Journal of Phonetics 106 (2024) 101354

Contents lists available at ScienceDirect

Journal of Phonetics

journal homepage: www.elsevier.com/locate/Phonetics

Variation in fine phonetic detail can modulate the outcome of sound change: The case of stop gradation and laryngeal contrast implementation in Jutland Danish

Rasmus Puggaard-Rode

Institute for Phonetics and Speech Processing, Ludwig-Maximilians-Universitt Munich, Akademiestraße 7, 81799 Munich, Germany

ARTICLE INFO

Article history:
Received 1 September 2023
Received in revised form 20 July 2024
Accepted 16 August 2024

Keywords:
Laryngeal contrast
voice onset time
closure voicing
lenition
generalized additive models
Danish
regional variation

ABSTRACT

This paper provides evidence for the assumption that the precise phonetic implementation of laryngeal contrast in obstruents can have an influence on higher order linguistic structure. Traditional varieties of Jutland Danish – which are all broadly 'aspirating' varieties – are used as a case study. The paper shows that the precise implementation of the aspirated–unaspirated contrast in stops varied systematically in these varieties, and that this covaries with the morphophonological process of stop gradation. Stop gradation is a lenition process which is historically found in the entire Danish-speaking area, but with quite varying outcomes, which were mapped extensively by dialectologists more than a century ago. Using a large legacy corpus of sociolinguistic interviews from the 1970s, this study shows that more sonorous outcomes of stop gradation covary with higher rates of continuous closure voicing in /b d g/ and shorter aspiration in /p t k/, and *vice versa* for less sonorous outcomes of stop gradation.

1. Introduction

There are many degrees of freedom in how laryngeal contrasts in obstruents are precisely realized. For example, when Lisker and Abramson (1964) first coined the term voice onset time (VOT), the available data suggested that voiceless unaspirated and aspirated stops cross-linguistically clustered into a clear bimodal distribution. However, as data from more languages has been collected, that distribution is looking increasingly like an unbroken continuum, with little indication of a cross-linguistic categorical divide between unaspirated and aspirated (Ladd, 2011). Within languages with aspiration-based contrasts, the extent of closure voicing varies (e.g. Beckman et al., 2013), and perturbations of fundamental frequency (F_0) vary on a language-by-language basis in ways that are not immediately predictable from how the contrast is otherwise realized (e.g. Chen, 2011).

It is clearly relevant for the phonetic sciences how contrasts are implemented, but it is less clear that fine-grained detail in phonetic implementation actually has an impact on higher-order linguistic structures. Many phonologists – in particular the proponents of 'laryngeal realism' (Honeybone, 2002) – now accept that it has consequences for phonology and sound change whether a two-way laryngeal contrast in stops is managed with closure voicing or aspiration. In so-called 'true voice languages' like Dutch and French, phonological regressive voicing assimilation processes are more likely to be found, while in so-called 'aspiration languages' like German and English, progressive aspiration assimilation processes are more likely to be found (Iverson and Salmons, 1995; Lombardi, 1999). Similarly, debuccalization – the process whereby consonantal oral place features are lost entirely, and segments like /s/ or /p/ are reinterpreted as /h/ – seems to require a glottal spreading gesture to be present in the first place (Honeybone, 2005). This begs the question whether phonological processes or sound changes are impervious to differences in laryngeal contrasts that are more fine-grained than simply voicing *vs.* aspiration. This paper argues that the fine phonetic detail underlying the implementation of laryngeal contrasts *can* play a role in sound change, and thus that phonology is at some level sensitive to detail beyond the broad descriptive features of voicing and aspiration. We argue that evidence for this is found in the variable outcomes of Danish stop gradation, and

E-mail address: r.puggaard@phonetik.uni-muenchen.de

https://doi.org/10.1016/j.wocn.2024.101354
0095-4470/

how these outcomes covary regionally with the precise phonetic implementation of laryngeal contrasts.

Stop gradation is a subset of a more general series of sound changes in Danish known as *consonant gradation*, which began around the year 1400 and is likely still ongoing (Brink and Lund, 1975; Brink and Lund, 2018). It is a historical lenition process whereby all stops reduced in weak prosodic positions, and /b d g/ in particular developed allophones that differed quite dramatically from their realization in strong prosodic positions, such as the so-called 'soft d' [ɣ̞] in Modern Standard Danish (Brotherton and Block, 2020).[1] While stop gradation in some form or other affected all parts of the Danish-speaking area, the outcomes were quite variable. This variability was already mapped extensively in the late 19th century in the dialect atlas of Bennike and Kristensen (1898–1912), and the precise morphophonological patterns have been described in various individual dialects in the structuralist era of Danish dialectology that followed. However, there has been little to no speculation previously about the causes of the variable patterns.

It is commonly assumed that the allophones currently found in strong prosodic positions were historically found in *all* positions, i.e. that /b d g/ were historically realized as stops in both strong and weak prosodic positions. In this vein, we might expect that the phonetic realization of stops in strong prosodic positions can provide a clue as to why the outcomes of stop gradation are so variable. Recent phonetic research using a legacy corpus of Danish traditional varieties has shown that the granular phonetic detail of how aspiration was implemented varied quite a bit (Puggaard, 2021; Puggaard-Rode, 2023b); variation such as this may be directly linked to the more categorical variation found in stop gradation patterns. This paper explores the phonetic realization of laryngeal contrast in more detail in the traditional varieties of Danish spoken in Jutland. If fine-grained detail in phonetic implementation does not impact higher-order linguistic structure, we would not expect any correlation between the variability in stop phonetics and the variability in stop gradation outcomes. However, if we *do* find interpretable covariation between the granular patterns in strong positions and the categorical patterns in weak positions, this is a good indication that these granular patterns can and do interact with higher-order linguistic structures.

Approximately half of the population of Denmark live on the Jutland peninsula, which shares a land border with Germany to the south; for ease of reference, Fig. 1 is a map of Denmark showing the location of some of the landmarks mentioned throughout the paper. It is not straightforward to research the traditional regional varieties of Danish. In the mid-20th century, a targeted political campaign started in favor of a single national spoken standard variety based on High Copenhagen Danish, and this greatly accelerated the already waning status of the traditional dialects (see e.g. Kristiansen, 1990; Kristiansen, 2003; Pedersen, 2003; Holmen, 2024). By now, traditional dialects have essentially disappeared from a large part of the Danish-speaking area, having been either replaced by the spoken standard variety (which will be referred to as Modern Standard Danish throughout the paper), or with newer regional varieties which are more geographically diffuse and serve a different social function (Maegaard and Monka, 2019). For this reason, this study relies on a legacy corpus of sociolinguistic interviews with speakers of traditional dialects (Arboe Andersen, 1981; Goldshtein and Puggaard, 2019). These recordings were made with elderly speakers in rural areas, and arguably capture a population that was minimally affected by the standardization efforts of the 20th century and spoke varieties that had developed with relatively little influence from any national standard language.

Fig. 1. Map showing the location of Jutland in Denmark (in yellow) and showing the location of some landmarks mentioned throughout the paper. Plotted in R using the `ggplot2`, `eurostat`, and `sf` libraries (Wickham, 2016; Lahti et al., 2017; Pebesma, 2018).

In Jutland, stop gradation mostly follows a straightforward geographical pattern: the categorical outcomes in the north were highly sonorous, and this sonorancy gradually decreases further to the south. In order to probe whether these categorical patterns covary with granular phonetics patterns, this paper reports two phonetic corpus studies: the first concerns variation in the duration of the aspirated release in /p t k/ (see also Puggaard, 2021), and the second concerns the proportion of fully voiced /b d g/ tokens. The data is modeled with spatial generalized additive mixed models using two-dimensional smooth effects over geographical coordinates to gauge the geographical component of phonetic variability (see e.g. Wieling et al., 2011; Wieling et al., 2014; Tavakoli et al., 2019; Koshy and Tavakoli, 2022).

The results of the study reveal a remarkable degree of similarity between the variability in stop gradation described in traditional dialectology and the observed variability in the fine phonetic detail of stop realization. In brief, in the areas to the

[1] The so-called 'soft d' is often transcribed as [ð] in other sources (e.g. Grønnum, 1998; Basbøll, 2005). This is a historical relic (Schachtenhaufen, 2023), and the sound is not a fricative in Modern Standard Danish (Brotherton and Block, 2020). Research by Juul et al. (2016) suggests that the [ɣ̞] notation captures the acoustics of the 'soft d' well, but ongoing articulatory research suggests that it may not capture the articulation well (Puggaard-Rode and Burroni, 2024); in the absence of a better solution, [ɣ̞] is used in this paper to highlight that the sound is a semivowel.

north where stop gradation had a highly sonorous outcome, the proportion of fully voiced /b d g/ tokens is also higher, and the aspirated release in /p t k/ is shorter; conversely, in the areas to the south where stop gradation had a less sonorous outcome, closure voicing is rarer in /b d g/ and the aspirated release is longer in /p t k/. In between, there is a seemingly gradual cline which also mirrors the patterns of variability in stop gradation. The gradual nature of the covariation suggests that the leniting sound changes in weak position are indeed sensitive to a degree of phonetic detail that goes beyond categorical differences such as those between 'aspiration' *vs.* 'true voice'.

Section 1.1 below provides some general theoretical background on the relationship between (leniting) sound changes and fine phonetic detail. Section 1.2 presents the primary patterns of stop gradation in Modern Standard Danish, and shows how these patterns have been said to vary in the Danish dialectological tradition. Section 1.3 presents the research questions and hypotheses of the paper, and outline how the present study operationalizes these research questions.

1.1. Leniting sound changes and fine phonetic detail

'Fine phonetic detail' refers to phonetic detail beyond what is typically phonetically transcribed, or what is typically considered relevant in the description of phonological feature cues, or what is typically considered the primary cues to phonological contrast (Carlson and Hawkins, 2007; Hawkins, 2010). Fine phonetic detail communicates a range of social information (e.g. Foulkes and Docherty, 2006), and is used in the organization of spoken interaction (e.g. Kelly and Local, 1989), and much of what is labelled fine phonetic detail is clearly audible and used in speech perception (e.g. Hawkins, 2003; Nguyen et al., 2009). While such detail is often explicitly ignored in abstract models of phonology, it plays a major role in exemplar models of phonology and speech perception (e.g. Pierrehumbert, 2001).

It is well-known that differences in fine phonetic detail can lead to sound change. This can be categorical in nature, as in the well-known and broadly attested example of velar palatalization before front vowels, e.g. [k] → [tʃ]. Like many other such changes, this is rooted in the phonetic detail of both articulation and perception. Fine control of the tongue body is relatively limited, so dorsal consonants are generally very prone to coarticulation (Ouni, 2014), and as such velars tend to be fronted before front vowels, although not nearly to the same extent as the coronal [tʃ] (Ohala, 1992). However, the perceptual result of velar fronting is a release burst with broad-band noise at high frequencies, similar to the frication phase of [tʃ] (Guion, 1998). The sound change follows from a combination of these articulatory and perceptual observations.

Sound change can also result from practical aspects of the communicative context. As put forward by the H&H Theory (e.g. Lindblom, 1990), speakers will systematically produce clearer, more hyperarticulated speech when they judge that this is necessary for successful communication, and produce more reduced and hypoarticulated speech when the meaning is relatively contextually predictable. Over time, this can e.g. cause systematic phonological changes in lexical items that are more frequent or tend to be more contextually predictable, as predicted by exemplar models of phonology (e.g. Pierrehumbert, 2001; Wedel, 2006). A less obvious outcome of this mechanism is that neutralizing or leniting phonological rules strongly tend to target the ends of lexical domains (Wedel et al., 2019), and conversely that onset consonants tend to be stronger and onset inventories larger than their coda counterparts (Beckman, 1997; Hall et al., 2018). This is because words are identified incrementally, and as such, phonetic cues early in the word are logically more crucial for word identification (Magnuson et al., 2007).

Lenition processes, whether diachronic or synchronic, can broadly be divided into *sonorization* and *opening* processes (Lass, 1984). Sonorization processes include degemination and voicing; opening processes include spirantization, approximantization, debuccalization, or outright deletion (e.g. Lavoie, 2001; Blevins, 2004). In the various lenition trajectories proposed in the phonological literature, the logical endpoint is always deletion regardless of which precise path a segment takes (see Ewen and van der Hulst, 2001; Honeybone, 2008). Voiceless stops such as [p] may lenite in a sonorizing direction (developing voicing, i.e. [p] > [b]) followed by several steps of opening and eventually deletion (i.e. [b] > [v] > [w] > Ø), or they may lenite in an opening direction (spirantization, i.e. [p] > [f]), followed by the development of voicing, more steps of opening, and eventually deletion (i.e. [f] > [v] > [w] > Ø). There are multiple paths to zero, but those paths tend to converge down the line.

Although this has not been discussed much in the literature, there are good reasons why the precise details of how a laryngeal contrast is implemented could affect lenition processes. For example, intersonorant stop voicing processes are often the result of a reduced closure phase, which gives the percept of stop voicing due to the greater relative duration of voicing bleed from the preceding segment (Blevins, 2004; Davidson, 2016). Since the duration of voicing bleed is in itself language-specific (e.g. Beckman et al., 2013; Puggaard-Rode et al., 2022), intervocalic voicing should also be a more likely phonological process or sound change in a language where voicing bleed is relatively extensive. The extent of voicing bleed in turn depends on the nature, timing, and magnitude of glottal gestures that enforce voicelessness during the closure, which are also language-specific (compare e.g. the studies of English and Danish by Hirose and Gay, 1972; Hutters, 1985).

1.2. Stop gradation

In Danish phonology, 'strong' prosodic positions are onsets before a full vowel, and weak prosodic positions are either onsets before neutral vowels, or codas, including word-final codas (e.g. Rischel, 1970). Neutral vowels are schwa [ə] and its r-colored counterpart [ɐ] (see Heger, 1975), as well as [i] in select suffixes. Syllables with neutral vowels are never stressed, and the schwas were historically full vowels which weakened in unstressed positions; this development (known as 'infortis weakening') precedes stop gradation by at least a few centuries (Skautrup, 1944). Syllables with full vowels can be either stressed or unstressed. There is no direct relationship between the strong/weak distinction and stress, as evidenced by the fact that coda positions in stressed syllables with full vowels are treated as weak. According to Rischel's (Rischel, 1970) distributional analysis of Danish consonants, most consonant phonemes take different allophones in strong and weak position (see also Basbøll, 2005; Grønnum, 2005). As we will see in Section 1.2.2 below, some dialects treat codas and 'weak onsets' differently.

Section 1.2.1 gives a brief overview of the relevant stop gradation patterns in Modern Standard Danish. Subsequently, Section 1.2.2 covers the variable outcomes of stop gradation in the traditional varieties of Danish spoken in Jutland.

1.2.1. Stop gradation in Modern Standard Danish

In Modern Standard Danish, there are no voiced obstruents in strong position (Fischer-Jørgensen, 1954; Puggaard-Rode et al., 2022). The laryngeal contrast between the two stop series /b d g/ and /p t k/ is primarily regulated through differences in the timing and magnitude of laryngeal gestures (Hutters, 1985), and the presence or absence of aspiration or affrication noise (Fischer-Jørgensen, 1972b). /b d g/ are unaspirated [p t k], and there is evidence that the voicelessness is actively enforced with a small glottal spreading gesture (Fischer-Jørgensen and Hirose, 1974; Hutters, 1984; Hutters, 1985; Puggaard-Rode et al., 2022). /p t k/ are aspirated [pʰ tʰ kʰ]. A common phonological analysis of Danish consonants holds that /p t k/ deaspirate in weak position, while /b d g/ select a variety of semivocalic allophones which often differ radically from their strong counterparts (e.g. Rischel, 1970; Basbøll, 2005; Grønnum, 2005). These patterns are summarized in (1), where WP is short for weak position and SP is short for strong position.[2]

(1)	a.	/p t k/	→	[pʰ tʰ kʰ]	/	SP
				[p t k]	/	WP
	b.	/b/	→	[p]	/	SP
				[p] or [ʊ̯]	/	WP
	c.	/d/	→	[t]	/	SP
				[ɣ̯]	/	WP
	d.	/g/	→	[k]	/	SP
				[ɪ̯]	/	WP, _ [-back, -high]
				[ʊ̯]	/	WP, _ [+back, -high]
				Ø	/	WP, _ [+high]

Evidence in favor of this phonological analysis comes from alternations such as those in (2), which are typically due to stress shifting suffixes (2a, 2c) or suffixes that create coda obstruent clusters, where strong allophones are also used (2b, 2d).

(2)	a.	*skalp*	'scalp' (n.)	[skæˀlp]
		skalpere	'scalp' (v.)	[skælˈpʰeːˀɐ]
	b.	*købe*	'buy'	[ˈkʰøːøp] or [ˈkʰøːʊ]
		købte	'bought'	[ˈkʰøptə]
	c.	*valid*	'valid'	[ʋæˈliɣ̯ˀ]
		validere	'validate'	[ʋæliˈteːˀɐ]
	d.	*bage*	'bake'	[ˈpæːɪ]
		bagværk	'baked goods'	[ˈpɑʊ̯ʋæɐ̯k]
		bagt	'baked'	[pɑkt]

[2] Note that stop gradation does not consistently apply for /b/; gradation in (1b) only affects select lexical items, and there is great stylistic and interspeaker variability in which and how many lexical items are affected. However, there are several indications from dialectology and beyond that stop gradation in /b/ used to be more widespread in earlier stages of the language (e.g. Jørgensen, 2021).

More detail on these phonological alternations can be found in Horslund et al. (2022) and Puggaard-Rode (2023a), who argue on multiple grounds that part of the traditional analysis in (1) should be thought of as a diachronic description rather than a phonological analysis with any synchronic validity. As we will see below, the differences between strong and weak 'stop allophones' in the traditional Jutland Danish varieties are rather less dramatic than in Modern Standard Danish. In Section 4.3, we return to the broader theoretical implications of the discrepancy between 'allophone' transparency in different dialects in light of the results of this study.

1.2.2. Stop gradation in traditional Jutland Danish varieties

There is a strong tradition of dialectology in Danish linguistics going back to at least the late 19th century. This tradition has led to highly detailed descriptions of the morphophonology of many regional varieties of Danish (Hovdhaugen et al., 2000). Since the dialectological tradition has largely been couched in the glossematic branch of structural linguistics, which was explicitly uninterested in details of phonetic implementation (Hjelmslev, 1943), the categorical morphophonology of traditional regional varieties is much better described than their phonetics. Stop gradation is one such well-described morphophonological process. The various patterns of stop gradation were mapped in quite some detail in the dialect atlas by Bennike and Kristensen (1898–1912).[3]

While stop gradation was highly variable throughout the Danish-speaking area, the variability on the Jutland peninsula was more systematic than in other areas. This is especially true for the weak 'allophones' of /b/ and /g/.

In the case of/b/ (see Fig. 2), stop gradation resulted in a bilabial approximant [β] in the northernmost part of Jutland, specifically in the area of Vendsyssel–Thy which is separated from the peninsula proper by the Limfjord (see Fig. 1). The bulk of the central part of the peninsula has a voiced fricative [v], except for a small relic area towards the east where /b/ did not lenite. Further south, [v] emerged in medial position only, and [f] emerged in absolute final position; this is likely due to the cross-linguistically common pattern is final obstruent devoicing, which is discussed further below. Furthest south, [f] emerged across the board.[4] These varying alternations have a significant impact on the varieties' phonology, as lenition to [β] or [v] would cause positional neutralization between /b v/, while lenition to [f] would cause positional neutralization between /b f/.

The variation patterns of /g/ (see Fig. 3) were very similar. In a somewhat smaller part of Northern Jutland roughly corresponding to the traditional area of Vendsyssel, stop gradation resulted in a voiced fricative [ɣ] which alternated with a semivowel [ɪ̯] after front vowels.[5] Otherwise, [ɣ] was the outcome of stop gradation throughout most of the peninsula, except in the

[3] As with most other dialect atlases of that time, these maps suggest hard categorical boundaries between isoglosses; this probably does not reflect reality, where we would rather expect smooth, gradual regional transitions (Chambers and Trudgill, 1998).

[4] Fig. 2 only shows present-day Denmark, but the traditional Danish-speaking area covered by Bennike and Kristensen extended further down into present-day Schleswig–Holstein in Germany. This means that the Danish-speaking area which developed [f] is somewhat larger than shown in Fig. 2; this also holds true for Fig. 3 and Fig. 4 below.

[5] This 'voiced fricative' may well have been an approximant; Bennike and Kristensen and most later Danish dialectologists use a local precursor to the International Phonetic Alphabet called *Dania* (Jespersen, 1890), and this transcription system does not systematically distinguish between voiced fricatives and approximants. Accordingly, some transcriptions used here such as [βɣ] are 'translated' from their Dania counterparts [ƀ q].

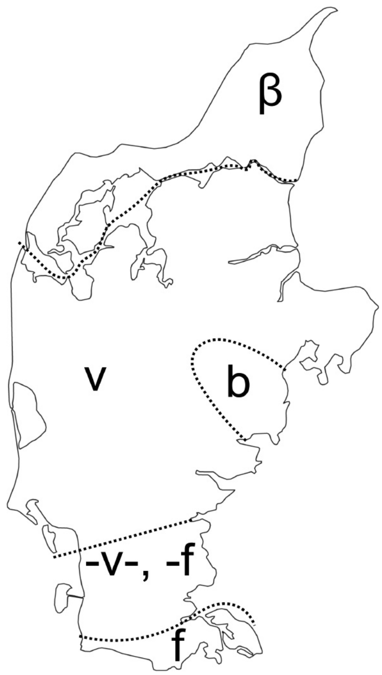


Fig. 2. Map showing the outcomes of stop gradation in /b/ in Jutland. Adapted from Bennike and Kristensen (1898–1912, K49.).

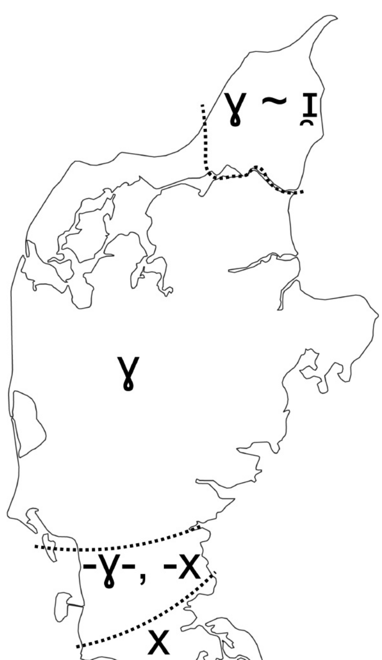


Fig. 3. Map showing the outcomes of stop gradation in /g/ in Jutland. Adapted from Bennike and Kristensen (1898–1912, K.51–52.).

south. Here, we find a pattern similar to the outcomes for /b/, where one area to the south developed [ɣ] medially and [x] in absolute final position, and the area furthest to the south including part of present-day Germany developed [x] across the board.

Taken together, the outcomes of stop gradation in /b g/ suggest that the phonological context (i.e. strong *vs.* weak position) modulates aperture in the phonological stops almost invariably throughout the peninsula, while geography further modulates the degree of sonorization that the phonological stops undergo. The similarities between /b g/ are not surprising, as stops often display phonetic class behavior within phonological categories (e.g. Chodroff and Wilson, 2017; Chodroff et al., 2019). The maps show a geographical sonority cline with increasingly sonorous outcomes of stop gradation moving south–north. These patterns suggest that /b g/ in weak positions have developed further along the lenition trajectories in the north than in the south. They also suggest that the laryngeal contrast in the south is not voicing-based, as a leniting change of the type [b] > [f] would be very unlikely; no such assumption can be made about the northern varieties.

It is worth discussing whether the allophones [f x] are not in fact a result of stop gradation, but rather the outcome of final devoicing. In this scenario, the outcome of stop gradation would have been [β ɣ] and a subsequent, unrelated development would have devoiced these fricatives, yielding [f x]. One fact that superficially speaks in favor of this is the effect of ‘infortis weakening’ in Jutland; infortis weakening, which was mentioned in the previous section, refers to the development of schwa from full vowels in unstressed syllables. In Jutland, infortis weakening further led to the loss of schwa in word-final position (Skautrup, 1944); as a result, the proportion of weak positions which are word-final codas is higher in Jutlandic varieties than in Modern Standard Danish. However, this was the case throughout Jutland, so it cannot explain the variation seen in Fig. 2 and Fig. 3. Weak positions could still refer to either codas or onsets in the traditional dialects of Jutland, so final devoicing can also not explain why weak allophones are consistently voiceless in the southernmost dialects. Overall, final devoicing has low explanatory value in this case, except for those dialects where [f x] are *only* found finally. We return to this in the discussion.

The patterns for /d/ (see Fig. 4)) are much less clear. Here, the outcomes of stop gradation were seemingly highly sonorous throughout Jutland, but the particular sonorant consonant varied.[6] As above, it is difficult to judge exactly what [ð] refers to in the Dania transcriptions used by traditional dialectologists; we have little reason to believe that it was a fricative, but it may not have been quite as semivocalic as the Modern Standard Danish ‘soft d’. Recall however that complete elision, as found in the northernmost part of the peninsula (i.e. Vendsyssel), is the logical endpoint of any lenition trajectory; the original map also carves out a small area below Vendsyssel in northern Jutland where the outcome of stop gradation was a ‘weakened [ð] which often elides in coda’ (Bennike and Kristensen, 1898–1912, K.50, author’s translation).

In spite of /d/ having quite different lenition trajectories than /b g/, coronal stops are not excluded from the phonetic studies below. It is unlikely that the different lenition trajectories are due to differences in laryngeal behavior between /d/ and /b g/; these differences are likely *because* /d/ is coronal. It is quite common for coronals to show peculiar phonological behavior (see Hall, 1997), including in lenition processes (see e.g. Grijzenhout, 1995).

[6] In fact, Fig. 4 is a simplified version of the original map by Bennike and Kristensen (1898–1912), which also notes some very small areas with specific alternations that are not relevant for our purposes here.

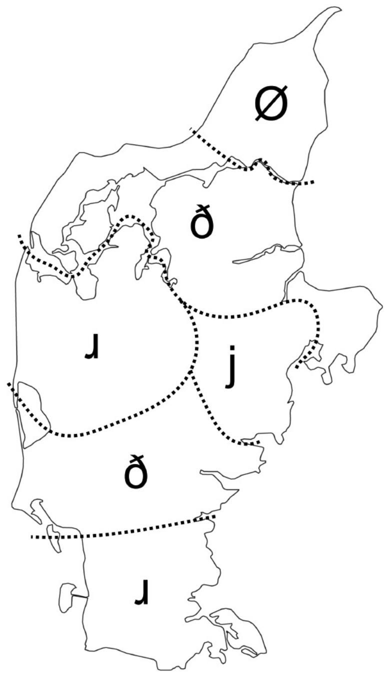


Fig. 4. Map showing the outcomes of stop gradation in /d/ in Jutland. Adapted from Bennike and Kristensen (1898–1912, K.50.).

1.3. Research questions and hypotheses

In this study, we are primarily interested in the following question: are sound changes and phonological processes sensitive to the phonetic details of laryngeal contrast beyond broad descriptive features like aspiration *vs.* voicing? We operationalize this question by comparing the well-documented geographically variable outcomes of stop gradation in Jutland with geographical variation in the fine phonetic detail of stop realization, in particular the implementation of the laryngeal contrast.

The hypotheses outlined below follow the assumption that stop gradation is a result of the general tendency for phonological rules that result in lenition or neutralization to affect codas and word endings (see Section 1.1). This has almost invariably led to an increase in aperture in the various traditional varieties of Danish, but the precise outcome of stop gradation is affected by how precisely the laryngeal contrasts in individual varieties were realized. If this assumption is true, we expect to find that the decrease in sonority in weak reflexes in Jutland moving north–south is mirrored by a decrease in phonetic stop 'sonority' in strong position in Jutland moving in a north–south direction, where 'phonetic sonority' refers to a level of fine phonetic detail that traditional Danish dialectologists were either unable to capture or were explicitly uninterested in.

/b d g/ were the historical sources of the allophones discussed above, but we can learn more about variability in the phonological systems by looking at how the phonetic implementation of the laryngeal contrast varies at large rather than just how /b d g/ vary. We operationalize the above notion of 'phonetic sonority' as differences in the duration of aspirated releases in /p t k/, i.e. differences in positive VOT, and differences in closure voicing patterns in /b d g/. We pose the following concrete research questions:

Does the duration of the aspirated release of /p t k/ show meaningful patterns of geographical variation that correspond to the variable outcomes of stop gradation? The research hypothesis, which we will call the *Aspiration Hypothesis*, is that the duration of aspiration varies geographically, such that it is relatively long in the south and shortens with increasing latitude.

Do closure voicing rates in /b d g/ show meaningful patterns of geographical variation that correspond to the variable outcomes of stop gradation? The research hypothesis, which we will call the *Voicing Hypothesis*, is that the occurrence of closure voicing varies geographically, such that voicing is relatively common in the north, and decreasingly common with decreasing latitude.

The Aspiration Hypothesis and the Voicing Hypothesis follow from the principles and assumptions laid out in Section 1.1. If support is found for these hypotheses, this suggests 1) that the variable outcomes of stop gradation in Jutland Danish are the result of differences in fine phonetic detail at the laryngeal level, and accordingly 2) that the precise implementation details of a laryngeal contrast can have an impact on higher-order processes such as phonological change. While keeping in mind that correlation does not equal causation, it is motivated at length in the preceding sections why a potential correlation between stop gradation and stop phonetics would be meaningful.

The statistical models of aspiration duration and closure voicing rates probe the influence of geography on phonetic implementation, but they also include a wide range of other predictor variables (phonetic contextual and otherwise) which are known to or expected to influence aspiration duration and voicing rates. These variables are not related to the primary hypotheses of the study, but the results may nevertheless be of general interest for developing models of how aspiration duration and voicing rates covary with their phonetic environment. For this reason, the predictor variables are introduced in some detail in Section 2.3 and discussed in some detail in Section 4.1; readers who are primarily interested in the Aspiration Hypothesis and Voicing Hypothesis as posed above can safely skip these sections.

The structure of the rest of the paper is as follows: Section 2 presents the corpus used in the study, describes the acoustic analysis procedures, discusses the various predictor variables in detail, and presents the statistical methodology. Section 3 presents the results of the statistical models, and Section 4 discusses the results in light of the theory and research questions presented in this and previous sections, including a discussion of how the situation in the Jutlandic varieties relates to the situation in Modern Standard Danish.

2. Methods and materials

2.1. The corpus

As mentioned in Section 1, the Danish dialect landscape has been drastically transformed over the course of the past century, and in large parts of the country it would no longer be possible to find speakers of the traditional dialects. For this reason, this study makes use of a legacy corpus of sociolinguistic recordings with mostly elderly dialect speakers. The

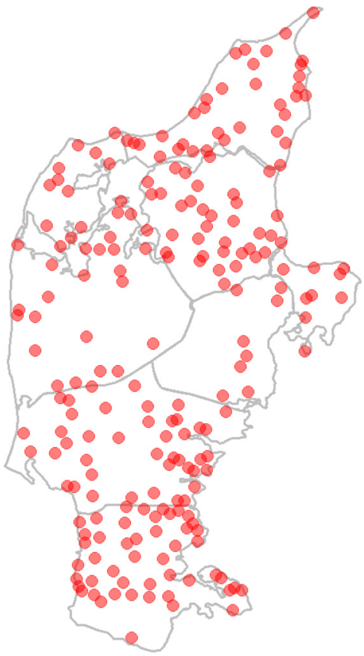


Fig. 5. Locations of informants in the present study. The lines on the map in this and subsequent plots indicate traditional dialect areas as defined by Skautrup et al. (1944–1970). Plotted in R using the `ggplot2` library (Wickham, 2016).

corpus consists of tape recordings that were collected during a five-year collaborative project by the Peter Skautrup Center for Jutlandic Dialect Research and the Department of Dialect Research at the University of Copenhagen from 1971–1976 (Arboe Andersen, 1981; Pedersen, 1983; Goldshtein and Puggaard, 2019; Puggaard-Rode, 2023a). The project aimed at recording speakers from every fourth parish in the country, and almost achieved this goal, resulting in 525 sociolinguistic interviews with elderly rural informants who were specifically chosen for their dialect 'purity'.[7] The project had two main goals: to document traditional varieties which were quickly losing ground for posterity, and to gather materials for ongoing dialect dictionary projects. Phonetic research did not factor into the considerations, and little effort was made to avoid e.g. background noise and overlap. The corpus adds up to around 370 hours of speech data, and the original tape recordings have all been digitally restored by the Royal Danish Library and are freely available online in high quality.[8] The existence of this corpus is the only reason why this study is possible. The geographical distribution of participants is shown in Fig. 5. The coverage is quite good and relatively evenly spread except for a sparsity of recordings around the center of the peninsula.

A little less than half of the recordings in the corpus are from Jutland. This study makes use of recordings from 213 different parishes in Jutland, excluding only recordings which are uncharacteristically short, recordings where the audio quality is uncharacteristically poor, or recordings of group interviews. In the few cases where multiple recordings were made in the same parish, one recording was selected on the basis of audio quality. When interviews were spread across multiple tapes, the second one was used, since the flow of speech tends to become more natural as the recording progresses and informants get used to the presence of the recording device.

The mean age of participants at the time of recording was 77.4 years, excluding 13 participants for whom the age is not known; 49 of the 213 informants were women. This is obviously a fairly age-biased population, and deliberately so. Age is known to affect temporal characteristics of speech including positive VOT, such that elderly speakers generally have slower speech, but (usually) shorter positive VOT (Smith et al., 1987; Larson et al., 1992; Torre and Barlow, 2009).[9] Age is unlikely to affect the main conclusions drawn from the study, as all participants were more or less elderly at the time of recording. However, the age bias does mean that one should be careful comparing the exact VOT values reported here to the results of studies without a similar age bias.

The corpus is especially suitable for our purposes, since most of the speakers were born in the last few decades of the 19th century, making them more or less the same generation as the informants for Bennike and Kristensen's (Bennike and Kristensen, 1898–1912) dialect atlas; Bennike and Kristensen were teachers at a *højskole* (a Danish boarding school for young adults) and their informants were pupils at the school. Although this does not make the speakers recorded in the 1970s perfect representatives of the dialect landscape in the late 19th century – there are multiple studies showing that speakers do change their speech patterns throughout the lifespan (e.g. Harrington et al., 2000; Sankoff and Blondeau, 2007; Kang and Han, 2013) – Labov (1994) does convincingly argue for the usefulness of apparent-time data, and the choice of particularly conservative informants for the corpus likely means that the corpus provides a decent snapshot of the speech patterns from that particular generation of Jutland Danish speakers.

2.2. Token selection and acoustic analysis

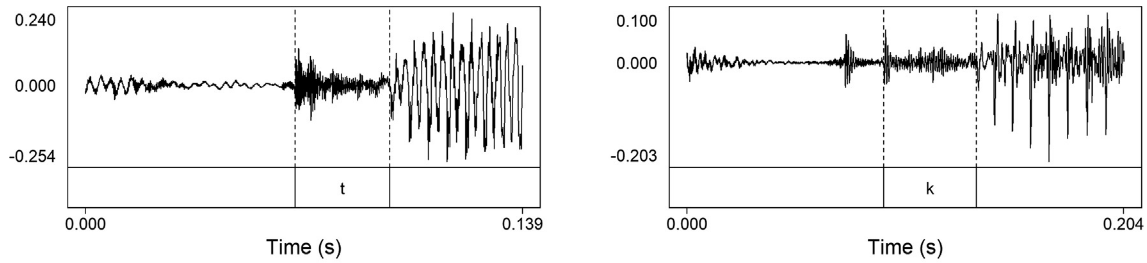
A large number of stop tokens were extracted from the corpus presented in the previous subsection. The vast majority of the recordings in the corpus have not been transcribed, and the few existing transcriptions are fully analog and not particularly helpful for phonetic analysis (Goldshtein and Puggaard, 2019). As such, the first analysis step was to listen through (parts of) recordings to determine the locations of stops. Since this is a very time-demanding task, this puts a natural limit on the number of tokens that could be included in the study, and there are many more stops in the corpus than those used in the present study.

The selection of tokens followed these criteria: Tokens of /p t k/ were included only if they were in simple onset or followed by the palatal glide [j]; /Cj/ clusters were included since it was often difficult to determine whether the glide was a separate segment or the result of phonological palatalization. Tokens were excluded if a stop release could not be clearly delimited. The first 50 tokens from each recording that matched these criteria were included in the study.

[7] See Goldshtein and Ahlgren (2021) for a critical discussion of the notion of dialect purity and how this affected the interviews.

[8] Recordings can be accessed via this URL: dansklyd.statsbiblioteket. dk/samling/dialektsamlingen/. More metadata and information about how to access the specific recordings used in this study can be found in this paper's accompanying data and code.

[9] This relationship between age and positive VOT is particularly clear for male speakers (Torre and Barlow, 2009), and particularly clear in /p t/, whereas the results for /k/ are mixed.



(a) Straightforward /t/ token.

(b) Token of /k/ with two bursts.

Fig. 6. Example of annotated aspiration phases in two tokens. Plotted in R using the `praatpicture` library (Puggaard-Rode, 2024).

Due to the great variability in phonetic implementation, aspiration-related landmarks were segmented manually in Praat (Boersma and Weenink, 2021). The duration of the aspirated release, i.e. positive VOT, is defined as the time differential between the stop release and the onset of voicing (Lisker and Abramson, 1964). The acoustic landmark used to identify the stop release was a sudden increase in amplitude after a period of relative silence (corresponding to the stop closure). This is determined from the waveform rather than the spectrogram due to the higher temporal accuracy of the waveform (following Abramson and Whalen, 2017). Whenever multiple bursts were present, the final one was segmented, following Cho and Ladefoged (1999, 215); this phenomenon is fairly common in the recordings, likely due to the speakers' age (Parveen and Goberman, 2012).[10] The landmark used to represent the onset of voicing was the first zero-crossing preceding the onset of periodicity in the waveform, which Francis et al. (2003) identifies as the landmark most closely corresponding to physiological measures of voicing onset. Fig. 6 shows an example of annotated aspiration landmarks in a fairly straightforward /t/ token, and in a /k/ token with two bursts. The VOT measurements of /p t k/ are identical to those reported by Puggaard (2021) and included in that paper's accompanying data.

Tokens of /b d g/ were also included only if they were in simple onset or followed by [j]. Function words were excluded unless they were stressed or post-pausal, and the extremely frequent function word *det* 'it, that' was excluded across the board. In each recording, all instances of /b d g/ that met these criteria (and at least impressionistically sounded like stops) were included in the analysis up to the point where the 50th instance of /p t k/ had been found.

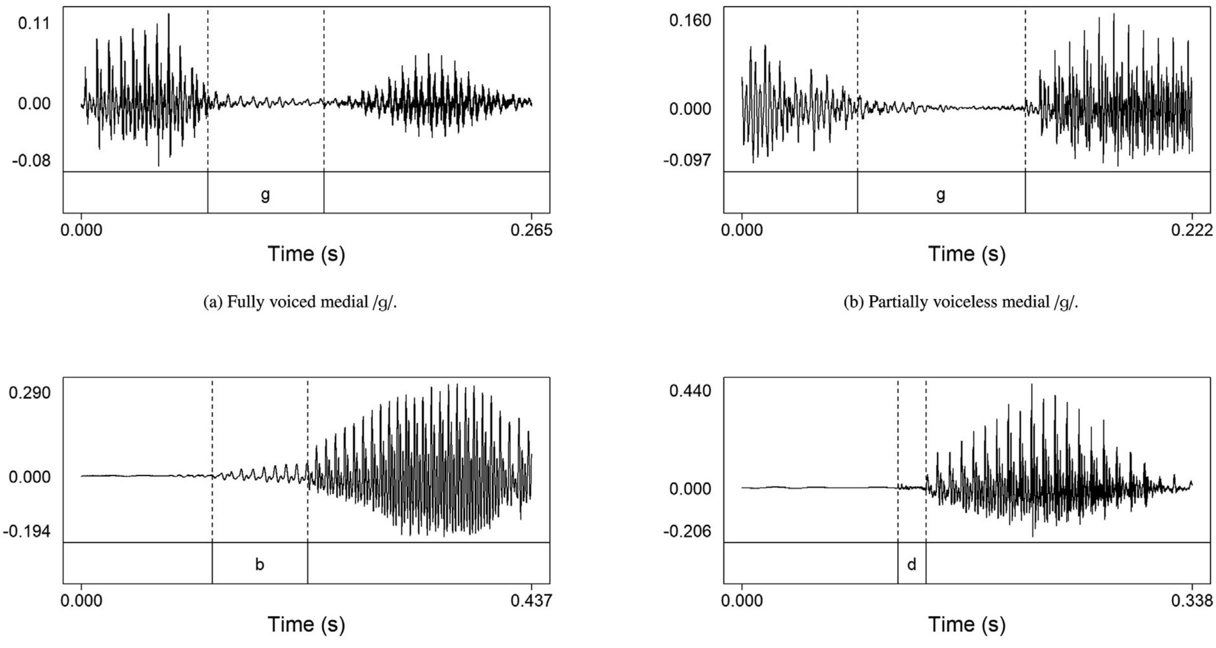
For each token of /b d g/, it was determined whether or not it was fully voiced. In post-pausal position, stops were considered fully voiced if prevoicing, i.e. periodicity prior to the release, was present. As with the landmarks for aspirated releases, this was determined on the basis of the waveform. The initiation of pre-voicing in post-pausal position generally requires articulatory adjustment above the glottis even if the vocal folds are positioned in a way that is amenable to voicing (Solé, 2018); recall from Section 1.2.1 that the vocal folds are usually lightly spread during the closure in Modern Standard Danish /b d g/. In other positions, stops were considered fully voiced if voicing (i.e. periodicity) was continuous throughout the closure. In intersonorant position, voicing will naturally continue throughout most of the closure without any articulatory adjustment due to the high transglottal pressure differential following a sonorant (Westbury and Keating, 1986); in Modern Standard Danish, the glottal spreading gesture during /b d g/ usually counteracts this (Hutters, 1985; Puggaard-Rode et al., 2022).

This dichotomy between fully voiced and not fully voiced follows the study of Modern Standard Danish by Puggaard-Rode et al. (2022). It is fairly common for studies to report categorical measures of voicing (see e.g. Davidson, 2016; Sonderegger et al., 2020; Tanner et al., 2020), although often including a distinction between fully voiceless and partially voiced stops. These two categories are collapsed in this study, primarily for the three following reasons: 1) It is much more difficult to statistically model multi-valued categorical dependent variables than binary ones; 2) stops are essentially never fully voiceless intervocalically (e.g. Shih et al., 1999), and at least in this data, they are very rarely partially voiced in absolute initial position. Blevins et al. (2020) use the autocorrelation coefficient in windowed portions of the signal to estimate a proportional measure of voicing probability. We opt against this here, because it is impossible to annotate stop closures consistently when some tokens are post-pausal without pre-voicing; without annotated closures, it would have to be determined on an *ad hoc* basis where such measures are taken. Another potential continuous measure is the duration of pre-voicing, i.e. negative VOT, but this is not a particularly meaningful measure in medial position. A binary voicing decision arguably captures well whether there is an articulatory target for active devoicing in medial stops (as in Modern Standard Danish), and whether there is an articulatory target for active voicing in post-pausal stops.

In order to cross-validate the binary voicing decision, we used the epoch detection and pitch tracking software `reaper` (Talkin, 2015) to estimate the proportion of 5 ms frames that are voiced in the 100 ms prior to the stop release. Using this voicing proportion measure, we can predict the binary voicing decision with approx. 78.5% accuracy.[11] While this is of course a very rough measure of voicing proportion leading up to the release, and cannot be taken as a gold standard, the high correlation between the two measures is reassuring. The voicing pro-

[10] This choice may have a non-trivial influence on the resulting measurements (Gráczi and Kohári, 2014), but since there are no indications that the presence of multiple bursts varies regionally, it should not affect how the results are interpreted.

[11] We arrived at this number by iteratively fitting 100 simple logistic regression models on different subsets of the data with the binary voicing decision as the dependent variable, and the `reaper`-estimated voicing proportion leading up to the release as the independent variable. Each model used a random 80% subset of the data for training and a random 20% subset for validation; during validation, these models predict the correct binary voicing decision label with a mean accuracy of 78.5%.



(a) Fully voiced medial /g/.

(b) Partially voiceless medial /g/.

(c) Pre-voiced post-pausal /b/.

(d) Voiceless post-pausal /d/.

Fig. 7. Examples of fully voiced and (partially) voiceless stops in medial and postpausal position. Plotted in R using the `praatpicture` library (Puggaard-Rode, 2024).

Table 1
Number of tokens included in the analysis by laryngeal category and place of articulation.

Phoneme	Number of tokens
/p/	1,386
/t/	5,169
/k/	4,095
/p t k/ total	10,650
/b/	2,212
/d/	2,369
/g/	2,273
/b d g/ total	6,854

portion measure is not used further in the statistical modeling of the paper, but is shared along with the accompanying data and code for the paper.

Fig. 7 gives examples of post-pausal and intersonorant /b d g/ that are either fully voiced or not fully voiced. As with Fig. 6 above, only waveforms are shown, since the decision was made on the basis of the waveform.

The number of measured tokens by place of articulation and laryngeal category is given in Table 1;[12] the relative rarity of /p/ tokens reflects a general pattern in the Danish lexicon (see e.g. Hansen, 1962, II:165ff.).

2.3. Predictors

In the statistical models of aspiration and voicing presented in Section 2.4, a host of categorical predictors are included which are known or expected to influence positive VOT and the likelihood of voicing. These are all nuisance variables, but they do allow us to test predictions and lend credence to previous findings about how such variables affect aspiration and voicing. The predictors are introduced in turn in the following. As mentioned in Section 1.3, these variables are not directly related to the paper's primary research questions, and readers who are interested primarily in the sound change aspect of this paper can safely skip the following exposition, but readers interested in implementing a similar study should be aware that these may be important controls.

PLACE. Cross-linguistically, it is generally the case that aspirated stop releases lengthen with more anterior places of articulation, such that, in our case, bilabials are expected to be shortest and velars are expected to be longest (Lisker and Abramson, 1964; Cho and Ladefoged, 1999; Chodroff et al., 2019). Puggaard (2021) found support for this in Jutland Danish, but it is not in line with previous research on Modern Standard Danish, where /t/ has the longest aspiration (Fischer-Jørgensen, 1980; Mortensen and Tøndering, 2013; Puggaard-Rode, 2022). This may be because /t/ is saliently affricated in Modern Standard Danish (Fischer-Jørgensen, 1972b; Puggaard-Rode, 2022); this feature is known to be much less prominent in Jutland (Puggaard-Rode, 2023b). Similarly, the likelihood of voicing should decrease with more anterior places of articulation (e.g. Gamkrelidze, 1975; Keating, 1984). Both patterns are likely in part due to the aerodynamic voicing constraint, i.e. the transglottal pressure drop required to maintain vocal fold vibration (see e.g. Halle and Stevens, 1971; Ohala, 1983; Westbury and Keating, 1986). Due to the relatively close proximity between the glottis and velum, the air pressure behind a velar stop closure will rise relatively quickly, and when pressure reaches a certain threshold, the vocal folds will cease to vibrate; due to the greater distance between the glottis and lips, vocal fold vibration will continue longer before a bilabial closure, all else being equal.[13] For

[12] This paper's accompanying data and code also contains plots giving the number of tokens by phoneme for each of the predictors included in the statistical models.

[13] This effect is mostly not due to the volume differences of the cavity between the glottis and the occlusion, but rather due to differences in the surface area of soft compliant tissues which line the walls of the cavity (Ohala and Riordan, 1979).

the same reason, air pressure behind a velar closure will be high at the time of release, and it will take somewhat longer to achieve the pressure drop required for vocal fold vibration to begin (e.g. Hardcastle, 1973). Other phonetic factors contributing to the place patterns in VOT are discussed in detail by Cho and Ladefoged (1999).

PALATALIZATION is expected to result in a prolonged voiceless release; this is in line with Puggaard's (Puggaard, 2021) findings. We might also expect palatalization to decrease the probability of voicing, as the tighter constriction in the oral cavity may result in a faster build up of air pressure during the closure, although Puggaard-Rode et al. (2022) did not find support for this in Modern Standard Danish. Palatalization may here refer either to the presence of a palatal glide /j/ after the stop, or to phonological palatalization of the stop itself (see Section 2.2).

BACKNESS. It is not straightforward to predict how vowel backness affects aspiration and voicing; from an aerodynamic perspective, we may expect back vowels to lengthen aspiration, as there is a constriction closer to the glottis that may impede air pressure drop immediately after the stop release. This is because the tongue body starts positioning for the vowel during the stop closure, especially so during bilabials, but even during alveolars and velars where the articulators needed for the vowel position are also directly involved in forming the stop closure (Gay, 1977; Löfqvist and Gracco, 1999; Löfqvist and Gracco, 2002). In lingual stops, the precise place of occlusion is also affected by the vocalic context, such that it is further back towards the glottis before back vowels (Butcher and Weiher, 1976). The ensuing predictions are partially in line with Gósy's (Gósy, 2001) study of VOT in Hungarian, where VOT is longer before back vowels in bilabials and alveolars, but not in velars; this could suggest that differences in occlusion are insufficient to cause a stable difference in VOT. However, Puggaard (2021) previously found the opposite, namely that non-back vowels increased positive VOT, which may be related to non-back vowels having a more salient effect on the release acoustics (as shown by Puggaard-Rode, 2022; Puggaard-Rode, 2023b). An aerodynamic account may also predict decreased chances of voicing before back vowels since both the vocalic and consonantal constrictions are potentially closer to the glottis.

STRESS. The influence of stress on aspiration and voicing rate is not entirely straightforward. Stress has been shown to lengthen aspiration in languages like English, German, and Modern Standard Danish (Lisker and Abramson, 1967; Kirby et al., 2020; Puggaard-Rode, 2022), and this was also the pattern found by Puggaard (2021). In plain voiceless stops, stress may not affect positive VOT (as in Spanish, see Simonet et al., 2014) or may even decrease it (as in Dutch Cho and McQueen, 2005). Similarly, stress may increase the duration of pre-voicing in languages where closure voicing is the primary cue to the laryngeal contrast (e.g. Simonet et al., 2014), or it may decrease the chances of continuous medial voicing in languages with a laryngeal contrast that relies mostly on aspiration, as shown for English (Davidson, 2016) and Modern Standard Danish (Puggaard-Rode et al., 2022). The laryngeal contrast in Jutland Danish varieties by and large seems to be more aspiration-oriented than voicing-oriented, so we would predict longer aspiration and decreased voicing rate in stressed syllables.

ROUNDNESS. Positive VOT has been shown to be longer before rounded vowels in bilabials, and longer before unrounded vowels in stops at other places of articulation in French (Fischer-Jørgensen, 1972a). Puggaard (2021) did not find support for such an interaction in Jutland Danish, but rather found that rounded vowels generally increased positive VOT. There are no obvious aerodynamic reasons for this, but as with backness, it may be the case that vowel rounding has a salient effect on the acoustic characteristics of stop releases and lengthened aspiration enhances this effect (see Puggaard-Rode, 2022). We have no specific predictions for how vowel rounding may affect voicing rates, although the covariate is included in both models to keep them as similar as possible. Note that vowel rounding in Danish is independent from backness; in Modern Standard Danish, there are rounded vowels in both the front and back dimensions at at least four different heights (Grønnum, 1995).

HEIGHT. High vowels have been shown to increase positive VOT in multiple languages, including Modern Standard Danish (e.g. Klatt, 1975; Fischer-Jørgensen, 1980; Higgins et al., 1998; Esposito, 2002; Bijankhan and Nourbakhsh, 2009; Berry and Moyle, 2011). Mortensen and Tøndering (2013) failed to replicate this in /p t k/ in Modern Standard Danish; Puggaard (2021), however, did find this for a subset of the Jutland Danish data under analysis here. This possibly has an aerodynamic explanation: voicing onset may be delayed in high vowels due to the tighter constriction, and as such higher pressure, in the oral cavity. For the same reason, we may expect continuous voicing to be less common before high vowels, although Puggaard-Rode et al. (2022) did not find evidence for this in Modern Standard Danish, and Ohala (1983) found little evidence of such an effect cross-linguistically. Alternatively, high vowels tend to have a salient influence on following release characteristics (Puggaard-Rode, 2022). This is especially true in velars, which are highly coarticulated with following vowels (see Section 1.1). The Modern Standard Danish vowel system is exceptionally complex and makes use of at least five phonological vowel heights (Grønnum, 1995), although phonological vowel systems are not the same in all varieties (Ejstrup and Hansen, 2003). In order to keep the analysis relatively simple, we follow Mortensen and Tøndering (2013) in coding only three levels of vowel height (*high*, *mid*, and *low*).

BOUNDARY. All stops in the corpus were coded as either post-pausal or not post-pausal. Positive VOT has been shown to be longer in utterance-initial position in e.g. Korean and English (Cho and Keating, 2001; Cho and Keating, 2009). Davidson (2016) showed that pre-voicing in English /b d g/ is significantly less common in post-pausal position (note that this is highly variable, see e.g. Flege, 1982; Keating, 1984). Continuous closure voicing is not particularly uncommon in intersonorant position in Modern Standard Danish, but pre-voicing in post-pausal position is essentially non-existent (Fischer-Jørgensen, 1954; Puggaard-Rode et al., 2022).

SEX. Women have been shown to have longer positive VOT than men in English (e.g. Swartz, 1992; Whiteside and Irving, 1998), especially among older speakers (Torre and Barlow, 2009); note however that Puggaard (2021) did not find evidence for a sex effect in the present corpus. Swartz (1992) also found that men were significantly more likely to prevoice

/b d g/ than women; Puggaard-Rode et al. (2022) failed to find support for such an effect in Modern Standard Danish. Both sex effects could be aerodynamically motivated using the same basic reasoning as we have previously done: men have larger supralaryngeal cavities than women on average (Fitch and Giedd, 1999), which makes them physiologically more amenable to maintaining voicing during closure for longer and establishing voicing after closure more quickly.

2.4. Statistical analysis

In order to test the research questions presented in Section 1.3, the data described in Section 2.2 was statistically modeled with two separate spatial generalized additive mixed models (GAMMs); one modeling positive VOT in /p t k/, testing the Aspiration Hypothesis, the other modeling the likelihood of (continuous) closure voicing in /b d g/, testing the Voicing Hypothesis.

GAMMs are suitable for analyzing variables which vary dynamically over time or space. Unlike traditional linear mixed-effects regression models, where the relation between a predictor and a response variable is always linear, GAMMs can flexibly model non-linear (so-called *smooth*) relationships between predictors and responses. They incorporate both linear, smooth, and random effects, and the smooth effects can be multidimensional. It is very often the case in phonetic research that we cannot assume linear relationships between predictors and responses, so GAMMs have been in broad use in recent years when analyzing e.g. time series (see Wieling, 2018), articulatory signals (e.g. Wieling et al., 2016; Carignan et al., 2020), EEG registration (e.g. Baayen et al., 2018), spectral shape (e.g. Nance and Kirkham, 2020; Puggaard-Rode, 2022), or indeed geographical variation (Wieling et al., 2011; Wieling et al., 2014; Koshy and Tavakoli, 2022; Puggaard-Rode, 2023b).

Both GAMMs are fitted using fast restricted maximum likelihood estimation with discretized values for covariates to decrease computing load (Wood et al., 2017). Geography is included in the models through two-dimensional thin plate regression spline smooths (Wood, 2003), which is a suitable smoothing spline basis for multidimensional variables on the same scale, such as geographical coordinates (Wieling et al., 2014). The following linear predictors are also included: PLACE, PALATALIZATION, BACKNESS, STRESS, ROUNDNESS, HEIGHT, BOUNDARY and SEX. Linear by-speaker random slopes are further included for all within-subjects factors. In order to aid interpretability of the parametric component of the model and the intercept, the linear predictors are all coded with sum contrasts (for binary variables) or Helmert contrasts (for more complex variables) (see Schad et al., 2020).[14] The coding scheme is summarized in Table 2. The models are summarized below, where the response variable Y refers to positive VOT in one model, and the log likelihood of closure voicing in the other; $f(\ldots)$ indicates a smooth term, i indexes each observation, j indexes each speaker, and E_i is the residual error. The VOT model is fitted using the scaled-t error distribution to account for heavy-tailed residuals; the residuals of this model are approximately normal. The model of voicing is fitted using a binomial error distribution with the logit link.

[14] Note that contrast coding does not affect the smooth components of GAMMs since smooths are always centered around zero.

Table 2
Overview of contrast coding for categorical variables.

Variable	Contrast
PLACE	- 1/3 bilabial, - 1/3 alveolar, + 1/3 velar - 1/2 bilabial, + 1/2 alveolar
PALATALIZATION	- 1/2 palatalized, + 1/2 non-palatalized
BACKNESS	- 1/2 back, + 1/2 non-back
STRESS	- 1/2 unstressed, + 1/2 stressed
ROUND	- 1/2 unrounded, + 1/2 rounded
HEIGHT	- 1/3 low, - 1/3 mid, + 1/3 high - 1/2 low, + 1/2 mid
BOUNDARY	- 1/2 not post-pausal, + 1/2 post-pausal
SEX	- 1/2 female, + 1/2 male

$$
\begin{aligned}
&Y_{ij} = f(lon_i, lat_i) + place_i + palatalization_i + backness_i \\
&+ stress_i + round_i + height_i + boundary_i + sex_i + speaker_{ij} \\
&+ speaker_j place_i + speaker_j palatalization_i \\
&+ speaker_j backness_i + speaker_j stress_i + speaker_j round_i \\
&+ speaker_j height_i + speaker_j boundary_i + E_i
\end{aligned}
$$

All statistics are calculated in R (R Core Team, 2022). GAMMs are fitted using the `mgcv` package (Wood, 2017; Wood, 2022). As with ‘regular’ linear or logistic mixed effects models, summaries of parametric model components from `mgcv` report regression coefficients and their standard errors, test statistics (t-values and z-values respectively), and p-values computed from those. Since these terms are coded with orthogonal contrasts, the intercept can be straightforwardly interpreted. In the VOT model, it refers to the weighted population mean; in other variables, when the estimate is a positive number, it refers to the mean increase in VOT associated with the positive pole of that variable in the contrast coding relative to the negative pole, and *vice versa* for negative estimates. In the voicing rate model, the intercept refers to the weighted log odds of voicing, i.e. after other variables are controlled for. As with the VOT model, in other variables, the polarity of the log odds estimate matches the polarity of the contrast coding, such that a negative log odds refers to higher probability of voicing in the negative pole of that variable. The log odds estimates are used for computing standard errors, z-values, and p-values, but log odds are not particularly easy to interpret in themselves. For this reason, odds and odds ratios (*OR*) are also reported; these are simply exponentiated from the log odds, and can be straightforwardly interpreted as the change in probability associated with a given variable (Sonderegger, 2023, Chap. 6). When *OR* is above 1, the probability of continuous voicing is higher in the positive pole of the variable, and when *OR* is below 1, the probability of continuous closure voicing is higher in the negative pole of the variable.

Summaries of smooth model components are quite different; these report estimated degrees of freedom (reflecting the linearity of the variable), referential degrees of freedom (reflecting the complexity of fitting a variable), as well as F-values and p-values. Referential degrees of freedom and F-values together reflect the fitting–complexity tradeoff of including a variable, and p-values are calculated from these (Wood, 2013). The p-values are an attempt at estimating the variable’s overall significance, but due to the dynamic nature of these variables, this estimation is not particularly informative in itself.

For this reason, we mostly rely on plots to determine the effect of our geographical predictor. This can be done straightforwardly by overlaying a raster plot of the fitted effect on a map of Jutland. Two further types of plot are included to determine the stability of the effects: 1) Equivalent raster maps which are only colored in areas where the fitted effect differs significantly from the model intercept; i.e., when the fitted effect differs from zero by more than two standard errors in that area, corresponding to 'significance' at the usual $p < 0.05$ level (recall that smooth model components are always zero-centered). 2) Separate plots showing the upper and lower limits of 95% confidence intervals of the fitted effect (following Marra and Wood, 2012).

3. Results

This section presents the results of the two GAMMs presented in Section 2.4, starting with the VOT model testing the Aspiration Hypothesis in Section 3.1, and then the voicing rate model in Section 3.2 testing the Voicing Hypothesis (see Section 1.3).

3.1. Voice onset time

The Aspiration Hypothesis is tested with a model which has positive VOT in /p t k/ as its dependent variable. This model has a fairly high effect size of $R^2 = 0.413$. The parametric coefficients, corresponding to the 'nuisance' variables presented in Section 2.3, are summarized in Table 3.

The weighted population mean of approx. 51 ms is comparable to Modern Standard Danish when similar delimitation criteria are used for VOT landmarks (Puggaard-Rode, 2022), albeit somewhat shorter. Most of the fixed effects significantly influence the duration of the aspirated release, and all significant effects are in the predicted direction. Aspiration is longer in velar than non-velar stops, and is much longer in alveolar than bilabial stops.[15] VOT is much longer in palatalized stops. It is also longer before non-back vowels, before rounded vowels, and before high vowels; there is no evidence of a VOT difference in mid and low vowels. Stress increases VOT quite a bit; the effect of boundary is much smaller, but post-pausal aspiration is slightly longer. Female speakers have longer VOT than male speakers.

The fitted geographical effect is shown in Fig. 8. It shows a clear pattern of variation in the north–south dimension and a somewhat weaker pattern in the east–west dimension. Aspiration is longer in the south and shorter in the north, and there is a gradual, largely linear cline in between.[16] The shortest aspiration is found along the northern coast, and the longest aspiration is found in south–eastern parts of the peninsula. The difference between the longest and shortest fitted VOT is approx. 14 ms.

Fig. 9 shows the fitted geographical effect where areas are only colored in where the fitted positive VOT differs signifi-

[15] The model does not explicitly test whether alveolars have longer aspiration than velars; Puggaard (2021) found very similar VOT for /t k/, but slightly longer VOT in /k/, which is quite unlike the patterns in Modern Standard Danish (Puggaard-Rode, 2022), possibly due to the lack of /t/-affrication in most if not all traditional Jutlandic dialects (Puggaard-Rode, 2023b).

[16] The largely linear nature of the geographical effect is confirmed by the low estimated degrees of freedom (just slightly over 2) of this variable.

Table 3
Summary of the parametric coefficients of the VOT model.

Variable	Estimate	*SE*	*t*	*p*
intercept	51.41	0.99	52.07	<.001
PLACE: +velar, -non-velar	5.14	0.53	9.64	<.001
PLACE: +alv, -lab	8.69	0.67	13.03	<.001
STRESS	6.59	0.45	14.50	<.001
SEX	−6.26	1.48	−4.23	<.001
PALATALIZATION	13.42	1.29	10.37	<.001
BACKNESS	5.35	0.63	8.49	<.001
ROUNDNESS	5.49	0.60	9.22	<.001
HEIGHT: +high, -non–high	3.19	0.40	7.92	<.001
HEIGHT: +mid, -low	−0.24	0.53	−0.46	0.644
BOUNDARY	1.66	0.74	2.25	0.024

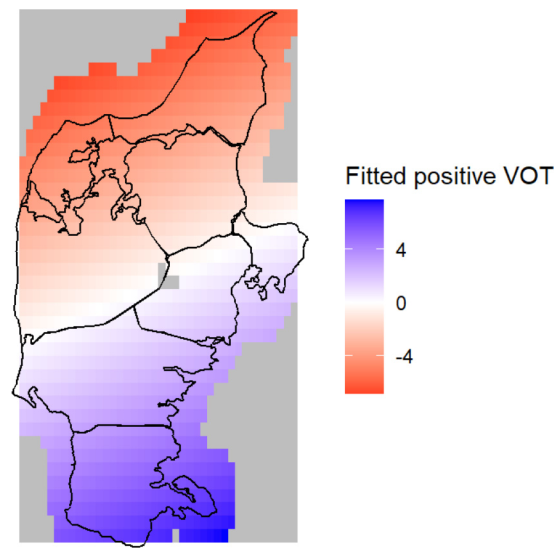


Fig. 8. Fitted VOT values attributed to the geographic variable overlaid on a map of Jutland. Plotted with `ggplot2` (Wickham, 2016).

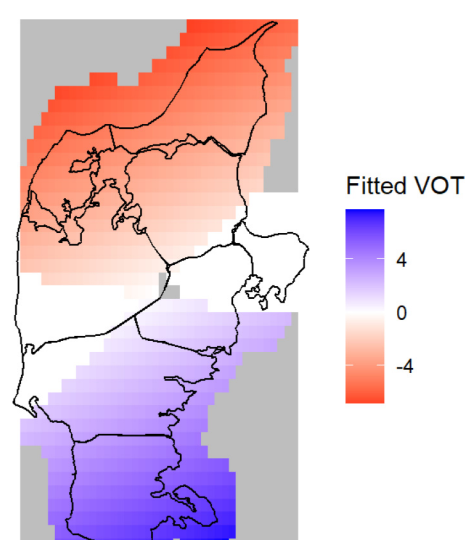


Fig. 9. Fitted VOT values attributed to the geographic variable overlaid on a map of Jutland, with colors removed where $p > 0.05$. Plotted with `ggplot2` (Wickham, 2016).

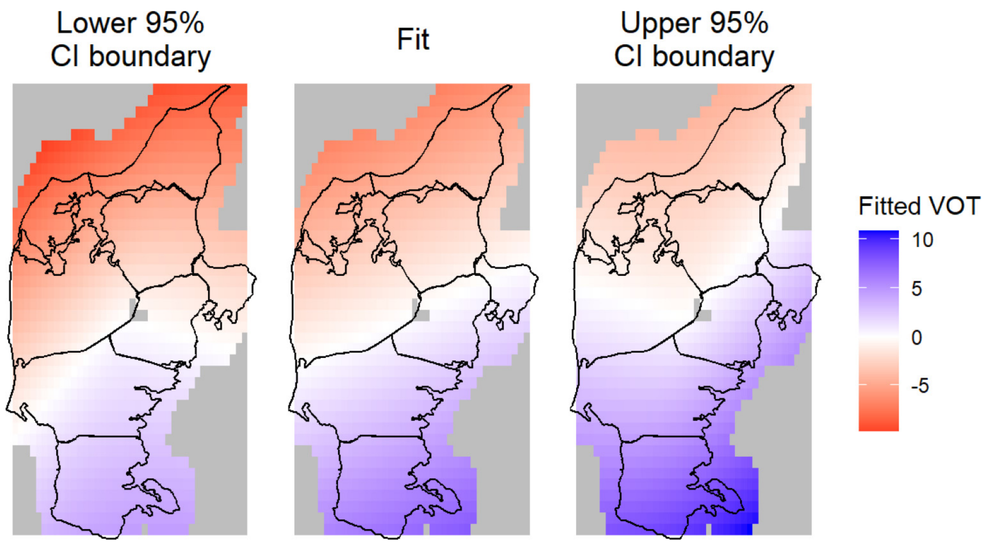


Fig. 10. Fitted VOT values attributed to the geographic variable as well as upper and lower bounds of 95% confidence interval overlaid on a map of Jutland. Plotted with `ggplot2` (Wickham, 2016).

cantly from zero, and Fig. 10 shows the effect along with the upper and lower bounds of 95% confidence intervals. These plots show that the effect is quite stable: standard errors are not abnormally high, and the effect throughout the bulk of the peninsula reaches significance (i.e. $p < 0.05$).

As previously mentioned, the GAMM modelling VOT actually fits a subset of the same data with the same annotations as Puggaard (2021), although some covariates were added here and the model structure is different; (Puggaard, 2021) presented a model of positive VOT in all stops (see also Puggaard-Rode, 2023a). The principal results are all the same; (Puggaard, 2021) also found gradually decreasing VOT moving south–north in a similar pattern, and the parametric effects were all significant in the same direction except for SEX, which did not approach significance in the previous study. The results are discussed further in Section 4.1 below.

3.2. Voicing

The Voicing Hypothesis is tested with a model that has a binary voicing variable (present *vs.* absent) in /b d g/ as its dependent variable. This model has a medium effect size of $R^2 = 0.315$. The parametric coefficients, corresponding to the 'nuisance' variables presented in Section 2.3, are summarized in Table 4.

The weighted probability of encountering a fully voiced stop is approximately 8 times lower than encountering a stop that is not fully voiced. This makes voicing somewhat more likely overall than in a mostly comparable study of Modern Standard Danish (Puggaard-Rode et al., 2022). Unlike in the VOT model, the bulk of the variables have little to no influence on the probability of continuous voicing, particularly the aerodynamic variables pertaining to the quality of the following vowel; this is in line with the results found for Modern Standard Danish. The probability of voicing is somewhat higher in /b/, although the difference is fairly marginal. There is a more pronounced gender difference, with men showing higher continuous voicing rates, as predicted. There is a significant but relatively marginal effect of stress, such that rates of continuous voicing is higher in unstressed syllables. Finally, there is a very strong effect of boundary, such that voicing in postpausal position is much less likely than otherwise.

The fitted geographical effect is shown in Fig. 11. It shows a similar pattern to the fitted effect of VOT shown in Fig. 8, but the pattern for voicing rate is somewhat more complex. Again, there is a gradual cline of probability of continuous voicing decreasing in a north–south direction. The effect is less linear, and very high rates of continuous closure voicing are here limited to the extreme north, with somewhat lower voicing rates along the western coast. (Note that a log odds difference of

Table 4
Summary of the parametric coefficients of the voicing model.

Variable	Estimate	Odds/*OR*	*SE*	*z*	*p*
intercept	−2.08	1 : 8.01	0.16	−13.17	<.001
PLACE: +velar, -non-velar	−0.05	1 : 1.06	0.07	−0.79	0.431
PLACE: +alv, -lab	−0.29	1 : 1.34	0.08	−3.44	0.001
STRESS	−0.25	1 : 1.28	0.07	−3.68	<.001
SEX	0.78	2.19 : 1	0.17	4.71	<.001
ROUNDNESS	0.11	1.12 : 1	0.10	1.09	0.277
BACKNESS	−0.03	1 : 1.03	0.12	−0.23	0.819
BOUNDARY	−3.74	1 : 42.25	0.24	−15.51	<.001
HEIGHT: +high, -non–high	0.04	1.04 : 1	0.08	0.45	0.652
HEIGHT: +mid, -low	−0.01	1 : 1.01	0.08	−0.14	0.886
PALATALIZATION	0.26	1.3 : 1	0.17	1.52	0.129

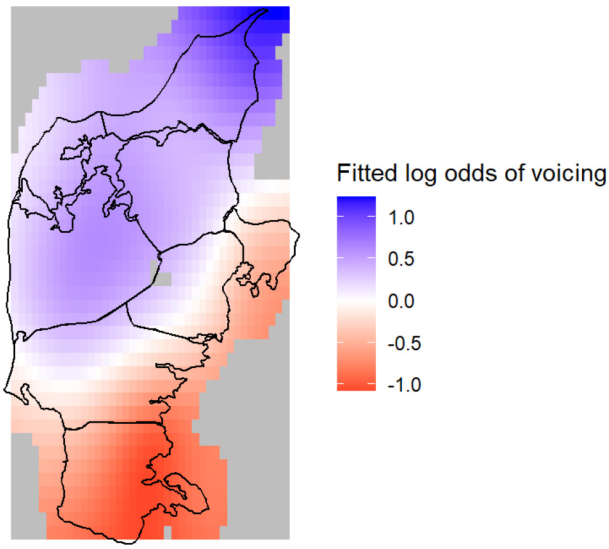


Fig. 11. Fitted probability of continuous voicing attributed to the geographic variable overlaid on a map of Jutland. Plotted with `ggplot2` (Wickham, 2016).

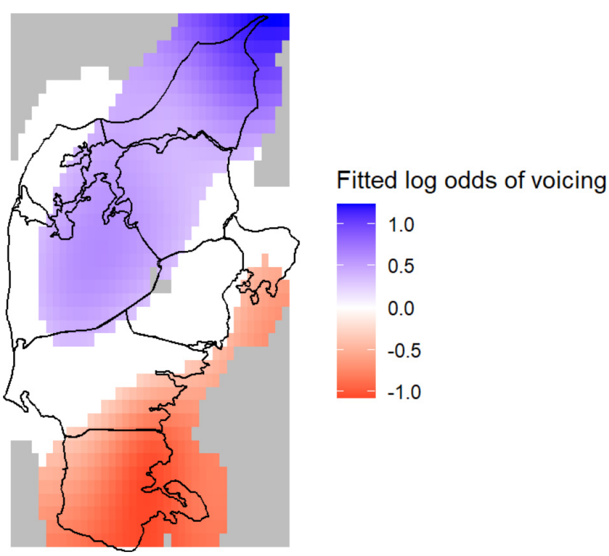


Fig. 12. Fitted probability of continuous voicing attributed to the geographic variable overlaid on a map of Jutland, with colors removed where $p > 0.05$. Plotted with `ggplot2` (Wickham, 2016).

± 1.0 is equivalent to an increased or decreased probability of approximately 1-to-2.7 relative to the global mean.).

As above, Fig. 12 shows the fitted geographical effect where it differs significantly from zero, and Fig. 13 shows the lower and upper bounds of 95% confidence intervals. The effect is somewhat less stable than in the VOT model, but still quite stable, particularly in our regions of interest.

4. Discussion and conclusions

This section discusses the results of the study in light of the research questions and predictions posed in Section 1.3 and Section 2.3. Section 4.1 covers the influence of the non-geographical covariates on aspiration duration and voicing rates, and Section 4.2 discusses the geographical patterns of variation in aspiration duration and voicing rates and how they relate to the corresponding patterns of variability in stop gradation, i.e. the Aspiration Hypothesis and the Voicing Hypothesis presented in Section 1.3. Section 4.3 returns to the question of how this relates to the patterns found in Modern Standard Danish, and Section 4.4 discusses the larger theoretical implications of the study. Finally, Section 4.5 provides some brief conclusions and outlook.

4.1. Non-geographical effects on stop realization

Before moving on to the Aspiration Hypothesis and the Voicing Hypothesis and the larger theoretical implications of the study, we will return to the non-geographical components of the statistical models, i.e. the predictors presented in Section 2.3. As with Section 2.3, readers who are mostly interested in the geographical components of the study and implications for sound change can safely skip this section.

Several predictors were included in the models which are known or expected to affect the duration of aspirated releases and/or voicing rates, most of which have to do with either prosodic prominence or the aerodynamics of voicing. Almost all of these predictors were found to significantly influence positive VOT such that aspiration is longer when stops are released into a tighter constriction: when stops are palatalized, when the following vowel is high, when the speaker is female (and has a smaller oral cavity on average). Aspiration lengthens with prosodic prominence, such that it is longer in stressed syllables or when the stop is in post-pausal position. Aspiration also lengthens with more posterior occlusions, such that VOT after velars is longer than after non-velars, and longer after alveolars than after bilabials; however, the difference between bilabials and alveolars is probably too large to be explained by aerodynamics alone, so the more salient release of alveolars is presumably partially responsible for this. Aspiration is also longer before rounded vowels, and the best explanation for this is that anticipatory rounding also affects the release burst (see Puggaard-Rode, 2022). This is also the likeliest explanation for why aspiration is longer before non-back vowels, since a purely aerodynamic account would predict longer aspiration before back vowels.

It should be noted that most of these effects, while stable, are quite small. Some estimates of ‘just noticeable differences’ (JND) in VOT suggest a threshold between 10–20 ms is required for differences to be perceptible (Rosner, 1984; Elliott et al., 1986), while other studies have shown that 10 ms differences are generally perceptible in some parts of the VOT space and not others (Elliott, 1986), and 10 ms VOT differences have been shown to trigger neural responses (Blumstein et al., 2005); note that the latter study simple shows that 10 ms differences *are* perceptible, it does not indicate that shorter differences are *not* perceptible. These variable results are further complicated by at least three factors: 1) the fact that spectral (non-temporal) cues have also been shown to play a role in the perceptibility of VOT differences (Soli, 1983); 2) the fact that JNDs differ in different areas of the VOT space, such that shorter differences are perceptible close to 0 ms;[17]

[17] As discussed by Rosner (1984), this reflects a general property of JNDs in perception known as Weber’s law.

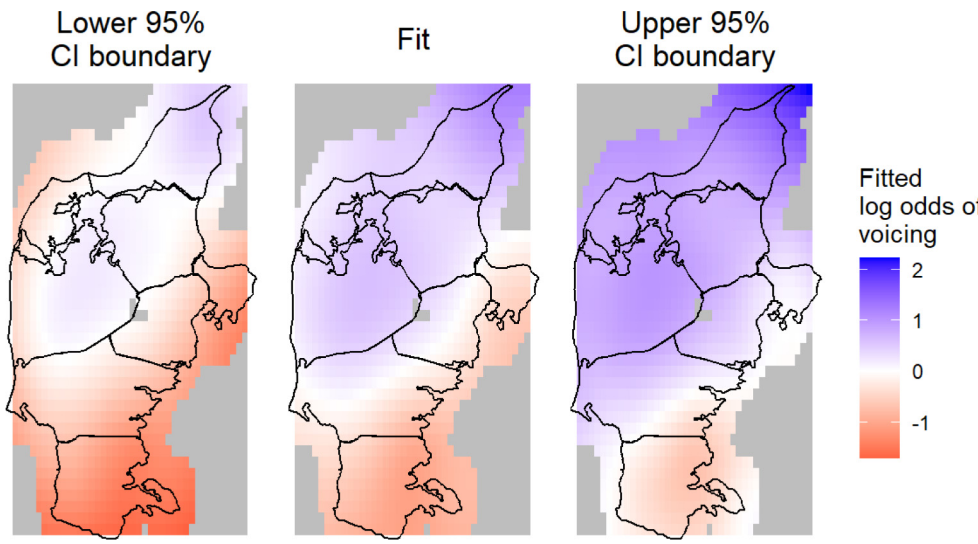


Fig. 13. Fitted probability of continuous voicing attributed to the geographic variable as well as upper and lower bounds of 95% confidence interval overlaid on a map of Jutland. Plotted with `ggplot2` (Wickham, 2016).

3) and the fact that this literature largely relies on the behavior of native speakers of English – it is not clear how well a particular JND estimate translates across different speaker populations with different phonological contrasts. With that caveat, if we assume that VOT differences of approx. 10 ms are perceptible, then the estimated differences for several predictors are too short to be perceptible, and only the PLACE and PALATALIZATION are potentially of any consequence. This is a further argument in favor of the effects largely being aerodynamic by-products of the phonetic context.

Much fewer covariates significantly affect the probability of continuous voicing. This may in part be due to differences in statistical power; the voicing model relies on fewer observations, and some of the significant effects in the VOT model are rather marginal. The model summary, however, shows that most of the phonetic contextual aerodynamic effects have predicted odds ratios very close to 1:1, suggesting that they truly do not influence the likelihood of continuous closure voicing. This is in line with what Puggaard-Rode et al. (2022) showed for Modern Standard Danish. Male speakers do have a significantly (if somewhat marginally) higher probability of closure voicing than female speakers, which Puggaard-Rode et al. (2022) did not find evidence for in Modern Standard Danish. The probability of continuous voicing is also significantly (if marginally) higher for bilabials than alveolars, while velars do not differ from non-velars; this is the opposite of Modern Standard Danish, where there was a clear difference between velars and non-velars but none between alveolars and bilabials. This may be because bilabials seem to be consistently voiced in all positions by a few speakers in the northernmost part of the peninsula, as described qualitatively by Puggaard-Rode (2023a, Chap. 6). As pointed out by Puggaard-Rode et al. (2022), it is possible that some of these variables affect the relative duration of closure voicing in medial position but do not actually affect the likelihood of continuous closure voicing, i.e. that most contextual aerodynamic effects affect closure voicing to an extent that is only measureable with a more fine-grained measure of voicing.

More successful predictors of voicing rates are those related to prosodic prominence. Voicing is less likely in stressed syllables (although this effect is also relatively marginal) and much less likely in post-pausal position. While prevoicing proper *does* (very rarely) occur – unlike in Modern Standard Danish – continuous voicing within a prosodic domain is much more common.

4.2. Geographical variation in stop realization

In this section, we return to the concrete research questions and hypotheses presented in Section 1.3.

The non-parametric component of the statistical model presented in Section 3.1 finds a stable pattern of geographical variability in the duration of aspirated releases in /p t k/. The model finds relatively long aspiration in southern parts of Jutland, relatively short aspiration in northern parts of Jutland, and a seemingly gradual cline in between. This pattern is almost linear, and largely limited to the north–south dimension. This result supports the Aspiration Hypothesis: positive VOT in /p t k/ varies geographically, and it does so in a meaningful way with respect to the variable outcomes of stop gradation. Similarly, the model presented in Section 3.2 finds a stable pattern with higher voicing rates in the northern parts of Jutland, lower voicing rates in the southern parts of Jutland, and a complex gradual non-linear cline in between. This result supports the Voicing Hypothesis. Taken together, the results suggest a laryngeal contrast that is gradually more oriented towards closure voicing in the north and towards aspiration in the south, although the contrast is still first and foremost aspiration-oriented throughout the peninsula.

Traditional dialectologists proposed isoglosses with hard boundaries between areas with different stop gradation patterns, showing highly sonorous outcomes in the northern part of Jutland and increasingly less sonorous outcomes moving further to the south. This reflects the historical development of the unaspirated stops /b d g/ in weak prosodic positions. We assume that this variability reflects differences in how the stops in weak position were phonetically realized prior to stop gradation. This is impossible to test empirically, as there are no recordings that date back sufficiently far, so this study has looked closer at the exact realization of the laryngeal contrast in strong prosodic positions.

We investigated the fine phonetic detail of stop realization in elderly speakers from Jutland in the 1970s whose speech was relatively unaffected by the ongoing standardization. The results show a generally more voicing-oriented laryngeal contrast in areas where stop gradation had highly sonorous outcomes, and a more aspiration-oriented laryngeal contrast in areas where stop gradation had less sonorous outcomes, generally at a level of phonetic granularity beyond what is usually covered by phonological analyses or phonetic transcription. To the north, where stop gradation usually resulted in approximants, voicing rates in /b d g/ were relatively high, and aspiration in /p t k/ was relatively short. Conversely, to the south, where stop gradation usually resulted in voiceless fricatives, voicing rates in /b d g/ were relatively low, and aspiration in /p t k/ was relatively long.

In almost all parts of the Danish-speaking area, stop gradation resulted in an increase in aperture. If voicing is an important cue to e.g. /g/, and aperture increases, it follows that the resulting segment would also be voiced, i.e. [ɣ] or something more open. If voicing is not an important cue to /g/, or voicelessness in /g/ is even enforced with a glottal spreading gesture as in Modern Standard Danish (see Section 1.2.1), it follows that an increase in aperture would also result in a voiceless fricative, i.e. [x]. In more 'sonorous, voicing-prone' areas, it is possible that an intermediate step in a lenition trajectory preceded the state of affairs reported by Bennike and Kristensen (1898–1912), e.g. /g/ > [x] > [ɣ]; in this case, the varieties would differ primarily in how far along the lenition trajectories they are. This is relatively unlikely, and is not necessarily a counterargument to our hypothesis, for these two reasons: 1) Voiceless outcomes of stop gradation have never been attested in Northern Jutland, so the more direct path /g/ > [ɣ] seems more likely; 2) even *if* varieties in the north are simply further along lenition trajectories, the variable realization of the laryngeal contrast is the most likely trigger for why varieties in the north started leniting sooner (or have traveled faster along a lenition trajectory).

In Section 4.1, it was proposed that the influence of non-geographical predictors on aspiration duration likely in large part comes down to aerodynamic by-products of the phonetic context. This cannot be claimed for the geographical variability in aspiration duration, as there are no reasons why areal VOT variability would be a by-product of anything other than different articulatory targets in terms of the timing and magnitude of the glottal spreading gesture responsible for aspiration. The predicted VOT difference (at least between the geographical areas with the highest and lowest fitted values) should be noticeable in itself, but it is also likely that these differences are accompanied by other differences in fine phonetic detail which are not covered here; one such difference that has already been described for Jutland Danish is spectral shape during the release burst (Puggaard-Rode, 2023b).

As with aspiration, the only viable explanation for the areal variability in voicing rates is that speakers have different laryngeal articulatory targets. Unlike in Modern Standard Danish, where voicelessness in /b d g/ is actively enforced with a small glottal spreading gesture (Fischer-Jørgensen and Hirose, 1974; Hutters, 1984; Hutters, 1985), it seems that at least in the northern Jutland varieties, there is no mechanism in place to block voicing. This should significantly increase the rate of intersonorant voicing (see Westbury, 1983). The situation is quite different in post-pausally pre-voiced stops, where the initiation of voicing requires active adjustment (Westbury, 1983; Westbury and Keating, 1986; Solé, 2018). If we imagine a continuous scale rather than a hard boundary between a 'true voice' system and an 'aspiration' system, traditional Jutland Danish varieties essentially occupy continuous points on that scale moving south–north. The geographical patterns of variation are remarkably similar to the dialectal variation in stop gradation outcomes described by traditional dialectologists and summarized in Section 1.2.2.

The only viable reason for the covariable differences in the duration of aspirated releases and voicing rates in Jutland is that speakers have different articulatory targets for the laryngeal contrast in stops, and in all likelihood, these differences are also reflected in other acoustic cues that speakers can attend to. The further covariability with stop gradation outcomes could in theory be conditioned by other factors, such as differences in stress, granular differences in place of articulation, differences in the implementation of final devoicing (which is arguably related to articulatory targets for laryngeal contrasts), or simply random variability. To our knowledge, differences in stress and final devoicing have not been documented in the (extensive) literature on Danish dialects; granular variability in the place of articulation of /t/ specifically have been mentioned *en passant* in some treatments of individual dialects (Nielsen, 1984; Espegaard, 1995), which may well play a part in the more complex outcomes of stop gradation for /d/, but this is likely not possible to test in the available recordings due to sound quality issues; random variability is simply a very unsatisfactory explanation, which should not be resorted to when there are better explanations at hand. The simplest explanation for the three-way covariability is that the phonetic variation observed in this study underpins the phonological variability in stop gradation.

4.3. The situation in Modern Standard Danish

The outline in Section 4.2 leaves an unsolved conundrum: the laryngeal contrast in Modern Standard Danish stops is highly aspiration-oriented, but the outcome of stop gradation is highly sonorous (see Section 1.2.1). This is the opposite pattern of what was described above for the traditional Jutland varieties.

This anomaly can be explained if High Copenhagen Danish – which served as the basis for Modern Standard Danish (Kristiansen, 2003; Pedersen, 2003) – used to have a more voicing-oriented contrast in stops, and that at least the first historical stages of stop gradation preceded the development of a more aspiration-oriented contrast. This would essentially sever any direct synchronic connection between the unaspirated stops [p t k] and semivowels such as [ʊ̯ ɤ̯ ɪ̯], which is intuitively appealing in light of the myriad inconsistencies and irregularities in analyses which assume that they are allophones (see Horslund et al., 2022). In comparison, stop gradation in the Jutland Danish varieties has more of the hallmarks of synchronically active phonological processes. Puggaard-Rode et al. (in press) propose a possible diachronic trajectory of the relevant changes in Modern Standard Danish.

This idea is uncontroversial in the Danish historical linguistics tradition, where earlier stages of Danish are routinely described as having had voiced stops (Brøndum-Nielsen, 1928; Skautrup, 1944; Hansen, 1962; Brink and Lund, 1975). It is, however, controversial within the 'laryngeal realism' approach to phonological laryngeal contrasts, where aspiration in Germanic languages is assumed to date back to the split between Proto-Indo-European and Proto-Germanic (Honeybone, 2002; Iverson and Salmons, 2003a). However, in light of the variability of Jutland Danish varieties, it is not necessarily the case that High Copenhagen Danish used to be a 'true voice' system; rather, if we think of the distinction between prototypically 'aspirating' and prototypically 'true voice' as a continuum rather than as a dichotomy, High Copenhagen Danish may have been somewhat further removed from the 'aspirating' pole than the present day variety. In that sense, High Copenhagen Danish would not be an outlier; closure voicing in /b d g/ to various degrees of consistency has been reported in many Germanic languages, particularly if we look beyond the standard varieties (Flege, 1982; Braun, 1996; Iverson and Salmons, 2003b; Ringen and Suomi, 2012; Ringen and Van Dommelen, 2013; Kirby and Tan, 2023).

4.4. Implications for the linguistic role of fine phonetic detail

This study has uncovered systematic covariation between Danish stop gradation and the phonetic implementation of the laryngeal contrast in stops. The traditional Jutland Danish varieties would all fall under the umbrella of 'aspirating varieties' in a 'true voice' *vs.* 'aspirating' dichotomy, although they vary in how exactly the aspirating contrast is implemented. This phonetic variation is in the fine details of implementation, i.e. the kind that is usually ignored when making phonetic transcriptions or describing the phonological system of a language. Yet, this level of detail arguably affected the historical trajectories of the sounds in a way that has a direct impact on their synchronic phonological organization; for example, it causes /g/ to contextually merge with /j/ in some varieties and not others, and it causes /b/ to merge with /v/ in some dialects and /f/ in other dialects.

The broader theoretical implication of this finding is that higher-order linguistic structure can be impacted down the line by very granular phonetic details. The particular case of Jutland Danish stop gradation shows that granular details in how a laryngeal contrast is implemented can affect the outcome of historical lenition processes. The 'laryngeal realism' approach to laryngeal phonology proposes that the implementation of laryngeal contrast is coded phonologically and impacts the phonological behavior of relevant segments, but this approach generally does not incorporate detail at a sufficiently fine-grained level to capture differences between the Jutlandic varieties covered here. This does not suggest that the 'voicing' *vs.* 'aspiration' distinction is not tremendously useful, but it does suggest that it is sometimes insufficient to capture phonologically relevant detail.

Beyond lenition and beyond laryngeal phonology, the results generally suggest that the details of contrast implementation in consonants can impact the outcome of sound change. Section 1.1 discussed the well-known process of velar palatalization before front vowels; this change, and many others like it, has a 'fine phonetic' aspect to it, but the relevant phonetic detail is (presumably) in the coarticulatory triggering environment, not in the general implementation of velars in these languages. Consider also the development of lexical tone from consonant-intrinsic F_0 (e.g. Ohala, 1973). The relevant phonetic detail in this change is a secondary cue to laryngeal contrasts, but this secondary cue is fairly stable regardless of how the laryngeal contrast is realized (Kingston and Diehl, 1994). A more analogous example could be the suggestion by e.g. Kingston (2005) that the development of lexical tone from a syllable-final glottal stop will differ depending on the exact phonetic implementation of the glottal stop; the phonetic precursors for this hypothesis are well-documented (e.g. Edmondson and Esling, 2006; DiCanio, 2012), but direct evidence of this impacting sound change is scarce.

It is generally difficult to find direct evidence of sound change being impacted by the fine phonetic detail of contrast implementation, since it probably requires evidence of phonetic–phonological covariability in a linguistic area that has developed relatively freely; it is rarely possible to meet these conditions. The data used for this study arguably comes close to meeting these conditions, in spite of other issues, such as the age-biased population, the possibility that other unexplained factors also played a role in shaping the outcome of stop gradation, and (potentially) the lack of experimental control.

4.5. Conclusions and outlook

In this paper, we used the variable outcomes of stop gradation in traditional Jutland Danish as a case study to investigate whether the precise implementation of laryngeal contrasts in obstruents can affect higher-order linguistic structure. We showed that these broadly 'aspirating' varieties display a neat pattern of covariation between the fine phonetic detail of how the unaspirated–aspirated contrast is implemented, and the stop lenition patterns in weak prosodic positions. Using a large legacy corpus, the study uncovered a striking three-way pattern of covariation, such that areas with very sonorous outcomes of stop gradation also had a higher probability of closure voicing in /b d g/ and shorter aspirated releases in /p t k/, and *vice versa*.

Given the extensive standardization that has characterized the Danish dialect landscape since the recordings were made, it is an open question how much of the variability described in this paper is still present, especially since it is not clear to which extent standardization has affected variability in fine phonetic detail. This is a very interesting question, as it may have complicated the relatively straightforward relationship between the strong and weak prosodic positions outlined here. We leave this topic for further research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and code

The recordings used in this study are freely available online from this URL: https://dansklyd.statsbiblioteket.dk/samling/dialektsamlingen/. Other analysis data, fitted model objects, and code, can be accessed from https://doi.org/10.17605/OSF.IO/HYNQX/. A version of this paper with embedded R code demonstrating all analytical steps is available from https://rpuggaardrode.github.io/hisphoncog/.

Acknowledgment

This work has benefitted greatly from helpful comments, suggestions, and discussions at various stages of the process. Thanks to Janet Grijzenhout, Bert Botma, James Kirby, Camilla Søballe Horslund, Henrik Jørgensen, Yonatan Goldshtein, Anna Jespersen, Ander Egurtzegi, Oliver Niebuhr, Cesko Voeten, Martin Krämer, Inger Schoonderbeek Hansen and everyone at the Peter Skautrup Center, audiences at *HISPhonCog* 2023, *FiNo* 2020, *LabPhon* 2020, and *ICLaVE* 2019. Special thanks to the editor Holger Mitterer and anonymous peer reviewers.

References

Abramson, A. S., & Whalen, D. H. (2017). Voice Onset Time (VOT) at 50. Theoretical and practical issues in measuring voicing distinctions. *Journal of Phonetics, 63*, 75–86. https://doi.org/10.1016/j.wocn.2017.05.002.

Arboe Andersen, T. (1981). *Dialektbånd og databehandling. Ord & Sag, 1*, 11–18.

Baayen, R.H., van Rij, J., de Cat, C., Wood, S.N. (2018). Autocorrelated errors in experimental data in the language sciences. Some solutions offered by generalized additive mixed models. In D. Speelman, K. Heylen, D. Geeraerts (Eds.), Mixed-effects regression models in linguistics. Springer. Quantitative Methods in the Humanities and Social Sciences (pp. 49–69). https://doi.org/10.1007/978-3-319-69830-4_4.

Basbøll, H. (2005). The phonology of Danish. *The Phonology of the World's Languages*. Oxford University Press.

Beckman, J. (1997). Positional faithfulness, positional neutralisation and Shona vowel harmony. *Phonology, 14*, 1–46. https://doi.org/10.1017/S0952675797003308.

Beckman, J., Jessen, M., & Ringen, C. (2013). Empirical evidence for laryngeal features. aspirating vs. true voice languages. *Journal of Linguistics, 49*, 259–284. https://doi.org/10.1017/S0022226712000424.

Bennike, V., Kristensen, M. (1898–1912). Kort over de danske folkemål med forklaringer. Gyldendalske Boghandel.

Berry, J., & Moyle, M. (2011). Covariation among vowel height effects on acoustic measures. *Journal of the Acoustical Society of America, 130*, 365–371. https://doi.org/10.1121/1.3651095.

Bijankhan, M., & Nourbakhsh, M. (2009). Voice onset time in Persian initial and intervocalic stop production. *Journal of the International Phonetic Association, 39*, 335–364. https://doi.org/10.1017/S0025100309990168.

Blevins, J. (2004). Evolutionary Phonology. *The emergence of sound patterns*. Cambridge University Press. https://doi.org/10.1017/CBO9780511486357.

Blevins, J., Egurtzegi, A., & Ullrich, J. (2020). Final obstruent voicing in Lakota. *Phonetic evidence and phonological implications. Language, 96*, 294–337. https://doi.org/10.1353/lan.2020.0022.

Blumstein, S. E., Myers, E. B., & Rissman, J. (2005). The perception of voice onset time. An fMRI investigation of phonetic category structure. *Journal of Cognitive Neuroscience, 17*, 1353–1366. https://doi.org/10.1162/0898929054985473.

Boersma, P., Weenink, D. (2021). Praat. Doing phonetics by computer. Version 6.2.04. URL: http://www.fon.hum.uva.nl/praat/.

Braun, A. (1996). Zur regionalen Distribution von VOT im Deutschen. In A. Braun (Ed.), Untersuchungen zu Stimme und Sprache. Franz Steiner. Zeitschrift für Dialektologie und Lingvistik (pp. 19–32).

Brink, L., & Lund, J. (1975). *Dansk rigsmål. Lydudviklingen siden 1840 med særligt henblik på sociolekterne i København*. Gyldendal.

Brink, L., & Lund, J. (2018). Udtale: Yngre nydansk. In E. Hjorth (Ed.), *Dansk sproghistorie 2* (pp. 197–228). Ord for ord for ord: Aarhus Universitetsforlag.

Brotherton, C., Block, A. (2020). Soft d in Danish. Acoustic characteristics and issues in transcription. Proceedings of the Linguistic Society of America 5, 792–797. https://doi.org/10.3765/plsa.v5i1.4739.

Brøndum-Nielsen, J. (1928–1971). Gammeldansk grammatik i sproghistorisk fremstilling. Schultz.

Butcher, A., & Weiher, E. (1976). An electropalatographic investigation of coarticulation in VCV sequences. *Journal of Phonetics, 4*, 59–74. https://doi.org/10.1016/S0095-4470(19)31222-7.

Carignan, C., Hoole, P., Kunay, E., Pouplier, M., Joseph, A., Voit, D., Frahm, J., & Harrington, J. (2020). Analyzing speech in both time and space. generalized additive mixed models can uncover systematic patterns of variation in vocal tract shape in real-time MRI. Laboratory. *Phonology, 11*. https://doi.org/10.5334/labphon.214.

Carlson, R., Hawkins, S. (2007). When is fine phonetic detail a detail? In J. Trouvain, W. J. Barry (Eds.), Proceedings of the 16th International Congress of Phonetic Sciences. Saarland University (pp. 211–214).

Chambers, J., & Trudgill, P. (1998). *Dialectology. Cambridge Textbooks in Linguistics* (2 ed.,). Cambridge University Press. https://doi.org/10.1017/CBO9780511805103.

Chen, Y. (2011). How does phonology guide phonetics in segment-f0 interaction? *Journal of Phonetics, 39*, 612–625. https://doi.org/10.1016/j.wocn.2011.04.001.

Cho, T., & Keating, P. A. (2001). Articulatory and acoustic studies on domain-initial strengthening in Korean. *Journal of Phonetics, 29*, 155–190. https://doi.org/10.1006/jpho.2001.0131.

Cho, T., & Keating, P. A. (2009). Effects of initial position versus prominence in English. *Journal of Phonetics, 37*, 466–485. https://doi.org/10.1016/j.wocn.2009.08.001.

Cho, T., & Ladefoged, P. (1999). Variation and universals in VOT. Evidence from 18 languages. *Journal of Phonetics, 27*, 207–229. https://doi.org/10.1006/jpho.1999.0094.

Cho, T., & McQueen, J. M. (2005). Prosodic influences on consonant production in Dutch. Effects of prosodic boundaries, phrasal accent and lexical stress. *Journal of Phonetics, 33*, 121–157. https://doi.org/10.1016/j.wocn.2005.01.001.

Chodroff, E., Golden, A., & Wilson, C. (2019). Covariation of stop voice onset time across languages. Evidence for a universal constraint on phonetic realization. *Journal of the Acoustical Society of America, 145*, 106–115. https://doi.org/10.1121/1.5088035.

Chodroff, E., & Wilson, C. (2017). Structure in talker-specific phonetic realization. Covariation of stop consonant VOT in American English. *Journal of Phonetics, 61*, 30–47. https://doi.org/10.1016/j.wocn.2017.01.001.

Davidson, L. (2016). Variability in the implementation of voicing in American English obstruents. *Journal of Phonetics, 54*, 35–50. https://doi.org/10.1016/j.wocn.2015.09.003.

DiCanio, C. T. (2012). Coarticulation between tone and glottal consonants in Itunyoso Trique. *Journal of Phonetics, 40*, 162–176. https://doi.org/10.1016/j.wocn.2011.10.006.

Edmondson, J. A., & Esling, J. H. (2006). The valves of the throat and their functioning in tone, vocal register and stress. *Laryngoscopic case studies. Phonology, 23*, 157–191. https://doi.org/10.1017/S095267570600087X.

Ejstrup, M., Hansen, G. F. (2003.) Danish vowels in spontaneous speech in three modern regional variants. In M.J. Solé, D. Recasens, J. Romero (Eds.), Proceedings of the 15th International Congress of Phonetic Sciences. Universitat Autonoma De Barcelona, pp. 2119–2122.

Elliott, L. L. (1986). Discrimination and response bias for CV syllables differing in voice onset time among children and adults. *Journal of the Acoustical Society of America, 80*, 1250–1255. https://doi.org/10.1121/1.393819.

Elliott, L. L., Busse, L. A., Partridge, R., Rupert, J., & DeGraaff, R. (1986). Adult and child discrimination of CV syllables differing in voicing onset time. *Child Development, 57*, 628–635. https://doi.org/10.2307/1130341.

Espegaard, A. (1995). Nogle nordjyske mål. Forlaget Vendsyssel.

Esposito, A. (2002). On vowel height and consonantal voicing effects. *Data from Italian. Phonetica, 59*, 197–231. https://doi.org/10.1159/000068347.

Ewen, C. J., & van der Hulst, H. (2001). The phonological structure of words. *An introduction. Cambridge Textbooks in Linguistics*. Cambridge University Press. https://doi.org/10.1017/CBO9780511612787.

Fischer-Jørgensen, E. (1954). Acoustic analysis of stop consonants. *Le Maître Phonetique, 32*, 42–59. Stable:44705403.

Fischer-Jørgensen, E. (1972a.) ptk et bdg français en position intervocalique accentuée. In A. Valdman (Ed.), Papers in linguistics and phonetics to the memory of Pierre Delattre. Mouton. number 54 in Janua Linguarum, (pp. 143–200). https://doi.org/10.1515/9783110803877-014.

Fischer-Jørgensen, E. (1972b). Tape cutting experiments with Danish stop consonants in initial position. *Annual Report of the Institute of Phonetics, University of Copenhagen, 6*, 104–168. https://doi.org/10.7146/aripuc.v6i.130910.

Fischer-Jørgensen, E. (1980). Temporal relations in Danish tautosyllabic CV sequences with stop consonants. *Annual Report of the Institute of Phonetics, University of Copenhagen, 14*, 207–261. https://doi.org/10.7146/aripuc.v14i.131741.

Fischer-Jørgensen, E., & Hirose, H. (1974). A preliminary electromyographic study of labial and laryngeal muscles in Danish stop consonant production. *Status Report on Speech Research, 39*(40), 231–253.

Fitch, W. T., & Giedd, J. (1999). Morphology and development of the human vocal tract. A study using magnetic resonance imaging. *Journal of the Acoustical Society of America, 106*, 1511–1522. https://doi.org/10.1121/1.427148.

Flege, J. E. (1982). Laryngeal timing and phonation onset in utterance-initial English stops. *Journal of Phonetics, 10*, 177–192. https://doi.org/10.1016/S0095-4470(19)30956-8.

Foulkes, P., & Docherty, G. (2006). The social life of phonetics and phonology. *Journal of Phonetics, 34*, 409–438. https://doi.org/10.1016/j.wocn.2005.08.002.

Francis, A. L., Ciocca, V., & Yu, J. M. C. (2003). Accuracy and variability of acoustic measures of voicing onset. *Journal of the Acoustical Society of America, 113*, 1025–1032. https://doi.org/10.1121/1.1536169.

Gamkrelidze, T. V. (1975). On the correlation of stops and fricatives in a phonological system. *Lingua, 35*, 231–261. https://doi.org/10.1016/0024-3841(75)90060-1.

Gay, T. (1977). Articulatory movements in VCV sequences. *Journal of the Acoustical Society of America, 62*, 183–193. https://doi.org/10.1121/1.381480.

Goldshtein, Y., & Ahlgren, L. M. (2021). Ideologies of language and place. Conflicting expectations to dialectal speech between informants and dialectologists. *Journal of Postcolonial Linguistics, 5*, 178–203.

Goldshtein, Y., & Puggaard, R. (2019). Overblik over danske dialektoptagelser. *Ord & Sag, 39*, 18–28.

Grijzenhout, J. (1995). *Irish consonant mutation and phonological theory*. Utrecht University. OTS Dissertation Series.

Gráczi, T. E., Kohári, A. (2014). Multiple bursts in Hungarian voiceless plosives and VOT measurements. In S. Fuchs, M. Grice, A. Hermes, L. Lancia, D. Mücke (Eds.), Proceedings of the 10th International Seminar on Speech Production. University of Cologne, (pp. 158–161).

Grønnum, N. (1995). Danish vowels. *Surface contrast versus underlying form. Phonetica, 52*, 215–220. https://doi.org/10.1159/000262173.

Grønnum, N. (1998). Illustrations of the IPA. Danish. *Journal of the International Phonetic Association, 28*, 99–105. https://doi.org/10.1017/S0025100300006290.

Grønnum, N. (2005). *Fonetik og fonologi. Almen og dansk* (3 ed.,). Akademisk Forlag.

Guion, S. G. (1998). The role of perception in sound change of velar palatalization. *Phonetica, 55*, 18–52. https://doi.org/10.1159/000028423.

Gósy, M. (2001). The VOT of the Hungarian voiceless plosives in words and in spontaneous speech. *International Journal of Speech Technology, 4*, 75–85. https://doi.org/10.1023/A:1009608900453.

Hall, K. C., Hume, E., Jaeger, T. F., & Wedel, A. B. (2018). The role of predictability in shaping phonological patterns. *Linguistics Vanguard, 4*. https://doi.org/10.1515/lingvan-2017-0027.

Hall, T. A. (1997). The phonology of coronals. In *Number 149 in Current Issues in Linguistic Theory*. https://doi.org/10.1075/cilt.149.

Halle, M., & Stevens, K. N. (1971). A note on laryngeal features. *Quarterly Progress Report, Research Laboratory of Electronics, Massachusetts Institute of Technology, 101*, 198–213. https://doi.org/10.1515/9783110871258.45.

Hansen, A. (1962–1971). Den lydlige udvikling i dansk. G.E.C. Gad.

Hardcastle, W. J. (1973). Some observations on the tense–lax distinction in initial stops in Korean. *Journal of Phonetics, 1*, 263–272. https://doi.org/10.1016/S0095-4470(19)31390-7.

Harrington, J., Palethorpe, S., & Watson, C. I. (2000). Monophthongal vowel changes in Received Pronunciation. An acoustic analysis of the Queen's Christmas broadcasts. *Journal of the International Phonetic Association, 30*, 63–78. https://doi.org/10.1017/S0025100300006666.

Hawkins, S. (2003). Roles and representations of systematic fine phonetic detail in speech understanding. *Journal of Phonetics, 31*, 373–405. https://doi.org/10.1016/j.wocn.2003.09.006.

Hawkins, S. (2010). Phonetic variation as communicative system. Perception of the particular and the abstract. In C. Fougeron, B. Kühnert, M. D'Imperio, N. Vallée (Eds.), Laboratory Phonology 10. De Gruyter Mouton. number 4–4 in Phonology and Phonetics (pp. 479–510). https://doi.org/10.1515/9783110224917.

Heger, S. (1975). Danish r and adjacent short stressed vowels. *Annual Report of the Institute of Phonetics, University of Copenhagen, 9*, 137–169. https://doi.org/10.7146/aripuc.v9i.130973.

Higgins, M. B., Netsell, R., & Schulte, L. (1998). Vowel-related differences in laryngeal articulatory and phonatory function. *Journal of Speech, Language, and Hearing Research, 41*, 712–724. https://doi.org/10.1044/jslhr.4104.712.

Hirose, H., & Gay, T. (1972). The activity of the intrinsic laryngeal muscles in voicing control. *Phonetica, 25*, 140–164. https://doi.org/10.1159/000259378.

Hjelmslev, L. (1943). *Omkring sprogteoriens grundlæggelse*. Munksgaard.

Holmen, A. (2024). Danish language legislation and de facto language policies. *Current Issues in Language Planning*. https://doi.org/10.1080/14664208.2024.2326335.

Honeybone, P. (2002). *Germanic obstruent lenition. some mutual implications of theoretical and historical phonology*. University of Newcastle upon Tyne. PhD dissertation.

Honeybone, P. (2005). Diachronic evidence in segmental phonology. The case of obstruent laryngeal specifications. In M. van Oostendorp, J. van de Weijer (Eds.), The internal organization of phonological segments. Mouton de Gruyter. number 77 in Studies in Generative Grammar (pp. 318–351). https://doi.org/10.1515/9783110890402.317.

Honeybone, P. (2008). Lenition, weakening and consonantal strength. Tracing concepts through the history of phonology. In J. Brandão de Carvalho, T. Scheer, P. Ségéral (Eds.), Lenition and fortition. Mouton de Gruyter. number 99 in Studies in Generative Grammar (pp. 9–92). https://doi.org/10.1515/9783110211443.1.9.

Horslund, C. S., Puggaard-Rode, R., & Jørgensen, H. (2022). A phonetically-based phoneme analysis of the Danish consonant system. *Acta Linguistica Hafniensia, 54*, 73–105. https://doi.org/10.1080/03740463.2021.2022866.

Hovdhaugen, E., Karlsson, F., Henriksen, C., & Sigurd, B. (2000). *The history of linguistics in the Nordic countries*. Societas Scientarum Fennica.

Hutters, B. (1984). Vocal fold adjustments in Danish voiceless obstruent production. *Annual Report of the Institute of Phonetics, University of Copenhagen, 18*, 293–385. https://doi.org/10.7146/aripuc.v18i.

Hutters, B. (1985). Vocal fold adjustments in aspirated and unaspirated stops in Danish. *Phonetica, 42*, 1–24. https://doi.org/10.1159/000261734.

Iverson, G. K., & Salmons, J. C. (1995). Aspiration and laryngeal representation in Germanic. *Phonology, 12*, 369–396. https://doi.org/10.1017/S0952675700002566.

Iverson, G. K., & Salmons, J. C. (2003a). Laryngeal enhancement in early Germanic. *Phonology, 20*, 43–74. https://doi.org/10.1017/S0952675703004469.

Iverson, G. K., & Salmons, J. C. (2003b). Legacy specification in the laryngeal phonology of Dutch. *Journal of Germanic Linguistics, 15*, 1–26. https://doi.org/10.1017/S1470542703000242.

Jespersen, O. (1890). Danias lydskrift. *Dania. Tidsskrift for Folkemål og Folkeminder, 1*, 33–80.

Juul, H., Pharao, N., & Thøgersen, J. (2016). *Moderne danske vokaler. Danske Talesprog, 16*, 35–72.

Jørgensen, H. (2021). Konsekvens i renæssancens retskrivning? In J. Bjerring-Hansen, S.S. Boeck, E.S. Jensen (Eds.), Nogle betænkninger om dansk sprog og litteratur. Festskrift til Marita Akhøj Nielsen. University Press of Southern Denmark. Universitets-jubilæets danske samfund (pp. 273–294).

Kang, Y., & Han, S. (2013). Tonogenesis in early Contemporary Seoul Korean. A longitudinal case study. *Lingua, 134*, 62–74. https://doi.org/10.1016/j.lingua.2013.06.002.

Keating, P. A. (1984). Physiological effects on stop consonant voicing. *UCLA Working Papers in Phonetics, 59*, 18–28.

Kelly, J., & Local, J. (1989). *Doing phonology. Observing, recording, interpreting*. Manchester University Press.

Kingston, J. (2005). The phonetics of Athabaskan tonogenesis. In S. Hargus, K. Rice (Eds.), Athabaskan prosody. John Benjamins. volume 269 of Current Issues in Linguistic Theory (pp. 137–184). https://doi.org/10.1075/cilt.269.09kin.

Kingston, J., & Diehl, R. L. (1994). Phonetic knowledge. *Language, 70*, 419–454. https://doi.org/10.1353/lan.1994.0023.

Kirby, J. P., Kleber, F., Siddins, J., & Harrington, J. (2020). Effects of prosodic prominence on obstruent-intrinsic f0 and VOT in German. *Proceedings of Speech Prosody, 10*, 210–214. https://doi.org/10.21437/SpeechProsody.2020-43.

Kirby, J. P., Tan, M. (2023). Analyzing variability in closure voicing and co-intrinsic f0 in Central Standard Swedish. In R. Skarnitzl, J. Volín (Eds.), Proceedings of the 20th International Congress of Phonetic Sciences. Guarant (pp. 2244–2248).

Klatt, D. H. (1975). Voice onset time, frication, and aspiration in word-initial consonant clusters. *Journal of Speech and Hearing Research, 18*, 686–706. https://doi.org/10.1044/jshr.1804.686.

Koshy, A., & Tavakoli, S. (2022). Exploring British accents. Modelling the trap–bath split with functional data analysis. *Journal of the Royal Statistical Society C, 71*, 773–805. https://doi.org/10.1111/rssc.12555.

Kristiansen, T. (1990). Udtalenormering i skolen. Skitse af en ideologisk bastion. Gyldendal.

Kristiansen, T. (2003). Danish. In A. Deumart, W. Vandenbussche (Eds.), Germanic standardizations. Past to present. John Benjamins. number 18 in Impact. Studies in Language and Society (pp. 69–91). https://doi.org/10.1075/impact.18.04kri.

Labov, W. (1994). Principles of linguistic change. *Internal factors. Number 20 in Language in Society* (Volume 1). Blackwell.

Ladd, D. R. (2011). Phonetics in phonology. In J. Goldsmith, J. Riggle, A.C. Yu, (Eds.), The handbook of phonological theory. 2 ed. Wiley-Blackwell. Blackwell Handbooks in Linguistics (pp. 348–373). https://doi.org/10.1002/9781444343069.ch11.

Lahti, L., Huovari, J., Kainu, M., & Biecek, P. (2017). Retrieval and analysis of Eurostat open data with the eurostat package. *The R Journal, 9*, 385–392. https://doi.org/10.32614/RJ-2017-019.

Larson, G. W., Hayslip, B., & Thomas, K. W. (1992). Changes in voice onset time in young and older men. *Educational Gerontology, 18*, 285–297. https://doi.org/10.1080/0360127920180310.

Lass, R. (1984). *Phonology. An introduction to basic concepts. Cambridge Textbooks in Linguistics*. Cambridge University Press.

Lavoie, L. (2001). Consonantal strength. Phonological patterns and phonetic manifestations. In *Outstanding Dissertations in Linguistics*. https://doi.org/10.4324/9780203826423.

Lindblom, B. (1990). Explaining phonetic variation. A sketch of the H&H theory. In W.J. Hardcastle, A. Marchal (Eds.), Speech production and speech modelling. Kluwer. number 55 in Nato Science Series D, (pp. 403–439). https://doi.org/10.1007/978-94-009-2037-8_16.

Lisker, L., & Abramson, A. S. (1964). A cross-language study of voicing in initial stops. *Acoustical measurements. Word, 20*, 384–422. https://doi.org/10.1080/00437956.1964.11659830.

Lisker, L., & Abramson, A. S. (1967). Some effects of context on voice onset time in English stops. *Language and Speech, 10*, 10–28. https://doi.org/10.1177/002383096701000101.

Lombardi, L. (1999). Positional faithfulness and voicing assimilation in Optimality Theory. *Natural Language and Linguistic Theory, 17*, 267–302. https://doi.org/10.1023/A:1006182130229.

Löfqvist, A., & Gracco, V. L. (1999). Interarticulator programming in VCV sequences. Lip and tongue movements. *Journal of the Acoustical Society of America, 105*, 1864–1876. https://doi.org/10.1121/1.426723.

Löfqvist, A., & Gracco, V. L. (2002). Control of oral closure in lingual stop consonant production. *Journal of the Acoustical Society of America, 111*, 2811–2827. https://doi.org/10.1121/1.1473636.

Maegaard, M., Monka, M. (2019). Patterns of dialect use. language standardization at different rates. In: M. Maegaard, M. Monka, K.K. Mortensen, A.C. Stæhr (Eds.), Standardization as sociolinguistic change. A transversal study of three traditional dialect areas. Routledge. Routledge Studies in Language Change (pp. 27–46). https://doi.org/10.4324/9780429467486-2.

Magnuson, J. S., Dixon, J. A., Tanenhaus, M. K., & Aslin, R. N. (2007). The dynamics of lexical competition during spoken word recognition. *Cognitive Science, 31*, 133–156. https://doi.org/10.1080/03640210709336987.

Marra, G., & Wood, S. N. (2012). Coverage properties of confidence intervals for generalized additive model components. *Scandinavian Journal of Statistics, 39*, 53–74. https://doi.org/10.1111/j.1467-9469.2011.00760.x.

Mortensen, J., Tøndering, J. (2013). The effect of vowel height on voice onset time in stop consonants in CV sequences in spontaneous Danish. In Proceedings of Fonetik 2013. The XXVIth Annual Phonetics Meeting. Linköping University (pp. 49–52).

Nance, C., & Kirkham, S. (2020). The acoustics of three-way lateral and nasal palatalisation contrasts in Scottish Gaelic. *Journal of the Acoustical Society of America, 147*, 2858–2872. https://doi.org/10.1121/10.0000998.

Nguyen, N., Wauquier, S., Tuller, B. (2009). The dynamical approach to speech perception. From fine phonetic detail to abstract phonological categories. In F. Pellegrino, E. Marsico, I. Chitoran, C. Coupé (Eds.), Approaches to phonological complexity. Mouton de Gruyter. number 16 in Phonology and Phonetics (pp. 191–218). https://doi.org/10.1515/9783110223958.191.
Nielsen, B. J. (1984). Bidrag til vendelbomålets fonologi. Del I: Dialekten i Tornby. Akademisk Forlag.
Ohala, J. J. (1973). The physiology of tone. In L.M. Hyman (Ed.), Consonant types and tone. University of Southern California. number 1 in Southern California Occasional Papers in Linguistics (pp. 1–14).
Ohala, J. J. (1983). The origin of sound patterns in vocal tract constraints. In P. F. MacNeilage (Ed.), *The production of speech* (pp. 189–216). Springer. https://doi.org/10.1007/978-1-4613-8202-7_9.
Ohala, J. J. (1992). What's cognitive, what's not, in sound change. In G. Kellerman, M.D. Morrissey (Eds.), Diachrony within synchrony. Language history and cognition. Peter Lang. number 14 in Duisburg Papers on Research in Language and Culture (pp. 309–355).
Ohala, J. J., & Riordan, C. J. (1979). Passive vocal tract enlargement during voiced stops. In J. J. Wolf & D. H. Klatt (Eds.), *Speech communication papers presented at the 97th Meeting of the Acoustical Society of America* (pp. 89–92). Massachusetts Institute of Technology.
Ouni, S. (2014). Tongue control and its implication in pronunciation training. *Computer Assisted Language Learning, 27*, 439–453. https://doi.org/10.1080/09588221.2012.761637.
Parveen, S., & Goberman, A. M. (2012). Presence of stop bursts and multiple bursts in younger and older adults. *Asia Pacific Journal of Speech, Language and Hearing, 15*, 265–275. https://doi.org/10.1179/136132812804731811.
Pebesma, E. (2018). Simple features for R. Standardized support for spatial vector data. *The R Journal, 10*, 439–446. https://doi.org/10.32614/RJ-2018-009.
Pedersen, I. L. (2003). Traditional dialects of Danish and the de-dialectalization 1900–2000. *International Journal of the Sociology of Language, 159*, 9–28. https://doi.org/10.1515/ijsl.2003.012.
Pedersen, K. M. (1983). Om transskription af båndoptagelser og anvendelse af teksterne til leksikografiske og syntaktiske undersøgelser. *Et EDB-projekt. Folkmålsstudier, 28*, 131–138.
Pierrehumbert, J. B. (2001). Exemplar dynamics. word frequency, lenition and contrast. In: J.L. Bybee, P.J. Hopper (Eds.), Frequency and the emergence of linguistic structure. John Benjamins. number 45 in Typological Studies in Language (pp. 137–157). https://doi.org/10.1075/tsl.45.08pie.
Puggaard, R. (2021). Modeling regional variation in voice onset time of Jutlandic varieties of Danish. In H. Van de Velde, N.H. Hilton, R. Knooihuizen (Eds.), Language variation. European perspectives VIII. John Benjamins. number 25 in Studies in Language Variation, pp. 79–110. https://doi.org/10.1075/silv.25.04pug.
Puggaard-Rode, R. (2022). Analyzing time-varying spectral characteristics of speech with function-on-scalar regression. *Journal of Phonetics, 95*. https://doi.org/10.1016/j.wocn.2022.101191.
Puggaard-Rode, R., 2023a. Stop! Hey, what's that sound? The representation and realization of Danish stops. Number 631 in LOT Dissertation Series, Netherlands Graduate School of Linguistics. https://doi.org/10.48273/LOT0631.
Puggaard-Rode, R., 2023b. The/t/ release in Jutland Danish. Decomposing the spectrum with functional PCA, in: Skarnitzl, R., Volín, J. (Eds.), Proceedings of the 20th International Congress of Phonetic Sciences. Guarant, pp. 3262–3266.
Puggaard-Rode, R., 2024. praatpicture. A library for making flexible Praat Picture-style figures in R, in: Fougeron, C., Perrier, P. (Eds.), Proceedings of the 13th International Seminar on Speech Production. International Speech Communication Association, pp. 131–134. https://doi.org/10.21437/issp.2024-34.
Puggaard-Rode, R., Burroni, F., 2024. Articulation of the Danish soft d. A pilot study using electromagnetic articulography. (Paper presented at Fonologi i Norden 9, Stockholm University).
Puggaard-Rode, R., Horslund, C. S., & Jørgensen, H. (2022). The rarity of intervocalic voicing of stops in Danish spontaneous speech. *Laboratory Phonology, 13*. https://doi.org/10.16995/labphon.6449.
Puggaard-Rode, R., Jørgensen, H., Horslund, C. S. (in press). A diachronic account of Present Day Standard Danish stop gradation. Phonological reorganization through prosodically conditioned chain shifts and mergers. (Paper accepted for publication in Diachronica).
R Core Team (2022). R. A language and environment for statistical computing. Version 4.2.2. URL: https://www.R-project.org/.
Ringen, C. O., & Suomi, K. (2012). The voicing contrast in Fenno-Swedish stops. *Journal of Phonetics, 40*, 419–429. https://doi.org/10.1016/j.wocn.2012.02.010.
Ringen, C. O., & Van Dommelen, W. A. (2013). Quantity and laryngeal contrasts in Norwegian. *Journal of Phonetics, 41*, 479–490. https://doi.org/10.1016/j.wocn.2013.09.001.
Rischel, J. (1970). Consonant gradation. a problem in Danish phonology and morphology. In H. Benediktsson (Ed.), The Nordic languages and modern linguistics. Vísindafélag Íslendinga (pp. 460–480).
Rosner, B. S. (1984). Perception of voice-onset-time continua. A signal detection analysis. *Journal of the Acoustical Society of America, 75*, 1231–1242. https://doi.org/10.1121/1.390775.
Sankoff, G., & Blondeau, H. (2007). Language change across the lifespan./r/ in Montreal French. *Language, 83*, 560–588. https://doi.org/10.1353/lan.2007.0106.
Schachtenhaufen, R. (2023). *Ny dansk fonetik* (2 ed.,). Modersmål-Selskabet.
Schad, D. J., Vasishth, S., Hohenstein, S., & Kliegl, R. (2020). How to capitalize on a priori contexts in linear (mixed) models. a tutorial. *Journal of Memory and Language, 110*. https://doi.org/10.1016/j.jml.2019.104038.
Shih, C., Möbius, B., Narasimhan, B. (1999). Contextual effects on consonant voicing profiles. A cross-linguistic study. In J.J. Ohala, Y. Hasegawa, M. Ohala, D. Granville, A.C. Bailey (Eds.), Proceedings of the 14th International Congress of Phonetic Sciences (pp. 989–992).
Simonet, M., Casillas, J. V., & Díaz, Y. (2014). The effects of stress/accent on VOT depend on language (English, Spanish), consonant (/d/,/t/) and linguistic experience (monolinguals, bilinguals). *Proceedings of Speech Prosody, 7*, 202–206. https://doi.org/10.21437/SpeechProsody.2014-28.
Skautrup, P. (1944–1970). Det danske sprogs historie. Gyldendal.
Skautrup, P., Rasmussen, O., Sørensen, V., Arboe, T., Hansen, I. S., Grøftehauge, N., Svendsen, M. M. M., Bøegh, K. F. (1970). Jysk ordbog.
Smith, B. L., Wasowicz, J., & Preston, J. (1987). Temporal characteristics of the speech of normal elderly adults. *Journal of Speech, Language, and Hearing Research, 30*, 522–529. https://doi.org/10.1044/jshr.3004.522.
Soli, S. D. (1983). The role of spectral cues in discrimination of voice onset time differences. *Journal of the Acoustical Society of America, 73*, 2150–2165. https://doi.org/10.1121/1.389539.
Solé, M. J. (2018). Articulatory adjustments in initial voiced stops in Spanish, French and English. *Journal of Phonetics, 66*, 217–241. https://doi.org/10.1016/j.wocn.2017.10.002.
Sonderegger, M. (2023). *Regression modeling for linguistic data*. MIT Press.
Sonderegger, M., Stuart-Smith, J., Knowles, T., Macdonald, R., & Rathcke, T. (2020). Structured heterogeneity in Scottish stops over the twentieth century. *Language, 96*, 94–125. https://doi.org/10.1353/lan.2020.0003.
Swartz, B. L. (1992). Gender difference in voice onset time. *Perceptual and Motor Skills, 75*, 983–992. https://doi.org/10.2466/pms.1992.75.3.983.
Talkin, D. (2015). REAPER. Robust Epoch and Pitch EstimatoR. URL: https://github.com/google/REAPER.
Tanner, J., Sonderegger, M., & Stuart-Smith, J. (2020). Structured speaker variability in Japanese stops. Relationships within versus across cues to stop voicing. *Journal of the Acoustical Society of America, 148*, 793–804. https://doi.org/10.1121/10.0001734.
Tavakoli, S., Pigoli, D., Aston, J. A. D., & Coleman, J. S. (2019). A spatial modeling approach for linguistic object data. Analyzing dialect sound variations across Great Britain. *Journal of the American Statistical Association, 114*, 1081–1096. https://doi.org/10.1080/01621459.2019.1607357.
Torre, P., & Barlow, J. A. (2009). Age-related changes in acoustic characteristics of adult speech. *Journal of Communication Disorders, 42*, 324–333. https://doi.org/10.1016/j.jcomdis.2009.03.001.
Wedel, A. B. (2006). Exemplar models, evolution and language change. *The Linguistic Review, 23*, 247–274. https://doi.org/10.1515/TLR.2006.010.
Wedel, A. B., Ussishkin, A., & King, A. (2019). Crosslinguistic evidence for a strong statistical universal. Phonological neutralization targets word-ends over beginnings. *Language, 95*, 428–446. https://doi.org/10.1353/lan.2019.0082.
Westbury, J. R. (1983). Enlargement of the supraglottal cavity and its relation to stop consonant voicing. *Journal of the Acoustical Society of America, 73*, 1322–1336. https://doi.org/10.1121/1.389236.
Westbury, J. R., & Keating, P. A. (1986). On the naturalness of stop consonant voicing. *Journal of Linguistics, 22*, 145–166. https://doi.org/10.1017/S0022226700010598.
Whiteside, S. P., & Irving, C. J. (1998). Speakers' sex differences in voice onset time. a study of isolated word production. *Perceptual and Motor Skills, 86*, 615–654. https://doi.org/10.2466/pms.1998.86.2.651.
Wickham, H. (2016). ggplot2. Elegant Graphics for Data Analysis. Use R, Springer. https://doi.org/10.1007/978-0-387-98141-3.
Wieling, M. (2018). Analyzing dynamic phonetic data using generalized additive mixed modeling. A tutorial focusing on articulatory differences between L1 and L2 speakers of English. *Journal of Phonetics, 70*, 86–116. https://doi.org/10.1016/j.wocn.2018.03.002.
Wieling, M., Montemagni, S., Nerbonne, J., & Baayen, R. H. (2014). Lexical differences between Tuscan dialects and Standard Italian. Accounting for geographic and sociodemographic variation using generalized additive mixed modeling. *Language, 90*, 669–692. https://doi.org/10.1353/lan.2014.0064.
Wieling, M., Nerbonne, J., & Baayen, R. H. (2011). Quantitative social dialectology. Explaining linguistic variation geographically and socially. *Plos One, 6*. https://doi.org/10.1371/journal.pone.0023613.
Wieling, M., Tomaschek, F., Arnold, D., Tiede, M., Bröker, F., Thiele, S., Wood, S. N., & Baayen, R. H. (2016). Investigating dialectal differences using articulography. *Journal of Phonetics, 59*, 122–143. https://doi.org/10.1016/j.wocn.2016.09.004.
Wood, S. N. (2003). Thin plate regression splines. *Journal of the Royal Statistical Society B, 65*, 95–114. https://doi.org/10.1111/1467-9868.00374.
Wood, S. N. (2013). On p-values for smooth components of an extended generalized additive model. *Biometrika, 100*, 221–228. https://doi.org/10.1093/biomet/ass048.
Wood, S. N. (2017). Generalized additive models. In *An introduction with R. Texts in Statistical Science*. https://doi.org/10.1201/9781315370279.
Wood, S. N. (2022). `mgcv`. Mixed GAM computation vehicle with automatic smoothness estimation. version 1.8-41. URL: https://CRAN.R-project.org/package=mgcv.
Wood, S. N., Li, Z., Shaddick, G., & Augustin, N. H. (2017). Generalized additive models for gigadata. Modeling the U.K. Black Smoke network daily data. *Journal of the American Statistical Association, 112*, 1199–1210. https://doi.org/10.1080/01621459.2016.1195744.