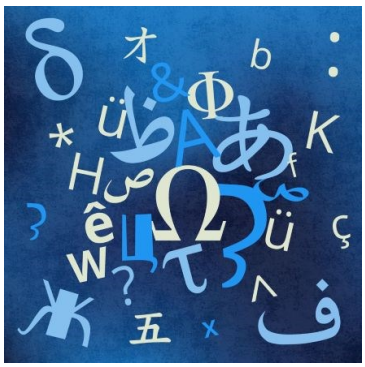

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Phonetic Aspects of Language Change

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Abstract

Sound change is one of the most visible dimensions of language evolution, alongside shifts in meaning and vocabulary, and is influenced by social, systemic, and phonetic factors. The phonetic dimension emphasizes the anatomical, physiological, and perceptual mechanisms that structure variation and provide the raw material for change. Broadly speaking, phonetic aspects of change can be separated into bias factors, constraints on selection, and mechanisms governing innovation and propagation. Bias factors refer to articulatory, acoustic, and perceptual contingencies which give rise to a structured and nonrandom pool of variation. However, not all variation results in change. The selection of variants is constrained by systemic factors such as structural or cognitive biases, lexical or morphological structure, and enhancements to the salience or perceptibility of contrasts. Innovation occurs when individual listeners or speakers reanalyze or reorganize the phonetic signal, with theories differing on whether this is primarily the result of gestural reorganization, perceptual errors, gradual reweighting of cues, or stochastic selection among variants. Individual differences in production, perception, and cognitive processing style also play a role in shaping the trajectory of change. Computational modeling provides a way to explore how phonetic biases interact with structural pressures, individual differences, and population-level processes. Parallel biases and constraints in the kinematic-visual modality are also active in signed languages. In both modalities, careful attention to phonetic aspects provides the foundation for understanding nonrandom, recurrent patterns of phonological change in human languages.

Keywords: sound change, phonetic bias, phonologization, coarticulation, sign language

Subject: Phonetics and Phonology, Historical and Diachronic Linguistics, Sign Languages, Linguistics

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1. The Phonetic Basis of Sound Change

Next to changes in semantic properties of words and the addition of new lexical items, one of the most salient aspects of language change is *sound change*: the emergence of new forms of pronunciation and changes to existing ones.[1] Sound changes can be broadly characterized in terms of social, structural, and phonetic motivations. The essential role of social factors in structuring variation in sound change is the focus of much work in variationist sociolinguistics (Mallinson, 2015), perhaps most closely associated with William Labov and his collaborators (Weinreich et al., 1968 and much subsequent work). Structural (or systemic) motivations include factors such as phonotactics, intonational structure, frequency, or lexical and morphological sensitivity. This article focuses primarily on the phonetic aspects: those concerning the anatomic and physiological influences on speech production, features of the acoustic signal and how they are perceived and processed, and the mechanisms involved in both their production and perception (Beddor, 2017; Huffman, 2016; Whalen, 2019). To the extent that today's phonetic variation forms the basis for tomorrow's sound change, understanding the principles that structure phonetic variation is critical for understanding sound change.

The study of the phonetic underpinnings of sound change is probably most closely associated with the Neogrammarians (Osthoff & Brugmann, 1878; Paul, 1886) and their American structuralist adherents (Bloomfield, 1933). Phonetically oriented approaches seek plausible explanations for diachronic changes grounded in theories of speech production, speech perception, and the acoustic and aerodynamic properties of speech (or in the case of signed languages, their kinematic-visual analogs; see Section 6). The prototypical sound change is arguably *phonologization* (Hyman, 1976, 2013; Kiparsky, 2015), whereby an intrinsic or automatic phonetic property, or *precursor*, becomes extrinsic, that is, no longer predictable from its context. For example, fundamental frequency at vowel onset varies with the voicing of the preceding consonant, with voiceless consonants typically conditioning higher pitch on the following vowel than voiced consonants (House & Fairbanks, 1953). If the contrast in voicing is lost, these pitch differences can become the sole indicator of the phonological contrast, leading to the emergence of lexical tone (Michaud & Sands, 2020). From a phonetic perspective, then, the origin of the sound change can ultimately be traced to a synchronic pattern of phonetic variation. This has led to a rich tradition of research seeking to understand the principles that structure this variation, the phonetic preconditions that lead to certain changes, and how phonetic variation is produced, perceived, learned, and propagated within speech communities.

2. From Variation to Change

To understand how sound change can emerge from synchronic phonetic variation, it is useful to adopt a conceptual framework for organizing changes into different types or classes. Traditional frameworks of this type have focused on the articulatory nature of many changes, locating the onus of change on the speaker (Bloomfield, 1933; Kiparsky, 1995; Osthoff & Brugmann, 1878). Other approaches, while in no way denying the existence of articulatory-driven variation, have emphasized the crucial role of the listener (Beddor, 2009; Blevins, 2004; Lindblom et al., 1995; Ohala, 1981). A recent and influential typology of a different nature is due to Garrett and Johnson (2013), who instead proposed a typology of biases grounded in general properties of speech production and perception. While arguably not exhaustive, this approach has the advantage of focusing attention on the phonetic aspects that give rise to variation, without making any strong claims about whether the locus of change is to be found in production or perception.

Garrett and Johnson (2013) highlight three aspects that must arguably be addressed by any comprehensive model of change: the existence of *structured* variation; constraints on the *selection* of variants; and how changes come to be *actuated* or *innovated* by individuals. The schematic interaction of these components is sketched in Figure 1. In this conception, the fundamental catalyst or source for sound changes is sought in phonetic biases,

which may be articulatory (involving either aspects of motor planning or gestural mechanics of implementation), acoustic-perceptual, or aerodynamic in nature. Phonetic biases can be thought of as generating a "pool" of synchronic variation (Ohala, 1989), which is structured in the sense that it is nonrandom and directional: As a result of acoustic, articulatory, and perceptual contingencies, some variants are more likely to occur than others. For example, voiced velar /g/ is more likely to be devoiced than labial /b/, for reasons having to do with the aerodynamic requirements for voicing (Ohala, 1983, Section 3.3). The result is that the pool of variation is predicted to contain many more [k] variants of /g/ than [p] variants of [b].

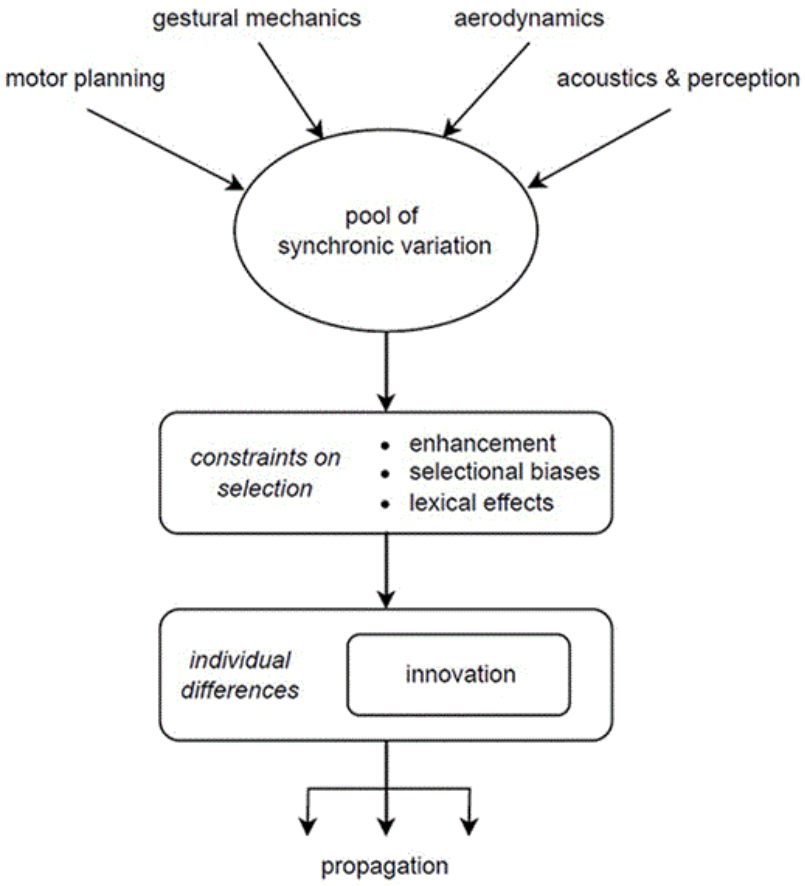

Figure 1. Factors influencing the evolution of phonetically based sound change (after Garrett & Johnson, 2013, p. 60).

Source: Author created image.

The variants in the pool are then subject to a process of selection in which systemic constraints favor or disfavor particular variants. An example of a systemic constraint is *enhancement*: the introduction or strengthening of a phonetic feature that increases the perceptual distinctiveness of a contrast (Garrett & Johnson, 2013; Keyser & Stevens, 2006). For example, lip rounding often accompanies back vowels, because the lengthening of the effective post-constriction vocal tract length results in greater dispersion of the vowels in the vowel space, thereby enhancing the overall perceptual contrast in the vowel system (Stevens et al., 1986). Systemic constraints such as enhancement are seen as second-order, in the sense that they operate on the set of variants produced by the (first-order) phonetic bias factors. Thus, while producing labial consonants as velar before back vowels would similarly enhance the perception of backness and hence the overall contrast between vowels, it is unlikely because the change of /p/ to /k/ is already unexpected on articulatory grounds and is correspondingly rare (Kümmel, 2007, p. 221).

Finally, a selected variant must be innovated in the speech of at least one language user, in the sense that it comes to be used more often than competing variants. While phonetic and systemic biases make some

innovations more likely than others, they do not explain why a change takes off in one speech community but not another, or in a given community at one time and not another (Weinreich et al., 1968). At this stage, social, cognitive, and physiological differences between individuals may influence whether some individuals come to prefer a particular variant, at which point it may (or may not) become established in the wider speech community.

The primary focus of this article is on describing the phonetic factors that bias the distribution of variants. While most attention is given to the articulatory, aerodynamic, and acoustic-perceptual factors active in spoken language (Section 3), analogous biases are also active in sign languages (Section 6). Aspects of the selection, (re)analysis, innovation, and propagation of variants are also reviewed (Sections 4–5), recognizing that the strict linear separation implied by Figure 1 is a considerable oversimplification. For more on the role of non-phonetic factors in the "life cycle" of sound change, see Kiparsky (1995), Blevins (2004), Bermúdez-Otero (2007, 2015), Hyman (2013), Garrett (2015), Hamann (2015), Fruehwald (2017), Salmons (2021) and references therein.

3. Phonetic Bias Factors

As noted in Section 2, phonetic change is largely *nonrandom* and *directional*: Certain changes are more common than others, and a change from A to B is often more common than a change from B to A (Blevins, 2004, 2015). For instance, in sound changes involving the voiceless interdental fricative [θ], the outcome of change is frequently another fricative (Kümmel, 2007), and vowel pitch is typically (but not invariably) raised after voiceless aspirated stops (Michaud & Sands, 2020; Shi et al., 2020). Changes are also typically asymmetric: a change from [θ] > [f] is more common than a change from [f] > [θ] (Blevins, 2019, Section 3.4), and while phonation contrasts frequently transphonologize into pitch-based systems, the reverse is vanishingly rare (Uchihara, 2016). Nonrandomness can also be seen in asymmetric segment inventories: If a voiced plosive is missing, it will typically be /ɡ/, and if a voiceless plosive is missing, it will be /p/ (Gamkrelidze, 1973, 1975; Maddieson, 1984, 2013, Section 3.3). Other examples of directionality include velar palatalization: [ki] > [tʃi] is widely attested, but the converse [tʃi] > [ki] is not found (Guion, 1998, Section 3.4); English [ɪ] is more frequently misperceived as [ɛ] than [ɛ] as [ɪ] (Peterson & Barney, 1952); and the Thai High(-rising) tone is more likely to be misperceived as (high-)Falling than the converse (Onsuwan et al., 2012).[2]

As shown in Figure 1, the inputs to the "pool" of synchronic variation can be broadly organized in terms of whether they are primarily gestural-motoric, aerodynamic, or acoustic-perceptual in nature. The following sections give a brief overview and some examples of each type.

3.1 Motor Planning: Priming and Inhibition

In the process of constructing and retrieving the motor plans necessary to produce spoken utterances (and presumably, hand shapes in sign), errors (i.e., unintended sequences of gestures) may occur as the result of either motor *priming* or *inhibition* (Roon & Gafos, 2016; Tilsen, 2019). Motor priming refers to the subthreshold activation of upcoming commands in motor planning. These activations can influence one another, or *blend*,[3] during the planning phase. Plans which are temporally proximal and/or articulatorily similar have a higher likelihood of influencing one another, which can result in errors that are anticipatory (*sea shanty > she shanty*), preservative (*gave the boy > gave the goy*), or transpositional (*light a fire > fight a liar*; Fromkin, 1971). Blending resulting from the retiming of motor commands has also been proposed to underlie the appearance of truncation in lexical tone production (Burroni & Kirby, 2025). Inhibitory mechanisms in motor planning are implicated by work suggesting that the activation of the planning units that make up an utterance proceeds in parallel, but that all but the first unit must be suppressed before utterance onset (Tilsen, 2013). This gives rise to dissimilation of movement targets from their competitors, an effect that can be seen most clearly in tongue twisters, where the intended sequence involves a repetition (e.g., *she sells sea shells by the sea shore*) but the output is frequently alternating (e.g., *she sells *shea *sells by the . . .*).

It is challenging to identify sound changes which can be unambiguously attributed to motor plan blending or inhibition. One plausible candidate type is consonant harmony (Hansson, 2020), in which non-local segments agree in some feature. Consonant harmony is a common feature of Semitic languages such as Chaha, where consonants in a stem must agree in laryngeal features; compare *jɨ-kəft* 'he opens' vs. *jɨ-dərg* 'he fights' (Rose & Walker, 2004, p. 475). On the basis of parallels with patterns observed in speech errors, particularly the predominance of anticipatory assimilations, Hansson (2010) argues that consonant harmony likely originates in motor planning errors. Similarly, Garrett and Johnson (2013) propose that nonlocal metathesis (e.g., Spanish *milagro* 'miracle' < Latin *mīrāculum*, Greek *térēn* 'tender, delicate' but Latin *tener*) probably has its roots in motor planning errors. Instance of nonlocal dissimilation such as Grassman's Law, where the first of two aspirated consonants deaspirates (e.g., Greek /tʰríkʰ-s/ *θρίξ* 'hair' but /tríkʰ-es/ *τρίχες* 'hairs'), have also been argued to be the result of motor planning inhibition[4] (Garrett & Johnson, 2013, pp. 74–77), as have anticipatory dissimulations in the realization of lexical tones (Burroni, 2023; Tilsen, 2013).

3.2 Gestural Mechanics: Coarticulation and Blending

Once a motor plan has been programmed, the actual movements of the articulators may also interact, introducing variability in phonetic realization, typically in the form of *coarticulation* (Recasens, 2018). Coarticulation is classically accounted for in terms of *overlap* and *blending* of articulators (Joos, 1948; Öhman, 1966, 1967), ideas that have been formalized in the framework of *Articulatory Phonology* (Browman & Goldstein, 1986, 1989, 1992; Pouplier, 2020). Gestural overlap refers to the fact that independent articulators can vary in their relative phasing, leading to contextual variation. For instance, if the velum lowering gesture required to produce a nasal consonant is phased in such a way as to overlap with the tongue dorsum gesture associated with a following vowel, the vowel will become contextually nasalized (Beddor, 2007, 2009; Solé, 1992, 1995). This may lead to the emergence of contrastive nasalization if the nasal consonant is subsequently lost (e.g., French *son* /sõ/ < Latin *sonus* 'sound', *un* /œ̃/ < Latin *ūnus* 'one'; cf. Italian *suono, uno*). The shift from pre- to post-aspirated stops, as in Andalusian Spanish /paʰta/ > [patʰa] or [patˢa] 'pasta' can similarly be modeled as a progressively earlier phasing of a closure gesture for /t/ relative to an unchanging open glottal gesture for voicelessness (Cronenberg et al., 2020; Parrell, 2012).

When a sequence of sounds is produced predominantly with the same articulator, the competing demands may result in some type of blending or averaging (de Jong et al., 1993; Fowler & Saltzman, 1993; Recasens, 2019). Examples include /s/-retraction in clusters in many English varieties with a post-alveolar approximant (Baker et al., 2011; Stevens & Harrington, 2016; Warren, 2006), which derives from competing demands on the tongue

tip to realize alveo-dental and post-alveolar targets in rapid sequence. Vowel-to-vowel coarticulation (Farnetani & Recasens, 2010; Öhman, 1966), in which the articulatory configuration for one vowel is influenced by that of an adjacent vowel, may also result from the coproduction of gestures in time (Fowler, 1984), leading to sound changes such as primary umlaut in Germanic (Iverson & Salmons, 1996).

3.3 Aerodynamic Constraints

Even when the articulators are static, the production of speech sounds—which ultimately involve rapid fluctuations in air pressure—are constrained by aerodynamic properties of the vocal tract. Certain phonetic bias factors thus follow from these properties. Two factors are of particular interest for phonetic variation and change. First is the *aerodynamic voicing constraint*: For vocal fold vibration to obtain, subglottal air pressure must be greater than the supraglottal air pressure (Ohala, 1983; Westbury & Keating, 1986). For voiced plosives, this presents an inherent difficulty, as air cannot escape the downstream closure and supraglottal air pressure therefore rises quickly. All else being equal, this constitutes a bias toward devoicing of plosives (Ohala, 1983, 1997, 2011).

A second source of aerodynamic bias factors involves the effects of vocal fold adduction on the pressure difference across the oral constriction required to produce plosive bursts, frication noise, and tongue-tip trills. Intensity of frication noise varies with both oral pressure and constriction aperture (Stevens, 1971). For optimal voicing, oral pressure needs to be kept at a minimum, but just the opposite is required to achieve optimal frication or a noisy release burst (Ohala, 1997; Solé, 2024). Thus, for a given supraglottal constriction, the amplitude of plosive bursts or frication noise will be reduced when the vocal folds are adducted, that is, in a voicing configuration. As a result, voiced fricatives will tend to be realized with less intense turbulence and are often weakened to glides or rhotics, or lost entirely (Ohala, 1997; Ohala & Solé, 2010). Similarly, fricatives in syllable codas frequently elide or aspirate, for example, French *nous* [nu], *vous* [vu] < Latin *nos, vos*. Solé (2010) showed that fricatives in syllable codas tend to have less intense frication noise, the result of aerodynamic conditions disfavoring high airflow rates in coda position.

3.4 Acoustic-Perceptual Similarities

The final class of bias factors are those conditioning perceptual similarity (whether symmetric or asymmetric) between speech sounds, due either to acoustic similarities between the intended and perceived utterances or to biases inherent to the human perceptual system. While all sound change presumably requires perceptual reconfiguration at some point, whether due to reanalysis, cue reweighting, or gestural reparsing (see Section 4), these factors can be seen as distinct from inherent phonetic biases, which may make certain variants more likely than others.

The most compelling examples of sound changes due to acoustic-perceptual biases are those involving asymmetric misperception, although even these are disputed (Garrett & Johnson, 2013; Recasens, 2015). The classic example is probably velar palatalization, where velars are realized as palatals before front vowels and glide (e.g., Latin *centum* > Italian *cento*, Old English *cinn* > Modern English *chin*). Ohala (1992) argued that such changes were unlikely to be the result of incremental articulatory changes, in part because of their asymmetric nature: /ki/ > [tʃi] is common, but the converse is vanishingly rare (Guion, 1998; Kümmel, 2007). The acoustic-perceptual basis for the change is instead argued to lie in the fact that /ki/ and /ti/ differ primarily in terms of the presence (for /ki/) of a spectral peak around 3–4 kHz (Blumstein & Stevens, 1979). If this peak is removed or obscured, /ki/ will tend to be misheard as /ti/, but if such a peak is added to /ti/, it is not typically misperceived as /ki/ (Chang et al., 2001). This is argued to be due to the greater likelihood of missing, rather than hallucinating, critical acoustic information.

A second possible example is the change of [θ] > [f], attested in many English and Scots dialects (e.g., Cockney English *thin* [ˈfɪn], *brother* [ˈbrʌvə]: Wells, 1982) as well as in Veneto Italian (Mackay, 1995) and some Oceanic (Blust, 2009), Semitic, and Athabaskan languages (Blevins, 2019). The fact that [θ] is misperceived as [f] much more often than the converse (Harris, 1958; McGuire & Babel, 2012; Miller & Nicely, 1955) points toward an acoustic-perceptual trigger, but most phonetic studies have found relatively symmetric spectral similarities between the two sounds (Heinz & Stevens, 1961; Hughes & Halle, 1956; Jongman et al., 2000; Tabain, 1998), leaving the typological rarity of *f > θ changes unexpected. However, Shadle et al. (1992), comparing the spectra of [θ] and [f], found that they are virtually indistinguishable except in the transition regions, where there is an earlier boost in the transition frequencies for [f]. This may go some ways toward explaining the asymmetry: If the spectrum for [θ] encodes less distinctive place information, it would follow that it is more likely to be confused with [f] than the other way around.

The emergence of distinctive vowel nasalization in environments where there is no evidence of an earlier flanking nasal consonant (cf. Section 3.2), e.g., Hindustani [sãp] from Sanskrit *sarpa* 'snake' or [ã:kʰ] < *akṣi* 'eye', has also been argued to have an acoustic-perceptual basis. Ohala and Ohala (1992) proposed that such changes result from the fact that consonants with high rates of airflow, such as voiceless fricatives and aspirated stops, require a larger-than-normal glottal opening, which is likely to spread somewhat to adjacent vowels. This slightly open glottis creates acoustic effects (essentially, slightly lowered amplitude and weakened lower formants with increased bandwidth due to the anti-resonances created by a branched resonator) that mimic those produced by nasalization. This general type of account may also be extended to explain instances of so-called "rhinoglottophilia" (Matisoff, 1975), such as the changes *Ciɦ > C-ŋ and *Cuɦ > C-ŋw in North Central Hlai (Norquest, 2007) or the spontaneous nasalization preceding glottal fricatives in Hayu (Michailovsky, 1975). Interestingly, the reverse pattern—aspirates arising from historical nasals—is also attested, for example, in Owerri Igbo (Hyman, 1972, pp. 177–178), Southern Thai (Matisoff, 1975, p. 267), and Basque (Igartua, 2015), providing a counterexample to the canonically asymmetrical nature of phonetically based sound change.

3.5 Converging Bias Factors

It is not always, or perhaps even typically, possible to classify (potential) sound changes as arising from a single type of bias factor (gestural-motoric, aerodynamic, or acoustic-perceptual). A good example of the complex interplay between bias factors are the co-intrinsic pitch perturbations associated with consonant voicing (Chen, 2011; Hanson, 2009; Ting et al., 2025), which are presumed to underlie the emergence of many types of tonal contrast (Hombert et al., 1979). Many of the strategies that can be employed to overcome the aerodynamic voicing constraint (see Section 3.2) or to implement voicelessness will also have effects on vocal fold length and tension; the resulting pitch perturbations may thus be regarded as fundamentally coarticulatory (i.e., gestural) effects. At the same time, the oral flow rate can be significantly higher at the release of an aspirated plosive compared to an unaspirated plosive (Dixit & Brown, 1985; Emanuel & Counihan, 1970), which may result in greater Bernoulli forces being exerted on the vocal folds, further increasing the rate of vocal fold vibration (Hombert et al., 1979). There may thus be a small but constant aerodynamic component that interacts with a larger but more fragile (i.e., liable to be impacted by the immediate prosodic context) effect on coarticulation and its requisite demands on the fundamental frequency contour (Kohler, 1985). Finally, acoustic-perceptual biases may also play a role. Gao and Kirby (2023) found that, when Voice Onset Time was neutralized, French listeners relied more heavily on CF0 to identify voiced, but not voiceless, plosives. They suggested that this may be due to the auditory relationship between prevoicing and low F0 (Kingston & Diehl, 1994), which does not exist between raised F0 and voice lag, such that the loss of prevoicing triggers an attentional shift to low onset F0 as a kind of perceptual repair.

Another example in which acoustic, gestural, and aerodynamic factors interact in a complex fashion is in the emergence of F0-based contrast in Phnom Penh Khmer (Kirby, 2014; Noss, 1966; Wayland & Guion, 2005). In

this language, words with /Cr-/ onset clusters in the standard/literary language are produced without /r/ but with a low or falling pitch and increased aspiration, often accompanied by changes in vowel quality (e.g., /kruː/ > [kʰùː] 'teacher', /kraː/ > [kʰɔ̀] 'poor'). Wayland and Guion (2005) proposed that the bias factor responsible for the pitch lowering was fundamentally aerodynamic: The devoicing of /r/ conditioned a drop in transglottal airflow, reducing the rate of vocal fold vibration and giving rise to a falling F0 contour. However, they suggested the diphthongization was due to a coarticulatory effect of the trill on the following vowel, again implicating multiple bias factors. In addition, acoustic-perceptual factors may also have played a role: Kirby (2014) proposed that devoicing of the trill may have caused breathy voicing at the following vowel onset, which in turn conditioned the percept of lowered F1 (Lotto et al., 1997).

4. From Bias Factors to Sound Change

It is clear the existence of structured phonetic variation does not automatically lead to change. Indeed, there is abundant evidence that listeners are aware and make active use of coarticulation to efficiently parse the speech signal and that considerable information is encoded in the variation of coarticulatory patterns (Cutler, 2012). Yet, at some point, whether at the level of the individual speaker or that of the speech community, the normative target may shift. This section briefly reviews work that considers how phonetic variants come to be phonologized as sound changes.

4.1 Systemic Constraints on Variant Selection

In the model sketched in Figure 1, the selection of phonetic variants is subject to structural or systemic constraints on selection. As mentioned in Section 2, systemic constraints may be regarded as second-order factors, in the sense that they operate on the set of variants produced by the (first-order) phonetic bias factors. Garrett and Johnson (2013) discuss three systemic constraints that influence whether a phonetic precursor is likely to become a sound change: *enhancement*, *selectional bias*, and *lexical and morphological effects* (although this should not be thought of as an exhaustive list).

Broadly speaking, enhancement typically refers to a change in the magnitude and/or temporal alignment of an existing gesture, or the introduction of a new gesture, which has the effect of increasing the salience of an existing contrast.[5] For example, there are a variety of strategies that can be employed to overcome the aerodynamic voicing constraint (Section 3.3) and sustain vocal fold vibration during a stop closure, either passively (Ohala & Riordan, 1979) or actively (Ohala, 1997; Westbury, 1983). These actions can be regarded as enhancing the contrast in the sense that they avoid it being neutralized, but enhancement may also target acoustic-auditory properties directly. To continue with the example of voicing, Kingston and colleagues have proposed that the [voice] contrast can be enhanced by undertaking gestures that increase the salience of a "low-frequency property," which includes glottal pulsing, low F0, and low F1 (Kingston & Diehl, 1994; Kingston et al., 2008).

Selectional biases refer to aspects of existing linguistic structure that may influence whether one of two equally robust phonetic precursors is more likely to be selected. For example, the phonologization of phonetic differences in vowel length is much more likely in languages with preexisting vowel length contrasts (Kavitskaya, 2001). Similarly, in metathesis, changes in segment order have a strong tendency to conform to preexisting phonotactic patterns (Blevins & Garrett, 1998). More controversially, some researchers have also proposed that universal cognitive biases facilitate (or inhibit) the phonologization of sound patterns (Moreton, 2008; Wilson, 2006; Yu, 2011).

A language's lexical and morphological structure may act as a filter on selection by inhibiting changes that would create "pernicious" homophony in, for example, inflectional paradigms (Blevins & Wedel, 2009). The

influence of morphological structure has also been demonstrated to influence phonetic realization in terms of segment duration (Seyfarth et al., 2018), gestural magnitude (Strycharczuk & Scobbie, 2016; Turton, 2017), and degree of gestural overlap (Cho, 2001; see Strycharczuk, 2019, for further examples and references). Other factors, such as lexical frequency, have also been argued to exert an influence on whether phonetic variation is ultimately phonologized (Bybee, 2001, 2002; Kaplan, 2013; Todd et al., 2019).

4.2 Innovation: From Phonetic Variation to Phonological Change

While the existence of asymmetric and structured phonetic variation suggests certain changes will be more common than others, it is not itself a theory of change. An outstanding theoretical and experimental challenge has been to spell out the conditions under which synchronic coarticulatory effects are phonologized, that is, under what conditions innovation, or actuation, obtains. Two leading models that have addressed this challenge are those of Ohala (1981, 1989) and Beddor (2009, 2012).

In Ohala's model, phonetic variation rarely leads to sound change, because adult listeners are sensitive to the kinds of variation induced by phonetic biases and implicitly correct for them in speech perception, a phenomenon known as *compensation for coarticulation* (Mann, 1980; Mann & Repp, 1981; Pardo & Fowler, 1997). For example, in the context of one or more surrounding alveolars, a back vowel may be produced as a more fronted variant, such that a sequence such as /dud/ comes to be realized as something like [d̟u̟d]. However, listeners can nevertheless recover the /u/ vowel intended by the speaker by "factoring out" or normalizing for the proportion of /u/-fronting that they have learned is due to the alveolar context (Harrington et al., 2008; Lindblom, 1963; Lindblom et al., 1995; Ohala, 1981). As a result, even when presented with a coarticulated acoustic signal, listeners are successful at mapping it onto the phonological category intended by the speaker. It is only when a listener fails to compensate for contextual or coarticulatory effects (what Ohala terms *hypocorrection*) that an innovation in that listener's grammar is considered to have taken place. In other words, sound changes are due to abrupt perceptual parsing errors on the part of the listener (Baudouin de Courtenay, 1972; Passy, 1890).

For Beddor, the source of innovation is not listener error but individual variation in parsing variability. In this model, phonetic variation is phonologized in an incremental fashion, as the relationship between coarticulatory source and effect changes. Specifically, Beddor proposes that listeners may treat covarying cues to a phonological contrast as *perceptually equivalent*, giving rise to different possible patterns of cue weighting. Over time, one pattern can become dominant, giving rise to sound change. An extensively studied example concerns vowel-nasal sequences. At least in American English, the degree of nasalization in the vowel of a word like *bend* is inversely correlated with that of the following consonant. Beddor (2009) showed that listeners are sensitive to the total duration of nasality in the sequence, but not to whether it is present in the consonant or the vowel specifically. It is this inverse correlation in production, combined with equivalence in perception, that is central to Beddor's account. However, it is worth noting that other kinds of changes involving the reweighting of coarticulatory source and effect, such as the phonologization of CF0 (Section 3.4), do not show either of these properties (Gao & Kirby, 2024).

The notion of listener variation in parsing strategies is also reflected in the models proposed by Blevins (2004, 2006) and Lindblom (1990); Lindblom et al., 1995). In the *Evolutionary Phonology* framework of Blevins (2004), the mechanism of CHOICE provides the possibility for a listener to select among multiple potential variants that arise due to intraspeaker phonetic variability. This is closely related to Lindblom's (1990) idea of a "hyper- to hypospeech" continuum, where hyperarticulated variants are characteristic of clear speech and hypoarticulated variants of casual speech. For Lindblom, variant selection can be influenced not only by whether the listener is engaged in a signal- versus message-oriented mode of perception or perceptual parsing, but also by the speaker, who may elect to produce a clear speech (hyperarticulated) variant specifically

in environments where they deem the listener's informational needs to be high. In Evolutionary Phonology, however, variant selection under the CHOICE mechanism is seen as stochastic rather than goal-oriented.

4.3 Individual Differences

Although sound change research typically makes a strong assumption of uniformitarianism (Yu, 2020), it is increasingly clear that individual differences play a critical role in whether, and how, phonetic variants are taken up as sound changes. Although an individual's position in the social network has long been known to be important for propagation of changes (Milroy & Milroy, 1985), individual differences may also play a role at the point of selection, and the extent to which biases even form part of an individual's "pool" may vary. For example, the degree to which listeners compensate for coarticulation varies, and Yu (2013, 2021) has argued specifically that listeners who compensate less for coarticulation may be more likely to initiate sound change, because they should be more likely to perceive a phonetic target as acoustically irregular.

Other studies have investigated individual differences in the relationship between production and perception. There is some evidence that "innovative" individuals at the forefront of sound change are both more sensitive perceptually to the presence of coarticulatory cues and simultaneously have more extensive coarticulation in their own productions (Beddor et al., 2013, 2018; Brunelle et al., 2020; Coetzee et al., 2018; Yu, 2019; Zellou, 2017). However, sensitivity in perceiving cues is not always matched to the extent to which they are manifested in production at the individual level (Harrington et al., 2019; Pinget et al., 2020; Schertz & Clare, 2020), so at present the evidence for production-perception parity is best described as mixed. One possibility is that there is greater parity in stable patterns of variation than in certain stages of changes in progress, or for some types of patterns than others. For example, arguably more compelling evidence of a production-perception link has been found for coarticulatory nasalization (Beddor et al., 2018; Zellou, 2017) than for a symmetric role of F0 in the production and perception of voicing (Clayards, 2018; Schertz et al., 2015; Shultz et al., 2012).

Phonetic biases can differentially impact communities as well as individuals. For example, Butcher (2019) argued that the high incidence of *otitis media* in Australian Aboriginal communities has, over time, led to historical changes disfavoring voicing distinctions (which require acuity in perceiving low-frequency acoustic properties) and sounds like fricatives and affricates (requiring correspondingly high-frequency acuity). Such examples remind us that while making inferences about the causes and conditions of sound change requires that we adopt a broadly uniformitarian stance—that is, the assumption that the processes operating on language in the present are much the same as those that operated in the past—it is important not to overlook the importance of variation within and across individuals and speech communities.

5. Computational Modeling of Phonetic Change

The potentially complex interactions between phonetic bias factors, systemic constraints on variant selection, and individual differences, together with the difficulty of conducting falsifiable experimental studies to test specific hypotheses about change, have motivated the use of computational modeling as a "virtual laboratory" for studying sound change. Although computational models cannot themselves explain how or why certain changes do (or do not) take place, they can be used to simulate and test hypotheses about how speech sounds are produced, perceived, and transmitted, and how these processes may contribute to phonetic change over time.

In the literature on computational modeling of language change, two implementational approaches can be distinguished. On the one hand are analytic approaches, which try to understand the consequences of a (typically) small number of assumptions in a statistical or mathematical framework. In the literature on language change, dynamical systems approaches have dominated (Niyogi, 2006; Niyogi & Berwick, 1996, 2009;

Sonderegger & Niyogi, 2010, 2013). With this approach, the distribution of some parameter(s) of interest are specified, such as the proportion of the members of a population who display some property or frequency of use of a particular variant. The dynamical system equations can then be used to calculate how this proportion or frequency evolves over time. Examples of this type of approach that have explicitly addressed issues in sound change include Niyogi (2006, pp. 251 ff.), who modeled a phonological merger in Wenzhou Wu Chinese, and Kirby and Sonderegger (2013, 2015, 2024), who focused on mapping out the space of stable and unstable states corresponding to umlaut in a population as model parameters are systematically varied.

Another strand of this literature takes a simulation-based approach to explore the (usually nonlinear) interaction of a (potentially) large number of parameters.[6] In an agent-based simulation architecture, agents are specified for production, learning, and memory strategies, and interact with one another according to a set of predetermined rules. The analysis involves examining both internal state of individual agents as well as the results at the population level. Agent-based models initially gained popularity in the study of sound change as a means of studying exemplar dynamics (Baker, 2008; Pierrehumbert, 2001, 2002; Wedel, 2006) but have also been used to explore the interaction of systemic and phonetic bias (Kirby, 2013; Sóskuthy, 2015), the emergence of vowel harmony (Mailhot, 2013) and vowel quality mutations (Flego, 2022), the dynamics of transmission and diffusion (Stanford & Kenny, 2013), and the evolution of dispersed segment inventories (Boersma & Hamann, 2008; de Boer, 2000).

Agent-based simulations of phonetic change have become increasingly sophisticated, as exemplified by the "interactive-phonetic" model developed by Harrington and colleagues (Gubian et al., 2023; Harrington & Schiel, 2017; Harrington et al., 2018, 2019; Jochim & Kleber, 2024; Stevens & Harrington, 2022). This strand of work considers interactions between a population of agents seeded with data taken from phonetic studies of real speakers, with highly articulated representations of phonetic and phonological categories and rules for how they are updated and change as agents interact. The simulation dynamics can then be compared to the trajectories of known sound changes. For example, von Bressensdorf et al. (2025) used the IP model to simulate the evolution of metaphony in Italian dialects, using data from dialects in which the change is more or less advanced (Greca et al., 2024). In their simulations, agents representing speakers of the more conservative dialect approximated those of the more innovative dialect, but not vice versa, consistent with the asymmetric directionality frequently observed in sound change. Again, while such a result does not "prove" the correctness of the model, consistency between model predictions and empirical observations suggests that the assumptions encoded in the model are reasonable ones.

While creating and interpreting computational models can be challenging, the approach brings with it many potential advantages. Implementing a computational model of phonetic change entails making assumptions explicit, promoting reproducibility and extendibility and facilitating the systematic exploration of the ramifications of different assumptions. Modeling can also be a useful means of exploring possible accounts of a change in the absence of access to empirical data. Finally, even simple models can be used to make qualitative predictions, provide a baseline against which to judge alternative explanations, and generate new hypotheses that can then be investigated empirically or experimentally. As computational models continue to develop, they promise to further enrich the understanding of how phonetic biases, systemic constraints, and individual differences interact in sound change.

6. Phonetic Aspects of Change in Signed Languages

Phonetic change is not unique to spoken language. In the speech modality, phonetic properties of interest include the laryngeal and supralaryngeal articulators, their positions and resulting changes to the cavity configuration, and their temporal coordination. In signed languages, there also exist relationships between the anatomy and physiology of the production system and the physical forms of lexical items, contextual effects (of prominence, position, rate) on the realization of lexemes, socio-indexical variation in the realization of forms, and individual differences in production and perception (Tyrone, 2020). There is clearly coarticulation between signs; analogs to processes such as lenition, assimilation, and metathesis; and manual gestures also need to be perceptually parsed (Section 4.2). Thus, phonetics can be argued to exert an influence on language change in much the same way in signed as in spoken languages, in the sense that phonetic biases structure the pool of variation from which variants are selected.

Far from being unanalyzable holistic units, signs have an internal, sub-lexical structure involving multiple phonetic dimensions (Battison, 1978; Stokoe, 2005). Articulatory dimensions of interest in sign phonetics include hand shape, movement, location (place of articulation), and orientation, as well as "nonmanuals," such as facial expressions and body movements, which often signal syntactic and/or prosodic structure (Pfau & Quer, 2010; Sandler, 2012). Just as in spoken language, these dimensions are subject to assimilation, reduction, and enhancement, which can serve as the seeds of diachronic change.

Synchronically, sign hand shapes often assimilate, particularly within compounds (Frishberg, 1975); location tends to lower with signing rate (Tyrone & Mauk, 2010); and synergies between coordinated articulator movements are observed (Brentari, 2019), all of which can be seen in changes in historical time. A further tendency observed in Frishberg's seminal study of change in American Sign Language (Frishberg, 1975) is that hand shapes, movements, and locations of two-handed signs tend to become more symmetrical: a hand shape or movement realized by the dominant hand will come to be shared by both dominant and non-dominant hands, and in some cases, one-handed signs will become two-handed, mirroring one another (Wilcox & Occhino, 2016).

Although much remains to be learned about how production and perception interact in sign, there exists evidence that modality-specific perceptual biases exist, which presumably function similarly to acoustic-perceptual biases in spoken language change. For example, signs sharing movement and location parameters seem to be perceived as more similar than signs sharing either movement or location with hand shape (Hildebrandt & Corina, 2002). Analogous to acoustic confusion matrices (Miller & Nicely, 1955), certain hand shapes are more likely to be confused than others (Lane et al., 1976), and different types of movement appear to have different degrees of saliency (Poizner, 1983).

As in spoken language change, in sign languages it can be challenging to determine what is stable variation across generations and what constitutes actual diachronic change (Brentari, 2019). Nevertheless, it is clear that both phonetic as well as systemic biases are active in signed languages, and that while the phonetic biases are modality-specific, they similarly contribute to a pool of phonetic variation, which forms the basis for subsequent change. The relationship between production and perception in signed languages, and how it may relate to diachronic change, is an area ripe for further study (Tyrone, 2020).

7. Summary

This article has reviewed a general theory of how phonetic variation contributes to language change. In this type of model, sound change is conceptualized as being drawn from a structured, nonrandom pool of variation. In spoken languages, the conditions that give rise to variation can broadly be classified as gestural-motoric, acoustic-perceptual, or aerodynamic in nature. However, many sound changes may ultimately be traced to more than one source. The uptake (selection) of a variant can be conceptually distinguished from the phonetic aspects that give rise to it. Selection is constrained by a range of structural, social, and cognitive factors, and researchers differ in what they regard to be the mechanisms governing how phonetic variation is ultimately phonologized. Computational modeling is increasingly applied to explore how phonetic biases interact with other constraints on sound change, and to simulate how changes may unfold in populations of speakers. Phonetic change is not unique to spoken language; analogous biases and constraints are observed in the phonologization of variation in signed languages. Further study of the phonetic principles underlying synchronic variation is necessary to advance the understanding of diachronic change. Other areas of active research include whether the locus of change is to be found in production or perception; how systemic constraints vary within and across individuals; and how social, structural, and phonetic forces interact in conditioning the propagation of innovative forms in speech communities.

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Notes

1. It is not always clear when a change in pronunciation constitutes a "sound change," and the term is used in different ways by different researchers. For an overview and some discussion see Hall-Lew et al. (2021).

2. Even when directional asymmetries are relatively robust, the principle(s) (phonetic or otherwise) that underlie them may not always be clear, as is the case for the English and Thai examples just cited.

3. Note that this use of blending is distinct from the overlap of articulatory gestures, as discussed in Section 3.2.

4. A competing line of explanation sources nonlocal dissimilatory changes in perceptual *hypercorrection* (Ohala, 1981, 1993, cf. Section 4.2): the incorrect attribution of an intended phonetic variation as contextual.

5. In fact, it may be more accurate to think of (a preference for) contrast maintenance as being the constraint and enhancement a systemic response.

6. The distinction between analytic and simulation- or agent-based approaches is not always clear-cut. For example, while Sóskuthy (2015) employed a simulation-based approach, the focus was on properties of the parameter space, rather than the state of behavior of individual agents. Similarly, Kirby and Sonderegger (2024) proceeded by simulation to determine the evolution of population parameters for complex models where no general closed-form analytic solution was available.