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PLANTING THE SEED FOR SOUND CHANGE: EVIDENCE FROM REAL-TIME MRI OF VELUM KINEMATICS IN GERMAN

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Velum movement signals generated from real-time magnetic resonance imaging videos of thirty-five German speakers were used to investigate the physiological conditions that might promote sound change involving the development of contrastive vowel nasality. The results suggest that, in comparison to when a nasal consonant precedes a voiced obstruent, the velum gesture associated with a nasal consonant preceding a voiceless obstruent undergoes gestural rescaling and temporal rephasing. This further suggests that the diachronic development of contrastive vowel nasality comprises two stages: the first stage involves gestural shortening and realignment, while the second stage involves a trading relationship between source and effect.*

Keywords: real-time MRI, vowel nasalization, sound change, actuation, speech gestures, German

1. Introduction.

1.1. Vowel nasalization and sound change. The concern of this study is with the phonetic origin or initiation of sound change (Solé 2012, Yu 2013), with a particular focus on the articulatory dynamics of anticipatory coarticulatory vowel nasalization (Bell-Berti & Krakow 1991, Cohn 1993a, Delvaux et al. 2008, Kent et al. 1974, Moll & Daniloff 1971, Solé 1992, 1995), wherein the velum lowers during an oral vowel (V) in anticipation of a following nasal consonant (N) in VN sequences. Characteristics of coarticulatory vowel nasalization are known to vary between languages (Beddor & Krakow 1999, Cohn 1990, Solé 1995), speakers (Beddor et al. 2018, Carignan 2019, Kim & Kim 2019), and listeners (Fowler & Brown 2000, Kawasaki 1986, Zellou 2017) and to be affected by both prosodic factors (Cho et al. 2017, Jang et al. 2018, Krakow 1994, Zellou & Scarborough 2012) and lexical factors (Scarborough 2013, Scarborough & Zellou 2013). Coarticulatory vowel nasalization has also often been considered a primary source of sound change that can lead to the development of phonological nasal vowels and the associated lenition or deletion of the nasal consonant (Beddor 2009, Delattre 1954, Krakow et al. 1988, Ohala 1993, Zellou & Tamminga 2014). The transition from synchronic variation to diachronic change has sometimes been modeled as a discrepancy between production and perception in the way that phonological categories are parsed or associated (Fowler 2005, Fowler & Smith 1986) with independently controlled, time-

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varying articulatory gestures (Carignan 2018a, Harrington 2012, Kuang & Cui 2018, Lee & Jongman 2019, Ohala 1993, Pinget 2015, Pinget et al. 2019).

Two well-known models have been proposed to explain how synchronic coarticulatory variation in VN sequences can lead to the diachronic development of phonologically contrastive vowel nasalization (V ~ Ṽ)—namely, those put forth by Ohala (1993, 2005) and Beddor (2009, 2012). In the model proposed by Ohala, coarticulatory variation rarely leads to sound change. This is because adult listeners' sensitivity to (Alfonso & Baer 1982, Ali et al. 1971, Beddor et al. 2013, Lahiri & Marslen-Wilson 1991, Martin & Bunnell 1982) and quite possibly experience of (Kang et al. 2016) coarticulation allow them to account for the phonetic effects arising from coarticulation and thereby map phonological categories to speech signals in the same way that they were originally associated in speakers' productions. According to Ohala, it is only when occasionally listeners fail to normalize or compensate for coarticulation in this way (Mann & Repp 1981, Mitterer 2006, Viswanathan et al. 2010) that the conditions for sound change are met (Ohala & Feder 1994).

Like Ohala, the various studies by Beddor (2009, 2012, 2015) are concerned with modeling sound change in terms of the relationships between the production and perception of coarticulation. While there does exist this superficial similarity between Beddor's and Ohala's models, they are also fundamentally different. In Ohala 1993, the origin of many types of sound change is a perceptual parsing error. In Beddor's model, there is no listener error: sound change arises instead out of the same flexible strategies routinely deployed in speech perception for assigning different weights to acoustic cues that are distributed throughout the speech signal. Another difference is that in Beddor's model, phonologization develops through incremental changes in the relationships between coarticulatory source and effect (see discussion below). By contrast, phonologization (and sound change in general) is abrupt for Ohala (1993): just as the ambiguities in a Necker cube can reveal to the viewer two categorically different visual interpretations of the same drawing, so too can the listener sometimes switch between two categorically different ways of parsing coarticulation from the speech signal. Sound change can therefore come about in Ohala's model if one interpretation is favored over another—see Harrington et al. 2019 for a further discussion. Yet another crucial difference between the models is that for Ohala (1993) the distinction between the origin of sound change and its spread throughout the community is sharp: only the former, but not the latter, is scientifically testable according to Ohala. By contrast, Beddor's model provides the basis for explaining 'how the phonetic variants in the ambient language might serve as a source of new sound patterns that spread through a speech community' (Beddor 2015:1).

The starting point for Beddor's model is the well-known finding that there are multiple cues to speech-sound contrasts (Francis et al. 2000, Harmon et al. 2019, Holt & Lotto 2006, Lisker 1986) and that listeners vary in the attention or weight that they assign to these cues for disambiguating speech sounds (Beddor 2012, 2015, Chandrasekaran et al. 2010, Clayards 2018, Kim & Clayards 2019, Schertz et al. 2015). Compatibly with these findings, Beddor (2012, 2015) has shown that there are variable perceptual strategies for identifying nasalization in ṼN sequences (where Ṽ signifies a vowel with some coarticulatory nasalization): some listeners base their judgments mostly on information in N, others associate nasalization with ṼN (without parsing such judgments with either just Ṽ or just N), while yet others' perceptions of nasalization are swayed to a greater extent by information in Ṽ alone (see Stevens & Reubold 2014 for a similar argument for preaspiration).

One of the critical stages in the development of contrastive vowel nasalization is when speech production begins to align with perception in this second and third group of listeners—that is to say, when listeners who perceptually parse nasalization from Ṽ in the ṼN context also begin to produce highly nasalized vowels in the same context (Beddor 2015). Beddor argues that this change ultimately leads to a pattern of covariation in production, wherein the coarticulatory source (N in ṼN sequences) comes into an inverse relationship with the corresponding effect of the coarticulation (Ṽ in ṼN sequences). This trading relationship between source and effect manifests as an increase in coarticulatory nasalization in the vowel and a concomitant decrease in the duration of the nasal consonant in certain phonetic contexts. Synchronically, such covariation has been observed particularly in ṼN sequences followed by a voiceless obstruent in languages such as Italian (Busà 2003, 2007) and Japanese (Hattori et al. 1958), but is especially marked in American English /Vnt/ vs. /Vnd/ sequences (Beddor et al. 2007, Beddor 2009, Cohn 1990, Huffman 1993, Malécot 1960, Raphael et al. 1975)—for example, *bent* vs. *bend*, where the former (as compared to the latter) is characterized by extensive (or even total) temporal nasalization in the vowel and relatively little (or even no) realization of a nasal consonant (Cohn 1990, Moll & Daniloff 1971, Solé 1995). Compatibly, the diachronic development of contrastive vowel nasalization due to the loss of the following nasal consonant in VNC sequences (where C is an obstruent) has been shown to be more likely when the following consonant was historically voiceless (Hajek 1997, Ohala & Ohala 1991, Ruhlen 1978, Tuttle 1991, Sampson 1999) and especially a voiceless fricative (Busà 2007, Kavitskaya 2014).

Understanding how such production-perception relationships could give rise to sound change requires detailed knowledge of the different ways in which a vowel and a following nasal consonant variably overlap in speech production, especially with regard to the kinematics of the velum gesture associated with the nasal consonant. Despite some progress in identifying nasalization from the acoustic signal using measures such as the relative amplitudes of nasal and oral formants (A1-P0 and A1-P1; Beddor 2009, Chen 1997, Zellou 2017), accurately tracking the time course and magnitude of velum raising and lowering from speech acoustics both across speakers and within individual tokens is notoriously difficult (Barlaz et al. 2018, Carignan 2018b, Feng & Castelli 1996, Saxon et al. 2019, Styler 2017). Moreover, acoustic measures of this type are useful only for examining nasalization in vowels, where oral formants are present alongside nasal formants in the acoustic spectrum; such measures therefore cannot be used to identify and characterize nasalization throughout an entire ṼN(C) sequence. While aerodynamic (Cohn 1993b, Delvaux et al. 2008), nasometric (Bae et al. 2007, Dalston et al. 1991), photoelectric (Ohala 1971, Solé 1995), pneumatic (Kuehn & Moon 1998, Moon et al. 1994), and mechanical (Horiguchi & Bell-Berti 1987) methods can be used to characterize nasalization in both vowels and consonants, these measurements are inherently indirect estimates of velum lowering—that is, they measure the effect that velum lowering has on some medium rather than the height of the velum itself. A new contribution in the current study is therefore the use of real-time magnetic resonance speech imaging (Barlaz et al. 2015, Carignan et al. 2015, Pruthi et al. 2007, Silva et al. 2012) for tracking the movement of the velum directly (Byrd et al. 2009, Carignan et al. 2019, Martins et al. 2012, Proctor et al. 2013) in order to investigate the kinematics of velum movement in /Vnt/ and /Vnd/ sequences in German, for a large number of both participants and items.

In contrast to, for example, American English (Beddor 2009, Mielke et al. 2017, Solé 2007, Zellou 2017), there is no evidence to our knowledge of a sound change in progress in German in which vowel nasalization is becoming contrastive. In other words, as far as we are aware, /Vnt/ sequences in German do not exhibit increased coarticulatory vowel nasalization compared to /Vnd/ sequences and concurrent loss of the nasal consonant, as has been observed in English. For this reason, German is suitable for an investigation of the conditions under which coarticulatory nasalization could develop into the very earliest stage of sound change. Investigating the phonetic conditions that might promote sound change by observing a language in which the change has not (yet) occurred is not unique to the current study. As Solé (2009) convincingly argues using acoustic measurements, there is no evidence that vowel nasalization is in the process of becoming phonologized in Spanish. Yet, using aerodynamic measurements related to nasal leakage in Spanish, Solé (2014) is nevertheless able to draw a number of conclusions about how phonetic nasal leakage could have led to the phonologization of vowel nasality in languages of Austronesia, Papua, and South America, languages that are structurally distinct from Spanish. We therefore situate our study within the broader research tradition developed over the last fifty years of analyzing the phonetic origin of sound change in many (often unrelated) languages—that is, using laboratory methods to explain the phonetic (in this case physiological) conditions that could lead to sound change (in this case contrastive vowel nasalization).

1.2. NC̥ REPULSION. The more general type of synchronic variation that we investigate in this study arises from the phonetic repulsion of a nasal consonant followed by a voiceless obstruent, that is, NC̥ REPULSION. In some phonological frameworks, this repulsion has been formulated as an *NC̥ constraint against nasals being followed by voiceless obstruents (Pater 1999) and analogously as a preference for voiced obstruents in NC clusters (Itô & Mester 1986). The phonetic basis for this constraint has been argued from both a physiological/aerodynamic perspective and an acoustic/perceptual perspective (Ohala & Ohala 1993, Ohala & Busà 1995, Ohala et al. 1998, Shosted 2006, Solé 2007).

From a physiological perspective, the incompatibility is that, whereas a voiceless obstruent typically requires a high intraoral air pressure to sustain a turbulent airstream either for the production of a fricative (Stevens 1971) or for a strongly released voiceless stop (Ali et al. 1979), intraoral pressure in the nasal preceding the stop is typically low because of nasal venting (Solé 2009). By contrast, a nasal and a voiced obstruent in sequence are aerodynamically compatible because the low intraoral air pressure due to nasal venting contributes to the maintenance of a high transglottal pressure difference that helps to sustain vocal-fold vibration in a fully voiced stop (Solé 2009; see also Ohala & Ohala 1991 for evidence that nasal venting extends into a following voiced, but not voiceless, stop).

From an acoustic perspective, nasal consonants are characterized by low-frequency energy due to a nasal murmur (Fujimura 1962, House & Stevens 1956), whereas voiceless obstruents lack energy in this region and are characterized by a much higher spectral center of gravity because of high-frequency energy caused by a turbulent airstream (Hughes & Halle 1956, Heinz & Stevens 1961); thus, nasal consonants and voiceless obstruents are acoustically incompatible. By contrast, a nasal murmur and the murmur of a following voiced stop are acoustically compatible because both are characterized by low-frequency energy (Ohala & Ohala 1993). Moreover, since voiceless obstruents are characterized by high-frequency noise energy, this energy may be a required cue for the percept of distinctive voicelessness, leading speakers to avoid nasal venting in order to maintain these cues for the perception of voicelessness (Ohala & Ohala 1991, Ohala & Ohala 1993, Beddor 2009).

Ohala and Ohala (1991) use acoustic criteria to explain sound changes in which an /n/ may be variably preserved before a voiced but not voiceless obstruent. Thus Sanskrit /tʃandra/ 'moon' became /tʃãːda/ in Old Hindi (without an /n/) but then /tʃãnd/ (with an /n/) in modern Hindi. The same pattern is observed in, for example, the insertion of a nasal consonant before a voiced obstruent where none was present historically (e.g. Latin ***hib**ernalis* 'wintry' but Italian ***inv**erno* 'winter'). By contrast, the /n/ in Sanskrit /danta/ 'tooth' was deleted in Old Hindi /dãːta/ and then not reinserted in Modern Hindi /dãt/. Synchronically, Ohala and Ohala (1991) also observed from aerodynamic data that a French speaker often inserted /m/ before a voiced obstruent in *saint bel* /sɛ̃**mb**ɛl/ but not *saint pour* /sɛ̃**p**uʁ/. Their explanation of these synchronic and diachronic observations is that there is ambiguity in whether or not a nasal consonant precedes a voiced stop because of the considerable acoustic similarities between a nasal murmur and the following voiced stop's voice bar (which is why a nasal consonant before a voiced stop may be deleted and then later reinserted, and why it can be variably present in production). Voiced nasal consonants and voiceless obstruents, by contrast, are acoustically incompatible, because the latter never have energy in the frequency region in which a nasal murmur is prominent (or rather if they did, they might no longer be perceived as voiceless). For this reason, a nasal consonant is never likely to be inserted diachronically or synchronically before an obstruent that is voiceless.

1.3. RESOLVING THE NÇ̥ INCOMPATIBILITY. One of the main issues to be considered here is how the velar gestural repulsion within the NÇ̥ environment is physiologically implemented, by comparing the shape and temporal alignment of the velum movement trajectory in the productions of /Vnt/ and /Vnd/ sequences. The starting point for this investigation is the model proposed in Beddor 2009 for American English in which, following ARTICULATORY PHONOLOGY (AP; Browman & Goldstein 1990a,b,c, 1992, Saltzman & Munhall 1989), speech production is controlled by autonomous gestures that can be variably phased (Nam 2007, Saltzman & Byrd 2000, Tiede et al. 2007). Specifically, we refer to the prediction that 'in languages in which vowel nasalization is not phonologized, the [velum] gesture itself would be relatively stable but its alignment with the oral articulators might be variable' (Beddor 2009:788). Using acoustic measurements of nasalization, Beddor (2009) observed that VNC sequences in American English exhibit an inverse relationship between the duration of vowel nasalization and the duration of the following nasal consonant. Based on this pattern, Beddor proposed that NÇ̥ repulsion was achieved in that case via temporally shifting a constant-sized velum gesture forward in time, resulting in a shortening of the nasal consonant interval (i.e. NÇ̥ repulsion) that coincides with a greater overlap between velum opening and the vowel interval (i.e. increased coarticulatory vowel nasalization).

The NÇ̥ constraint could influence the kinematics of the velum opening/closing gesture of the nasal consonant in various ways, represented schematically in Figure 1. This figure illustrates abstract representations—in the spirit of Fowler (1984)—of the relative phasing of different supralaryngeal gestural components of a /Vnt/ or /Vnd/ sequence: the tongue-body raising/lowering movement for the vowel (dashed line), the raising/lowering movement of the velum (solid line), and the raising/lowering movement of the tongue tip for the final alveolar cluster (dotted line). In this figure, and in all figures throughout the article related to velum movement, we conceptualize velum lowering in the sense of gestural magnitude, in which an increase along the y-axis corresponds to an increase in the amplitude/magnitude of the gesture. Thus, these gestural representations should not be interpreted directly as velum HEIGHT, wherein the 'peak' of the gesture would be the lowest point along the y-axis, that is, the maximal degree of velum lowering. Rather, the gestural representations used here depict the maximal degree of velum opening as the highest point along the y-axis—that is, a local maximum rather than a local minimum.

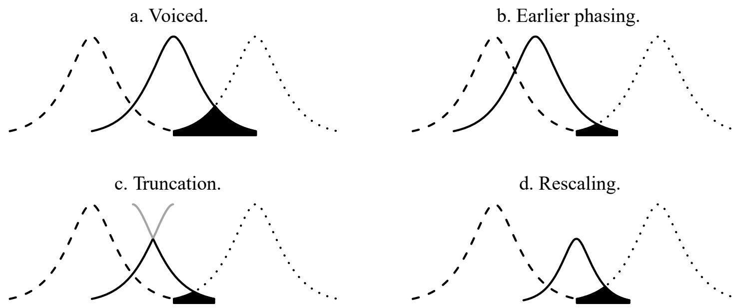


Figure 1. Schematic outlines of the amplitude (y-axis) of the relative phasing (x-axis) of the tongue body for the vowel (dashed), velum (solid), and tongue-tip (dotted) gestures. In (a), the final stop is voiced. The other panels show different types of gestural organization when the final stop is voiceless, as follows. (b) The velum gesture is aligned earlier in time. (c) The velum opening is truncated by an earlier phasing of the velum closing gesture (truncated intervals shown in gray). (d) The amplitudes of velum opening and closing are reduced, but the shape of the gesture is maintained. Black shading throughout indicates the temporal overlap of the velum gesture with the tongue-tip gesture for the obstruent cluster.

The scenario in Fig. 1a corresponds to the VNC̥ context, while those in Fig. 1b–d correspond to different kinds of gestural reorganization within the VNC̥ context. The shaded region of each of these schematized scenarios represents the overlap between the velum and oral gestures in an NC cluster; a reduction in the total area of this shaded region in comparison with Fig. 1a thus denotes successful NC̥ repulsion. The gesture can maintain its duration and magnitude, but undergo a temporal shift away from the voiceless consonant (i.e. earlier in time). This is the gestural change suggested by Beddor, demonstrated schematically in Fig. 1b. In this scenario, the articulatory gestures for velum opening and closing that characterize the nasal consonant in /Vnt/ are not changed with respect to /Vnd/ but are instead aligned earlier in time—that is to say, NC̥ repulsion in /Vnt/ is achieved by temporally shifting (with respect to /Vnd/) a constant-sized velum gesture (i.e. the gesture has the same duration and magnitude as for /Vnd/). The acoustic consequences of this earlier phasing are a greater extent of vowel nasalization and, concurrently, a lesser extent of consonant nasalization in /Vnt/ than in /Vnd/—that is, the inverse relationship observed in American English by Beddor (2009).

There are, however, a number of other articulatory maneuvers for achieving phonetic repulsion within the NC̥ environment that might also characterize the very earliest stages of sound change. In Fig. 1c, for example, successful repulsion is achieved through an earlier phasing of the velum closing gesture with respect to the velum opening gesture that precedes it. This model is based on the idea that the gestural phases of velum opening/lowering and closing/raising are each independently controlled by half a period of a critically damped, linear, second-order system oscillating around its rest position[1] (Byrd et al. 2000) and that these autonomous opening and closing maneuvers can be variably

[1] As opposed to a first-order mechanical system, in which energy is stored in a spring alone, a second-order system models energy storage within both a spring and a damper. A second-order system thus allows for greater complexity in characterizing system kinematics, including oscillation and critically damped movement.

phased with respect to each other (Fowler & Saltzman 1993). In Fig. 1c the earlier phasing of velum closing cuts off or 'truncates' the velum opening gesture (Cho 2002, Harrington et al. 1995, Hoole & Mooshammer 2002, Mooshammer & Fuchs 2002, Munhall et al. 1992), resulting in not only earlier velum closing but also a reduction in the maximal velar opening—that is, the peak of the solid black line in Fig. 1c is lower than the peak of the solid black line in Fig. 1a. Acoustically, the consequence of this type of maneuver would be a shorter, weaker-amplitude /n/ without any concurrent increase in observed coarticulatory nasalization in the vowel—in other words, in Fig. 1c compared to Fig. 1a, velum opening overlaps to a lesser extent with the following tongue-tip gesture, but it does not overlap to a greater extent with the preceding tongue-dorsum gesture for the vowel.

Alternatively, the gesture could undergo rescaling rather than truncation. When a gesture is rescaled, the magnitude of the gesture is scaled in linear proportion to its duration. This scenario is represented schematically by Fig. 1d: the shape of the gesture is maintained relative to Fig. 1a, but its magnitude and duration are reduced. As opposed to gestural truncation, gestural rescaling assumes that a single gesture is involved in velum opening and closing, and that the difference between the voiced and voiceless contexts is one of scale of the entire gesture. Whereas the possibilities in Fig. 1b,c satisfy NÇ̥ repulsion entirely through rephasing of the velum gesture (in whole or in part), gestural rescaling does so by changing the two parameters that control the velum gesture's linear second-order model. First, the amplitudes of the opening and closing gestural phases are reduced, consequently also reducing maximal velar opening—that is, the peak of the solid black gesture in Fig. 1d is lower than the peak of the solid black gesture in Fig. 1a. Second, the natural frequencies of these gestural phases are increased. This corresponds to an increase in stiffness of the analogous critically damped mass-spring system (Ackermann et al. 1995, Kühnert & Hoole 2004, Perkell et al. 2002). The primary difference between a truncated gesture and a rescaled gesture is one of shape: as Fig. 1c,d clearly show, a truncated gesture is predicted to exhibit greater 'peakedness' compared to a rescaled gesture (Harrington et al. 1995).

1.4. AIMS OF THE STUDY. In summary, the current study has two primary aims. The first is to determine which type of articulatory reorganization in Fig. 1b–d most closely matches the observed differences between German /Vnt/ and /Vnd/ velum kinematics (if any), as gleaned from real-time magnetic resonance imaging. In particular, the model in Fig. 1b in which there is only a rephasing but no other change to the velum-gesture kinematics (i.e. the model suggested by Beddor 2009, 2012) predicts more nasalization in the vowel, and less nasalization in the following consonant cluster. By contrast, the models in Fig. 1c,d predict only a reduction in the size of the velum opening; moreover, Fig. 1d (i.e. gestural rescaling) predicts a decrease in vowel nasalization if there is no change to the timing in the maximum opening of the velum gesture. It could be that the model in Fig. 1b is appropriate for American English given the evidence that vowel nasalization has been (or is in the processing of being) phonologized in /Vnt/ but not /Vnd/ (Beddor et al. 2007, Malécot 1960, inter alia). By contrast, one or both of the other models shown in Fig. 1c,d might more closely characterize German, which, as already indicated, shows no such evidence of phonologization of vowel nasalization. Testing this is one of the main aims of this study. The other is to consider the implications of these findings for the origin of the very first stages along the path of sound change by which coarticulatory vowel nasalization is phonologized.

2. METHODS.

2.1. REAL-TIME MAGNETIC RESONANCE IMAGING. Real-time magnetic resonance imaging (rt-MRI) data were collected at 50.05 frames per second using a 3T MRI system

(Magnetom Prisma Fit, Siemens Healthineers, Erlangen, Germany) at the Max Planck Institute for Biophysical Chemistry (Göttingen, Germany). The method relies on highly undersampled radial gradient-echo acquisitions in combination with serial image reconstruction by regularized nonlinear inversion (Uecker et al. 2010). Extending preliminary applications to characterize natural speech at slower speeds (Niebergall et al. 2012), the current study employs a temporal resolution of 19.98 ms (nine radial spokes, repetition time 2.22 ms, echo time 1.47 ms, flip angle 5°). Rt-MRI movies cover a $192 \times 192\ mm^2$ field-of-view at 1.41 mm in-plane resolution in a midsagittal plane of 8 mm thickness. This in-plane resolution yielded images of 136 × 136 voxels (i.e. 3D volume elements obtained from the MRI scan). Synchronized, noise-suppressed audio was collected during the scanning session using an Optoacoustics FOMRI III fiber-optic dual-channel microphone (Optoacoustics LTD) and further processed in MATLAB (The Mathworks Inc. 2017) for additional reduction of scanner noise.

2.2. Speakers and material. Data are presented here for thirty-five native speakers of German (twenty-two female), aged between nineteen and thirty-five years ($M = 24.37$, $SD = 4.28$). Thirty-six speakers were originally recorded, but the data for one speaker were excluded due to intractable problems with image registration and subsequent issues with the velum signal generated from the registered images (§2.3). The remaining thirty-five speakers all spoke standard German, with only minor regional variation typical of the western central part of Germany; see Appendix A for speaker demographics.

The corpus used in the MRI scanning sessions consists of ≈300 German lexical items, balanced for coda composition over a wide range of phonetic contexts. A total of 1,365 items from forty-three words containing postvocalic alveolar NC sequences were analyzed in the current study: 366 /Vnd/ items and 999 /Vnt/ items. In all items, the target V was one of the vowels /a, aː, ɛ, eː, ɪ, iː, ɔ, o, œ, yː, øː, aʊ, aɪ/. All items were either monosyllabic words with (C)CVNC structure or disyllabic CV_1NCV_2 words with a trochaic lexical stress pattern in which V_1 was nuclear-accented and V_2 was a prosodically weak (and typically centralized) vowel /ə, ɐ, a/. See Appendix B for the corpus subset and item counts, as they pertain to this study.

During the scanning sessions, the words appeared on a computer screen, as projected/reflected onto a mirror placed inside the MRI scanner. The target words appeared in a variety of carrier phrases in which the location of the nuclear accent and words in the carrier phrase were varied (see Appendix C). In the present study, the target word was always sentence-medial and in nuclear accent position (condition 1 in Appendix C). Each target word was generally produced only once by each speaker, in order to avoid type I error inflation arising from multiple repetitions of the same item (Winter 2015). For convenient elicitation in the scanner, target sentences were grouped into blocks of about a dozen items (depending slightly on prosodic condition). Occasionally a whole block was repeated, either due to technical issues with the scanner or because of a large proportion of mispronunciations. Thus, for some speakers, some words have more than one repetition in the final item set.

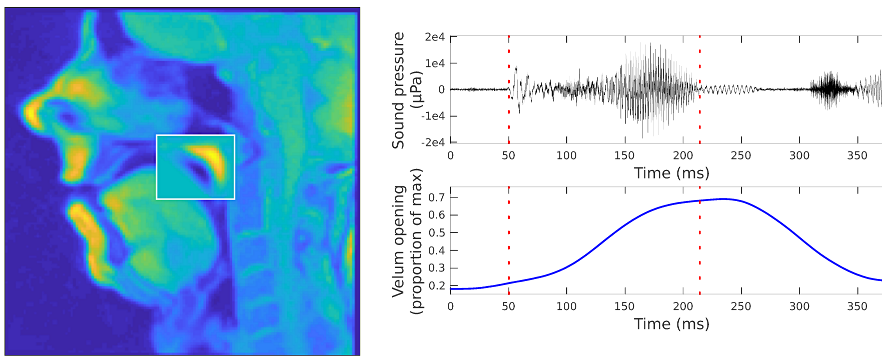
The noise-suppressed audio was used for segmentation of the vowel in each token, which was carried out manually in Praat (Boersma & Weenink 2017) via inspection of a broadband spectrogram. The vowel onset was defined as the release of the onset C (in the case of a preceding obstruent) or as an abrupt change in the frequencies of the first three formants (in the case of a preceding sonorant). The vowel offset (i.e. the boundary between V and N) was defined as the appearance of nasal murmur and concurrent reduction in amplitude of the first three formants.

2.3. GENERATING A VELUM OPENING SIGNAL. The rt-MRI data were processed in MATLAB, using the methods described in Carignan et al. 2020. For each speaker's rt-MRI data set, image registration (via rigid transformation) was carried out with reference to the superior portion of the head—that is, superior to approximately the tip of the nose—in order to correct for minor movements of the head throughout the scanning session. A velum opening/closing (henceforth 'velum movement' or 'velum opening') signal was created from the registered images, according to the following method. First, a region of interest (ROI) was manually selected around the bounds of the spatial range of velum opening/closing for each speaker. On average, there were 588 voxel sites (*SD* = 148) present within the by-speaker ROIs. All words in the corpus containing VN sequences were used as training items for the purpose of generating a velum opening signal; these words generally included a post-N obstruent, ensuring that the set of training items for each speaker manifested a maximal range of velar position—that is, from most open to most closed and all positions in between. The voxels in the ROI were extracted for the images pertaining to these training items, and the voxel intensities were used as dimensions in PRINCIPAL COMPONENTS ANALYSIS (PCA) models. The scores from the first principal component (PC1) were logged for each image frame, resulting in a time-varying signal with a sampling rate of 50.05 Hz. Given that there is only one primary degree of freedom associated with the movement of the velum in VN sequences (i.e. the opening/closing dimension), PC1 serves as a reliable proxy for this dimension of movement since PC1 is by definition the component that captures the most variance in the ROI that surrounds the velum. Since PCA models were constructed on a by-speaker basis, PC1 captures this articulatory dimension in a way that factors out individual speaker morphology, thus allowing similar interpretation of PC1 scores across all speakers. PC1 explained an average of 52.7% (*SD* = 9.4) of total voxel-intensity variance within the by-speaker ROIs. In other words, on average, PC1 captured more than half of the total variance in nearly 600 dimensions.

The PC1 scores were scaled for each speaker between 0 and 1, with reference to the minimum and maximum PC1 scores for the speaker's data set; the resulting value can thus be interpreted as a proportion of the total range of velum movement produced by each speaker. Since the sign of the PC1 dimension is arbitrary—for example, it is an equally likely result that positive PC1 loadings (PC1 coefficients, i.e. the correlations between the voxel sites and the unit-scaled first principal component) for a given speaker relate to velum opening as it is that positive loadings relate to velum closing—the PC1 loadings were manually inspected for each speaker in order to fulfill two goals: (i) ensure that PC1 faithfully captures velum opening/closing, and (ii) verify the sign of the PC1 dimension. With regard to the first goal, PC1 captured velum opening/closing in every case, as evidenced by the fact that the PC1 loadings mapped on to the velum in its open and closed position for each speaker. With regard to the second goal, the sign of the speaker-scaled PC1 scores was flipped as necessary such that an increase in the PC1 scores is interpreted as an increase in the degree of velum opening in each case (i.e. so that an increase in the score correlates with a lower velum). An example of the PC1 loadings for one of the speakers is shown in Figure 2a, with the ROI depicted within the white box.[2] The positive loadings (bright voxels) and negative loadings (dark voxels) are associated with the velum in its closed and opened states, respectively; if left uncor-

[2] Note that this figure and several of the others are presented in color in the electronic versions of this article, but in grayscale in the print version; color versions of the figures are also available open access along with other supplementary materials at http://muse.jhu.edu/resolve/123.

rected, positive PC1 scores would thus relate to velum closing and negative PC1 scores to velum opening. This is therefore a case in which the sign of the PC1 scores was flipped, in order to ensure that the time-varying signal can be interpreted as the magnitude of velum opening rather than the magnitude of velum closing in each case. Thus, for all speakers, smaller values represent a more closed velum, while larger values represent a more open velum.

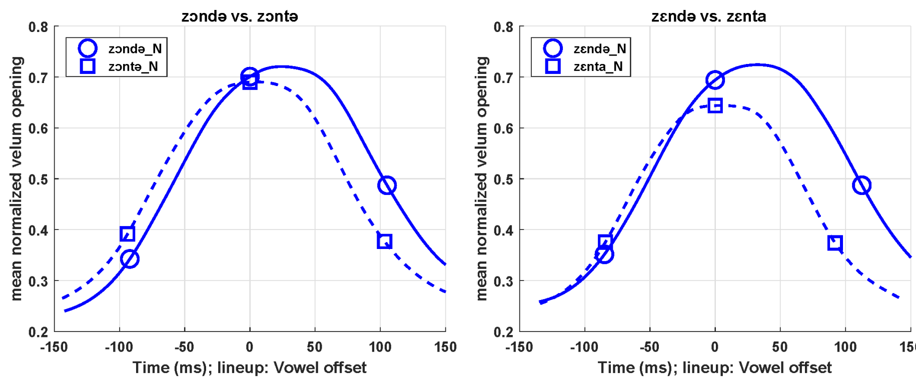


a. Example: PC1 coefficients/loadings. b. Example: PC1 score velum opening signal.

FIGURE 2. Example of PCA-based generation of velum movement/opening signal. The figure in (a) highlights the velum PC1 coefficients/loadings for the speaker. The figure in (b) shows the audio waveform (top) and the corresponding velum opening signal (bottom) for a token of *Panther* 'panther'. Vertical dotted lines in (b) demarcate the acoustic vowel interval.

The velum movement signal was upsampled by a factor of 10 (i.e. up to 500.5 Hz) using the standard settings in MATLAB's 'resample' function (Kaiser FIR filter, 201 coefficients, 55 dB stop-band attenuation), in order to obtain greater temporal resolution for determining key time points in the signal (§2.4). Figure 2b shows an example of the resulting processed and upsampled velum opening signal for a token of *Panther* [pantɐ] 'panther'; for both the audio signal (top panel) and the velum opening signal (bottom panel), the onset and offset of the vowel interval (as determined by the acoustics; §2.2) are denoted by vertical dotted lines. In this example we can see that, although the peak of the velum opening gesture occurs within the nasal consonant (after the vowel offset), the onset of the velum gesture occurs much earlier: it starts during the acoustic closure of [p], well before the acoustic onset of periodicity for the vowel. This suggests a relatively large degree of anticipatory coarticulatory nasalization in this particular token. Figure 3 displays examples of aggregated velum opening trajectories for the minimal pairs *Sonde* /zɔndə/ 'probe' vs. *sonnte* /zɔntə/ 'basked' (Figure 3a) and *sende* /zɛndə/ '(s/he) sends' vs. *Senta* /zɛnta/ '(woman's first name)' (Figure 3b), averaged over all thirty-five speakers. In this figure, the trajectories have been time-aligned with the (acoustic) vowel offset, which is denoted by the middle set of symbols (i.e. circles and squares at time = 0 along the x-axis). The left set of symbols denotes the vowel onset (as determined by the acoustics), and the right set of symbols denotes the release of the obstruent /t/ or /d/ (as determined by the acoustics). Voicing of the oral coda consonant is denoted by both line type and symbol shape (/Vnd/ = solid line + circles, /Vnt/ = dotted line + squares).

The velum trajectories were manually inspected for all items. In some cases, items were excluded where the algorithmically determined onset of velar opening (§2.4) occurred so early that it could not plausibly be attributed to the velum gesture for the nasal



a. Velum trajectories for *Sonde* 'probe' vs. *sonnte* 'basked'.

b. Velum trajectories for *sende* '(s/he) sends' vs. *Senta* '(woman's first name)'.

FIGURE 3. Aggregated velum trajectories for two minimal pairs. Voicing context is denoted by line and symbol (/Vnd/ = solid line + circles, /Vnt/ = dotted line + squares). Trajectories are time-aligned to the acoustic offset of the vowel (0 on x-axis), and symbols are displayed for the acoustic onset of the vowel (left set) and the acoustic release of the obstruent (right set).

consonant (but was more likely determined by the intrinsic velar height of the target vowel). Item exclusion was by far the most frequent for words with a /ʔ/ onset (which does not constrain velar position) followed by a low vowel, especially /aː/ (see Appendix B for a comparison of the total number of included items across words).

2.4. QUANTIFYING VELUM KINEMATICS. Several measurements were derived from key kinematic time points occurring in the velum movement signal of each token. These time points are exemplified in Figure 4 for a token of *Bunde* 'bunches'. In this figure, sections of the gesture associated with the time points described below are displayed with different line types, and the scaled velocity profile is superimposed with a solid gray line (with zero velocity denoted by the horizontal dashed gray line). The onset and offset of the velum gesture were determined by identifying time points where the velum movement signal reaches 20% velocity thresholds (Kroos 1996, Kroos et al. 1997). Point b_1 is the point of maximum velocity, and point a_1 is the first time point before b_1 that crosses a threshold of 20% of the velocity value at point b_1; thus, point a_1 is considered to be the onset of the velum gesture. Likewise, point b_2 is the point of minimum velocity, and point a_2 is the first time point after b_2 that crosses a threshold of 20% of the velocity value at point b_2; thus, point a_2 is considered the offset of the velum gesture, and the interval between points a_1 and a_2 is therefore considered the velum gesture. Two time points relating to the velum-gesture plateau were identified: the first time point after b_1 that crosses a threshold of 20% of the velocity value at point b_1 (point c_1), and the first time point before b_2 that crosses a threshold of 20% of the velocity value at point b_2 (point c_2). Finally, the time point of maximum velum displacement was identified and is considered to be the peak of the gesture (point d). A total of nine metrics of velum-gesture timing and velum-gesture shape were obtained for each item with reference to these seven time points, as detailed below.

Four metrics of VELUM-GESTURE TIMING were created: the duration of the velum gesture, as well as the time points of the velum-gesture onset, the velum-gesture peak, and the velum-gesture offset. The three time point measures (onset, peak, offset) were each made with respect to the time point of the vowel offset (identified according to the acoustics; §2.2). In this way, the 'onset' measure can be interpreted as the duration of

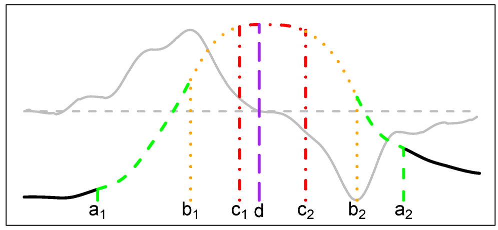


FIGURE 4. Kinematic time points for the velum gesture associated with a token of *Bunde* 'bunches'. The scaled velocity profile is displayed by the solid gray line, with 0 velocity denoted by the horizontal dashed gray line. Time points are shown for the gesture onset (a_1), the point of maximum velocity (b_1), the beginning of the gesture plateau (c_1), the gesture peak (d), the end of the gesture plateau (c_2), the point of minimum velocity (b_2), and the gesture offset (a_2).

vowel nasalization, and the 'offset' measure can be interpreted as the duration of consonant nasalization. With reference to the time points exemplified in Fig. 4, the four temporal metrics are defined as follows:

- DURATION: time (ms) between a_1 and a_2
- ONSET: time (ms) of a_1, relative to the acoustic vowel offset
- PEAK TIMING: time (ms) of d, relative to the acoustic vowel offset
- OFFSET: time (ms) of a_2, relative to the acoustic vowel offset

Five metrics of VELUM-GESTURE SHAPE were created. First, the magnitude of the peak of the velum gesture was logged; this is a value between 0 and 1, representing the proportion of the total range of velum movement produced by each speaker. Second, kinematic stiffness was measured for both velum opening and velum closing.[3] Finally, two measures of the peakedness of the gesture were made: kurtosis (the fourth moment of a shape/curve; a measure of density at the peak of a curve compared to the density at the tails of the curve) and crest factor (a measure of how extreme a peak of a signal is relative to the surrounding values). For both kurtosis and crest factor, an increase in the measured value is interpreted as a more peaked shape associated with the velum gesture. With reference to the time points exemplified in Fig. 4, the five shape metrics are defined as follows:

- PEAK MAGNITUDE: value of the gesture displacement at d
- OPENING STIFFNESS: ratio of the velocity value at b_1 to the gesture displacement between a_1 and c_1
- CLOSING STIFFNESS: ratio of the (absolute) velocity value at b_2 to the gesture displacement between a_2 and c_2
- KURTOSIS: the kurtosis of the gesture displacement between b_1 and b_2
- CREST FACTOR: after subtracting a baseline value (the mean of displacement at a_1 and displacement at a_2), the ratio of the value of gesture displacement at d to the average displacement in the interval between a_1 and a_2

With regard to the ways in which NÇ̥ repulsion might be satisfied, depicted above in Fig. 1b–d, we can make independent predictions for these four metrics of velum-

[3] The measurement and interpretation of STIFFNESS in this study are intended in the sense of a conventional mass-spring equation (i.e. stiffness = the ratio of force to displacement), as adopted by articulatory phonology (Ostry & Munhall 1985, Xu & Prom-on 2019), and do not necessarily relate directly to muscle stiffness. See Fuchs et al. 2011 for a critique of estimating gestural stiffness under the assumptions of a linear second-order system.

gesture timing and five metrics of velum-gesture shape.[4] These predictions are shown in Table 1, with reference to the velum gesture in the /Vnt/ context as compared to the velum gesture in the /Vnd/ context.

	REPHASING (Fig. 1b)	TRUNCATION (Fig. 1c)	RESCALING (Fig. 1d)
Duration		decrease	decrease
Onset	earlier		later
Peak (timing)	earlier	earlier	
Offset	earlier	earlier	earlier
Peak (magnitude)		decrease	decrease
Opening stiffness		increase	increase
Closing stiffness		increase	increase
Kurtosis		increase	
Crest factor		increase	

TABLE 1. Predictions for the nine metrics of velum-gesture timing and shape for each of the three scenarios depicted in Fig. 1. Predictions are given for the velum gesture in the /Vnt/ context compared to the velum gesture in the /Vnd/ context. Predictions corresponding to no difference between the two contexts are denoted by blank cells.

2.5. BAYESIAN REGRESSION MODELS. In order to test these predictions, we built Bayesian generalized mixed regression models (BRMs) using the ‘brms’ package (Bürkner 2020, Stan Development Team 2017) in R (R Core Team 2020). All models included voicing context (/nd/ vs. /nt/) coded as a factor with treatment contrast. Random intercepts for both speaker and word were included, together with random slopes for voicing over both speaker and word. Since the coda context necessarily includes the fixed effect itself (i.e. coda voicing), ‘word’ was defined as the combination of the onset and nucleus within the target (C)VNC sequence (e.g. [pa] of *Panther*) for the purpose of generating the random-effect structure. The models were run with four Markov chain Monte Carlo (MCMC) chains, 4,000 iterations, and 2,000 warm-up samples; in cases where models did not converge ($\hat{R} > 1$), the iterations and warm-up samples were increased until model convergence was achieved ($\hat{R} = 1$). A sensitivity analysis based on posterior *z*-scores and shrinkage (Betancourt 2018) indicated that the priors did not dominate the posterior distributions (i.e. the priors did not strongly influence the results). Model convergence was reached in all of the reported models, and no divergences in the MCMC chains were observed. The posterior predictive check plots suggested that the model specification captured the shape of the distribution of the data well enough in each case.

For each model, marginal posterior distributions were calculated for both /Vnd/ and /Vnt/ contexts, and both 95% and 66% credible intervals were generated from these posteriors. A credible interval (differently from a frequentist confidence interval) can be interpreted as the percentage probability that a parameter lies within that interval range; in the current study, this corresponds to an interval of possible values for the parameter μ, the mean. Null models without the fixed effect of voicing were also constructed, in order to calculate the Bayes factor relating the effect of voicing in each of the main models. In

[4] The observant reader may wonder at this point why we have not included a measurement of correlation between the duration of vowel nasalization (i.e. our ‘onset’ measure) and the duration of consonant nasalization (i.e. our ‘offset’ measure), as was performed in Beddor 2009. Indeed, we found a correlation between these two metrics, as predicted, but chose not to include those results here because of the possibility that this correlation may have arisen spuriously due to placement error associated with a boundary shared by the two metrics (i.e. the acoustic vowel offset in our case; Allen 1978, Haggard 1973, Ohala & Lyberg 1976).

this way, the Bayes factor as reported in this study is a ratio that contrasts the likelihood of the data fitting under the null hypothesis (there is no effect of voicing) with the likelihood of the data fitting under the alternative hypothesis (there is an effect of voicing). Bayes factors thus offer a way of estimating the strength of the evidence for one model over another and are thereby used here to test both predictions related to an effect and predictions related to no effect (see Table 1). In qualifying the evidence strength, we follow the recommendations in Raftery 1995: Bayes factor 1–3: 'weak evidence', 3–20: 'positive evidence', 20–150: 'strong evidence', > 150: 'very strong evidence'. Data, as well as R code for generating the BRMs and associated figures appearing in this article, are available in the online supplementary materials.[5] Although minimal model details are included in this article, the full BRM details (including information and justification for the priors, sensitivity analysis, and posterior predictive checks for each model) are provided in these additional materials.

The BRMs for velum-gesture duration, the timing of the velum-gesture onset, the timing of the velum-gesture offset, velum opening stiffness, velum closing stiffness, kurtosis, and crest factor were each built using a log-normal distribution, since these measures are expected to exhibit a right-skewed distribution (Gahl & Baayen 2019, Ratnikova 2017, Rosen 2005). The BRM for the time point of the velum-gesture onset was built using a log-normal distribution of positive values—that is, the absolute duration of the interval between the velum-gesture onset and the acoustic vowel offset—and posterior values were subsequently converted to relative time points (i.e. negative scale) for interpretation. The BRM for the time point of the velum-gesture peak was built using a Gaussian distribution; unlike the other measures of timing, the time point of the velum-gesture peak is not necessarily expected to exhibit a right-skewed distribution, since the peak can potentially occur before or after the vowel offset. The BRM for the velum-gesture magnitude was built using a beta distribution, since the magnitude values are on a 0–1 scale.

3. Results.

3.1. Velum-gesture timing. Figure 5 shows the marginal posteriors of the mean values for the four timing metrics: velum-gesture duration, velum-gesture onset (relative to the vowel offset), timing of the velum-gesture peak (relative to the vowel offset), and velum-gesture offset (relative to the vowel offset). For this figure, and all similar figures throughout the results section, separate density distributions are shown for the posterior values of /Vnd/ and /Vnt/ contexts. Beneath each density distribution, the 95% credible interval (CI) is denoted by the thin horizontal line, the 66% CI is denoted by the thick horizontal line, and the median is denoted by the dot. The results for each model are presented below with reference to the respective model intercepts, and ranges for the estimates of the mean are given with reference to the 95% CIs of the marginal posterior distributions.

The duration of the velum gesture in the voiced context is between 286 and 318 ms ($\hat{\theta} = 5.71$, $SD = 0.03$ (in log-odds)) and is 19–43 ms shorter in the voiceless context ($\hat{\theta} = -0.11$, $SD = 0.02$ (in log-odds)). The Bayes factor suggests that the data are 697 times more likely to occur under the model including the effect of voicing than one without it, providing very strong evidence for the effect of voicing. The velum-gesture onset occurs 91–115 ms before the (acoustic) vowel offset in the voiced context ($\hat{\theta} = 4.63$, $SD = 0.06$ (in log-odds)) and occurs 6–19 ms earlier in the voiceless context

[5] The supplementary materials are available at http://muse.jhu.edu/resolve/123.

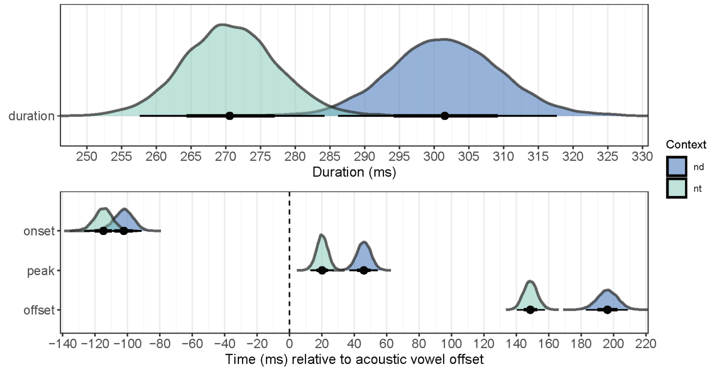


FIGURE 5. Marginal posteriors of the means of the velum-gesture duration, the time point of the velum-gesture onset, the time point of the velum-gesture peak, and the time point of the velum-gesture offset for /Vnd/ and /Vnt/ contexts. The 95% credible interval (thin line), the 66% credible interval (thick line), and the median (dot) are displayed below each density curve. Values in the bottom panel are given with respect to the acoustic vowel offset (point 0: indicated by the vertical dashed line).

($\hat{\theta} = 0.12$, $SD = 0.03$ (in log-odds)). The Bayes factor suggests that the data are 6.1 times more likely to occur under the model including the effect of voicing than one without it, providing positive evidence for the effect of voicing. The velum-gesture peak occurs 37–54 ms after the vowel offset in the voiced context ($\hat{\theta} = 45.86$, $SD = 4.38$) and occurs 20–32 ms earlier in the voiceless context ($\hat{\theta} = -25.69$, $SD = 3.11$). The Bayes factor suggests that the data are 2^{e6} times more likely to occur under the model including the effect of voicing than one without it, providing very strong evidence for the effect of voicing. The velum-gesture offset occurs 183–209 ms after the vowel offset in the voiced context ($\hat{\theta} = 5.28$, $SD = 0.03$ (in log-odds)) and occurs 36–59 ms earlier in the voiceless context ($\hat{\theta} = -0.28$, $SD = 0.03$ (in log-odds)). The Bayes factor suggests that the data are 1.7^{e8} times more likely to occur under the model including the effect of voicing than one without it, providing very strong evidence for the effect of voicing.

In summary, we have observed evidence that the velum gesture is temporally shortened in the /Vnt/ context compared to the /Vnd/ context (by 19–43 ms), rather than maintaining a constant duration. The shortened velum gesture is compatible with both gestural truncation and rescaling. This gestural shortening is due to a difference between the timing of the gesture onset in the two conditions and the timing of the gesture offset in the two conditions: the gesture offset occurs much earlier (36–59 ms) in the /Vnt/ vs. the /Vnd/ environment, whereas the gesture onset occurs only slightly earlier (6–19 ms). Moreover, the peak of the velum gesture is also shifted forward in time (i.e. closer to the vowel offset), occurring 20–32 ms earlier in the /Vnt/ vs. the /Vnd/ environment. The earlier onset of the velum gesture is compatible with gestural rephasing, whereas the earlier peak is compatible with both gestural rephasing and truncation, and the earlier offset is compatible with each of the gestural rephasing, truncation, and rescaling scenarios.

3.2. VELUM-GESTURE SHAPE. In the previous section, we observed that the peak of the velum gesture is shifted in time in linear relation to the asymmetric shifts exhibited by the gesture onset and offset. In other words, the degree of temporal shift of the peak (20–32 ms) is midway between the degree of temporal shift of the gesture onset (6–19 ms) and the degree of temporal shift of the gesture offset (36–59 ms), resulting in a strong correlation ($R = 0.99$) between the respective means of these shifts [12.5, 26, 47.5] and the means of the corresponding time points in the voiced context [−103, 45.5, 196]. This suggests that, to some extent, the shape of the velum gesture is maintained in the voiceless compared to the voiced environment, even though the duration of the velum gesture is shortened. In this section, we investigate the results for the metrics created to test for changes in gesture shape in a targeted manner.

Peak magnitude. Figure 6 shows the marginal posteriors of the mean speaker-scaled magnitude of the velum-gesture peak. At its peak, the velum gesture reaches an average of 68–75% of the maximum range of velum displacement in the voiced context ($\hat{\theta}$ = 0.93, *SD* = 0.10 (in beta odds)) and is reduced by 4–10% of the maximum range in the voiceless context ($\hat{\theta}$ = −0.32, *SD* = 0.07 (in beta odds)). The Bayes factor suggests that the data are seventy-six times more likely to occur under the model including the effect of voicing than one without it, providing strong evidence for the effect of voicing.

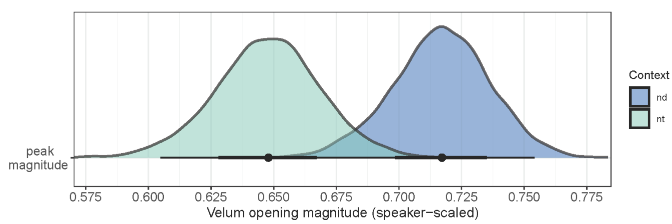


Figure 6. Marginal posteriors of the means of the magnitude of the velum-gesture peak for /Vnd/ and /Vnt/ contexts. The 95% credible interval (thin line), the 66% credible interval (thick line), and the median (dot) are displayed below each density curve.

Stiffness. Figure 7 shows the marginal posteriors of the mean velum-gesture opening stiffness and the mean velum-gesture closing stiffness. In the voiced context, the velum opening phase has a stiffness value of 12.5–14.4 ($\hat{\theta}$ = 2.60, *SD* = 0.03 (in log-odds)) and is 0.8–2.2 units greater in the voiceless context ($\hat{\theta}$ = 0.10, *SD* = 0.02 (in log-odds)). The Bayes factor suggests that the data are forty-two times more likely to occur under the model including the effect of voicing than one without it, providing strong evidence for the effect of voicing. The velum closing phase has a stiffness value of 13.4–14.9 in the voiced context ($\hat{\theta}$ = 2.64, *SD* = 0.03 (in log-odds)) and is 1.3–3.0 units greater in the voiceless context ($\hat{\theta}$ = 0.14, *SD* = 0.03 (in log-odds)). The Bayes factor suggests that the data are 1.7^{e3} times more likely to occur under the model including the effect of voicing than one without it, providing very strong evidence for the effect of voicing.

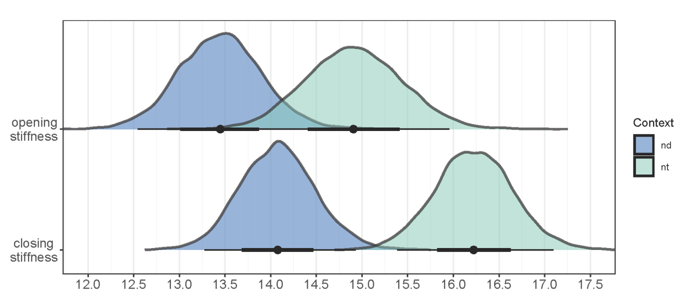


Figure 7. Marginal posteriors of the means of velum opening stiffness and velum closing stiffness for /Vnd/ and /Vnt/ contexts. The 95% credible interval (thin line), the 66% credible interval (thick line), and the median (dot) are displayed below each density curve.

As an interim summary of gesture shape, we have observed evidence that the velum gesture is reduced in magnitude in the /Vnt/ context compared to the /Vnd/ context, but that it also exhibits greater kinematic stiffness in the prevoiceless context. In both the prevoiced and prevoiceless environments, the velum-gesture closing phase exhibits greater stiffness than the velum-gesture opening phase. However, the overall stiffness is greater in the /Vnt/ context than in the /Vnd/ context, and this voicing-dependent difference is even larger in the velum closing phase (i.e. near the oral obstruent) than in the velum opening phase (i.e. within the vowel interval). The reduced peak magnitude and the increased opening stiffness and closing stiffness are compatible with both gestural truncation and rescaling.

GESTURE PEAKEDNESS. The effects observed in the previous section—reduced peak magnitude and increased kinematic stiffness for /Vnt/ compared to /Vnd/—are compatible with both the scenario of gestural truncation (Fig. 1c) and the scenario of gestural rescaling (Fig. 1d). We therefore turn now to the results for measures of the peakedness of the gesture, which are expected to differentiate the gestural shapes associated with these two scenarios. Figure 8 shows the marginal posteriors of the mean kurtosis and crest factor values. The kurtosis is 2.89–3.08 in the voiced context ($\hat{\theta} = 1.09$, $SD = 0.02$ (in log-odds)) and is changed between −0.04 and +0.13 in the voiced context ($\hat{\theta} = 0.02$, $SD = 0.01$ (in log-odds)). The Bayes factor suggests that the data were 118 times more likely to occur under the model WITHOUT the effect of voicing than one that includes it, providing strong evidence that there is no effect of voicing. The crest factor is 1.82–1.86 in the voiced context ($\hat{\theta} = 0.61$, $SD = 0.0$ (in log-odds)) and changes between −0.01 and +0.03 in the voiceless context ($\hat{\theta} = 0.01$, $SD = 0.01$ (in log-odds)). The Bayes factor suggests that the data were 187 times more likely to occur under the model WITHOUT the effect of voicing than one that includes it, providing very strong evidence that there is no effect of voicing.

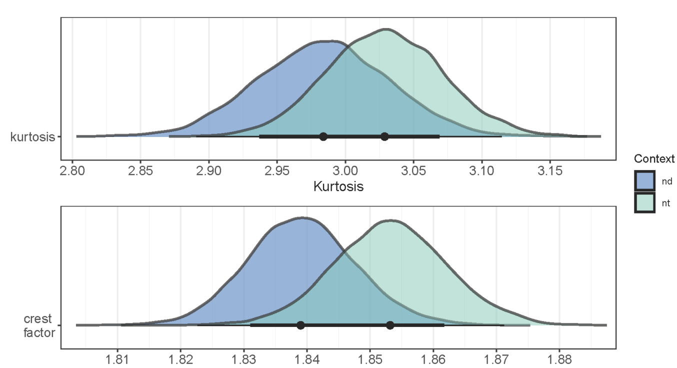


FIGURE 8. Marginal posteriors of the means of the velum-gesture kurtosis and crest factor for /Vnd/ and /Vnt/ contexts. The 95% credible interval (thin line), the 66% credible interval (thick line), and the median (dot) are displayed below each density curve.

In summary, we have observed evidence that the peakedness of the velum opening gesture is the same in the /Vnt/ environment as in the /Vnd/ environment, which is more compatible with gestural rescaling than with gestural truncation.

3.3. POST HOC ANALYSIS: DEGREE OF VOWEL NASALIZATION (INTEGRATED VELUM GESTURE). In §3.1, we observed evidence which suggests that the onset of the velum gesture is initiated earlier in the /Vnt/ context than in the /Vnd/ context, albeit to a relatively small degree (6–19 ms). This earlier onset of velum opening is interpreted as an increase of vowel nasalization in the temporal domain. However, in §3.2, we observed evidence which suggests that the velum magnitude is reduced in the /Vnt/ context compared to the /Vnd/ context, which is interpreted as a DECREASE in the effect of vowel nasalization in the AMPLITUDINAL domain (i.e. a smaller degree of velum lowering). Thus, it is possible that the decrease in magnitude offsets the increase in the temporal extent of nasality, resulting in no net increase in the OVERALL degree of vowel nasalization. In order to investigate whether there is any such net increase in the /Vnt/ context compared to the /Vnd/ context, we calculated the integral of the velum gesture within the vowel interval, in other words, the area under the curve of velum displacement that occurs within the acoustic vowel segment. By integrating the gesture in this way, we combine the two dimensions (time and magnitude) into a single dimension: TIME × MAGNITUDE.

The BRM for the integral of the velum gesture within the vowel interval was built using a log-normal distribution—since the BRM for the onset of the velum gesture was built using a log-normal distribution and the BRM for the magnitude of the velum-gesture peak was built using a beta distribution, a log-normal distribution is a reasonable prior assumption for the product of these two dimensions. Figure 9 shows the marginal posteriors of the mean integrated velum-gesture value. According to the model intercept, in the voiced context, the velum-gesture integral is between 35.1 and 49.1 integrated units ($\hat{\theta} = 3.73$, $SD = 0.09$ (in log odds)). In the voiceless context, the integrated time/magnitude increases by 1.45–6.3 units, at 95% confidence ($\hat{\theta} = 0.09$, $SD = 0.03$ (in log odds)). The Bayes factor suggests that the data were twice as likely to occur under the model without the effect of voicing than one that includes it, providing weak evidence that there is no effect of voicing. In practical terms, this should circumspectly be considered to be neither evidence FOR nor evidence AGAINST the effect of voicing.

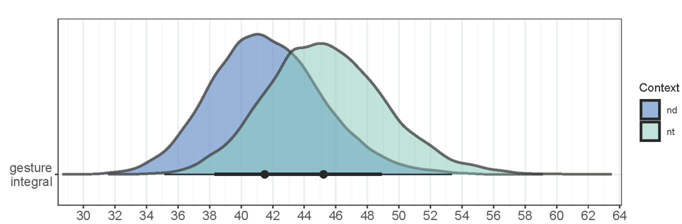


FIGURE 9. Marginal posteriors of the means of the integral of velum displacement within the vowel interval for /Vnd/ and /Vnt/ contexts. The 95% credible interval (thin line), the 66% credible interval (thick line), and the median (dot) are displayed below each density curve.

Based on these findings, it remains uncertain whether the slight increase of temporal coarticulatory vowel nasalization arising from the earlier onset of velum opening in the /Vnt/ context (§3.1) results in a net increase of the overall degree of vowel nasalization in the /Vnt/ vs. /Vnd/ environment: we have observed only weak evidence against the effect of voicing on the integrated velum gesture within the vowel interval.

4. DISCUSSION. Using acoustic measurements of nasalization, Beddor (2009) observed an inverse relationship between coarticulatory source (consonant nasalization) and effect (vowel nasalization) in /VN/ sequences of American English: increased [N] duration cooccurs with decreased [Ṽ] duration, and vice versa. Beddor proposed that this trading relation in production can be explained by the temporal shifting of a roughly constant-sized velum gesture: when the velum-gesture offset occurs earlier when preceding a voiceless consonant—an effect that arises due to physiological and/or acoustic constraints leading to NÇ repulsion (§1.2)—the velum-gesture onset likewise occurs earlier in the vowel, resulting in a decrease in the duration of the nasal consonant and a concurrent increase in the duration of coarticulatory vowel nasalization. This proposal is schematized in Fig. 1b of §1.3.

In the current study, we have used this proposal by Beddor as a starting point for the investigation of three scenarios that may potentially satisfy NÇ repulsion: EARLIER PHASING of the velum gesture (Fig. 1b), TRUNCATION of the velum gesture (Fig. 1c), and RESCALING of the velum gesture (Fig. 1d). We tested these proposals using a time-varying articulatory measurement of velum height gleaned from real-time MRI video of German. When preceding voiceless /t/, the kinematics of the velum opening gesture for the nasal /n/ in German were affected in a number of ways compared to when /n/ precedes voiced /d/. We summarize these effects as follows:

(i) The duration of the gesture was shortened by 19–43 ms.
(ii) The gesture began slightly earlier (6–19 ms), resulting in slightly greater duration of vowel nasalization.
(iii) The gesture peak began earlier (20–32 ms), shifting closer to the acoustic boundary between the vowel and the nasal consonant.
(iv) The gesture ended much earlier (36–59 ms), resulting in a much shorter nasal consonant.
(v) The gesture peak was smaller in magnitude (a decrease of 4–10% of the maximum range of velum opening).
(vi) The stiffness of both velum opening and velum closing was increased, and more so for velum closing.
(vii) There was no difference in the peakedness of the gesture.

Table 2 repeats the predictions given in Table 1 of §2.4, and summarizes the effects we have observed. At first glance, it appears that none of the three scenarios tested here (i.e. earlier velum phasing, velum-gesture truncation, velum-gesture rescaling) best represents the results observed in the current study. However, it is of course possible that a combination of these scenarios may be compatible with the observed effects. With this possibility in mind, we propose that NÇ repulsion is achieved in German through a combination of GESTURAL RESCALING (i.e. decreased duration and peak magnitude, increased stiffness) and EARLIER PHASING (i.e. earlier onset, peak, and offset). In other words, we propose that the velum gesture is both rescaled and rephased in the /Vnt/ context.

	REPHASING (Fig. 1b)	TRUNCATION (Fig. 1c)	RESCALING (Fig. 1d)	**OBSERVED**
Duration		decrease	decrease	**decrease**
Onset	earlier		later	**earlier**
Peak (timing)	earlier	earlier		**earlier**
Offset	earlier	earlier	earlier	**earlier**
Peak (magnitude)		decrease	decrease	**decrease**
Opening stiffness		increase	increase	**increase**
Closing stiffness		increase	increase	**increase**
Kurtosis		increase		
Crest factor		increase		

TABLE 2. Predictions for the nine metrics of velum-gesture timing and shape for each of the three scenarios depicted in Fig. 1, along with our study observations. Both predictions and observations are given for the velum gesture in the /Vnt/ context compared to the velum gesture in the /Vnd/ context. Predictions and observations corresponding to no difference between the two contexts are denoted by blank cells.

We have synthesized our observations in Figure 10 using a schematized representation of the alignment between oral (lingual) gestures (gray curves) and velum gestures (black curves) in VN sequences followed by a voiced or a voiceless obstruent. In this figure, the context of a VN sequence preceding a voiced obstruent is shown in the top panel (with an acoustic waveform of the English word *band* juxtaposed as a visual aid), and the context of a VN sequence preceding a voiceless obstruent is shown in the bottom panel. Line 'a' represents the onset of the velum gesture, line 'b' represents the boundary between V and N, and line 'c' represents the offset of the velum gesture; gray dotted lines are shown for the onset of the vowel (left) and the offset of the obstruent (right) as visual aids. Our proposal for the effect of a voiceless obstruent on the kinematics associated with the velum gesture of a preceding nasal consonant in VNC sequences is as follows: (i) the gesture is shortened at the right edge, near the oral consonant (line 'c' is shifted leftward to a relatively large degree); (ii) the gesture does not reach the same peak magnitude as is achieved before a voiced consonant; (iii) the gesture peak is shifted toward the vowel; and (iv) the onset of the gesture begins slightly earlier within the vowel interval (line 'a' is shifted leftward to a relatively small degree).

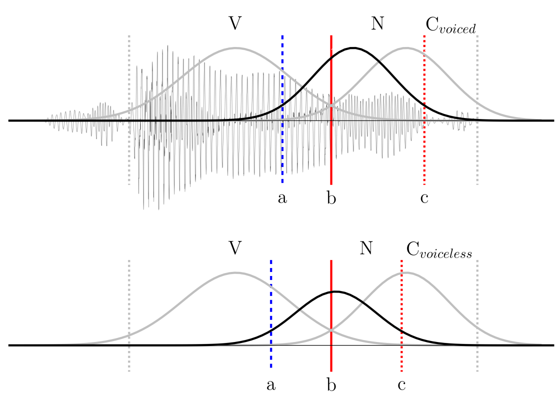


FIGURE 10. Our proposal for the velum opening gesture preceding a voiced oral stop (top) and a voiceless oral stop (bottom). The vowel and oral stop lingual gestures (denoted by solid gray lines) are given as reference. The interval of vowel nasalization is between lines 'a' and 'b', while the interval of consonant nasalization is between lines 'b' and 'c'.

Although we have observed evidence of a minor increase in the temporal degree of coarticulatory vowel nasalization (line 'a' of Fig. 10 shifts slightly leftward, i.e. forward in time), this is not due to temporal maintenance of the duration of the velum gesture. Moreover, we have observed evidence of a reduction in the magnitude of the velum gesture: the peak of the black curve in Fig. 10 is lower, as is the height of the black curve within the vowel interval (i.e. the black curve intercepts line 'b' at a lower point in the voiceless vs. the voiced scenario). It is possible that the reduction in the magnitude of the gesture counteracts the increase in the temporal degree of coarticulatory vowel nasalization, resulting in no net increase in the overall degree of nasalization in the vowel. Using the integral of the velum gesture within the vowel interval as a measure of the overall degree of nasalization, the results are most compatible with the interpretation that the degree of vowel nasalization by this measure is the same in /Vnt/ and /Vnd/ contexts. If it is indeed the case that there is no net effect of the degree of vowel nasalization due to the interaction of these two domains (i.e. increase in the temporal domain but decrease in the amplitudinal domain), it is possible that the earlier onset of the velum gesture in the /Vnt/ environment is a compensatory articulation used by speakers to counteract the reduced amplitudinal degree of nasalization (i.e. decreased velum opening magnitude). We are unable to further address this question with our current data, and future research would likely benefit from pursuing this possibility in a more direct and targeted manner, including exploring whether such a compensatory action might have an effect on the perceived degree of vowel nasalization.

4.1. Trading relation in two stages. The results observed in this study suggest that the NÇ̥ constraint results in a reduction of the velum gesture, and that the effects of this gestural reduction are primarily found within the nasal consonant interval: the duration of the nasal consonant is shortened and the magnitude of the gesture peak within the nasal consonant is diminished. The effects of the gestural reduction within the vowel interval are much smaller, and in some cases, we cannot determine whether there is an effect at all. In other words, the voiceless context reduces the source ([N] in /VN/ sequences) without necessarily increasing the effect ([Ṽ] in /VN/ sequences).[6]

The results for these German data further suggest that a trading relationship between source and effect does not arise directly from the phonetic constraint of a voiceless consonant, but perhaps occurs at a later stage in diachronic development. We propose that the effect we have observed here (i.e. rescaling/rephasing of the gesture in the voiceless context) acts as the catalyst for sound change to occur at a later diachronic stage, in that it creates an environment that is amenable to the development of a perceptual trading relation between source and effect. Our study has shown that the reduction of N in NÇ̥ does not necessarily lead to increased vowel nasalization, as has been shown for English and some other languages based on perceptual, acoustic, and aerodynamic data (Beddor et al. 2007, Cohn 1993a, Malécot 1960). If, as we have found, N is reduced but the degree of coarticulatory nasalization in the preceding vowel stays more or less the same, then there is necessarily a proportional increase in the degree of coarticulatory nasalization in the vowel relative to the source, the N, that gave rise to it. In other words, the proportion of the total realization of nasalization in the VN sequence is decreased for N and, thus, consequently increased (proportionally) for Ṽ.

It is this change in the proportionality by which nasalization is distributed between V and a following N in VNÇ̥ that might then form the basis of a perceptual reweighting of cues. It is of course well known that there are multiple cues to speech sounds that have different perceptual weights (Clayards 2018, Francis et al. 2000) and that listeners can reweight these cues in response to a change in the acoustic input (Francis & Nusbaum 2002, Harmon et al. 2019). We suggest that the first stage of the sound change arises if the (proportional) increase of nasalization in the vowel due to the diminished N leads to a reweighting of perceptual cues such that listeners begin to pay greater attention to the nasalization in the vowel. The second stage is if the cues to nasalization in the vowel and N begin to enter into a trading relationship, leading to the phonologization (Hyman 2013, Kiparsky 2015) and to the stabilization of vowel nasalization (Bermúdez-Otero & Trousdale 2012, Ramsammy 2015), in which the nasalization cues in the vowel are enhanced well beyond those predicted to occur by coarticulation alone (Kirby 2013, Solé 2007). Under this proposal, a language like German represents the phonetic effects

[6] It should be reiterated that we have only found weak evidence against an increase in the net effect of vowel nasalization. Under a conservative interpretation, this is neither evidence for nor evidence against the effect. Nevertheless, we have failed to find evidence for an increase in overall vowel nasalization that is concomitant with the (very strong) evidence that we have found for a decrease in overall consonant nasalization.

that are observable at the first stage of sound change (when the effects are primarily mechanical), whereas certain varieties of American English represent the phonetic effects that are observable at the second stage of sound change (when the effects begin to be controlled by the speaker; Solé 2007).

A two-stage development for the trading relation between source and effect can therefore account for the discrepancy between the results observed here for German (where the velum-gesture duration is not maintained) and those observed by Beddor (2009, 2012) for American English (where the velum-gesture duration is roughly maintained). It has been argued that vowel nasality has become phonologized to some extent in American English, most notably in VN sequences followed by a voiceless consonant (Beddor 2009, Mielke et al. 2017, Solé 2007, Zellou 2017); that is to say that velum lowering in this context has become ‘a required configuration for the vowel rather than being coarticulatorily linked to the consonantal closure’ (Beddor 2009:788). If this is indeed the case, we conjecture that certain varieties of American English have undergone the second stage of development, wherein a perceptual trading relation between coarticulatory source and effect has resulted in velum lowering becoming a required configuration for V in VNÇ sequences (Beddor 2009, 2012, 2015, Beddor et al. 2013). When a phonetic effect (such as vowel nasalization) becomes phonologized in a given language, the articulatory distinction is sometimes enhanced beyond what is observed in purely phonetic variation (Hyman 2013, Solé 2007). As such, velum lowering as a required configuration for the vowel in American English could manifest in a longer duration of vowel nasalization for /Vnt/ compared to what we have observed here for German, resulting in little to no difference in the overall temporal extent of nasalization (i.e. Ṽ + N) between /Vnt/ and /Vnd/ sequences of American English, effectively resembling temporally similar velum gestures in both contexts. We propose that German, by contrast, has not undergone this second stage of sound change development, and therefore the mechanical effect of the phonetic constraint in the voiceless context is manifested instead in the shorter velum-gesture duration in /Vnt/ compared to /Vnd/ sequences that we have observed here.

Appendix A: Speaker demographics

AGE	SEX	HOMETOWN	AGE	SEX	HOMETOWN
22	M	Bremen, Bremen	28	F	Lennestadt, NRW
25	F	Frankfurt am Main, Hessen	30	F	Brilon, NRW
31	M	Bernburg, Sachsen-Anhalt	22	F	Rheinland
26	F	Neuenbeken, NRW	19	F	Sankt Augustin, NRW
25	F	Lintig, Niedersachsen	22	F	Hann. Münden, Niedersachsen
22	M	Göttingen, Niedersachsen	22	F	Miehlen, Reinland-Pfalz
20	F	Bad Bodenteich, Niedersachsen	25	F	Oldenburg, Niedersachsen
35	M	Halle, Sachsen-Anhalt	23	M	Salzgitter, Niedersachsen
20	F	Gütersloh, NRW	23	F	Hohenkirchen, Niedersachsen
28	F	Schwerte, NRW	35	M	Bad Lauterberg, Niedersachsen
25	M	Beverungen, NRW	22	F	Kiel, Schleswig-Holstein
21	F	Hameln, Niedersachsen	25	F	Otterberg, Reinland-Pfalz
22	F	Göttingen, Niedersachsen	19	F	Dransfeld, Niedersachsen
33	M	Wettenberg, Hessen	25	F	Clausthal, Niedersachsen
22	F	Leer, Niedersachsen	22	M	Eschwege, Hessen
23	F	Fürth, Bayern	22	M	Seesen, Niedersachsen
19	M	Stade, Niedersachsen	28	M	Bregenstedt, Sachsen-Anhalt
22	M	Glückstadt, Schleswig-Holstein			

Table A1. Speaker demographic information. M = male, F = female, NRW = North Rhine-Westphalia.

APPENDIX B: CORPUS

SPELLING	GLOSS	IPA TRANSCRIPTION	TOTAL # OF ITEMS ANALYZED
ahnde	'punish'	/ʔaːndə/	2
ahnte	'guessed'	/ʔaːntə/	3
Ende	'end'	/ʔɛndə/	14
Ente	'duck'	/ʔɛntə/	9
Bande	'gang'	/bandə/	37
bannte	'averted'	/bantə/	35
Bunde	'bunches'	/bʊndə/	36
bunte	'colorful'	/bʊntə/	32
diente	'served'	/diːntə/	33
finde	'find'	/fɪndə/	35
Finte	'trick'	/fɪntə/	36
gönnte	'indulged in'	/gœntə/	36
lehnt	'leans on'	/leːnt/	33
Linde	'linden'	/lɪndə/	36
lohnt	'pays off'	/loːnt/	35
lohnte	'payed off'	/loːntə/	38
Panda	'panda'	/panda/	34
Panther	'panther'	/pantɐ/	33
pennt	'falls asleep'	/pɛnt/	37
Ränder	'rims/borders'	/ʀɛndɐ/	30
rannte	'ran'	/ʀantə/	28
Rente	'pension'	/ʀɛntə/	24
rinnt	'trickles'	/ʀɪnt/	27
Sande	'sand(s)'	/zandə/	33
sandte	'sent'	/zantə/	38
sahnt	'creams'	/zaːnt/	37
sahnte	'creamed'	/zaːntə/	34
schient	'splints'	/ʃiːnt/	36
schonte	'rested'	/ʃoːntə/	36
sehnte	'longed for'	/zeːntə/	34
sende	'send'	/zɛndə/	36
Senta	'(woman's name)'	/zɛnta/	34
Sonde	'probe'	/zɔndə/	39
sonnte	'sunned'	/zɔntə/	36
stöhnt	'moans'	/ʃtøːnt/	38
staunt	'marvels'	/ʃta͡ʊnt/	33
sühnt	'expiates'	/zyːnt/	35
thront	'enthroned'	/troːnt/	31
tönte	'tinted'	/tøːntə/	35
wandte	'turned'	/vantə/	35
weinte	'cried'	/va͡ɪntə/	35
winde	'coil/wind'	/vɪndə/	34
Winter	'Winter'	/vɪntɐ/	34

TABLE A2. Corpus and item count for the study.

APPENDIX C: CARRIER PHRASES

The construction of the carrier phrases is exemplified below, where the target word is denoted by **X**. Only items produced in condition 1 were analyzed in the current study. In this condition, X is nuclear-accented and the pitch accent occurs on the syllable of X with primary lexical stress (NB: this was always the initial syllable since all polysyllabic words had a trochaic stress pattern). Verb forms at the end of the carrier phrase (separated by slashes below) were varied randomly over the relevant target items.

(A1) Carrier phrases in which the target word X was in nuclear accent position
- a. Monosyllabic target word
  Wieder **X** erzählt/erklärt/erkannt.
  '(S/he) told/explained/recognized **X** again.'
- b. Disyllabic target word
  Wieder **X** gedacht/gehört/gesehen/gesagt.
  '(S/he) thought/heard/saw/said **X** again.'

(A2) Carrier phrases in which the target word X was in a nuclear accent position and with narrow focus on X (these contexts were not analyzed in the present study)
- a. Monosyllabic target word
  Bis er **X** erklärt/erkennt.
  'Until (s/he) explains/recognizes **X**.'
- b. Disyllabic target word
  Bis er **X** schreibt/sagt.
  'Until (s/he) writes/says **X**.'

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