Variation in fine phonetic detail can modulate the outcome of sound change

The case of stop gradation and laryngeal contrast implementation in Jutland Danish

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This paper demonstrates 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 varies 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 voice onset time 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 & 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 neat 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, Jessen & Ringen 2013; Kirby & Tan 2023), 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 & 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. Evidence for this is found in the variable outcomes of Danish stop gradation, and 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 & Lund 1975; Brink & 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' [ɤ] in Modern Standard Danish (Brotherton & 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 & 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 current strong allophones were historically found in all syllabic 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 2023a); 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 vari-

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[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 & Block 2020). Research by Juul, Pharao & Thøgersen (2016) suggests that the [ɤ] notation captures the acoustics of the the 'soft d' well, but ongoing articulatory research suggests that it may not capture the articulation well (Puggaard-Rode & Burroni 2024); in the absence of a better solution, [ɤ] is used in this paper to highlight that the sound is a semivowel.

eties 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, Figure 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; 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 & Monka 2019). For this reason, this study relies on a legacy corpus of sociolinguistic interviews with speakers of traditional dialects (Arboe Andersen 1981; Goldshtein & 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.

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 positive voice onset time (VOT) in /p t k/ (see also Puggaard 2021), and the second concerns the relative 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, Nerbonne & Baayen 2011; Wieling et al. 2014; Wood 2017).

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 north where stop gradation had a highly sonorous outcome, the probability of closure voicing in /b d g/ is also higher, and VOT 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 VOT 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

Figure 1: Map showing the location of Jutland in Denmark (in yellow) and showing the location of some landmarks mentioned throughout the paper.

Modern Standard Danish, and show how these patterns have been said to vary in the Danish dialecto-logical 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 & Hawkins 2007; Hawkins 2010). Fine phonetic detail communicates a range of social information (e.g. Foulkes & Docherty 2006), and is used in the organization of spoken interaction (e.g. Kelly & Local 1989), and much of what is labelled fine phonetic detail is clearly audible and used in speech perception (e.g. Hawkins 2003; Nguyen, Wauquier & Tuller 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 hyperartic-ulated 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 phono-logical rules strongly tend to target the ends of lexical domains (Wedel, Ussishkin & King 2019), and conversely that onset consonants tend to be stronger and onset inventories larger than their coda coun-terparts (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 & 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 phonetic implementation may be expected to affect lenition processes. For example, inter-sonorant 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, Jessen & Ringen 2013; Puggaard-Rode, Horslund & Jørgensen 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 & 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 onsets before a neutral vowel and 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 1944–1970). 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 (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 and the two main approaches to their phonological analysis. 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, Horslund & Jørgensen 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 1972a). /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 & Hirose 1974; Hutters 1984; 1985; Puggaard-Rode, Horslund & Jørgensen 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.

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

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).

Evidence in favor of the traditional analysis comes from alternations such as those in (2).

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

The examples in (2) require a bit of unpacking. In (2a) and (2c), the alternation is the result of the verbalizing suffix [-ˈeːˀɐ], which causes stress shift and resyllabification, causing the weak codas in the roots to appear as strong onsets. The alternation in (2b) is the result of an exception to the description of stop gradation laid out above: strong allophones are usually selected in codas if they appear in consonant clusters before [t], although this depends on the morphological provenance of the [t]. We also see here and in (2d) that stop gradation feeds an obligatory process of schwa assimilation, which often causes

semivowels to surface as syllabic (e.g. Brink & Lund 1975; Basbøll 2005; Schachtenhaufen 2012); the infinitive mood in verbs is marked with an affix which is usually considered to be /-ə/ underlyingly but which never surfaces as [ə] outside of hyperdistinct speech. Instead, it causes adjacent sonorants to syllabify, as in [ˈkʰøːʊ̯] and [ˈpæːɪ̯] from [ʊ̯ ɪ̯] respectively in (2b) and (2d), or creates vowel copies of long vowels in the preceding syllable, as in [ˈkʰøːøp] in (2b), or simply deletes if none of those circumstances apply. Finally, (2d) reflects a morphophonological process of vowel shortening in compound heads which causes backing in low vowels [æ → ɑ], since short [æ] is restricted to syllables with coronal codas (Basbøll 1972); in light of (1d), this also causes /g/ to select a different weak allophone.[2] This process, however, is riddled with exceptions; not all roots with [æ] shorten in compounds, and not all roots with [ɑ] are interpreted as [+back] for the purposes of /g/ allophone selection, as further discussed by Horslund, Puggaard-Rode & Jørgensen (2022) and Puggaard-Rode (2023b: Chaps. 2–3). In fact, the example in (2d) is probably the only Danish root that shows the full three-way alternation between [k ɪ̯ ʊ̯], although several roots show alternations between the two semivocalic allophones without ever surfacing with a stop, compare e.g. *flag* 'flag' [flæːˀɪ̯] and *flagstang* 'flagpole' [ˈflɑʊ̯stɑŋˀ].

The 'allophones' in weak and strong position are in most cases very far removed from one another in terms of the lenition trajectories discussed above, making it unlikely that there is any strong phonetic link between them. This is further cemented by the myriad exceptions to their phonological generalizations. Indeed, Horslund, Puggaard-Rode & Jørgensen (2022) 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 (see also Ács, Fenyvesi & Jørgensen 2008; Ács & Jørgensen 2016). These arguments will not all be restated here, but crucially, one serious complication of the analysis is that the positional allophones [ʊ̯ ɪ̯] can have multiple phonological sources; [ʊ̯] can derive from either /b/, /g/, or /v/, and [ɪ̯] can derive from either /g/ or /j/. If we assume that the traditional analysis holds true, there is usually no way to disambiguate the phonological source of a semivowel, since most lexical items do not participate in the type of morphophonological alternation that would allow disambiguation. 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.

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

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[2]The interpretation of the feature [high] and hence the context for choosing the Ø-allophone in (1d) is currently undergoing change, such that the semivowels are deleted in more and more contexts. For example, [ˈpæːæ] is now a common alternative to [ˈpæːɪ̯] (Grønnum 2005: pp. 295). This further complicates the picture.

the dialect atlas by Bennike & 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 Figure 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 Figure 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/.
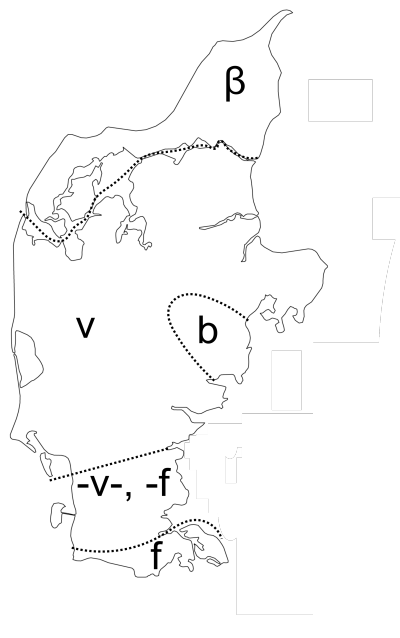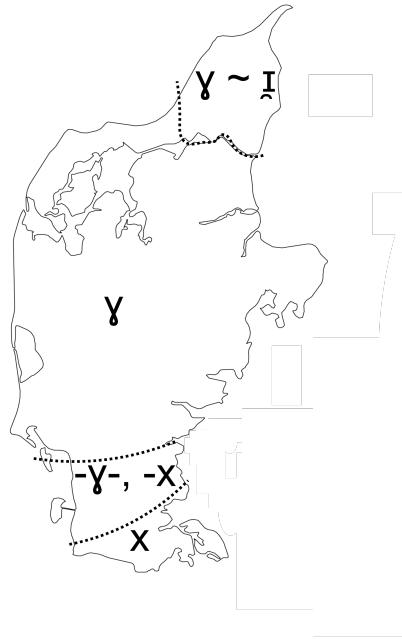

Figure 2: Map showing the outcomes of stop gradation in /b/ in Jutland. Adapted from Bennike & Kristensen (1898–1912: K49).

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[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 & Trudgill 1998).

[4]Figure 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 Figure 2; this also holds true for Figure 3 and Figure 4 below.

The variation patterns of /g/ (see Figure 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 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.

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

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 similar behavior of /b g/ is not surprising, as stops often display phonetic class behavior within phonological categories (e.g. Chodroff & Wilson 2017; Chodroff, Golden & Wilson 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

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[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 [β ɣ] are 'translated' from their Dania counterparts [ƀ ǥ].

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 γ], 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 1944–1970); 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 Figure 2 and Figure 3. Weak positions could still be in both coda and onset 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 Figure 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 & 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).

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 ends (see

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[6]In fact, Figure 4 is a simplified version of the original map by Bennike & Kristensen (1898–1912), which also notes some very small areas with specific alternations that are not relevant for our purposes here.
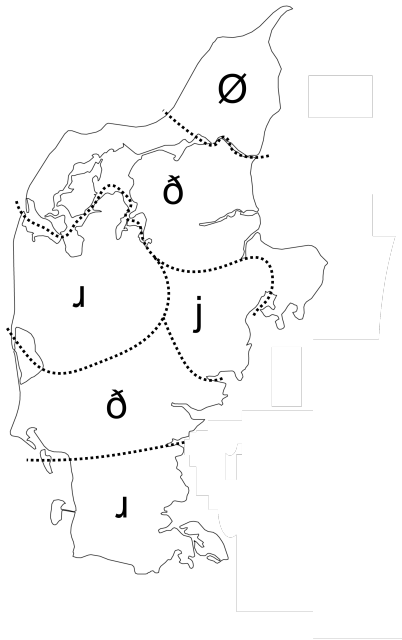
Figure 4: Map showing the outcomes of stop gradation in /d/ in Jutland. Adapted from Bennike & Kristensen (1898–1912: K.50).

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 the 'phonetic sonority' would refer 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 VOT in /p t k/, and differences in closure voicing patterns in /b d g/, and pose the following concrete research questions (RQs):

*RQ*1. Does VOT in /p t k/ show meaningful patterns of geographical variation that correspond to the variable outcomes of stop gradation? The null hypothesis $H1_0$ is that VOT does not vary geographically. The alternative hypothesis $H1_a$ is that VOT varies geographically, such that it is relatively high in the south and decreases with increasing latitude.

*RQ*2. Do closure voicing rates in /b d g/ show meaningful patterns of geographical variation that correspond to the variable outcomes of stop gradation? The null hypothesis $H2_0$ is that closure voicing rates

do not vary geographically. The alternative hypothesis $H2_a$ 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 alternate hypotheses $H1_a$ and $H2_a$ 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. 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 VOT 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 VOT and voicing rates. These variables are not related to the primary hypothesis of the study, but the results may nevertheless be of general interest for developing models of how VOT 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.

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 speakers of traditional dialects. The 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 & Puggaard 2019; Puggaard-Rode 2023b: 214ff.). 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

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

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 Figure 5. The coverage is quite good and relatively evenly spread except for a sparsity of recordings around the center of the peninsula.
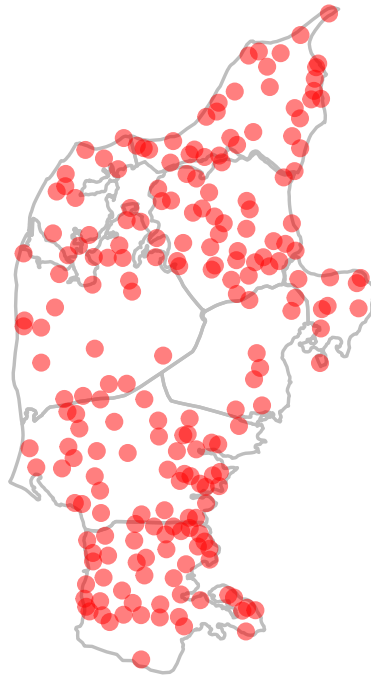
Figure 5: Locations of informants in the present study.

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

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[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 the accompanying data and code.

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 VOT, such that elderly speakers generally have slower speech, but (usually) shorter VOT (Smith, Wasowicz & Preston 1987; Larson, Hayslip & Thomas 1992; Torre & 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 the same 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 (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, Palethorpe & Watson 2000; Sankoff & Blondeau 2007; Kang & 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 & 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.

Due to the great variability in phonetic implementation, VOT-related landmarks were segmented manually in Praat (Boersma & Weenink 2021). VOT is defined as the time differential between the stop release and the onset of voicing (Lisker & 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. Whenever multiple bursts were present, the final one was segmented,

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

following Cho & Ladefoged (1999: 215); this phenomenon is fairly common in the recordings, likely due to the speakers' age (Parveen & 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, Ciocca & Yu (2003) identifies as the landmark most closely corresponding to physiological measures of voicing onset. Figure 6 shows an example of annotated VOT landmarks in a fairly straightforward /t/ token, and in a /k/ token with two bursts.

(a) Straightforward /t/ token.

(b) Token of /k/ with two bursts.
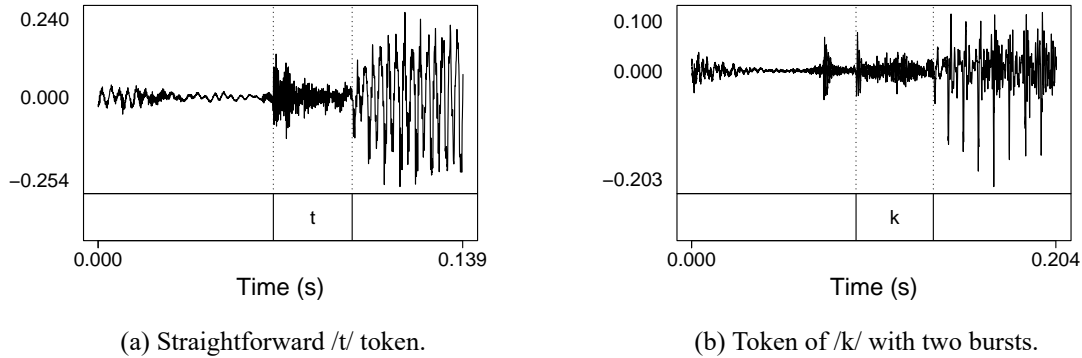
Figure 6: Example of annotated aspiration phases in two tokens.

The number of measured tokens by place of articulation is given in Table 3; the relative rarity of /p/ tokens reflects a general pattern in the Danish lexicon (see e.g. Hansen 1962–1971: II:165ff.). The VOT measurements of /p t k/ are identical to those reported by Puggaard (2021) and included in that paper's accompanying data.

Table 3: 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

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,

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[10]This choice may have a non-trivial influence on the resulting measurements (Gráczi & 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.

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that' was excluded across the board. In each recording, all instances of /b d g/ that met these criteria were included in the analysis up to the point where the 50th instance of /p t k/ had been found. For each token, 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; otherwise, stops were considered fully voiced if voicing (i.e. periodicity) was continuous throughout the closure. This dichotomy between fully voiced and not fully voiced follows the study of Modern Standard Danish by Puggaard-Rode, Horslund & Jørgensen (2022). Figure 7 gives examples of post-pausal and intersonorant /b d g/ that are either fully voiced or not fully voiced. The number of measured tokens by place of articulation is given in Table 3 above.
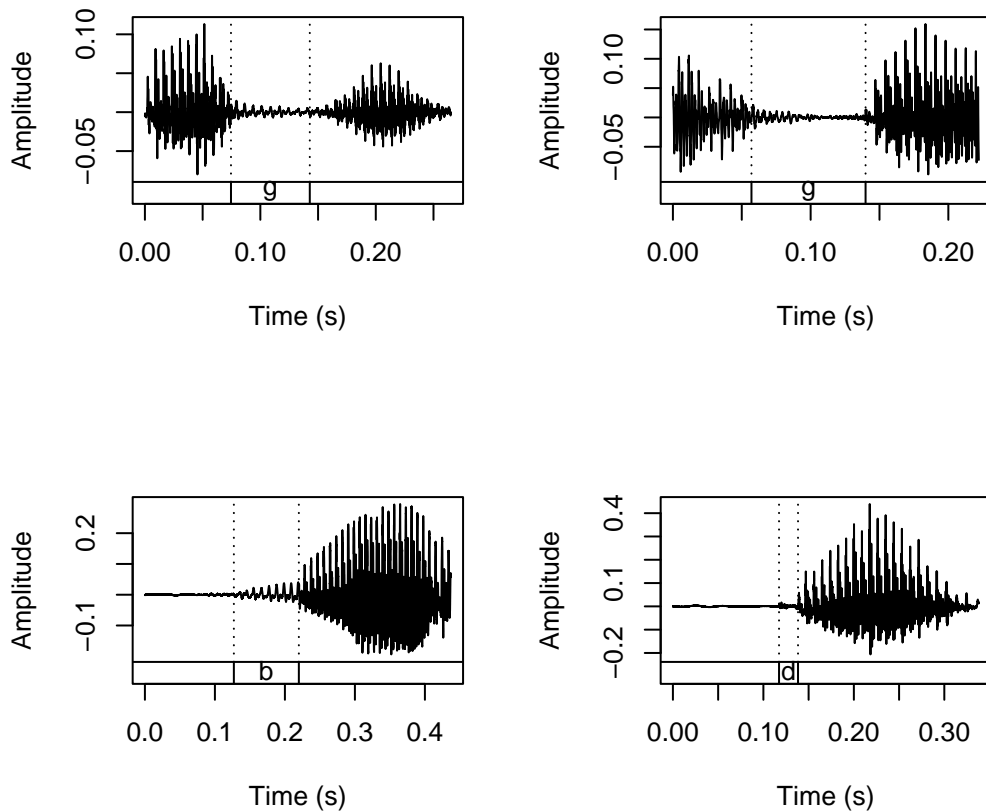
Figure 7: Top left: a /g/ token in intersonorant position that is fully voiced. Top right: a /g/ token in intersonorant position that is not fully voiced. Bottom left: a /b/ token in post-pausal position that is pre-voiced. Bottom right: a /d/ token in post-pausal position that is voiceless.

2.3 Predictors

In addition to the geographical predictor, the models also include a host of categorical predictors which are known or expected to influence VOT and the likelihood of voicing. For the purpose of the primary research question in this study, these are all nuisance variables, but they do allow us to test predictions and lend credence to previous findings about how such variables affect VOT and voicing. The predictors are introduced in turn in the following.

PLACE. Cross-linguistically, it is generally the case that VOT increases 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 & Abramson 1964; Cho & Ladefoged 1999; Chodroff, Golden & Wilson 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 VOT (Fischer-Jørgensen 1980; Mortensen & Tøndering 2013; Puggaard-Rode 2022). This may be because /t/ is saliently affricated in Modern Standard Danish (Fischer-Jørgensen 1972a; Puggaard-Rode 2022); this feature is known to be much less salient in Jutland (Puggaard-Rode 2023a). 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 & Stevens 1971; Ohala 1983; Westbury & 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.[11] For 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 & Ladefoged (1999).

PALATALIZATION is expected to increase VOT, as it tends to result in a prolonged voiceless release; this is in line with Puggaard's (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, Horslund & Jørgensen (2022) did not find support for this in Modern Standard Danish.

BACKNESS. It is not straightforward to predict how vowel backness affects VOT and voicing; from an aerodynamic perspective, we may expect back vowels to increase VOT, 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 & Gracco 1999; 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 & Weiher 1976). The ensuing predictions are partially in line with Gósy's (2001) study of VOT in Hungarian, where VOT is longer before back vowels in bilabials

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[11]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 & Riordan 1979).

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 VOT, which may be related to non-back vowels having a more salient effect on the release acoustics (as shown by Puggaard-Rode 2022; 2023a). 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 VOT and voicing rate is not entirely straightforward. Stress has been shown to increase positive VOT in aspirated stops in languages like English, German, and Modern Standard Danish (Lisker & 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, Casillas & Díaz 2014) or may even decrease it (as in Dutch, see Cho & McQueen 2005). Similarly, stress may increase negative VOT in stops which are phonologically pre-voiced (as shown for Spanish by Simonet, Casillas & Díaz 2014), or it may decrease the chances of continuous voicing in languages with a laryngeal contrast that relies mostly on aspiration, as shown for English (Davidson 2016) and Modern Standard Danish (Puggaard-Rode, Horslund & Jørgensen 2022). The laryngeal contrast in Jutland Danish varieties by and large seems to be more aspiration-oriented than voicing-oriented, so we would predict increased VOT and decreased voicing rate in stressed syllables.

ROUNDNESS. 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 1972b). Puggaard (2021) did not find support for such an interaction in Jutland Danish, but rather found that rounded vowels generally triggered longer 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 VOT 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 VOT in multiple languages, including Modern Standard Danish (e.g. Klatt 1975; Fischer-Jørgensen 1980; Higgins, Netsell & Schulte 1998; Esposito 2002; Bijankhan & Nourbakhsh 2009; Berry & Moyle 2011). Mortensen & 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 before 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, Horslund & Jørgensen (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 & Hansen 2003). In order to keep the

analysis relatively simple, we follow Mortensen & 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. VOT has been shown to be longer in utterance-initial position in e.g. Korean and English (Cho & Keating 2001; 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, Horslund & Jørgensen 2022).

SEX. Women have been shown to have longer VOT than men in English (e.g. Swartz 1992; Whiteside & Irving 1998), especially among older speakers (Torre & 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, Horslund & Jørgensen (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 & 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

The data was statistically modeled with two separate spatial generalized additive mixed models (GAMMs); one modeling VOT, the other modeling voicing likelihood. 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 & Kirkham 2020; Puggaard-Rode 2022), or indeed geographical variation (Wieling, Nerbonne & Baayen 2011; Wieling et al. 2014; Koshy & Tavakoli 2022; Puggaard-Rode 2023a).

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).[12] The coding scheme is summarized in Table 4. The models are summarized below, where the response variable Y refers to VOT in one model, and the log likelihood of closure voicing in the other; $f(...)$ 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.

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

Table 4: Overview of contrast coding for categorical variables.

Variable	Contrast
PLACE	-⅓ bilabial, -⅓ alveolar, +⅔ velar
	-½ bilabial, +½ alveolar
PALATALIZATION	-½ palatalized, +½ non-palatalized
BACKNESS	-½ back, +½ non-back
STRESS	-½ unstressed, +½ stressed
ROUND	-½ unrounded, +½ rounded
HEIGHT	-⅓ low, -⅓ mid, +⅓ high
	-½ low, +½ mid
BOUNDARY	-½ not post-pausal, +½ post-pausal
SEX	-½ female, +½ male

All statistics are calculated in R (R Core Team 2022). GAMMs are fitted using the `mgcv` package (Wood 2017; 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

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

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 & Wood 2012).

3 Results

This section presents the results of the two GAMMs, starting with the VOT model in Section 3.1, and then the voicing rate model in Section 3.2.

3.1 Voice onset time

The VOT model has a fairly high effect size of $R^2 = 0.413$. The parametric coefficients are summarized in Table 5.

Table 5: Summary of the parametric coefficients of the VOT model.

Variable	Estimate	SE	t-value	p-value
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

Variable	Estimate	SE	t-value	p-value
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

The weighted population mean of approx. 51 ms is comparable to Modern Standard Danish. Most of the fixed effects significantly influence VOT, and all significant effects are in the predicted direction. VOT is longer in velar than non-velar stops, and is much longer in alveolar than bilabial stops.[13] 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 VOT is slightly increased. Female speakers have longer VOT than male speakers.

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

Figure 9 shows the fitted geographical effect where areas are only colored in where the fitted VOT differs significantly from zero, and Figure 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 VOT in all stops (see also Puggaard-Rode 2023b: Chap. 6). 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.

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[13]The model does not explicitly test whether alveolars have longer VOT 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 salient /t/-affrication in most if not all traditional Jutlandic dialects (Puggaard-Rode 2023a).

[14]The largely linear nature of the geographical effect is confirmed by the low estimated degrees of freedom (just slightly over 2) of this variable.
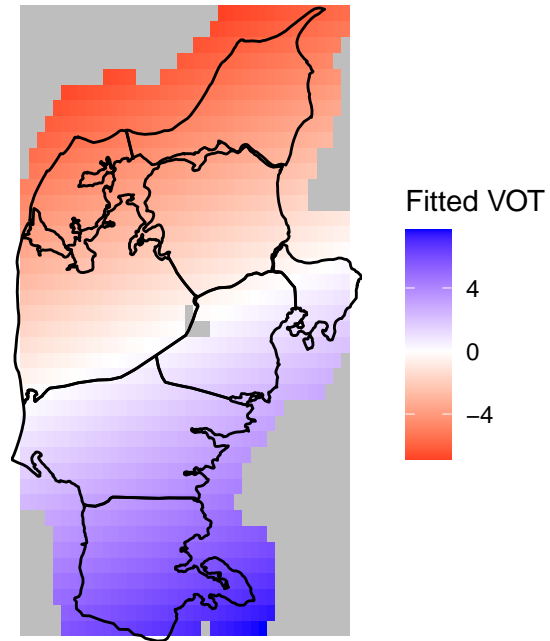
Figure 8: Fitted VOT values attributed to the geographic variable overlaid on a map of Jutland.
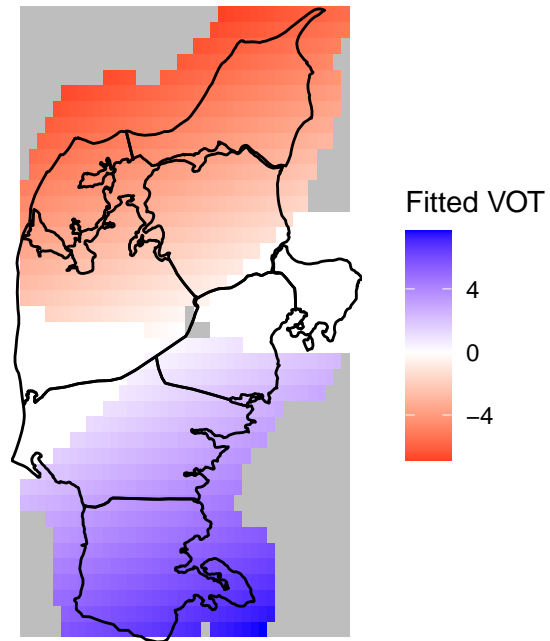

Figure 9: Fitted VOT values attributed to the geographic variable overlaid on a map of Jutland, with colors removed where $p < 0.05$.
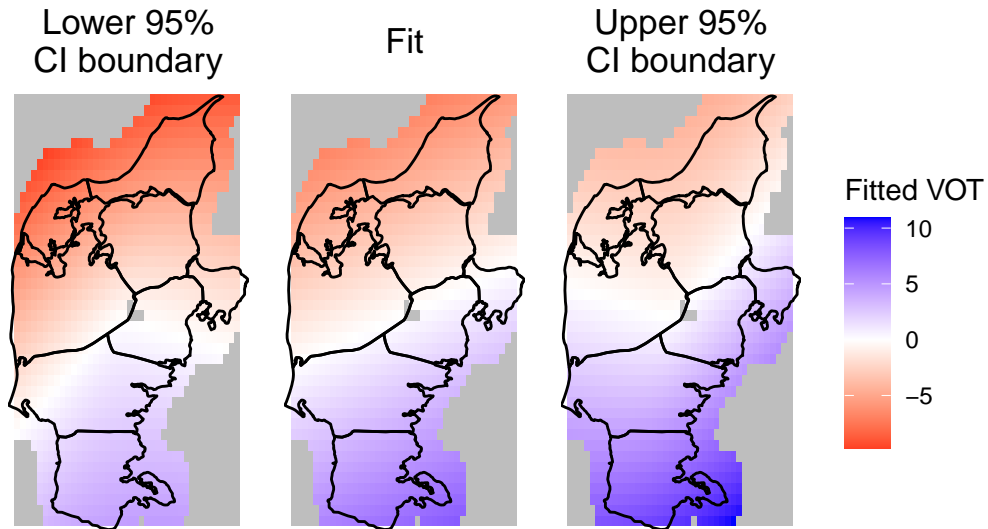
Figure 10: Fitted VOT values attributed to the geographic variable as well as upper and lower bounds of 95% confidence interval overlaid on a map of Jutland.

3.2 Voicing

The model of voicing rate has a medium effect size of $R^2 = 0.315$. The parametric coefficients are summarized in Table 6.

Table 6: Summary of the parametric coefficients of the voicing model.

Variable	Estimate	Odds/OR	SE	z-value	p-value
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

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, Horslund & Jørgensen 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 post-pausal position is much less likely than otherwise.

The fitted geographical effect is shown in Figure 11. It shows a similar pattern to the fitted effect of VOT shown in Figure 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 ±1.0 is equivalent to an increased or decreased probability of approximately 1-to-2.7 relative to the global mean.)
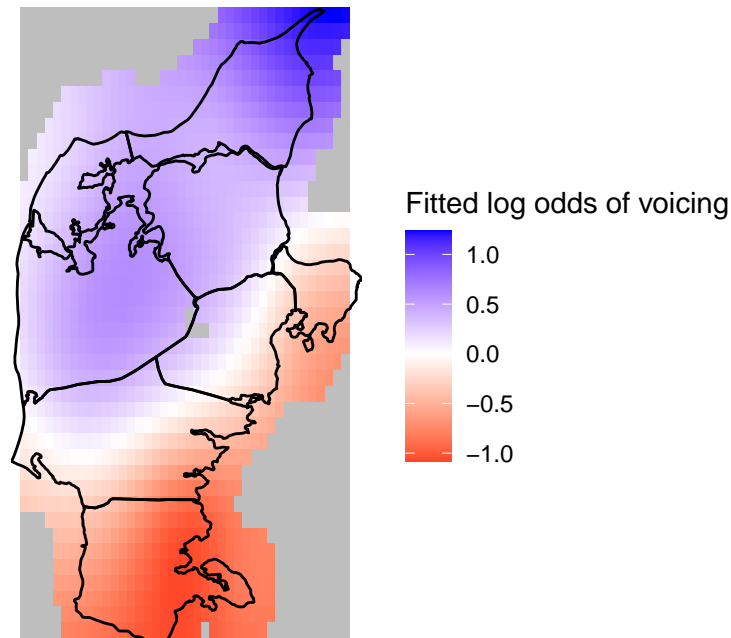
Figure 11: Fitted probability of continuous voicing attributed to the geographic variable overlaid on a map of Jutland.

As above, Figure 12 shows the fitted geographical effect where it differs significantly from zero, and

Figure 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.
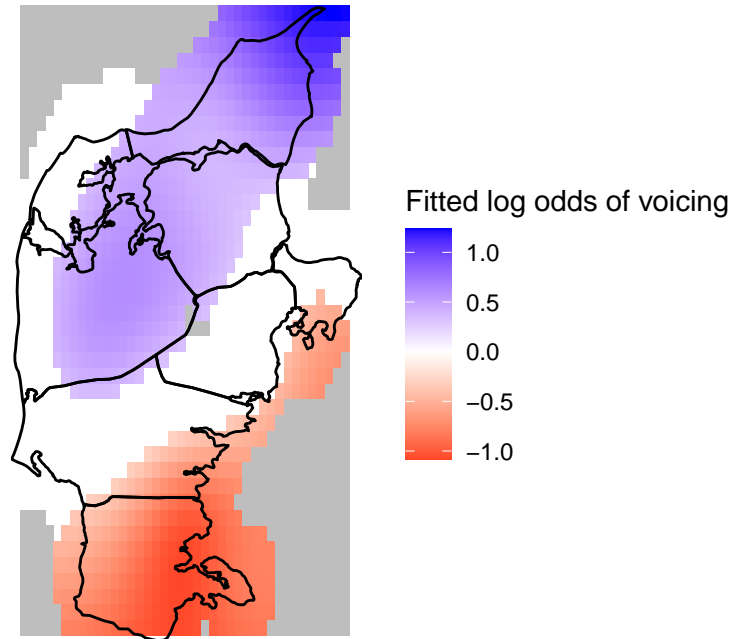
Figure 12: Fitted probability of continuous voicing attributed to the geographic variable overlaid on a map of Jutland, with colors removed where $p < 0.05$.

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. Section 4.1 covers the influence of the non-geographical covariates on VOT and voicing rates, and Section 4.2 discusses the geographical patterns of variation in VOT and voicing rates and how they relate to the corresponding patterns of variability in stop gradation. Section 4.3 returns to the question of how this relates to the patterns found in Modern Standard Danish. Finally, Section 4.4 provides some brief conclusions and outlook.

4.1 Non-geographical effects on stop realization

Before moving on to the primary research question, we will return to the non-geographical components of the statistical models, i.e. the predictors presented in Section 2.3. Several predictors were included in the models which are known or expected to affect VOT or voicing rates, most of which have to do with either prosodic prominence or the aerodynamics of voicing.
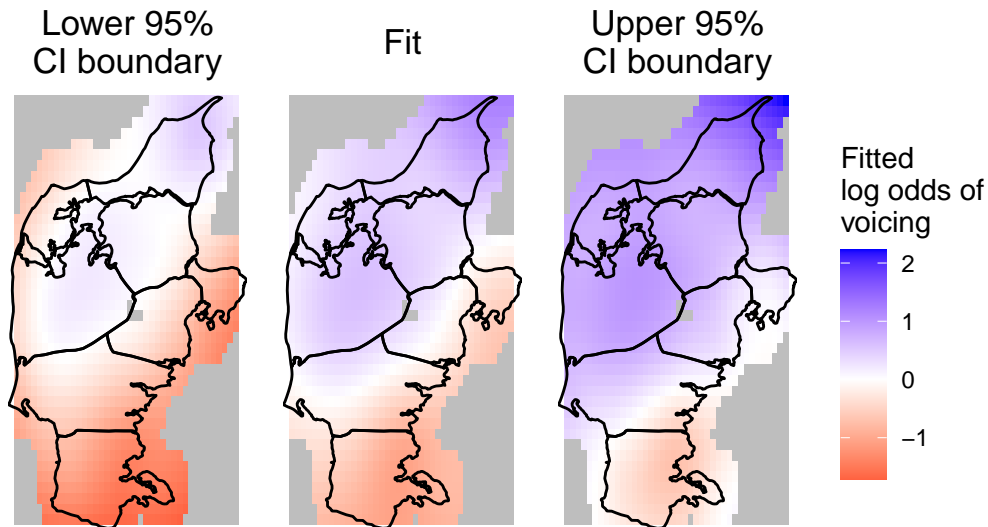
Figure 13: Fitted probability of continuous voicing attributed to the geographic variable as well as upper and lower bounds of 95% confidence interval overlaid on a map of Jutland.

Almost all of these predictors were found to significantly influence VOT such that VOT 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). VOT increases with prosodic prominence, such that it is longer in stressed syllables or when the stop is in post-pausal position. VOT also increases with more posterior occlusions, such that velars are longer than non-velars, and alveolars are longer than 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. VOT is also longer before rounded vowels, and the best explanation for this is that anticipatory rounding also has a salient effect on the release burst (see Puggaard-Rode 2022). This is also the likeliest explanation for why VOT is longer before non-back vowels, since a purely aerodynamic account would predict longer VOT before back vowels. It should be noted that most of these effects, while stable, are quite small, and that the estimated VOT differences for several of them are probably too short to be perceptible (see Blumstein, Myers & Rissman 2005). The effects of vowel height and boundary in particular are so short that they are unlikely to be consequential at all. 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 – but from the model summary it does seem as if

the phonetic contextual aerodynamic effects truly have no influence on the likelihood of closure voicing. This is in line with what Puggaard-Rode, Horslund & Jørgensen (2022) showed for Modern Standard Danish. Note, however, that male speakers do have a significantly (if somewhat marginally) higher probability of closure voicing than female speakers, which Puggaard-Rode, Horslund & Jørgensen (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 also goes against an aerodynamic explanation of the finding, since the physical distance between the velum and the alveolar ridge is much larger than that between the alveolar ridge and the lips. Rather, it 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 (2023b: Chap. 6).

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 pre-voicing proper *does* occur – unlike in Modern Standard Danish – continuous voicing within a prosodic domain is much more common.

4.2 Geographical variation in stop realization

In the previous section, it was proposed that the influence of non-geographical predictors on VOT likely in large part comes down to aerodynamic by-products of the phonetic context. This cannot be claimed for the geographical influence on VOT, in part because the difference (at least between the geographical areas with the highest and lowest fitted values) is clearly of a greater magnitude, and because 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. As with VOT, 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 & Hirose 1974; Hutters 1984; 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 some effort (Westbury 1983; Westbury & 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.

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 in weak prosodic positions. A possible reason for this variability in their development is that it reflects differences in how the stops in weak position were phonetically realized prior to stop

gradation. This is impossible to test empirically – there are no recordings that date back sufficiently far – so instead, we looked closer at the exact realization of the laryngeal contrast in strong prosodic positions, under the common assumption that present-day lenited segments were historically similar to their present-day un-lenited counterparts.

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 the subphonemic level. To the north, where stop gradation usually resulted in approximants, voicing rates in /b d g/ were relatively high, and VOT 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 VOT 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 & 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).

The systematic covariation between stop gradation and phonetic implementation of the laryngeal contrast arguably provides a clear case of how variability in fine phonetic detail can feed into the outcome of sound change. The traditional Jutland Danish varieties would all fall under the umbrella of 'aspirating varieties' in a 'true voice' *vs.* 'aspirating' dichotomy, but finer details in the implementation of the voiceless aspirated *vs.* voiceless unaspirated contrast still affected their historical trajectories in a way that has a direct impact on their synchronic phonological organization.

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, 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 ɣ̞ ɹ̞], which is intuitively appealing in light of the myriad inconsistencies and irregularities in analyses which assume that they are allophones (see Section 1.2.1). In comparison, stop gradation in the Jutland Danish varieties has more of the hallmarks of synchronically active phonological processes. Puggaard-Rode (2023b: Chap. 3) proposed 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 1928–1971; Skautrup 1944–1970; Hansen 1962–1971; Brink & 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 & 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 & Salmons 2003b; Helgason & Ringen 2008; Kirby & Tan 2023).

4.4 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 voice onset time, 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 subphonemic variability. 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 question for further research.

Availability of data and code

The recordings used in this study are freely available online from this URL: dansklyd.statsbiblioteket.dk/samling/dialektsam
Other analysis data, fitted model objects, and code, including a version of this paper with embedded
R code demonstrating all analytical steps, will be shared in an open repository if the paper is accepted.
These will be made available to reviewers upon request.

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