

[19] Estimation of synchronic typological probabilities faces even more difficulties than estimation of Historical Probabilities, such as dependency of typological estimates on areal or historical factors. A comparison of Historical Probabilities and observed synchronic typology can only be qualitative at this point, especially until more comprehensive and well-balanced surveys are available.

[20] Languages based on which the count is performed are given in Section B.

The following estimations of the synchronic typology of unnatural alternations can be computed (summarized in Table 8) based on surveys of unnatural processes in Beguš (2018, 2019) and Beguš and Nazarov (2018). post-nasal devoicing has been confirmed as a fully productive synchronic alternation in two related languages (Tswana and Shekgalagari) and as a morphophonological alternation in a few others (Buginese, Nasioi; see Beguš 2019). For the purpose of comparison, only fully productive alternations are counted in the synchronic typology. Because Tswana and Shekgalagari are closely related, post-nasal devoicing here is counted as a single occurrence. Intervocalic devoicing is attested only once as a morphologically conditioned synchronic process (Bloyd 2015), although detailed descriptions are lacking. Final voicing is, to the author's knowledge, not attested as a productive phonological alternation in any language, which is why its synchronic typological probability is estimated below $P(\frac{1}{600})$.[21] An approximate estimate of languages surveyed in these surveys of unnatural alternations is 600.

Table 8: A comparison of Historical Probabilities (P_χ) and observed synchronic typology (Typol.) with 95% BC_a CIs for natural and unnatural processes.

		95% BC_a CI			95% BC_a CI	
A_k	P_χ	Lower	Upper	Typol.	Lower	Upper
PNV	9.50	6.10	12.90	4.5	2.9	6.2
PND	0.01	0.006	0.02	0.5	0.0	1.2
IVV	12.9	9.2	16.7	8.1	6.0	10.2
IVD	0.002	0.001	0.007	0.2	0.0	0.5
FD	8.2	5.1	11.2	4.9	3.3	6.7
FV	0.003	0.001	0.01	0.0	0.0	0.0

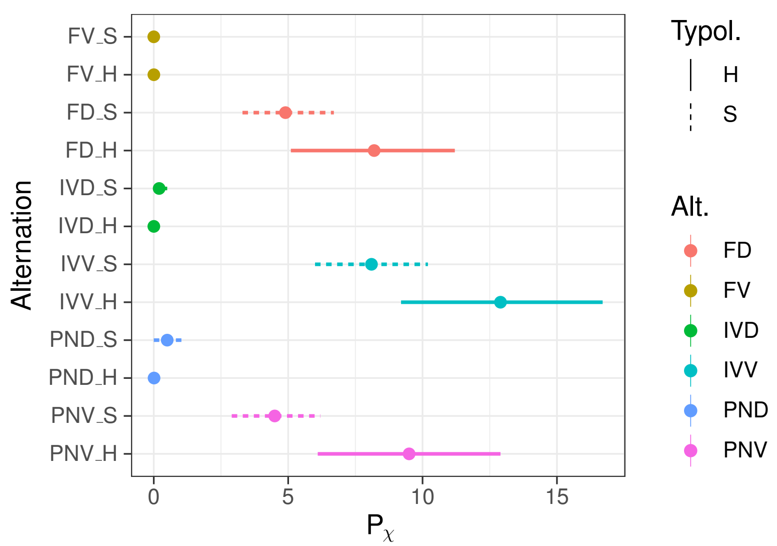

Figure 3: Observed Historical (H, solid line) and synchronic (S, dashed line) probabilities (in %) with 95% BC_a CIs from Table 8.

Table 8 and the corresponding plot of estimated Historical and synchronic probabilities with 95% BC_a CIs in Figure 3 suggest that the model correctly predicts natural alternations to be considerably more frequent than their unnatural alternations. Historical Probabilities and observed synchronic

[21] If we counted the best candidate for final voicing, Lakota, as featuring fully productive unnatural alternations (Rood 2016), the typological probabilities of final voicing would be estimated at $P(\frac{1}{600}) = 0.17\%$.

typology also match to the degree that the 95% BC_a confidence intervals of both Historical and synchronic typological probabilities overlap for the compared processes. It needs to be stressed here that for unnatural processes, the comparison of Historical Probabilities and observed synchronic typology is completely independent. In other words, the model estimates the probability of a combination of three sound changes, none of which are, by themselves, related to the unnatural synchronic alternation, from which synchronic typological probabilities are estimated.

6 Implications

The proposed technique also helps identify mismatches in predictions between the analytic bias and channel bias approaches to typology. If two typologically unequal alternations show no learnability differences, but have significantly different Historical Probabilities, it is reasonable to assume that the differences in the observed typology between the two alternations is influenced by the channel bias factor. On the other hand, if two typologically unequal alternations have equal Historical Probabilities and show differences in learnability, it is reasonable to assume that the differences result from the analytic bias factor.

The proposed model suggests that the observed rarity of unnatural alternations targeting feature [voice] is primarily influenced by the channel bias factor. The typology is predicted with relatively high accuracy (Section 5.3 and Figure 3), whereas learning experiments found no differences between the natural and unnatural alternations for any of the three pairs (Seidl et al. 2007, Do et al. 2016, Glewwe 2017, Glewwe et al. 2018).

The model predicts not only that unnatural alternations will be rare (Section 4), but also that, all else being equal, complex alternations will be less frequent than simple alternations. The minimality principle (Donegan and Stampe 1979, Picard 1994, Beguš 2019, and Section 2), which is at least a strong tendency, states that sound change is a change in one feature (or the deletion/reordering of feature matrices) in a given environment. This means that featurally complex alternations that change more than a single feature need to arise from the phonologization of more than one sound change. Because the probability of a combination of two sound changes will be lower than the probability of one sound change, all else being equal, featurally complex alternations are predicted to be typologically less frequent within the channel bias approach. Exactly the same generalization is, however, also predicted by the analytic bias approach to typology: numerous studies have confirmed that featurally complex alternations are consistently underlearned compared to featurally simple alternations (*complexity bias*; Moreton and Pater 2012a,b).

There is a crucial mismatch in predictions between the analytic bias and channel bias approaches with respect to unnatural alternations. The channel bias approach predicts that the more sound changes an alternation requires, the lower the Historical Probability of that alternation, regardless of its complexity (see Table 9). In other words, the prediction that complex alternations will be rare is violable: if the three sound changes of a Blurring Process result in a simple unnatural alternation, it will still be predicted that the simpler alternation will be less frequent than an unmotivated complex alternation because the first requires three sound changes to arise and the latter only two (Section 2).

We can estimate the Historical Probabilities for each step in the Blurring Process that leads to unnatural alternations. Let us take as an example post-nasal devoicing. The Historical Probabilities of each resulting alternation (after the first, second, and third sound changes) were estimated as described in Section 3.[22] Table 9 (column P_χ) illustrates that each additional sound change

[22]The probability of the initial stage before the first sound change operates is calculated simply as $1-P_{\chi1,2,3}$, where $P_{\chi1,2,3}$ is the sum of the Historical Probabilities of the first, first and second, and all three sound changes.

Table 9: Mismatches in predictions (framed) between the Channel Bias approach (P_χ) and the *complexity bias* approach ($P_{\mathbf{cplx}}$) for post-nasal devoicing. The *Sound Change* column represents the three sound changes from which the unnatural process post-nasal devoicing results, and the *Alternation* column represents the synchronic alternation after each of the three sound changes. The P_χ column gives the estimated probability of each alternation with 95% BC_a Lower and Upper CIs (Lo. and Up.). The *Features* column counts the number of features a learner has to learn for each synchronic alternation.

Sound change	**Alternation**	$\mathbf{P_\chi}$	**Lo.**	**Up.**	**Features**	$\mathbf{P_\chi}$	$\mathbf{P_{cplx}}$
	No alternation	83.5	—	—	0		
D > Z / [−nas]__	D → Z / [−nas]__	16.0	11.9	20.1	1	↓	↓
D > T	Z → T / [+nas]__	0.5	0.3	0.8	2	↓	↓
Z > D	PND	0.01	0.006	0.02	1	↓	↑

decreases the Historical Probability of the resulting alternation.

On the other hand, the analytic bias approach predicts that structurally more complex alternations will be typologically less frequent because they are more difficult to learn than structurally simple alternations (*complexity bias* has been confirmed almost without exception in many studies; Moreton and Pater 2012a,b.) While many criteria of complexity in phonological alternations can be invoked, we focus on an already established measure of complexity in Moreton et al. (2017) which explains learnability asymmetries in several studies (for an overview, see Moreton and Pater 2012a,b.) and is based on concept learning. The complexity of an alternation is measured primarily from the number of features manipulated by an alternation.

If we analyze each step in the Blurring Process in terms of such synchronic complexity, the first two sound changes indeed increase the complexity of the resulting alternation,[23] but the third sound change decreases its complexity. The alternation Z → T / [+nas] manipulates two feature values, [±continuant] and [±voice]. The alternation D → T / [−nas] (post-nasal devoicing) manipulates only [±voice]. From a phonological perspective, the first is more complex than the latter (Moreton et al. 2017).

Complexity bias thus predicts that the alternations that arise from the first and second sound changes in the Blurring Process will be increasingly rare, but predicts that the structurally simpler alternations resulting from the combination of all three sound changes will be comparatively more frequent than the complex alternation requiring only two sound changes.

The mismatched predictions illustrated in Table 9 provide new information for disambiguating analytic bias and channel biases. The analytic bias-channel bias complexity mismatch can be directly evaluated against the observed typology: if unmotivated structurally complex alternations that require two sound changes are typologically more common than structurally simpler unnatural alternations, channel bias has to be the leading cause of this particular typological observation. If, on the other hand, structurally more complex unmotivated alternations that require two sound changes are typologically less frequent than what would be predicted by the channel bias approach compared to structurally simpler unnatural alternations, we have a strong case in favor of the analytic bias influence, and more precisely in favor of *complexity bias* within the analytic bias

[23]The fact that the first two sound changes in the Blurring Process occur relatively frequently, despite increasing the complexity of the alternations, argues against the radical approach to the analytic bias-channel bias conflation problem that states that sound change probabilities are primarily influenced by learnability and hence that estimated channel bias influences are crucially conflated with analytic bias influences. If anything, analytic bias influences would militate against the first two sound changes operating in combination because the resulting alternations would be more difficult to learn. Because the Blurring Process does occur, it means that the driving force behind the sound changes in question operating are not crucially influenced by analytic bias (although analytic bias can of course still influence the relative frequencies of sound change).

approach to typology.

In fact, typological observations suggest that the complex synchronic alternation Z → T / [+nas]__ that results from the first two sound changes in a Blurring Process might be attested less frequently than would be predicted by channel bias, suggesting that *complexity bias* influences this distribution. The Historical Probability of Z → T / [+nas]__ is significantly higher than the Historical Probability of post-nasal devoicing. The difference is estimated at $\Delta P_\chi(Z \rightarrow T\ /\ [+\text{nas}]\_\_, \text{PND}) = 0.4\%$, $[0.2\%, 0.8\%]$. In other words, the Historical Probability of the alternation Z → T / [+nas]__ that arises through two sound changes is predicted to be approximately fifty times more frequent than the Historical Probability of post-nasal devoicing (see Table 9). Surface synchronic typology, however, does not conform to this generalization.

A system in which post-nasal devoiced stops contrast with voiced fricatives elsewhere (a complex alternation that arises via the combination of two sound changes) is synchronically confirmed in Konyagi, Punu, Pedi,[24] Sie, and potentially Nasioi (Dickens 1984; Hyman 2001; Merrill 2014, 2016a,b; Santos 1996; Brown 2017).[25] Other languages are more difficult to classify because some of them appear to feature full post-nasal devoicing only for a subset of places of articulation. While Z → T / [+nas]__ indeed appears to be more frequent than post-nasal devoicing, the magnitude of the difference appears to be smaller than predicted by the channel bias.

Even more intriguing is the high frequency at which the third sound change in the Blurring Process, occlusion of voiced fricatives to stops (Z > D), operates on synchronic systems that feature the alternation Z → T / [+nas]__ (after the first two changes). The Historical Probability of the third sound change that leads to post-nasal devoicing, occlusion of voiced fricatives for languages that have voiced fricatives in the system, estimated independently of the Blurring Process (i.e. estimated from an unconditioned diachronic sample) is $P_\chi(Z > D) = 20.4\%$, $[14.8\%, 25.5\%]$ (for languages that have voiced fricatives). Of the languages in the survey in Beguš (2019) that undergo the first two sound changes in the Blurring Process, which leads to post-nasal devoicing, six languages (out of ten, or approximately 60%)[26] feature occlusion of stops for at least one place of articulation or in at least one position in the word. If we count only cases in which the occlusion of fricatives targets more than two places of articulation, only Tswana, Shekgalagari, Makuwa, and Murik would count. It does appear, however, that the occlusion of voiced fricatives in a synchronic system that undergoes the first two sound changes is more frequent than the model predicts for the occlusion of voiced fricatives in general.

To test the hypothesis that the last sound change operates with higher frequency than would be predicted by only the channel bias approach, we can compare the unconditioned Historical Probability of the occlusion of fricatives with the Historical Probability of the occlusion of fricatives in those languages that have already undergone the first two sound changes in the Blurring Cycle that lead to post-nasal devoicing. In other words, we compare the probability of the occlusion of fricatives regardless of whether it simplifies the alternation (assuming only the channel bias influences) with the probability of the occlusion of fricatives operating in the Blurring Process, where it simplifies the alternation and consequently its learnability. Counts for the unconditioned Historical Probability of the occlusion of fricatives is based on the survey of sound changes in

[24]We count Kutswe and Pulana together with Pedi, because they are closely related. Even if we counted them spearately (Kutswe and Pulana as one langauge), the distribution is still significant ($p = 0.016$).

[25]Punu is a language that undergoes a different development from the one described in Section 2. In Punu, the resulting alternation is not post-nasal devoicing but the complex alternation between voiced fricatives elsewhere and voiceless stops post-nasally. For a discussion, see Hyman (2001).

[26]post-nasal devoicing occurrences in Tswana, Shekgalagari, and Makhuwa are counted as only one occurrence. South Italian dialects that devoice affricates are not counted. I also exclude Mpongwe from the count because of the limited description and marginal status of post-nasal devoicing there. I include Pedi which features Z → T / [+nas] (Dickens 1984) and Sie based on counts of the synchronic database of phonological rules in Mielke (2019).

Kümmel (2007). 44 languages with voiced fricatives (out of 216 surveyed) undergo the occlusion of voiced fricatives. As already mentioned, under the less conservative count, six out of ten languages with occlusion and devoicing of voiced fricatives show occlusion for at least one place of articulation or for at least one context (word-initially in Nasioi).[27] The difference between the two counts is statistically significant ($p = 0.009$, Fisher's Exact Test). This means that the last sound change in the Blurring Process that decreases the complexity of the resulting alternation operates at significantly higher rates than would be predicted if we only assumed channel bias influences.[28]

This suggests that the high occurrence of the third sound change in the Blurring Process (in the case of post-nasal devoicing, the occlusion of fricatives) is likely an influence of *complexity bias* within the analytic bias approach. While analytic bias likely does not crucially influence the probabilities of the first two sound changes in the Blurring Process in the direction that interests us because they increase complexity and therefore would be predicted to reduce learnability (just as is predicted by the channel bias approach),[29] it is likely that the occurrence of the third sound change, and therefore the lower probability of the more complex unmotivated alternation, is influenced precisely by *complexity bias*. The paper identifies and describes one such instance; investigation of further such cases should yield a better understanding on how learnability and sound change frequency interact.

7 Conclusion

This paper proposes a technique for estimating channel bias influences on phonological typology using the statistical technique bootstrapping. We estimate Historical Probabilities of alternations that are based on two diachronic factors: the number of sound changes required for an alternation to arise and their respective probabilities.

Several applications of the model are presented and applied to six natural and unnatural alternations targeting feature [voice]. The model (i) can estimate the Historical Probability of any synchronic alternation, both attested and unattested, (ii) compare the Historical Probabilities of two alternations and perform inferential tests on the comparison, and (iii) compare the Historical Probabilities to independently observed synchronic typology to evaluate the channel bias influences on typology. Finally, we identify mismatches in predictions between the analytic bias and channel bias approaches, which yields new insights into the discussion of different influences on phonological typology. The results suggest that the typological difference between natural and unnatural alternations targeting the feature [voice] is primarily due to channel bias, but that the relatively low frequency of complex alternations and the higher rate of the operation of sound changes that simplify an alternation are due to analytic bias.

These conclusions have direct theoretical implications. Synchronic grammar should ideally derive all observed patterns and at the same time exclude impossible processes. Typological observations often prompt adjustments in grammar design. The proposed framework suggests that some typological gaps are historical accidents that need not be encoded in synchronic grammars, and quantifies these gaps. On the other hand, this paper also suggests that some typological observations, such as the avoidance of complex alternations, cannot be explained only within the channel bias approach and that these preferences should indeed be encoded in synchronic grammar. The

[27] Cases with variation are counted as involving the sound change.

[28] This is exactly the opposite of what is proposed by Kiparsky (2008), who claims that the sound change that would result in an unnatural alternation would get blocked by the grammar.

[29] If both approaches predict the same, it is difficult to distinguish between the two. We are primarily interested in mismatches in predictions, because then we can test the hypothesis against the observed typology.

paper limits the application of the technique to six alternations targeting feature [voice]. Estimation of the channel bias and analytic bias influences should be performed on further alternations in order to gain a better understanding of which observations result from constraints in synchronic grammar and which from diachronic development.

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A Counts

A.1 post-nasal voicing

Three places of articulation: Milian, Lycian, Karian, Lydian; North-West Middle Indo-Aryan; New Indo-Aryan Dom-Lom-Rom, Sindhi, Lahnda, Punjabi, Western Pahari; Common East Iranian; Late Old Persian, Common West Middle Iranian; Middle Armenian, Common Armenian; Common Albanian; Middle Greek; Common South Italian; Spanish (Pyrenees); Scottish Gaelic, Manx; East Saami; East Saami (Skolt, Patsjoki, Inari); Central Saami; Mari; Hungarian; Common Permic; Enets; North, Middle (dialectal), South Selkup
Two places of articulation: Proto-Irish; Milian, Lycian, Karian; Ormuri; New Babilonian; Late Old Umbrian; North Selkup
One place of articulation: Tumshuqese; Old Greek Pamphylian; Parochi, Ormuri

A.2 Inter-vocalic voicing

Three places of articulation: Sarmatian, Alanian, Common Ossetian; Chwaresmian; Khotanese and Tumshuqese; Pamir (Yazghulami, Sughni); Bactrian; Yidgha-Munji ; Pashto; Common North-West Middle Iranian; Middle Persian, Common South-West Iranian; Karelian (Proper, Olonets, Ludic), Dialectal Ingrian, Veps; Dialectal South Estonian, Livonian; Common North-West Middle Indo-Aryan; Common Middle Indo-Aryan; Central Italian Marche, Umbrian, Latio, New Corsican; Common West Romance; Middle Selkup; Proto-Brittonic; Manx; South Norwegian, Swedisch (Bohuslän, West Västergötland); Common Old Danish; Common Permic; Kamassian, Koibalian; Pamir Sanglechi-Ishkashimi; Gorani, Azari, Sivendi ; Common Nuristani; Mordvinian; Mari; Dialectal South Selkup
Two places of articulation: South-West Iranian Kumzari; North Khanty (Obdorsk); Sogdian; Common Parachi-Ormuri; Enets; Tundra Nenets; South-West Iranian Bashkardi
One place of articulation: Waxi; Common Parachi-Ormuri; Proto-Anatolian

A.3 Final devoicing

Three places of articulation: Dardic (Kashmiri); Dardic (Dameli); Nuristani (Askunu, Kati, Prasun); Common Rhaeto-Romance, Common French, Franco-Provençal, Common Occitan,; Breton; Proto-Nordic; Old Low Franconian, Old High German Middle Franconian, North Thuringian; New Dutch; Middle Low German, New Low German; Bulgarian; Serbo-Croatian West Chakavian (Istrian), Common Slovenian; Common Slovak; Russian; West Russian; Ethiopian Tigrinya; Dardic (Kashmiri); Common Catalan; Old Bretton; Common Middle High German; New West Frisian
Two places of articulation: Sangsari
One place of articulation:Yaghnobi; Old Saxon; Old High German South Rhine Franconian, East Franconian

A.4 post-nasal devoicing

A.4.1 First change

Three places of articulation: Milian, Lycian, Karian; Common East Middle Iranian; Old Greek (Pamphylian, Central Krete, West Argolian, Laconia, Elis, Boiotic); Late Old Greek Helenic; Common South Italian; Milian, Lycian; Young Avestan; Parachi; Late Old Persian, Common West Iranian; Late Parthian, Common North-West-Iranian; Late Middle Persian, South-West Iranian (Dialectal); Common Celtic; Common Finnic; Mari; Common Akkadian (Dialectal); Middle Hebrew, Phoenician, Aramaic; East Balochi; Central Italian (Tuscany Dialectal); Common Middle Indo-Aryan; New West Middle Indo-Aryan; Common Nuristani; Khotanese and Tumshuqese; Common Parachi-Ormuri; Common New Italian, Common Rhaeto-Romance; Common French, Franco-Provençal; Common Catalan, Common Spanish; Portuguese European; Manx; Old Danish Common ; East Saami; Mordvinian; Permic
Two places of articulation: Central Kurdish (War.); Pamir Sanglechi-Ishkashimi; Ormuri; Yidgha-Munji ; Ethiopic Amharic; New High German , West Alemannic, Nord, East Middle Bavarian; Common North-West Midde Indo-Aryan; Common Middle Indo-Aryan; Dalmatian; Common Sardinian; Common West Romance

One place of articulation: Tigre, Tigrinya, Harari, Gurage; West Tocharian Dialectal; Common Middle Indo-Aryan; Ossetian; Late Baktrian; Old Greek Pamphylian; Vulgar Latin, Common Rommance; New High German Common Middle Bavarian; Central Italian (Tuscany Dialectal); Common Old Swedish; Middle Dutch; Low German (dialectal); New North Frisian (Sylt, Festland); Enets (karassinisch); New High German , South and East Moselle Franconian, Hessian, Palatine; Common Albanian; Pashto; Central Kurdish (Sul.); Umbrian; Yidgha, Munji (dialectal); Central Italian (Tuscany Dialectal); New North Frisian (Dialectal); New Dutch

A.4.2 Second Change

Three places of articulation: New Persian, North-West Iranian Dialectal; Scottish Gaelic, Manx; Common New Icelandic; Common New Danish (dialectal); Old High German East Franconian, Upper German; Proto-Armenian; Proto-Phrygian; Proto-Germanic; Hittite, Palaic, Luwian; Old Indo-Aryan dialectal; New High German Dialectal; Common Anatolian; Common Tocharian
Two places of articulation: South Italian (South Latio, North Camoanian)
One place of articulation: Old High German East Franconian, Upper German; Old High German Rhine Franconian; South Italian (East Apulia, East Sicilian dialectal)

A.4.3 Third Change

Three places of articulation: Slovenian Upper Carniolan (Dialectal)
Two places of articulation: New Persian (Mod.); Italian New Greek (Terra d'Otranto, Bova); Common Rhaeto-Romance; Low German (Ostfalian, Central Low Saxon); Common Old High German
One place of articulation: West New Aramaic; New Low German Westphalian dialectal; New High German South Bavarian West Cimbrian; North-East New Aramaic (Jewish Azerbaijan); Dialectal Arabic Bahrain Shia; Ugaritic; Common South-West Iranian, Old Persian; Pamir Ishkashimi; Yaghnobi; Waxi; Middle Norwegian; Middle Swedish; New Swedish; Common West Germanic; New English (dialectal); New North Frisian (Heligoland); Middle Low German, Middle Dutch; East Saami (Ter); South Saami (southern dialects); Veps, Livonian; Morvinian; South New Irish dialectal (Munster); Ormuri (Baraki Barak); Pashto dialectal (North-East, North-West); Common Old Armenian; New Greek (Bova); Occitan dialectal; New Low German (Mecklenburg); Arabic dialectal (Egyptian, Levantine, Maghrebi, Maltese); New South Arabic (Soqotri); Common Aramaic; North-East New Aramaic; Ossetian; Dialectal Albanian (östl); Late Old Frisian dialectal, Common New West Frisian; New East Frisian (Saterland); New East Frisian (Wangerooge); Lombardic

A.5 inter-vocalic devoicing

A.5.1 First Change

Three places of articulation: Milian, Lycian; Young Avestan; Parachi; Late Old Persian, Common West Iranian; Late Parthian, Common North-West-Iranian; Late Middle Persian, South-West Iranian (Dialectal); Common Celtic; Common Finnic; Mari; Common Akkadian (Dialectal); Middle Hebrew, Phoenician, Aramaic; East Balochi; Central Italian (Tuscany Dialectal); Common Middle Indo-Aryan; New West Middle Indo-Aryan; Common Nuristani; Khotanese and Tumshuqese; Common Parachi-Ormuri; Central Kurdish (War.); Common New Italian, Common Rhaeto-Romance; Common French, Franco-Provençal; Common Catalan, Common Spanish; Portuguese European; Manx; Old Danish Common ; East Saami; Mordvinian; Permic
Two places of articulation: Pamir Sanglechi-Ishkashimi; Ormuri; Yidgha-Munji ; Ethiopic Amharic; New High German , West Alemannic, Nord, East Middle Bavarian; Common North-West Middle Indo-Aryan; Common Middle Indo-Aryan; Dalmatian; Common Sardinian; Common West Romance;
One place of articulation: Tigre, Tigrinya, Harari, Gurage; West Tocharian Dialectal; Common Middle Indo-Aryan; Ossetian; Late Baktrian; Old Greek Pamphylian; Vulgar Latin, Common Rommance; New High German Common Middle Bavarian; Central Italian (Tuscany Dialectal); Common Old Swedish; Middle Dutch; Low German (dialectal); New North Frisian (Sylt, Festland); Enets (karassinisch); New High German , South and East Moselle Franconian, Hessian, Palatine; Common Albanian; Pashto; Central Kurdish (Sul.);

Umbrian; Yidgha, Munji (dialectal); Central Italian (Tuscany dialectal); Dialectal Selkup; New North Frisian (dialectal)

A.5.2 Second Change

Two places of articulation: New Dutch (dialectal); Spanish Aragonese Castillian, Andalusian; New Danish (South Jutland); Palatine, East Franconian, Upper Saxon dialectal
One place of articulation: Galician; Catalan (Apixtat), Ribagorza; Young Avestan, West Iranian (dialectal); New High German (Middle Franconian); New Low German dialectal; East and South Italian (dialectal)

A.5.3 Third Change

Three places of articulation: Waxi; Balochi
Two places of articulation: Central Italian (Tuskany dialectal)
One place of articulation: North-East New Aramaic; Arabic dialectal (Egyptian, Levantine, Maghrebi, Maltese); New South Arabic (Soqotri); Common Aramaic; North-East New Aramaic; Ossetian; Dialectal Albanian (östl); Late Old Frisian dialectal, Common New West Frisian; New East Frisian (Saterland); New East Frisian (Wangerooge); Lombardic; Pamir Sanglechi; New Greek Anatolian; Central Sardinian, Logudorese; Middle Norwegian, Middle Swedisch, Common Old Danish; New English (Shetland, Orkney, Manx); South Khanty, North Khanty (Nizjam, Sherkaly); Mansi; Serbo-Croatian Montenegrin; New Greek dialectal (Bova); Parochi

A.6 Final voicing

A.6.1 First Change

Three places of articulation: Hebrew; Amharic; Old Saxon, Old Dutch, Old High German

A.6.2 Second Change

Three places of articulation: Sarmatian, Alanian, Common Ossetian; Chwaresmian; Khotanese and Tumshuqese; Bactrian; Yidgha-Munji ; Pashto; Common North-West Middle Iranian; Middle Persian, Common South-West Iranian; Karelian (Proper, Olonets, Ludic), Dialectal Ingrian, Veps; Dialectal South Estonian, Livonian; Middle Selkup; South Norwegian, Swedisch (Bohuslän, West Västergötland); Common Old Danish; Kamassian, Koibalian; Gorani, Azari, Sivendi ; Mordvinian; Mari; Dialectal South Selkup
Two places of articulation: South-West Iranian Kumzari; Sogdian; Common Parachi-Ormuri; Enets; South-West Iranian Bashkardi; Tundra Nenets
One place of articulation: Common Parachi-Ormuri; Proto-Anatolian

A.6.3 Third Change

Three places of articulation: Ethiopian Gurage; Milian, Lycian; Common Dardian; Sindhi; New Greek; Common Albanian; Romanian; Common North Italian; Common Rhaeto-Romance, Common Gallo-Romance; Common Ibero-Romance; Old Irish; Common Brittonic ; Danish Jutlandic, Insular; Middle English; Common New Frisian, Middle Low German, Middle Dutch ; Mordvinian, Common Mari; Common Permic; Common Khanty, Mansi; Hungarian; Proto-Samoyedic; Common New High German

B Synchronic typology

B.1 Post-nasal voicing

Counts are based on a query for a change from [−voiced] to [+voiced] with the left environment conditioned on [+nasal] in the P-base database in Mielke (2019).

Mixe, Lowland (Coatlán variety); Maasai; Binumarien; Delaware (Unami); Pitjantjatjara/Western Desert Language; Guatuso (Maléku Jaíka); Bemba; Khmu?; Xhosa; Totonac, Misantla; Mixe, North Highland (Totontepec Mixe); Kui; Quichua, Ecuador (Puyo Pongo variety); Mwera; Passamaquoddy-Maliseet (Malecite-Passamaquoddy); Tamil; Muruwari; Malayalam; Ciyao (Yao); Nyangumata; Si-Luyana; Kpelle; Tiriyó (Trió); Pero (Gwandum dialect); Quechua, Ecuadorean Highland (as spoken in Bolivar Province); Limbu; Ojibwa, Eastern; Pero

B.2 Intervocalic voicing

Counts are based on a query for a change from [−voiced] to [+voiced] with the left environment conditioned on [+vowel] in the P-base database in Mielke (2019).

Af Tunni Somali (Tunni); Alabama; Ao; Auyana; Berbice Dutch Creole; Boruca; Bribri; Burmese; Danish; Efik; Estonian; Faroese; Faroese (in some districts); Guatuso (Maléku Jaíka); Kalenjin, Nandi; Kui; Kwamera; Lele; Loniu; Mangap-Mbula; Martuthunira; Mikasuki; Mixe, Lowland (Coatlán variety); Mixe, Lowland (Guichicovi variety); Mixe, Lowland (San Juan el Paraíso variety); Mixe, North Highland (Totontepec Mixe); Mixe, South Highland (Mixistlán variety); Mixe, South Highland (Tepantlali variety); Mixe, South Highland (Tepuxtepec variety); Mixe, South Highland (Tlahuitoltepec variety); Mohawk; Mupun; Mupun (Jipari dialect); Ngura; Nyangumata; Ojibwa, Eastern; Oneida; Palauan; Passamaquoddy-Maliseet (Malecite-Passamaquoddy); Pech (Paya); Pero; Popoluca, Sayula; Purik; Quechua, Ecuadorean Highland (as spoken in Bolivar Province); Senoufo, Supyire; So (Soo); Tangkhul; Tsimshian, Coast; Turkish; Tyvan (Tuvin); Xakas (Khakas)

B.3 Final devoicing

Counts are based on a query for a change from [+voiced] to [−voiced] with the right environment conditioned on word boundary in the P-base database in Mielke (2019).

Fe'Fe'-Bamileke; Ejagham; Slovene; Shilluk; Czech; Lithuanian; O'odham (Papago); Polish; Pero; Afrikaans; Kirghiz; Tigre; Turkish; Russian; Af Tunni Somali (Tunni); Amele; Ingessana; Boruca; Dutch; Armenian, Standard Eastern; Dhaasanac (Daasanach); Bulgarian; Arbore; Tirmaga; Serbo-Croatian (Cres Čakavian); Wolof; Faroese; Sepečides-Romani; Slovak; Nigerian English (Nigerian Pidgin); Afar;

C Supplementary materials

C.1 bsc()

The function *bsc()* takes two vectors of equal length as arguments: a vector with counts of languages with a sound changes required for an alternation A_k, and a vector of languages surveyed for each sound change. The function internally transforms the vectors with counts into a binomial distribution of successes and failures for each sound change in the count. It returns R bootstrap replicates of the Historical Probability of A_1, computed according to (1), (2), (3), and (4). Stratified non-parametric bootstrapping is performed based on the *boot* package: the output of *bsc()* is an object of class "boot". The output of *bsc()* should be used as an argument of *summary.bsc()* (see C.3), which returns the observed P_χ and 95% BC_a CIs. Two optional arguments of *bsc()* are *order* (if True, Historical Probabilities are divided by $n!$) and R, which determines the number of bootstrap replicates.

```
bsc <- function (counts, surveyed, order = T, R = 10000) {
  library(boot)
  if (length(counts) != length(surveyed)) {stop
    ("Vectors␣must␣be␣of␣equal␣length.")
  }
  binom <- unlist(mapply(c,
                          lapply(counts, function(x) rep(1, x)),
                          lapply(surveyed - counts, function(x) rep(0, x)),SIMPLIFY
                              =F)
```

```
  )
  snumb <- paste("s", 1:length(surveyed), sep="")
  ident <- rep(snumb, surveyed)

  scsample <- data.frame(binom,ident)

  if (order == TRUE) {n <- factorial(length(counts))}
  if (order == FALSE) {n <- 1}

  bsc <- function(x, id) {
    sc1 <- tapply(x[id,1], x[id,2], mean)
    sc <- prod(sc1) / n
    return(sc)
  }

  boot.scsample <- boot(scsample, statistic = bsc, R, strata = scsample[, 2]
                        )
  return(boot.scsample)
}
```

C.2 bsc2()

The function *bsc2()* compares the Historical Probabilities of two processes with BSC. It takes as an input the output of *bsc()* for the process in question. The function transforms the counts into a binomial distribution of successes and failures. It returns R bootstrap replicates of the difference in Historical Probability between the two alternations, computed according to (1), (2), (3), (4), and (5). Stratified non-parametric bootstrapping is performed based on the *boot* package: the output of *bsc2()* is an object of class "boot". The output of *bsc2()* should be used as an argument of *summary.bsc2()* (see C.4), which returns the observed ΔP_{χ} and 95% BC_a CIs for the difference. If 95% BC_a CIs fall above or below zero, it spells out that the difference is significant, and that it is not otherwise. Two optional arguments of *bsc()* are *order* (if True, Historical Probabilities are divided by $n!$) and R, which determines the number of bootstrap replicates.

```
bsc2 <- function(bsc.alt1a, bsc.alt2a, order = T, R = 10000){
  library(boot)
  bsc.alt1 <- bsc.alt1a$data
  bsc.alt2 <- bsc.alt2a$data
  bsc.alt1$scid <- "first"
  bsc.alt2$scid <- "second"
  bsc.diff.df <- rbind(bsc.alt1,bsc.alt2)
  bsc.diff.df$comb <- as.factor(paste(bsc.diff.df$scid,bsc.diff.df$ident, sep = ""
     ))

  bsc.diff.df$scid <- NULL
  bsc.diff.df$ident <- NULL

  if (order == TRUE) {  n1 <- factorial(length(unique(bsc.alt1$ident)))
  n2 <- factorial(length(unique(bsc.alt2$ident)))}
  if (order == FALSE) { n1 <- 1
  n2 <- 1}

  l <- length(unique(bsc.alt1$ident))
  m <- length(unique(bsc.alt2$ident))

  bsc.diff <- function(x, id) {
    sc1 <- tapply(x[id,1], x[id,2], mean)
    sca <- (prod(sc1[1:l]) / n1)
    scb <- (prod(sc1[(l+1):(l+m)]) / n2)
    sc <- sca - scb
```

```
    return(sc)
  }

  boot.diff <- boot(bsc.diff.df, statistic = bsc.diff, R, strata = bsc.diff.df[,2]
                       )
  return(boot.diff)
}
```

C.3 summary.bsc()

The function *summary.bsc()* computes the 95% BC_a CI for the bootstrap replicates based on the *bsc()* function (see C.1) using the *boot.ci()* function from the *boot* package and returns the observed and estimated Historical Probabilities. For details, see C.1.

```
summary.bsc <- function (bsc.alt) {
  bsc.ci.alt <- boot.ci(bsc.alt, type="bca")
  title <- "BOOTSTRAPPING SOUND CHANGES"
  prob <- paste("Estimated P =", round(bsc.alt$t0*100, digits = 5), "%")
  bca <- paste("Estimated 95 % BCa CI = [", round(bsc.ci.alt$bca[4]*100, digits = 4),"%,",
               round(bsc.ci.alt$bca[5]*100, digits = 4),"%]")
  #rnsc <- paste(pasteR, n.sc.paste, countsp, surveyed, sep = "\n")
  probbca <- paste(prob, bca, sep = "\n")
  cat(title, probbca, sep = "\n\n")
}
```

C.4 summary.bsc2()

The function *summary.bsc2()* computes the 95% BC_a CI for the bootstrap replicates based on the *bsc2()* function (see C.2) using the *boot.ci()* function from the *boot* package and returns the observed and estimated differences in Historical Probabilities of two alternations. For details, see C.1.

```
summary.bsc2 <- function (bsc2.alt) {
  bsc2.ci.alt <- boot.ci(bsc2.alt, type="bca")
  title <- "BOOTSTRAPPING SOUND CHANGES - COMPARE"
  prob <- paste("Estimated",expression(Delta), "P =", round(bsc2.alt$t0*100, digits = 5), "%")
  bca <- paste("Estimated 95 % BCa CI = [", round(bsc2.ci.alt$bca[4]*100, digits = 4),"%,",
               round(bsc2.ci.alt$bca[5]*100, digits = 4),"%]")
  if (bsc2.ci.alt$bca[4] > 0 & bsc2.ci.alt$bca[5] > 0) {
    sig <- "P(A1) is significantly higher than P(A2)."
  }
  else if (bsc2.ci.alt$bca[4] < 0 & bsc2.ci.alt$bca[5] < 0) {
    sig <- "P(A1) is significantly lower than P(A2)."
  } else {
    sig <- "P(A1) and P(A2) are not significantly different."
  }
  probbca <- paste(prob, bca, sep = "\n")
  cat(title, probbca,sig, sep = "\n\n")
}
```