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Advancements of phonetics in the 21st century: Theoretical and empirical issues in the phonetics of sound change

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A R T I C L E   I N F O

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A B S T R A C T

It has long been understood that speakers produce and listeners perceive non-random, systematic phonetic variants that serve as the raw material for sound change. This understanding underlies much of the current research on the phonetic underpinnings of change, which includes study of (i) general phonetic principles underlying variation, (ii) specific phonetic 'preconditions' and biases arguably linked to specific patterns of phonological instability and change, and (iii) the production and perception of variation by speaker-listeners in situations of actual ongoing change and by interacting agents in computational simulations of change. This paper shows how findings from these three broad areas of study have led to 21st century theoretical and empirical advancements in our understanding of phonetic change. Big-picture questions about the nature of change are approached through consideration of a series of smaller, more tractable questions (e.g., about the nature of, and relation between, innovative speaking and innovative listening for both stable patterns of variation and ongoing change). The paper's goals are to show, for these questions, their theoretical grounding, empirical challenges, preliminary answers and, in turn, the new theoretical directions emerging from those answers.

1. Introduction

Study of the phonetic underpinnings of sound change has a long history in which early work identified some of the core principles that continue to guide phonetic investigations of sound change. As early as 1895, Baudouin de Courtenay (1895/1972), in delineating the stages of what is now referred to as phonologization (Hyman, 1976), determined that although the "conditioned variants which depend on the phonetic environment . . . may go unnoticed," their detection by listeners is "by no means excluded" (1972:174), in which case these variants may become regularized alternations that could lead to phonemic split in a given language. For example, according to Baudouin de Courtenay, context-dependent "embryonic" divergences in voicing might underlie now phonologized voicing assimilation in Polish and Russian (e.g., /d/ realized as [t] before /p/ but /t/ realized as [d] before /b/). Paul (1888) also identified small but systematic deviations in production, such as those that suit the "convenience of . . . the organs of speech" (p. 50), as having the possibility of being perceived and becoming "a new creation from the old form" (p. 54) within that speech community. These and other 19th century phoneticians recognized that speakers produce non-random, systematic phonetic variants that serve as the raw material for change. These scholars also recognized that listeners, who are variously attentive to these variants, might contribute to change by reproducing them in their own speech.

The fundamental understanding that phonetic change is grounded in systematic phonetic variation has remained a cornerstone of 20th and 21st century approaches to change. Theories of the phonetics of sound change seek to explain phonetic variation and the forces that structure it in ways that capture how phonetic variation can contribute to, but need not result in, new articulatory and perceptual norms. Thus, theoretical approaches to change, like phonetic theories more broadly, study the articulatory and perceptual principles that give rise to variation. However, building on this shared theoretical foundation, phonetic theories of change especially address questions about how stable patterns of variation within a speech community become unstable patterns that lead to change; that is, they study how these basic principles apply to the initiation of change and, arguably, its spread through a community.

Empirically, many of the challenges faced by investigations that aim to explain patterns of sound change are shared by

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behavioral studies of other phonetic phenomena. However, one issue specific to the investigation of sound change is the identification of sound change in progress, that is, identification of patterns of unstable phonetic variation indicative of ongoing change, as assessed by, for example, intergenerational differences in patterns of variation. Here, a substantial empirical challenge has been that, as Milroy & Milroy have noted, the earliest stages of change, which may involve "fleeting, insignificant encounters" between more innovative speakers and other members of their community, "may be difficult, if not impossible" to directly observe (1985:370).

This paper addresses the ways in which sound change researchers have approached theoretical and empirical challenges in this century and assesses some of the advancements that have been made. Because this literature is far too large to cover comprehensively (and comprehensibly) in a single paper, I take an approach that is selective in two respects. First, phoneticians especially seek to explain changes found to recur, in roughly similar form, across languages (e.g., Blevins 2004, among many others), that is, changes thought to be the consequence of universal mechanisms of human speech production and perception. Although these 'phonetic' changes can be influenced by many factors, my consideration of the non-phonetic forces that structure phonetic variation in relation to change is limited to social factors, despite important work on the role of, for example, lexical frequency and phonological structure in phonetic change. Second, I have opted for more in-depth exploration of certain theoretical issues and empirical data over coverage of the fuller range of issues that drive current research on sound change. In particular, I dig especially deeply into phenomena (from the literatures on preconditions for change and ongoing change) for which new empirical data are available for both production and perception. This choice restricts coverage but ideally provides a more comprehensive understanding, for some processes, of how speakers and listeners are contributing to change.

My goal in this paper is to engage readers with selected current issues in the phonetic study of phonological instability and change in a way that shows why these issues matter, why they are challenging to solve, and where (in some cases quite preliminary) answers are taking us. I begin by identifying two major developments in phonetic theory, gesturalist and usage-based approaches, and illustrate the impact they have had on 21st century approaches to the study of sound change (section 2). I then elaborate on these 'big picture' sound change developments from three narrower perspectives: phonetic variation and preconditions for change, especially change linked to the dynamics of gestural overlap (section 3); the relation between innovative speaking and listening for individual language users and for speech communities undergoing change (section 4); and the transition from innovative speaking/listening to new phonetic norms (section 5). The final section (section 6) steps back and broadly assesses what we have learned about sound change over the last two decades.

2. Advancements in phonetic theory in relation to the study of change

Two theoretical developments in phonetics, both of which emerged prior to 2000, have had considerable impact on advancements in sound change research over the past 25 years.

2.1. The nature of produced, perceived, and stored phonetic structures

One influential development in phonetic theory is the increased emphasis on the dynamics of speech and especially the view that speech articulation can be represented in terms of vocal tract gestures. This perspective has been most explicitly developed in Articulatory Phonology (Browman & Goldstein, 1992; Pouplier & Goldstein, 2010), which holds that the gesture is the basic unit of speech. Gestures, which correspond to neither features nor segments, are dynamic actions of the vocal organs (e.g., lips, tongue tip, tongue dorsum, velum, glottis). As dynamic, physical events, gestures have extent in space and time; consequently, at any given moment in time, gestures overlap with each other. As one example, the tongue dorsum gesture for intervocalic [d] is largely determined by the flanking vowels, as can be seen for an American English speaker's productions of [idi], [ada], and [udu] in the ultrasound images in Fig. 1 (where the solid black contour in each set of images corresponds to maximum tongue tip raising for [d]).

Such overlapping dynamic gestures give rise to time-varying, context-dependent acoustic variation. From a perceptual viewpoint, it is reasonable to assume that listeners attend to, and make use of, these regularities in the input signal. Theoretical approaches to perception that are especially compatible with the view that gestures are the basic unit of speech hold that listeners use the information in the input signal to perceive gestures (Liberman & Whalen, 2000; Goldstein & Fowler, 2003). For example, the Direct Realist theory of speech perception (Fowler 1986, 2018) postulates that listeners perceptually recover gestures by tracking the time-varying acoustic effects of coarticulated gestures.

An important consequence of the gesturalist perspective is that it has broadly influenced the ways researchers think about, and study, the speech behaviors of speakers and listeners. Thus, regardless of whether the gesture is taken to be the basic unit of speech, there now appears to be general acceptance of the characterization of speech dynamics in terms of overlapping articulatory gestures (e.g., Ladefoged & Johnson, 2011: 69-72). There is, as well, increasing recognition, independent of assumptions about perceiving gestures, that the considerable but principled variation introduced by gestural overlap can facilitate perception. For example, results from eye-tracking studies, which monitor listeners' eye movements to visual displays in real time, indicate that, as the acoustic signal unfolds, listeners use anticipatory information (e.g., information in vowels about upcoming consonants, as in *neck* vs *net* or *bent* vs *bet*) to disambiguate words more accurately (Dahan et al., 2001) and more quickly (Beddor et al., 2013).

A second, quite distinct and influential theoretical development in phonetics is the emergence of exemplar models, which postulate that language users store speech experiences (Goldinger 1998). In this usage-based approach, a category, such as a representation of a word, is a distribution or 'cloud' of remembered experiences (exemplars) that contain phonetic detail and are socially indexed (e.g., Johnson, 1997; Hay et al., 2006). Many exemplar models further postulate that the stored

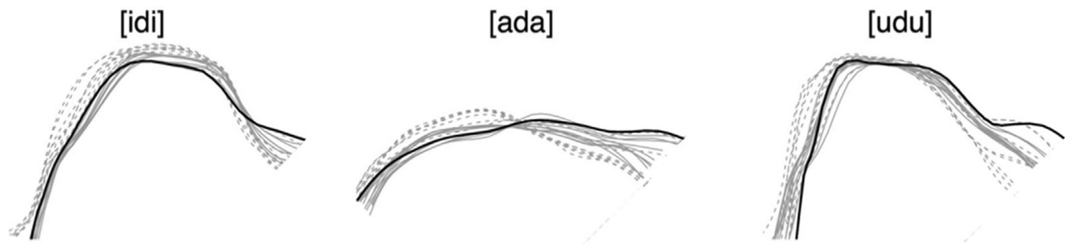

Fig. 1. Tongue contours from ultrasound images for an American English speaker's production of one token each of [idi], [ada], and [udu]. In each image, tongue tip is to the right; tongue root to the left. Solid black contour: maximum tongue tip raising; dashed grey contours: movement from initial V to [d]; solid grey: movement from [d] to final V.

phonetic details surface in language users' own productions through a production-perception loop (Pierrehumbert, 2001; Wedel, 2006)—a loop that effectively ensures that an individual's exemplar clouds will fluctuate over time. Because these stored details are the result of encounters between individuals in a speech community who happen to interact with each other, these models also capture the unpredictable nature of the speech experiences that are thought by many to contribute to more systematic change.

The broader impact of exemplar models is similar to that of the gesturalist perspective in that, independent of theoretical perspective, some notions that underlie, and findings that emerge from, that research paradigm have been highly influential. One aspect that has become important for the study of sound change—change that is often socially as well as phonetically structured—is that, because listeners are postulated to store socially indexed phonetic information, social cues are predicted to influence how spoken words are perceived and encoded (Sumner et al. 2014). Compatibly, there is now a substantial body of research showing that listeners' expectations about a speaker's social identity influence their linguistic judgments. For instance, an ongoing vowel change in New Zealand English, where /eə/ (*air*) is merging with /iə/ (*ear*), has progressed further in the speech of younger, working-class speakers than in the speech of other groups. In perceptual testing, Hay et al. (2006) found that, even when New Zealand listeners heard unmerged vowels, their tendency to expect merger (e.g., to expect [iə] for *air*) increased when they believed the talker was younger or from a lower social class.

A usage-based approach to lexical representations readily lends itself to capturing not only speaker-specific but also word-specific phonetic patterns (e.g., Pierrehumbert, 2002). Lexical frequency effects have been especially well-studied. For instance, Bybee (2002), building on findings that casual or conversational speech is characterized by reduction in gestural magnitude and increase in gestural overlap (e.g., Lindblom 1983, 1990; Browman & Goldstein, 1992), has suggested that such effects are especially likely to occur in high-frequency words, which are highly practiced. In support of this prediction, several sets of findings show that alveolar gestures in English are more likely to delete (Bybee, 2000) or reduce (Lin et al., 2014) in high- than low-frequency words, especially if those words are monomorphemic (e.g., [ol] *old*, [mɪs] *mist*; Purse et al., 2022).

2.2. Consequences for sound change research

These two theoretical developments, the gesturalist and exemplar perspectives, have contributed to advancements in sound change research, including new research paradigms and new answers to long-standing questions. In this section, I consider how these and related developments have influenced recent approaches to three foundational questions about how and why sounds change.

2.2.1. What changes in sound change?

'Sound change' encompasses diverse phonological phenomena; these include assimilation and dissimilation, lenition and fortition, merger and split, addition and loss. Experimental approaches to the study of phonetic change need to offer an explanatory account for the full range. In doing so, these approaches especially focus on how general principles of human perception and production might contribute to phonological instability and change.

One 'general principles' answer to 'what changes in sound change?' that has become increasingly influential in recent years is the proposal that all change, or nearly all change, can be linked to change in gestural overlap (coarticulation) or gestural reduction (undershoot). In an early proposal along this line, Browman & Goldstein (1991) not only linked casual speech processes to reduction in gestural magnitude and increase in overlap, but suggested that various types of sound change could be viewed as resulting from these two sources of variation. A yet stronger position has been taken in more recent work. For example, Bybee (2012) argued that the "phonetic path" to sound change (i.e., the path to sound change "proper"; 2012: 228) involves gestural retiming and reduction. Cronenberg et al. (2020) also situated change as nearly always arising out of the dynamic processes of gestural overlap and undershoot.

Especially over roughly the past 10–15 years, this broad perspective has contributed to shaping the questions being asked, and the techniques being used, by studies of ongoing change and studies of synchronic variation that might give rise to instability. The answers that have emerged show how gestural dynamics underlie not only patterns of change that more obviously have their origins in overlap and reduction, such as assimilation and lenition/loss, but also some perhaps initially less obvious candidates, such as mergers (e.g., Lawson et al., 2013; Mielke et al., 2017) and splits (Harrington et al., 2018; Stevens et al., 2019). The answers also show the extent to which gestural reduction and overlap interact with each other and with aerodynamic and prosodic factors to give rise to change (e.g., Solé, 2010; Recasens, 2014: 3ff). As one illustration, consider nasal consonant (N) loss in the development of distinctive vowel nasalization, where historical records from Romance and other languages show that N loss occurred first in voiceless (VNÇ̥) and only later in voiced (VNÇ) contexts (Hajek, 1997:141-143; Beddor, 2009). Aerodynamic factors have been argued to underlie earlier onset of the velum gesture in voiceless contexts (due to the difficulty of achieving the high intraoral pressure associated with voiceless obstruents with a lowered velum; Solé, 2007) and accompanying shortening or even loss of N (Beddor, 2009). Especially early seeds of this development, though, can be seen in voicing effects on the magnitude and timing of the velum gesture by speakers of German, whose velum kinematics show that, in voiceless contexts relative to voiced (e.g., /bantə/ *bannte* 'averted' vs /bandə/ *Bande* 'gang'), the velum gesture is reduced in amplitude, especially during the consonantal constriction, and also rephased, with peak amplitude being shifted towards the vowel (Carignan et al., 2021).

Stepping back from specific examples and returning to the bigger question of 'what changes in sound change,' situating change in the dynamics of gestural overlap and reduction might appear to identify articulation, and hence the speaker, as the primary source of change. Indeed, compelling arguments have been made in support of this position (Mowrey & Pagliuca, 1995; Bybee, 2012, among others). Others, though, have argued that while the speaker is the source of the variation that serves as the raw material for change, for at least some types of change it is the listener whose uptake of that variable information contributes, via listeners-turned-speakers, to new production norms (e.g., Ohala, 1981, 2012). My own reading of the phonetics of sound change literature from especially the past 10 years is that the issue of whether articulation or perception is in the lead has primarily been investigated for specific instances of *ongoing* change. In these studies, community members' production and perception of relevant forms are analyzed, often for both older and younger speakers, to determine whether produced or perceived forms tend to be the more innovative. I take up this issue in detail in section 4.2.

2.2.2. Why do sounds change?

I take as my starting point to addressing the general question 'why do sounds change' Ohala's (1981, 1993, 2012) highly influential answer to a more specific question: what is the listener's contribution to sound change, that is, why do sounds change in instances where change is arguably listener-based? Ohala's answer is shaped by the view that the speech signal is "inherently ambiguous" (1981: 178) with respect to its articulation. These ambiguities, which arise from vocal tract constraints that lead, for example, to gestural overlap, are understood as introducing noise into the signal–noise or distortions that listeners typically adjust for or factor out (see section 3.2). However, these perceptual adjustments may, on occasion, be imperfect and such imperfect accommodations have the potential to lead to change. For example, if, due to gestural overlap, a speaker produces a fronted [y]-like /u/ in the context of /t/ (e.g., English *suit*) or a nasalized vowel in the context of /n/ (e.g., *bent*) and a listener under- or hypo-corrects for that fronting or nasality—perhaps because the listener failed to detect the conditioning context—then that listener may interpret intended /ut/ input as /yt/ or /y/, or intended /ɛn/ as /ɛ̃n/ or /ɛ̃/. As speaker, this 'innocent misapprehender' might, in turn, produce [y] or [ɛ̃], as schematized in Fig. 2 for the latter outcome. As Ohala showed, the historical record of assimilatory changes is replete with instances of loss of the conditioning context but retention of the (originally) coarticulatory effect of that context.

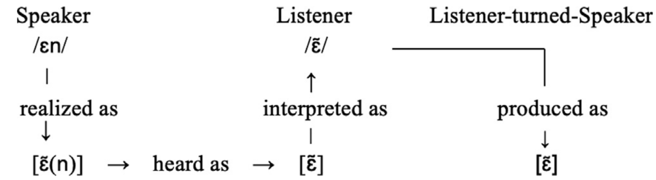

Fig. 2. Hypo-correction scenario in Ohala's 'innocent misapprehension' model (adapted from Ohala, 1981).

Thus, in Ohala's approach, listeners contribute to sound change via misperception of speakers' intended signals. However, the more recent perceptual evidence that listeners not only adjust for the acoustic consequences of gestural overlap, but also closely attend to those consequences (i.e., evidence emerging in part from gesturalist developments), raises the question of whether misperception indeed constitutes a consistent source of phonological change. That question leads, in turn, to a new one: if listeners are regarded as being generally *accurate* perceivers of coarticulated signals, how might they contribute to the (not uncommon) changes linked to gestural overlap that Ohala sought to explain?

The approach to this question proposed by Beddor (2009, 2012; Beddor et al., 2018) rests on the understanding that the acoustic encoding of gestural dynamics provides listeners with useful information about what a speaker is saying. In addition, though, that approach crucially relies on findings that members of a speech community differ from each other: as speakers, individuals differ in patterns of produced coarticulatory overlap (section 3.1); as listeners, they differ in how useful that information is for perceptually differentiating speech contrasts (sections 3.2). By hypothesis, it is these non-errorful listener-specific differences in the relative perceptual weights of co-occurring phonetic properties for a given contrast that have the potential to contribute to change. Revisiting the scenario for /ɛn/ in Fig. 2, in Beddor's approach, members of an American English speech community produce gradient realizations ranging from [ɛ̃n] to [ɛ̃] and have gradient perceptual weights, with some listeners requiring a nasal consonant but other listeners requiring only vowel nasality for a percept of, say, *(b)en(t)* (Beddor, 2012; Beddor et al., 2013). Change occurs gradually as community norms shift toward more innovative realizations and weights (in this case, more [ɛ̃]-like realizations and concomitant close attention to the vowel information). Recent apparent time studies of ongoing change provide supporting evidence of this type of gradual cue reweighting (e.g., Coetzee et al., 2018; Kuang & Cui, 2018; see section 4.2).

An exemplar approach to listeners' contributions to change would bear a very rough similarity to the path just sketched out in that both approaches assume that listeners are sensitive to phonetic detail. The nature of this sensitivity is quite different, though, in that the emphasis in the former is listeners' real-time use of phonetic information about gestural dynamics whereas the emphasis in the latter has primarily been on listeners' comparison of the phonetic details of incoming signals against stored representations (Pierrehumbert, 2001; Wedel, 2006). But the outcome of the attention to phonetic detail in both cases is that, at least in principle, misperception is not a necessary component of listener-motivated change and that listeners' contributions to change are incremental rather than abrupt.

2.2.3. What causes some innovative variants to spread?

Regardless of whether particularly innovative forms in the pool of phonetic variation are the result of articulatory behaviors of speakers or perceptual processing by listeners, there remains a basic question: why might some more innovative forms (e.g., more [bɛ̃t]-like realizations of *bent* or more [ʃ]treet--like realizations of *street*) become new phonetic norms in a speech community? Long-standing approaches to sound change postulate that, whereas the initiation of change has phonetic underpinnings, the spread of change depends on its social setting. For example, in his 1963 study of a sound change on Martha's Vineyard (whereby /aɪ/ and /aʊ/, as in *right* and *out*, have raised towards [əɪ] and [əʊ], respectively), Labov proposed that, "[a]t the first stage of change, where linguistic changes originate, we may observe many sporadic side-effects of articulatory processes which have no linguistic meaning .... Only when social meaning is assigned to such variations will they be imitated and begin to play a role in the language" (1963:293). Weinreich et al. similarly proposed that a new speech variant "assumes a certain social significance" (1968:185) as it spreads through the speech community. Ohala (1981, and elsewhere) also drew a sharp distinction between phonetic origin and social spread.

More recent perspectives on the question of why some innovative variants become new community norms have been informed in part (but by no means exclusively) by exemplar-based models of phonological representation and change. For example, new agent-based computational models of how biases in phonetic variation (e.g., bias towards [CṼC] realizations of /CVNC̥/ or towards fronted realizations of /u/ especially in coronal contexts) can become amplified over (simulated) time are advancing understanding of the role that social meaning may—but, importantly, need not—play in that amplification. Very recent studies of actual, co-occurring changes-in-progress in targeted speech communities are also addressing questions of these changes' social significance. And findings from imitation studies have informed understanding of the motivations—both phonetic and social—for why community members might adopt innovative forms. These developments are an indication of the extent to which the traditional assumption of a tight association between spread of an innovation and its social significance is being explored, and in some cases questioned, in 21st century approaches to phonetically motivated change. These developments form the theoretical and empirical bases of section 5.

3. Understanding the phonetic preconditions for change

Sound changes are, of course, specific to particular language varieties at particular points in time. As Labov (2010:90, 204) has pointed out, citing Meillet (1921), universal principles—such as principles of gestural overlap and reduction or principles of perceptual accommodation to the acoustic consequences of articulatory dynamics—cannot account for the sporadic nature of change. It is precisely this sporadic nature that led Ohala (1981, 2012) and many others to interpret the phonetic behaviors that especially contribute to change as involving performance that has 'slipped' or is otherwise non-ideal. Another influential approach that broadly situates change in non-ideal performance is that of Lindblom (1990, Lindblom et al. 1995), who viewed change as emerging from the "tug-of-war" (1990: 430) between the speaker-based constraints that give rise to economical forms of behavior (coarticulation, reduction) and the informational needs of the listener that are argued to potentially lead to higher biomechanical costs on the part of the speaker.

Gestural and exemplar approaches to speech have contributed to a shift towards grounding change less in non-ideal performance and more in the systematic yet variable behaviors of speakers and listeners. Studying change in relation to such phonetic behaviors requires understanding the articulatory and perceptual conditions, and the variation across members of a speech community, that might be especially conducive to change yet compatible with its sporadic nature. Recent advances in this area have emerged for both stable patterns of variation within a speech community and sound changes in progress. This section on preconditions for change considers the former (section 4.2 discusses the latter) and especially considers conditions linked to gestural overlap, where new developments in both production (section 3.1) and perception (3.2) have implications for the study of change.

3.1. Production: Recent progress in the study of gestural overlap in relation to change

Two types of advances in the study of coarticulation over the past two decades have been especially relevant to the study of sound change. One area of research has made progress in identifying and quantifying restrictions or constraints on gestural overlap. A second approach has advanced our understanding of the ways in which the coarticulated productions of individual speakers, which are necessarily governed by these constraints, nonetheless vary within a speech community.

Consider first recent advances in models of articulatory constraint. By way of background, I note that spatiotemporal demands on speech articulators constrain overlap and, consequently, contribute to delimiting patterns of synchronic alternation and diachronic change. In VCV sequences, for example, although the lingual configuration for each vowel can influence that of the other, the extent of this influence depends on the specific articulatory demands of the relevant vowels and consonants (e.g., Öhman, 1966). For instance, in sequences such as /ipa/ or /api/, restrictions on tongue dorsum variation for front /i/ result in /i/ being relatively resistant to the coarticulatory lowering and backing influences of /a/. This coarticulatory resistance is, in turn, manifested in patterns of vowel change and their synchronic outcomes, as can be seen in palatal vowel harmony systems. In these systems, which have arguably phonologized vowel-to-vowel coarticulatory influences in the front-back dimension, /i/ tends to not undergo harmony (as in Hungarian, where /i/ is neutral in a back harmonic domain; e.g., [papiːrnak] 'paper (dative)'), presumably because coarticulatorily constrained /i/ fails to exhibit salient acoustic effects of a harmonizing vowel (Gafos & Dye, 2011).

Study of these demands on articulators has led to new empirical findings and models of those findings. One model that has been extensively investigated is the degree of articulatory constraint (DAC) model, which postulates that the extent to which a segment undergoes and triggers coarticulation—that is, its coarticulatory resistance and influence—is determined by its production requirements (Recasens et al., 1997; Recasens & Espinosa, 2009b). DAC was originally formulated as a model of *lingual* activity in which segments are ranked, based on production measures of coarticulatory resistance and aggression, according to degree of tongue dorsum constraint; for example, labials and [ə] are assigned low, and alveopalatals and [i] high, DAC values. As applied to sound change, this hierarchy of resistance allows for predictions concerning likelihood of change; for example, consonants with lower (compared to higher) DAC values should be more likely to undergo elision or other weakening processes. These predictions have been tested extensively against patterns of change in Romance, for instance (Recasens, 2014). Subsequent methodological developments, though, have led to alternative measures of coarticulatory (in)dependence that generalize to other articulators (lips, jaw, tongue tip) and that provide a more quantitative measure of resistance and influence (Lindblom & Sussman, 2012; Iskarous et al., 2013; Abakarova et al., 2018). Because tests of these newer measures against empirical data are recent (e.g., Rodríguez & Recasens, 2017), their specific implications for sound change have yet to emerge, but their potential importance is clear in that, the more accurate and generalizable the model of coarticulatory demands on contiguous speech sounds, the sharper our predictions for relevant patterns of variation and change.

As I've indicated, a second area where the study of gestural overlap has made recent advances is in the understanding of individual speaker variation. Again, first some background: although the demands on gestural coordination and overlap that I have been describing are presumably relatively constant across speakers, systematic speaker-specific coarticulatory patterns are well documented and can be substantial. For example, some American English speakers begin to anticipate the lingual configuration for an upcoming stressed vowel across multiple unstressed vowels (e.g., across the three schwas preceding final [i] in "*(look) up at a key*") whereas other speakers exhibit little anticipation (Grosvald, 2009). Some Swedish speakers anticipate the lip position for an upcoming rounded vowel across multiple consonants (e.g., /akstu:/) but others produce a rounding gesture coordinated with rounded vowel onset (Lubker & Gay, 1982).

To some extent, such speaker-specific interarticulator timing strategies are to be expected given that speakers are coordinating multiple gestures, a coordination that is influenced by aerodynamic, prosodic, and other factors. But although the fact of individual variation is unsurprising, its nature and possible sources (e.g., physiological, cognitive, social; see section 4.1) are important to phonetic theory and theories of sound change. Yu & Zellou (2019) provide a broad overview of recent work on individual differences in production and perception. Applying a narrower lens, the study of coarticulatory vowel nasalization serves as an illustration of a gradual shift over the past couple of decades from documenting variation across languages (e.g., Cohn, 1990, Solé, 1992, Beddor & Krakow, 1999; Jang et al., 2018) and dialects (e.g., Hajek, 1997 for Italian) to reporting the timing patterns of individual speakers (e.g., Afrikaans: Coetzee et al. 2022; American English: Beddor, 2009; Zellou & Tamminga, 2014; Zellou, 2017; Beddor et al., 2018; Kim & Kim, 2019; Kakataibo: Avelino et al., 2020; Lakota: Scarborough et al., 2015; Spanish: Solé; 1992; Bongiovanni, 2021). As a result, there is an increasingly solid empirical base—from large and smaller speech communities; speech communities in which nasality is, or is not, socially indexed; and older and younger community members—for testing theories of individual variation and the role of that variation in sound change.

The hoped-for *convergence* of these two directions of study—that is, study of constraints on, and individual differences in, gestural overlap—is to bring us closer to partial answers to the question, classically formulated by Weinreich et al. (1968) as the actuation problem, of why change takes place in a given language at a given time. The directions of some partial answers are taking shape. For example, certain phonetic constraints have a greater potential to contribute to, say, assimilation or lenition in some languages than others in part because the relevant sequences (e.g., final VC sequences or CC clusters) are permitted in some but not other languages or occur especially frequently in some languages (e.g., Harrington et al., 2008). Researchers take a further step closer to 'why this language' by viewing coarticulatory resistance as the consequence not only of physical constraints but also of phonological pressures such as preservation (Desmeules & Brunelle, 2018) or enhancement (Cho et al., 2017) of linguistic contrasts. Identifying speaker-specific patterns of produced coarticulation is important for the 'why now' component of the question: are the phonetic pressures or biases *as realized in the productions of (interacting) members of a given speech community* conducive to change? An important additional step that pulls together these two threads has recently emerged in the use of agent-based computational models of change to simulate the consequences, over time, of biased phonetic variation within a speech community (see section 5.2).

3.2. Perception: Recent progress in the study of perceiving coarticulatory variation

Gestural overlap gives rise to structured acoustic variation and listeners have knowledge of that structure. They demonstrate this knowledge through two types of experimental findings that have formed the foundation for theories of listener-motivated change (see section 2.2.2). For both of these types of findings, recent developments have substantially reshaped earlier conceptions of the perception of coarticulated speech in relation to change.

One general finding is the phenomenon of perceptual compensation for coarticulation: listeners typically adjust for, or normalize, the acoustic consequences of coarticulation. For example, they adjust for the anticipatory effects of V-to-V overlap discussed in the preceding section. Consequently, in a perception experiment in which participants identify vowels drawn from, say, a front-to-back /e-o/ continuum varying in F2, ambiguous vowels will sound more like /o/ (i.e., more back) when followed by front /i/ (/p_pi/) but more like /e/ (more front) when followed by back /ɑ/ (/p_pɑ/), consistent with listeners attributing vocalic F2 frequencies in part to their coarticulatory source (Beddor et al., 2002). It is this general phenomenon that informed Ohala's (1981, 1993) (and others') model whereby change emerges from compensation errors in which predictable variation, such as anticipatory vowel fronting, is interpreted as inherent, potentially contributing to phonologization of the coarticulated form. However, there is now evidence, from both group-level and individual-level findings, that less-than-perfect parsing is more systematic than sporadic. At the group level, listeners have been found to be *partial* compensators who normalize coarticulatory effects to a degree that is broadly commensurate with the extent of produced coarticulation in their language variety (Beddor & Krakow, 1999; Beddor et al., 2002) and with their other linguistic experiences with coarticulatory contexts (S. Kang et al., 2016). At the level of individual listeners, the accumulating evidence is that listeners within a speech community differ systematically from each other in how much they adjust for coarticulatory effects (Yu, 2013; Yu & Lee, 2014; Zellou, 2017; among others), with some individuals being weaker compensators than others. Continuing with the V-to-V coarticulation example, when these weaker compensators choose between /e/ or /o/, their choice would be relatively unaffected by the /p_pɑ/ and /p_pi/ contexts. Thus, the updated picture in relation to Ohala's model is that hypocorrection may contribute to change in ways similar to the scenario in Fig. 2, but possibly due not to listeners' sporadic errors but rather to their parsing strategy.

The other robust finding regarding perception of coarticulated speech is that coarticulatory information is useful to listeners in ways that facilitate their perceptual decisions. For example, although listeners compensate for an upcoming vowel's frontness or backness, they also identify upcoming vowels more quickly and more accurately when a preceding vowel provides coarticulatorily appropriate information (Martin & Bunnell, 1982; Manuel, 1987). That coarticulatory information is useful for listeners is not a new finding, but what *is* relatively recent is study of attention to that information in real time as the acoustic signal unfolds. Results emerging from eye-tracking paradigms show that, in general, listeners use anticipatory information about an upcoming consonant or vowel nearly as soon as it becomes available. For instance, study of American English listeners' use of anticipatory vowel nasalization shows that, when deciding between *bent* and *bet*, listeners fixate on the image of *bent* during the nasalized vowel—that is, before they hear the disambiguating [n]—and the earlier the onset of nasality, the earlier the fixation on *bent* (Beddor et al. 2013). However, just as is the case for compensation for coarticulation, there are differences between individual listeners in the perceptual importance or weight they assign to coarticulatory information (Beddor, 2012; Shultz et al., 2012; Coetzee et al., 2022; recall section 2.2.2). Important for the study of sound change is that individual differences in these perceptual weights emerge not only for phonologically stable patterns of variation, but also—and possibly especially—for the unstable variation found in the study of sound changes in progress (Coetzee et al. 2018; Kuang & Cui, 2018; Schertz et al. 2019; see section 4.2).

What, then, is the current understanding of the contribution of an innovative listener to coarticulatorily motivated change? The innovative listener is arguably one who attends especially closely to the effects of gestural overlap on a nearby sound. Different theoretical approaches agree on this point, and experimental findings show that individual listeners and groups of listeners (e.g., younger compared to older listeners; listeners whose native languages differ in their coarticulatory patterns) differ along these lines. However, the acoustics of gestural dynamics have the potential both to introduce signal ambiguities (e.g., 'is this an intentionally nasalized vowel?') and to disambiguate ('there is an upcoming nasal consonant'). Unsurprisingly, these dual effects continue to contribute to differences in theoretical approaches to an innovative listener. In one approach, the innovative listener's attention to coarticulatory effects is due largely to ineffective transmission of the speaker's intended signal; change results from incomplete parsing of predictable variation (e.g., Harrington et al., 2008; Yu, 2013). In the other, attention is due to effective transmission of useful information (about gestural dynamics); change results from novel weighting of the predictable variation (Beddor 2009, 2012). That these debates are ongoing is shown, for example, by Carignan's (2018) direct test of the two perspectives, whose results provide evidence of both incomplete parsing and reweighting. Transcending these debates, though, an important emerging picture is that listener behaviors that contribute to change are more systematic than sporadic. But because these behaviors are narrowly systematic in the sense that they hold for particular individuals or groups of individuals or in particular phonetic or prosodic contexts, they remain consistent with the sporadic nature of change.

3.3. Trading relations in producing and perceiving gestural overlap as a possible path to change

One category of commonly occurring sound change thought to emerge from gestural overlap is transphonologization, whereby a coarticulatory effect (i.e., the consequence of overlap) becomes contrastive while the original source of that coarticulatory effect is reduced or completely lost. For example, over 20% of the world's languages have phonemic nasal vowels (Maddieson 1984) and most of these vowels evolved from earlier VN sequences in which the vowel was, at least at some stage, presumably coarticulatorily nasalized. An important question for experimental approaches to change is whether we can identify not only the conditions that contribute to spatiotemporal variation in produced and perceived effects of coarticulation (sections 3.1 and 3.2) but also in the conditions leading to accompanying variation in the *source* of coarticulation. One relatively recent proposal is that coarticulatorily based transphonologization may emerge from conditions that give rise to a trade-off between a coarticulatory source and its effect. By way of illustration, I consider trading relations relevant to two well-documented types of change, the development of distinctive vowel nasalization and tonogenesis.

Beddor (2009) postulated that a potential path to lenition and loss of N in VN > Ṽ is that phonetic contexts known to precipitate this historical change are associated with relatively early onset of the velum gesture and, correspondingly, a shorter nasal consonant. One relevant context is VNÇ where, as discussed in section 2.2.1, the aerodynamic requirements of voiceless obstruents contribute to the velum gesture for N beginning earlier (relative to VNÇ̥), and so being less closely tied to the onset of the consonantal constriction. Beddor found that, in American English, this earlier onset of velum lowering—which is variably realized across speakers and utterances—gives rise to a trading relation between Ṽ and N in both production and perception. Specifically, acoustic (Beddor, 2009) and airflow (Beddor et al., 2018) data show that the earlier phasing of the velum gesture for N in VNÇ̥ is accompanied by more extensive overlap with V, as schematized in Fig. 3. In this situation, across VNÇ̥ and VNÇ contexts and also across variable productions of VNÇ̥, the shorter the nasal consonant, the longer the duration of vowel nasalization. (Italian shows a similar relation for VNÇ where Ç̥ is a voiceless fricative; Busà, 2007.) This Ṽ and N trade off in production is paralleled by a perceptual trading relation—a trade-off so extensive that, for some American English listeners, CVNC words with early onset of vowel nasalization and a short nasal consonant (e.g., [bε̃$_{n}$t]) were perceptually indistinguishable, in an AX discrimination task, from acoustically very distinct words with late onset of coarticulation and a longer nasal consonant (e.g., [bεε̃͡nt]; Beddor, 2009).

The trading relation hypothesized to contribute to tonogenesis involves the influence of a stop's glottal state on f0: vocalic onsets have higher f0 after voiceless than after voiced stops due, for example, to greater vocal fold tension for voiceless stops (Löfqvist et al., 1989). In perception, the two relevant phonetic properties, VOT and f0, offset each other such that the higher the f0, the shorter the VOT needed to perceive a stop as voiceless or aspirated (e.g., as /pa/ and not /ba/ in English or as /pʰul/ 'grass' and not /pul/ 'fire' in Korean; Whalen et al., 1993; Lee et al., 2013). The corresponding trading relation in production—speakers for whom, for example, the shorter the produced VOT for a voiceless stop, the higher the produced f0 at vowel onset—has been argued to be driven not by the intrinsic VOT-f0 relation but rather by a strategy to enhance the phonation contrast (Kirby, 2013; Clayards 2018). Kirby (2013), for instance, has postulated that the realization of voicing contrasts can be imprecise due to the aerodynamic voicing constraint, which biases voiced stops to devoice due to supraglottal pressure buildup (Ohala, 1983). Speakers, though, can make these contrasts more precise by controlling f0. The interaction of the phonetic voicing constraint and a principle of enhancement arguably gives rise to the trading relation observed for American English: speakers who produce smaller VOT differences between voiced and voiceless stops have been shown to produce larger f0 differences (Shultz et al., 2012). As further support, Kirby's (2013) computational model of ongoing tonogenesis in Korean, seeded by phonetic cue distributions for Korean stops from the 1960s, demonstrated that varying VOT precision along with the likelihood of enhancement successfully predicted observed f0 and VOT patterns for speakers of Korean 40 years later.

Thus, trading relations are a specific instance of cue weighting relations that offer a potential route for phonetic biases to contribute to loss of the coarticulatory source as follows. As a contributor to VN > Ṽ, an innovative speaker-listener in a speech community produces a reduced nasal consonant that is offset by extensive vowel nasalization (Fig. 3), possibly extends this pattern to voiced as well as voiceless contexts, and perceives information on Ṽ and N as equivalent, such that hearing Ṽ is sufficient for an N percept. As a contributor to tonogenesis, the innovative speaker-listener attends, for example, to low f0 information in CV sequences to the extent that no voicing is needed for a voiced percept (or longer VOTs are tolerated for lax percepts) and produces f0 effects that extend well into the vowel even in the absence of stop voicing. Coetzee et al.'s (2018) data from Afrikaans, where there is evidence of incipient tonogenesis, provide a visual illustration. Fig. 4 gives, for each of the 23 participants in that study, their production (x axis) and perception (y axis) of voicing (where the larger the y axis value, the greater the perceptual attention to voicing). The younger Afrikaans participants toward the upper right corner (unfilled circles) of Fig. 4 would be particularly innovative in that community in that they consistently produce phonologically voiced stimuli (e.g., /bɑs/ *bas* 'tree bark') as voiceless ([pas]) and perceive even phonetically voiced stimuli ([bɑs]) as voiceless (/pɑs/ *pas* 'fit) when f0 information is ambiguous.

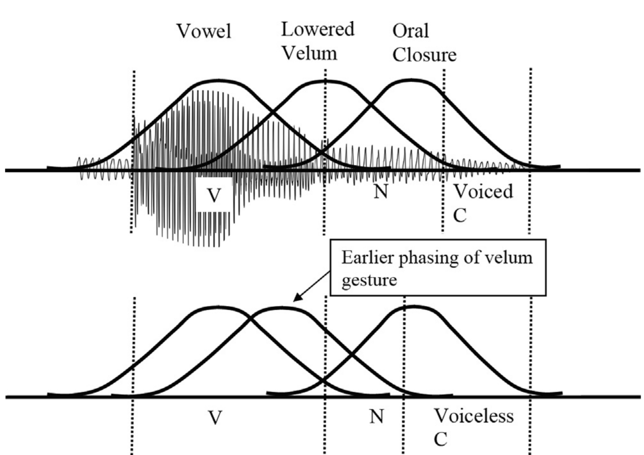

Fig. 3. Schematic representation for American English of different phasing of the velum lowering gesture in voiced (top) and voiceless (bottom) contexts, resulting in a trading relation: the earlier the phasing, the longer the duration of Ṽ and the shorter the N. (Dashed lines indicate acoustic segmentation.) Adapted from Beddor (2009).

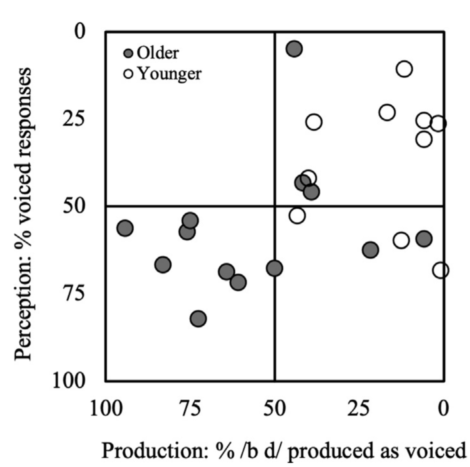

Fig. 4. Older and younger Afrikaans speakers' reliance on voicing in stop production (x axis: percent phonologically voiced stops produced with voicing) and perception (y axis: percent *difference* in voiced responses to stimuli with full voicing vs with no voicing but with neutral f0 information). Adapted from Coetzee et al. (2018).

The emergence of a trading relation between a coarticulatory source and its effects is presumably one of many patterns of variation that might lead to instability and loss of a conditioning context. The extent to which these trade-offs are a regular stage of relevant changes can be difficult to determine because studies of change in progress are typically not longitudinal but are rather static snapshots that risk capturing a later, post trade-off stage. Some studies of change in progress, though, do report co-variation between source and effect (e.g., Kuang & Cui, 2018; section 4.2). Moreover, some researchers take *absence* of a trade-off to be an indicator that a targeted pattern of variation in a speech community is not undergoing change or is at least not in an early stage of change (Tạ et al., 2022).

4. The relation between innovative speaking and innovative listening

Answers to some foundational questions in sound change research depend on understanding the relation between innovative speaking and innovative listening. In the past 10–15 years, considerable progress has been made on at least two of these questions. One question is especially important to proponents of the view that at least some changes are perceptually motivated: are listeners' percepts mirrored in their subsequent productions (section 4.1)? The other question is yet more basic and was foreshadowed in section 2.2.1 ('what changes in sound change?'): is the phonetic impetus for change primarily due to the behaviors of speakers or to those of listeners (section 4.2)?

4.1. The relation between production and perception for individual language users

Many theories of phonetics assume a close relation between speaking and listening. Gesturalist theories, for example, postulate that the vocal tract actions that are the forms of speaking are also the forms of listening (Liberman & Whalen, 2000), and Direct Realism in particular proposes that listeners' behavior is guided by their perception of speakers' vocal actions (Fowler, 1986). Most exemplar approaches also postulate a close relation between produced and perceived forms via their assumption that an individual's productions are drawn from their stored experiences of perceived input (Pierrehumbert, 2001). Many theoretical approaches to sound change necessarily assume a tight perception-production relation (e.g., Ohala, 1981; Harrington et al., 2008; Beddor, 2009; Yu, 2013) given that, if listeners contribute to change, their percepts must be manifested, presumably through their own productions.

Researchers have recently tested whether a speaker's production patterns are indeed mirrored in that same individual's percepts. This question has primarily been tested for patterns where co-varying phonetic properties have the potential to be differently weighted in production and perception. It's quite possible if not probable that different answers would emerge for different types of articulatory and perceptual phenomena. But even within this restricted set of tests, the safest assessment of this body of work is that it has yielded decidedly mixed results. For example, there is little to no supporting evidence regarding individuals' perception and production of VOT and f0—a relation presumably relevant to the development of tonogenesis. Although studies report considerable across-participant variation in the relative importance of these properties, with individuals differing from each other in the perceptual importance they assign to VOT relative to f0 as information for phonation contrasts, American English speakers' (Shultz et al., 2012) and Seoul Korean speakers' (Schertz et al., 2015) perceptual weights have not been found to be predictive of how these speakers produce VOT and f0 to differentiate voiced-voiceless or lax-aspirated contrasts, respectively. For Afrikaans, individuals who produce more prevoicing (for phonologically voiced stops) do correspondingly attend more to prevoicing in perception (Coetzee et al., 2018), but the age-based differences that can be seen in Fig. 4 for that participant population may underlie the pattern that emerges for individual speaker-listeners.

There is stronger evidence of a link between individuals' production and perception of coarticulatory nasalization—a finding thought to be relevant to the development of distinctive vowel nasalization. Zellou (2017) found, for individual American English speaker-listeners, that greater produced anticipatory nasalization correlated with greater perceptual compensation for vowel nasality. Beddor et al. (2018) also investigated nasalization in American English, but from a time-course perspective, and demonstrated that the timing of participants' onset of anticipatory nasal airflow was predictive of their perception: participants who produced earlier onset of coarticulatory nasalization showed, as listeners, greater use of that information in anticipating an upcoming nasal consonant (i.e., in anticipating a CVNC rather than CVC word) in an eye-tracking task. Using a similar paradigm to that of Beddor et al., Coetzee et al. (2022) found that the same basic pattern also holds for Afrikaans speakers. Although, as a group, speakers of two socioethnic varieties of Afrikaans, Kleurling Afrikaans and White Afrikaans, differ in the temporal extent of produced anticipatory nasalization, analysis of individual participant results within each variety showed structured variation in which produced coarticulation mirrored its perceptual usefulness.

These two snapshots, of produced and perceived phonation and nasalization, capture the difficulty of arriving at a general assessment of whether an individual's percepts are manifested in their productions (see Yu, 2019; Kim & Clayards, 2019 for more comprehensive overviews). Moreover, underlying these examples is another basic question for sound change research: *why* do individuals differ from each other in their production and perception? I have suggested already that variation is to be expected: in production, coproduced gestures, with potentially competing demands, are being coordinated in time and space; in perception, speech contrasts are conveyed by multiple acoustic properties that unfold over time and need not be equally informative for all listeners. However, beyond these general expectations for variation, can we link *specific* articulatory or perceptual behaviors to *specific* other characteristics, perhaps especially inherent non-linguistic characteristics? Some possible characteristics have emerged in recent work. On the listener side, research into this question has led to proposed links between an individual's perceptual strategies and their more general cognitive functions (e.g., Yu, 2013; Ou et al., 2015; see section 5.1). On the speaker side, some work has linked an individual's articulatory behaviors to anatomical factors. For instance, Dediu & Moisik (2019) found that individual differences in anterior vocal tract anatomy influence strategies for producing a bunched or retroflex North American English rhotic. They speculated that these anatomically motivated individual biases, which can have local as well as less localized consequences, could contribute to change if amplified.

Is consensus emerging concerning individual production-perception differences in relation to sound change? Not yet. While evidence in support of the assumption of a perception-production link has been found in several recent studies, such evidence is absent in a number of others. One informal observation is that sample size might be contributing to these differences in that recent studies testing a larger number of participants (roughly 40 or more) have identified a perception-production link (Zellou, 2017; Beddor et al., 2018; Yu, 2019; Coetzee et al., 2022), whereas those testing approximately half that number reported no link or only a weak one. Regardless of the source of the differences, though, there is substantial 'noise' in whether and how perception is mirrored in production. However, it doesn't necessarily follow that this noisiness weakens the basic assumption of many theorists regarding listeners-turned-speakers. As Stevens & Harrington (2014) have pointed out, what matters for theories of sound change is that *some* innovative listeners are similarly innovative speakers who manifest their percepts in their own productions. This outcome clearly emerges in the literature on individual differences.

4.2. The relation between production and perception in sound changes in progress

For certain categories of change, there has also been substantial progress in the past 15 years in our understanding of whether innovative speaking or innovative listening appears to be the primary driver of change. Much of this progress has come from the experimental study of production and perception, both by groups of participants (e.g., older vs younger) and individual speaker-listeners, in situations of ongoing change for a targeted sound pattern.

One prior consideration is that what constitutes (onset of) 'change' need not be clear given that the phonetic variation that serves as the raw material for change is ever present. Thus, even for situations in which the listener has been argued to be the source of change, such as the Ohala-type scenario in Fig. 2, it's not unreasonable to speculate that such a highly localized, individual-level change might be more likely to occur when that listener's interlocutor had produced, say, an especially nasalized vowel possibly with a very short or otherwise not salient [n]—a situation in which the speaker's innovative production (in the sense of different from the community norm; see, for example, Baker et al., 2011) contributed to the novel percept. Thus, there are challenges in identifying the locus of change at the level of individual speaker-listener exchanges. However, once an innovation is at the level of community spread, it should be the case that we can potentially assess whether it is primarily fueled by innovative productions or innovative percepts. Investigations that are especially helpful in this regard are apparent-time studies, that is, studies of community members who span different generations.

Many of the apparent time studies of an ongoing change for which there are both production and perception data are studies of coarticulatorily based change. In some cases, a coarticulatory property is spreading to new contexts whereas in others the property is being enhanced and its source is less consistently realized or otherwise reduced. Harrington et al.'s (2019) review of this literature, and of studies of ongoing mergers, is suggestive of perception leading production during change. The supporting evidence is further strengthened by the results of yet more recent studies (see Zellou & Beddor, submitted). I concentrate on those recent findings, although I first set the stage by recapping the findings for two earlier studies of Southern British English in which fronting of back /u/ (Harrington et al., 2008) and /ʊ/ (Kleber et al., 2012), originally triggered by coronal contexts (e.g., *duty*), is spreading to non-fronting contexts (e.g., *swoop*). For both vowel shifts, older speakers produce a fronted ([y]- or [ʏ]-like) variant in coarticulatory contexts with little extension to new contexts, whereas younger speakers produce more generally fronted realizations (i.e., fronting is no longer coarticulatory). For /u/, the perceptual data align with production: although older listeners normalize for coarticulatory effects of flanking consonants on vowels, younger listeners only show weak evidence of these adjustments. A misaligned production-perception relation, though, emerges for younger participants for the more recent change, /ʊ/ fronting, in that perceptual adjustments, especially for a *backing* context ([w_ɫ]), appear to have waned ahead of produced fronting.

Further evidence relevant to production-perception (mis)alignment emerges in recent studies that document ongoing changes in which a previously redundant (typically, coarticulatory) property is becoming contrastive or phonologizing, and the source of that originally redundant information is being lost—dephonologizing—through, for example, reduced contrast or deletion. Kuang & Cui (2018) documented an ongoing change in Southern Yi (Yunnan, China), whereby the contrast between tense and lax registers is shifting from a phonation contrast to one in which the (originally) coarticulatory effects of glottal constriction on vowel quality (e.g., lower and backer tense than lax vowels) are becoming primary, especially for non-high vowels. The data for older and younger Southern Yi speakers demonstrate two patterns of misalignment, both in the direction of perception leading production. For non-high /e/, where the shift is further along, both older and younger speakers primarily use vowel quality cues (especially F1) in perception, but older speakers' production lags in that their phonation differences outweigh vowel quality differences. For high /u/, production is similar for the older and younger speakers—phonation information remains primary—but perception is ahead for younger speakers, who place more weight on vowel quality (F1) in their perception than production. The pattern of findings, which shows that phonation and vowel quality cues are in a trading relation (larger F1 differences correlate with smaller H1-H2 differences) for the further advanced /e/ shift but not for /u/, is also suggestive that such co-variation facilitates change.

Two other apparent-time studies document a phonation contrast that may be evolving into a tonal (f0) contrast. Some dialects of Korean are undergoing this change for the lax-aspirated contrast (see section 4.1), with younger speakers now producing overlapping VOT values for these stops but distinctive f0 patterns. Schertz, Kang, & Han (2019) investigated this development for members of two Chinese Korean communities, Hunchun and Dandong. One main finding of that study is that younger Hunchun speakers, who, like older Hunchun speakers, generally do not exhibit evidence of an ongoing change in their lax and aspirated stop productions (Y. Kang et al., 2022), in perception weigh VOT differences for, say, /tʌ/ vs /tʰʌ/, less heavily (relative to f0) than older speakers do. Thus, for these younger listeners, perception leads production, although Schertz et al. are cautious in this interpretation given that these listeners may have more exposure to the speech of other younger (e.g., Seoul) Korean speakers who produce the change. Regardless of its source, though, the Hunchun pattern is not the pattern that emerges in Afrikaans, where the change has progressed further: younger and older speakers alike produce large post-stop f0 differences tied to phonological and not phonetic stop voicing (Coetzee et al., 2018). Older Afrikaans speakers, though, are more likely than younger both to produce prevoiced variants of phonologically voiced stops and to use prevoicing in making perceptual judgments. In general, then, production and perception are aligned in Afrikaans, but not fully so, as can be seen for the individual participant data in Fig. 4. Individuals whose production aligns with perception fall roughly along the diagonal (older participants who use prevoicing in the lower left quadrant; mostly younger participants who don't in the upper right). But for 'misaligned' participants (lower right), perception lags behind production: these speakers mostly devoice /b/ and /d/ in production but still attend to voicing in perception.

Brunelle et al. 2020 documented an ongoing change in Chru (Vietnam), in which a voicing distinction is evolving not into a tonal contrast, but rather into a register contrast. Across Chru participants, F1 (which is low for low register and higher for high register vowels) emerges as the primary acoustic correlate of the earlier voicing contrast (e.g., /d/-/t/) in production. F1 is, correspondingly, a main perceptual cue, leading Brunelle et al. to conclude that production and perception patterns roughly mirror each other, although a "significant minority of participants" (Brunelle et al. 2020:23) were found to retain perceptual sensitivity to VOT despite not using it systematically in production. Finally, Kleber (2020), using an apparent time approach to document a change in progress in Bavarian German in which a vowel length contrast is replacing an earlier inverse timing pattern between vowel and coda consonant duration (V:C vs VC:), found younger speakers' use of the new pattern to be in advance of that of older speakers in both perception and production. However, evidence of a smaller perception than production difference between the age groups in that study is suggestive of the perceptual change being in the lead.

The picture that is taking shape for these types of changes would appear to be that, especially at the community level, when there is an evident mismatch between production and perception, change in perception tends to be ahead of change in production. Thus, although data are largely equivocal for some changes in progress (e.g., Afrikaans, Chru, and Southern British /u/), the findings for others are broadly consistent with innovative perception norms being in advance of innovative production (e.g., Southern Yi, Bavarian German, younger speakers of the Hunchun dialect of Korean, and Southern British /ʊ/). However, a full understanding of the production-perception relation for these ongoing changes requires that we consider a recurring finding at the level of individual speaker-listeners, which is that, for some members of these speech communities (e.g., Akrikaans, Chru, Southern Yi), production—at least, as assessed experimentally—is systematically more innovative than perception. One suggestion in the literature is that 'perception lagging' may be especially likely in the later stages of a sound change. For example, Pinget et al.'s (2020) investigation of obstruent devoicing in five regional varieties of Dutch showed varying degrees of progression, with stop devoicing being at an early stage and fricative devoicing being more progressed and more regionally variable. Their analysis of individuals' production and perception showed that, for each change, participants at an earlier stage showed perception changing in advance of loss of voicing whereas participants towards the final stage tended to perceive voicing distinctions despite not producing them.

Another important aspect of these recent studies of change in progress, independent of how they inform the perception-production relation, is that they investigate change in phonetically understudied varieties and, in many cases, multilingual speech communities (Kuang & Cui, 2018: Southern Yi, Mandarin; Coetzee et al., 2018: Afrikaans, English; Schertz et al., 2019: Chinese Korean, Mandarin; Brunelle et al. 2020: Chru, Vietnamese). Because multilingual settings are most likely the norm, rather than the exception, in the world's speech communities (Thomason, 2001:30-31), their investigation adds confidence that the growing database will include patterns of change that might reflect phonetic drift (Sancier & Fowler, 1997; Chang, 2012; Tobin et al., 2017) and other aspects of change influenced by multilingualism.

5. Successful innovation

How does innovative speaking and listening give rise to a "successful innovation" (Milroy & Milroy 1985:368) that spreads through a speech community? As discussed in section 2.2.3 ('what causes some innovative variants to spread?'), there is a history of identifying the source of an innovation as phonetic in nature and the spread—or success—of that innovation as influenced by social factors. Yet, as also suggested in that section, new theoretical perspectives have spurred new questions, methods, and answers concerning what might lead an innovation to succeed.

Section 5 considers these developments, especially within the last 10–15 years. I address the basic question of why some innovative forms become new phonetic norms in a speech community through the lens of two sub-questions: how can we identify the (potential) leaders of change (section 5.1) and how are computational techniques being used to model variation and spread of change through a speech community (section 5.2). This work is informed by the long tradition within sociolinguistics of studying the leaders of change (e.g., Labov 1963 and subsequent work over the decades). As will become apparent in this presentation, also underlying these efforts are developments that emerge from the newer tradition, within phonetics, of exemplar approaches to encoding socially indexed variation and to the spread of that variation.

5.1. Identifying the leaders of change

Over the past decade, at least two distinct lines of inquiry have emerged whose aim is to identify the leaders of sound change. One line of research is conducted in the laboratory and aims to link individuals' phonetically innovative behaviors with particular social or cognitive characteristics—characteristics that might, in turn, contribute to these individuals' roles as leaders of change. The other approach uses sociolinguistic corpora and asks, for patterns of change within a speech community, whether leaders for one change are also leaders for other changes.

I begin with the laboratory studies, which assess the characteristics not of actual innovators or early adopters of an ongoing change, but rather of *potentially* successful innovators and *potential* early adopters of novel speech forms. For early innovation, the question is whether individuals whose phonetic behaviors might be viewed as, say, perceptually innovative in the context of change (e.g., section 2.2.2) perform differently from other listeners on non-phonetic measures of cognitive processing. When studying adopters of novel forms, the question is similar, but in this case the especially relevant phonetic behavior is individual speakers' imitation of, or accommodation to, the novel speech pattern of a model speaker—behavior known to show large across-speaker variation in degree and accuracy (e.g., Honorof et al., 2011)—in relation to socio-cognitive traits.

Yu and colleagues, for example, have explored these relations for both perceptual and articulatory accommodation from a sound change perspective. In both cases, they found individuals' phonetic behaviors to positively correlate with dimensions of socio-cognitive processing as measured by the autism-spectrum quotient (AQ) instrument. Yu (2013) tested listeners' degree of compensation for coarticulation and found that (neurotypical) female American English listeners who adjusted less for (C-to-V) coarticulation had lower AQ scores than males or than females with higher AQ scores, a finding consistent with female listeners who hypo-correct having better social skills (among other traits) and thus possibly being individuals with, for instance, more social contacts in their speech community. Yu et al. (2013) found that individuals who showed greater imitation of a novel pattern (heavy aspiration of initial English /p t k/) scored higher than weaker imitators on the AQ measure of (difficulty in) attention shifting, suggestive of the propensity to imitate possibly being linked to attunement to the phonetic details of a model talker's speech patterns.

A potential drawback of these laboratory-based links between individuals' intrinsic socio-cognitive makeup and their phonetic behaviors is that we don't know whether individuals who have these intersecting processing styles are, in fact, successful innovators or early adopters. Tamminga (2021) recently took on precisely this issue in a corpus-based study of vowel changes in Philadelphia English. That study assessed female speakers' innovativeness in their participation in ongoing vowel reversals (i.e., vowels changing course compared to their previous trajectory in that speech community) relative to these individuals' scores on socio-cognitive measures of traits speculatively linked to leaders of change, including the AQ measure used by Yu (2013; Yu et al., 2013). Those results, though, showed no correlation between phonetic measures (degree of participation in change) and socio-cognitive measures. As Tamminga discusses, there could be various reasons for this "not . . . entirely promising pathway" (2021:284), including that the individuals who are more innovative within the sample population may not include *especially* influential leaders of change.

Tamminga's (2021) corpus study, which included both an experimental component and a conversational recording, straddles the two new lines of research identified at the beginning of this section. As I've indicated, the second line studies patterns of variation and change found in sociolinguistic corpora and asks whether being a leader for one change predicts being a leader for other changes. One reason to expect that certain individuals should emerge as general leaders of change follows from the hypothesis just considered: if individuals' intrinsic cognitive processing style aligns with their phonetic behaviors, any such relation should hold *across* relevant phonetic patterns. Another reason follows from the proposed importance, for some types of change, of attaching social meaning to innovative variants in the course of their becoming new phonetic norms (e.g., Weinreich et al., 1968; Eckert & Labov 2017). As Brand et al. (2021) have observed, if especially innovative variants of different patterns have shared social meaning, they might tend to be used by the same speakers—in which case some individuals might be "uniformly advanced" (2021:3).

Whether some individuals *are* uniformly advanced, and hence leaders of sound change, has been studied in several recent investigations. Findings show that, within a given speech community, individual-level co-variation can occur across some variants but not others, and for some groups of community members but not others (see Tamminga, 2019; Brand et al., 2021 for reviews). For instance, Guy's (2013) study of sociolinguistic variation in Brazilian Portuguese did not find an overall correlation between an individual's production of two stigmatized variants, final /s/ deletion (e.g., [meno] *menos* 'less') and final vowel denasalization ([vaʒe] *vagem* 'green bean'), but did find a correlation between these variants for male speakers, who were far more likely than female speakers to denasalize. Along somewhat similar lines, Becker (2016) found for three innovative reversals of New York City English variants—increasing rhoticity ([biɹ] beer), /ɔ/ (*coffee*) lowering, and /æ/ (*ban*/*bat*) splitting—that most speakers did not exhibit co-varying usage of all three variants. However, stronger co-variation emerged for pairwise comparisons (e.g., innovative /ɔ/ lowering as predictive of high rhoticity) or when only younger participants were considered.

Guy (2013) and Becker (2016) suggested that this selective, rather than more uniform, coherence of phonetic patterns at the level of individual speakers is likely due to different phonetic variants indexing different social meanings for different speakers or groups of speakers. Their findings, though, also point to some of the methodological difficulties of identifying leaders of change for speaker samples that cut across social categories (such as age and gender) known to influence variation and change. Recently, Tamminga (2019) controlled for these difficulties by looking for innovative individuals across multiple ongoing changes within a homogenous speaker sample, in this case, young white women's participation in six Philadelphia vowel changes. For that demographic group, Tamminga found that participants who produced especially innovative realizations of one vowel pattern also produced innovative variants for the others, but only for the three changes that involved a shared social motivation (i.e., avoidance of especially salient local vowel features). Yet more recently, Brand et al. (2021) instead used a statistical modeling procedure that controlled for predictors of change (age, gender) and tested patterns of change across the entire vowel system for a large, heterogeneous sample of New Zealand English speakers. Their results similarly identify leaders (and laggers) for subsets of structurally independent ongoing changes, subsets that they speculate may have shared social meaning.

Stepping back, these two approaches to studying leaders of change, laboratory- and corpora-based, do not yet yield a converging story. Both approaches are motivated by theoretical perspectives that lead to the expectation that some producers of more innovative variants will be uniformly advanced, at least across certain categories of changes. And, as just shown, some very recent analyses of sociolinguistic corpora do provide support for this expectation. While Tamminga's (2021) finding that the socio-cognitive traits that have been linked to innovative phonetic behaviors in the laboratory do not match the traits of actual innovative speakers 'in the wild' should perhaps give us pause, ideally a fuller picture will emerge as researchers pursue these and other directions for determining who leads change. These alternative directions might include, for example, laboratory study of phonetic behaviors not only in relation to individuals' intrinsic cognitive traits but also in relation to their social role or status in their speech community (see Calloway, 2021, for recent work in this area).

5.2. Modeling the spread of change

An important advancement in the study of potentially successful innovators has been the use of agent-based computational models to simulate the spread of innovative variants over time within a community. The broad goal of these models, which rely on some of the basic principles of exemplar models, is to delineate how communicating agents, as proxies for interacting speakers and listeners, can effect change.

Although the scope of questions addressed by agent-based simulations of sound change is quite broad (see Harrington et al., 2019 for an overview), in keeping with my illustrative approach I focus on two models, those of Garrett & Johnson (2013) and Harrington & Schiel (2017). These are chosen because they implement the types of gradient, structured phonetic variation and perceptual adjustments for that variation that are a recurrent theme of this paper. In both models, incremental change occurs by means of imitation, specifically, by agent listeners storing perceived input that in turn influences their output. Both sets of models demonstrate how the phonetic bias factors that underlie certain types of more innovative productions can lead to their propagation through a speech community. The models differ, though, in the postulated nature of imitation.

By way of background, I note that the empirical findings for imitation and phonetic convergence—that is, for a speaker's phonetic patterns becoming more like that of a model talker or interlocutor—are sufficiently robust that questions about the underpinnings of convergence are less about whether there are social influences (there clearly are) and more about the motivation for convergence and how that motivation is mediated by other factors. Because imitation, although manifested in production, is the behavior of listeners-turned-speakers, questions about the mechanisms underlying convergence return us to the relation between perception and production (section 4.1), a relation that leads some theoretical approaches to predict imitation independent of any social factors. Within gesturalist approaches, for instance, imitation is "perceptually guided action" (Goldstein & Fowler, 2003:174) that follows from community members attuning their actions to each other. In exemplar approaches, because the (perceptually) activated experiences or traces for a particular word influence its production, a speaker's productions will converge towards those of an interlocutor (Goldinger, 1998). However, even theoretical accounts that predict converging productions on the basis of a tight perception–action link recognize that, in interactional settings, social affiliations and other social variables can guide imitation (Fowler, 2014; Goldinger, 2013). Thus, alongside clear findings of convergence toward the disembodied voice of a model talker (e.g., Honorof et al., 2011), that is, convergence without apparent social motivation, are equally clear findings of convergence being influenced by a model talker's social characteristics, which may be specific to the individual (Babel, 2010) or their group identity (Babel, 2012); by the social meaning or salience of the targeted variable (Walker & Campbell-Kibler, 2015); and by interlocutors' conversational roles in the interaction (Pardo, 2006; Pardo et al., 2010).

In their agent-based computational models, Garrett & Johnson (2013) build especially on the evidence that imitation is (in part) socially determined. Their models simulate change over time for two speech communities, one in which phonetic variation—specifically, variation in (de)spirantization of /z/—is socially indexed and another where it is not. The phonetic starting point for both communities is the same: each community produces the same number of /z/ variants that are centered around a target value except that a small minority of productions reflect a despirantization (lenition) bias (a bias motivated by aerodynamic constraints on producing voiced frication; Solé, 2002). Over time, that is, across iterations of the model, misrecognized tokens are removed, creating the potential for change. Garrett and Johnson speculated that, if a bias factor is socially neutral, language users will disregard or correct for that bias. This speculation was implemented in the model by having agents in the 'neutral' community ignore the bias variants. For this community, then, the biased (despirantized) variants were not added to agents' /z/ category and, consequently, change did not occur across iterations. However, language users for whom despirantization has social meaning will, by hypothesis, attend to that variation. This attention was modeled by having agents include the bias variants in their /z/ category—inclusion that, over time, resulted in community-specific change in the direction of approximant-like realizations.

Harrington & Schiel (2017), while recognizing social constraints on imitation, demonstrated that interactions between agents in a speech community in which there is biased phonetic variation can yield new phonetic norms over simulated time *independent* of social factors. They based their models on /u/-fronting data from Southern British English in which older speakers' /u/ productions are more retracted than those of younger speakers on average (Harrington et al., 2008; section 4.2), but older speakers' vowels are nonetheless oriented toward fronting. In models in which agents interact with and imitate each other, but agent-listeners only absorb an outlier into a target category if it is probabilistically closest to that category (i.e., transmission is error-free), Harrington & Schiel show, similar to Garrett & Johnson, that phonetic variation alone need not lead to change: models in which only younger or only older agents interacted with each other showed essentially stable patterns of high vowel variation over time. However, when the interacting, randomly paired agents included both older and younger agents—that is, when the variation included both younger agents' more fronted vowels and older agents' orientation towards fronting, the phonetic norm shifted over modeled time, with older agents' /u/ productions exhibiting vowel fronting in the direction of the younger agents' productions. Harrington and colleagues have subsequently further developed the implications of these (and other) results in an interactive-phonetic model of change. A critical insight of this work is that the stage in which stable variation becomes unstable change can be modeled as a largely non-social stage driven by accommodation among individuals who incidentally interact with each other rather than imitate socially preferred patterns (Harrington et al., 2018).

Although agent-based models make strong assumptions about, for example, imitation and retention of encountered variants, the simulations have the advantage of circumventing some well-known limitations of studying actual sound change in progress. Harrington et al. (2019), for example, point out the infeasibility of widespread community sampling that would have the time depth needed to study the progression from phonetic variation to new community norms. Although the simulations, by definition, don't model actual interactions, the more recent models of Harrington and colleagues (Harrington & Schiel, 2017; Harrington et al., 2018), for example, use as the starting inventories for agents actual acoustic signals drawn from productions of members of the targeted speech communities rather than the constructed signals used by some earlier models. Another move that is underway, including in my own lab, is to seed models with perception as well as production data for each agent as a means of better understanding how the production-perception relation (which does not always fully align in ongoing change; section 4.2) might influence change.

6. What have we learned in this century about the phonetics of sound change?

What do we know now about the phonetics of sound change that we didn't know in 2000? As has become apparent in this paper, answers to this question come from at least three major areas of inquiry. First, because produced and perceived phonetic variation underlies phonetic change, progress in understanding the principles that structure that variation also advances the understanding of change. This type of recent progress is far too extensive to capture in this paper—new methods and findings in areas as diverse as constraints on gestural overlap, produced and perceived cue weighting, real-time perceptual processing, social influences on perceptual judgments, and individual differences (to name just a few) have all contributed to refining theoretical approaches to change. The other two areas of inquiry are more specifically directed toward questions of sound change. In one area, researchers seek to identify the phonetic preconditions of a targeted pattern of change—for example, fricative lenition (Solé, 2010), velar softening (Recasens & Espinosa, 2009a), vowel harmony (Finley, 2012), distinctive vowel nasalization (Beddor, 2009; Carignan et al., 2021), secondary palatalization (Kirkham & Nance, 2022), or historical links between breathy voice and nasality (Garellek et al., 2016)—by studying how the relevant synchronic variation is produced, perceived, and/or learned by speaker-listeners from a speech community in which that variation is phonologically stable. In some cases, their findings have not only informed the likely phonetic origins of the targeted pattern, but also point toward more general phonetic phenomena, such as trading relations or interactions among gestural reduction, overlap, and speech aerodynamics, thought to underlie more general categories of change. The third area of study investigates the phonetics of sound change in progress. Especially in the past 10 years, there has been a surge of investigations of ongoing change, including change in understudied languages, that assess perception as well as production, guided by the hypothesis that innovative perceptual patterns of some community members may point toward incipient change in production. Results from these studies have substantially expanded our knowledge, for certain types of change, of the production-perception relation in situations of phonological instability including, in some cases, for socially structured change. A recent, also highly informative, extension of this third area of inquiry is computational simulations of phonological instability and change.

These empirical advances have been theoretically driven and, as would be expected, have given rise to theoretical innovations and new questions. I have suggested that one general theoretical shift has been toward understanding change less as due to 'slippage' and more as the incremental outcome of systematic yet variable behaviors of speakers and listeners. This shift, which can be viewed as emerging in part from gesturalist and exemplar perspectives on producing and perceiving phonetic variation, has both motivated and been motivated by research in the three areas of inquiry just noted. Thus, within the first area, there has been, for example, more systematic study of individual speaker-listener differences. Within the other two areas, but especially the third (study of ongoing change), researchers are increasingly turning toward investigating, for instance, how speakers produce and listeners perceive multiple co-varying properties for a phonological contrast whose relative weights change over time. Progress has also been made on major theoretical debates in the study of sound change that remain quite controversial, but for which we now have a deeper empirical base and new methods for addressing them. In particular, while the question of whether innovative speaking or listening is the primary driver of change remains open (for many reasons, some of which I hope to have elucidated in this paper), for certain types of ongoing change there are now considerable data on whether perception or production is in the lead. Another major issue concerns how especially innovative forms within the pool of phonetic variation spread within a speech community, leading to new community norms. Here, methodological developments are yielding new insights. Agent-based computational models are testing important assumptions about the role of social and phonetic forces in the spread of innovative forms over (simulated) time. Studies of patterns of co-variation among multiple ongoing changes in large speech corpora are testing assumptions about leaders of change. I take the fact that new questions, new data, and new theoretical perspectives are unfolding in so many areas of the study of sound change to be an indication of the vibrancy of this centuries old area of study.

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