Airflow in stop-vowel sequences of German

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This study reports on the results of an airflow experiment that measured the duration of airflow and the amount of air from release of a stop to the beginning of a following vowel in stop vowel-sequences of German. The sequences involved coronal, labial and velar voiced and voiceless stops followed by the vocoids /j, i:, ɪ, ɛ, ʊ, a/. The experiment tested the influence of the three factors voicing of stop, place of stop articulation, and the following vocoid context on the duration and amount of air as possible explanation for assibilation processes. The results show that the voiceless stops are related to a longer duration and more air in the release phase than voiced ones. For the influence of the vocoids, a significant difference could be established between /j/ and all other vocoids for the duration of the release phase. This difference could not be found for the amount of air over this duration. The place of articulation had only restricted influence. Velars resulted in significantly longer duration of the release phase compared to non-velars. A significant difference in amount of air between the places of articulation could not be found.

1 Introduction

The present article investigates the difference in the amount of airflow between voiced and voiceless stops followed by the vocoids /j, i̯, ɪ, ɛ, ʊ, a/ in German. Background for this investigation are phonological assibilation processes whereby stops are turned into affricates or fricatives before high vocoids, e.g. /ti/ surfaces as [s] in Finnish (Kiparsky 1973). In a typological study of assibilations in more than 30 typologically diverse languages, Hall & Hamann (to appear) postulated the following two implications:

(1) a) Assibilation cannot be triggered by /i/ unless it is also triggered by /j/.
b) Voiced stops cannot undergo assibilations unless voiceless ones do.

Following a study by Kim (2001) on assibilation in Korean, Hall, Hamann & Zygis (2004) give acoustic evidence for these implications in Polish and German. They measured the duration from stop burst until the beginning of the following vocoid /j, i/[1] (comprising burst frication, friction noise at the supralaryngeal place of articulation and aspiration), termed there and in the present article as 'friction' phase. This friction phase was significantly longer for /t/ than for /d/. Furthermore, for both voiced and voiceless stops, a following /j/ caused longer friction than a following /i/. Both observations are summarised in the following hierarchy of friction duration, where '>' stands for 'has longer friction duration than':

(2) /tj/ > /ti/ > /dj/ > /di/

The friction noise present in these sequences can be reinterpreted by listeners as lexically specified, i.e. as underlying fricative or as affricate, as Hall & Hamann (to appear) argue. Thus a longer friction phase is more likely to be reinterpreted as fricative than a shorter friction phase, which yields an acoustic motivation for the cross-linguistic implications in (1). The symbol '>' in the hierarchy in (2) can therefore also be read as 'is more likely to assibilate than'.

Hall et al. (2004) propose an aerodynamic explanation for the differences in friction length between voiced and voiceless stops: due to the open vocal folds, air can flow unimpeded for the voiceless stop, and more pressure builds up behind the constriction at closure, which results in longer (and stronger) friction at release. The difference between high vowel and glide is explained by referring to articulation and aerodynamics. The palatal glide might be articulated with a higher and more fronted tongue position than the high front vowel, and thus have a narrower constriction, which causes more air to built up behind the glide, again resulting in longer (and more forceful) friction. For earlier explanations along the same line, see Jäger (1978) and Ohala (1983).

The aim of the present study is to test the validity of the aerodynamic explanations by airflow measurements. If Hall et al.'s predictions are correct, then voiceless stops should not only show a longer duration of unimpeded airflow from the release of the stop until the beginning of the following vowel, see prediction (3a) below, but also a larger amount of air should be produced during this time interval, see prediction (3b). Furthermore, /j/ should cause a longer duration of airflow from burst until the onset of the following vowel and a larger amount of air over this time interval than /i/, cf. predictions (3c) and (d).

[1] The tense high front vowel is short in Polish and long in German. This difference is ignored in the present discussion of Hall et al.

(3) Four predictions:
 a) the voiceless stops show a longer duration of airflow in the friction phase than the voiced stops,
 b) the voiceless stops have a larger amount of air than the voiced stops over this time interval,
 c) the palatal glide causes a longer duration of airflow in the friction phase than the vowel /i/,
 d) the palatal glide causes a larger amount of air over this time interval than the vowel /i/.

Whereas Hall et al.'s investigation was restricted to coronal stops, the present study includes velar and bilabial stops, and in addition to the context of the palatal glide and the high front vowel /i/, the influence of a following /ɪ/, /ɛ/, /ʊ/ and /a/ on coronal stops is tested.

The predictions (3a) and (b) on the influence of stop voicing on the duration of airflow and amount of air lead to the following partial assibilation hierarchies in (4). These hierarchies have to be interpreted as /p/ has a longer duration of airflow in the friction phase and more air over this duration than /b/, and is thus more likely to assibilate than /b/, and so forth.

(4) p > b
 t > d
 k > g

The predictions on the influence of the following vowel or glide in (3c) and (d) can be extended to include further vowel contexts on the basis of the following principle. For a smaller area of constriction, i.e. a higher vowel, we expected a longer duration of airflow and larger amount of air. This results in the assibilation hierarchy in (5), where the vowels /ɪ/ and /ʊ/ are not ranked with respect to each other because they share the same vowel height.

(5) j > i: > {ɪ, ʊ} > e > a

The study by Hall et al. does not look at the influence of the place of articulation on the friction duration of stops and thus their likelihood to assibilate. We hypothesize that velars show a longer duration of airflow and amount of air in the friction phase than coronals. This is due to the shorter supralaryngeal cavity (looking downstream towards the glottis) in velars which results in more air pressure to built up behind the constriction, and which then yields a longer friction phase at the release and/or more air during the friction phase. For the same reason, coronals are expected to have a longer duration of airflow and amount of air than labials. These expectations are formalised in the following hierarchy, which again predicts the highest likelihood for the item on the left to assibilate, and lowest for the item on the right:

(6) velar > coronal > labial

The following section describes the experimental setup to test the three (partial) hierarchies (4) – (6). In section 3, results of this experiment are presented. Section 4 concludes.

2 Method

Our subjects were four native German speakers (two male and two female). Each subject was asked to repeat the items in Table 1 five times in the carrier sentence “habe … gesagt” ‘said …’. This item set includes coronal, labial, and velar stops, both voiced and voiceless, followed by /i:/, /ɪ/ and /ja/. For the coronals, we furthermore used the following vowels /e/, /ʊ/, and /a/. Though all of these items are phonotactically well-formed in German, the sequences with stop plus glide have a very restricted occurrence and are mainly the result of an optional gliding process (e.g. *Opiat* [op.’ja:t] ‘opiate’, *Median* [me.’dja:n] ‘median’), see Hamann (2003) and Hall (to appear). For this reason we chose nonsense words.

Table 1: Test items (nonsense words).

tiek	tick	tjack	diek	dick	djack
teck	tuck	tack	deck	duck	dack
piek	pick	pjack	biek	bick	bjack
kiek	kick	kjack	giek	gick	gjack

We measured the oral airflow with the PCquirer hardware from Scicon, and carried out the data analysis with PRAAT (Boersma & Weenink 2005). For every test item, we measured the duration from release of the stop until the onset of the following vowel (i.e. the friction phase). The onset of the following vowel was determined by the beginning of the second vowel formant (in ambiguous cases, we took the beginning of higher formants and of periodicity as additional criteria). An example audio waveform, spectrogram and waveform of the airflow is given in Figure 1 for the word *tjack*. This figure shows the points of measurement in the waveform of the airflow with dotted lines. In addition to the duration of the friction phase, we calculated the sum of the amount of air that was produced over this time interval (i.e. the integral).

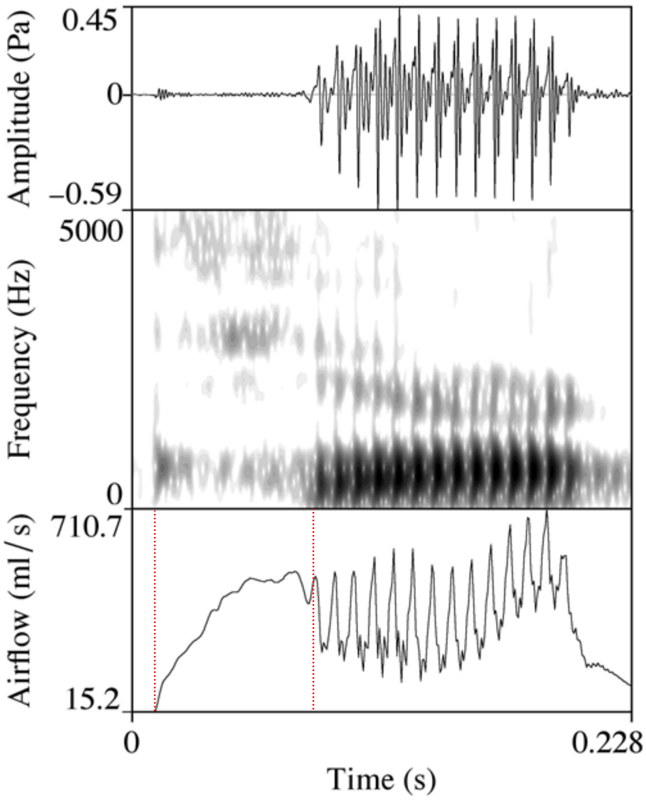

Figure 1: Waveform of the acoustic signal, spectrogram, and waveform of the airflow for *tjack*. The dotted lines in the airflow indicate the beginning and the end point of the measurements.

3 Results

The results are presented in the following order. In the first subsection (3.1), the influence of voicing of the consonant is given. In subsection 3.2, the influence of the following vocoid is presented, and in the last subsection (3.3), the influence of place of articulation is discussed. For each parameter, we give both the duration of friction and the amount of airflow produced over this duration. Due to the small number of repetitions, the following statistical analyses are all averaged over speakers. An interaction between speaker and duration could not be found, and an interaction between speaker and amount of air was observable only in half of the cases.

3.1 Influence of voicing

Figures 2 and 3 show the average duration (in ms) from burst until onset of the following vocoid and the average amount of air (in ml) over this duration for all stops and all four speakers. The vertical axes show the stops split by voicing, the different shading indicates the place of articulation (see the legends to the right).

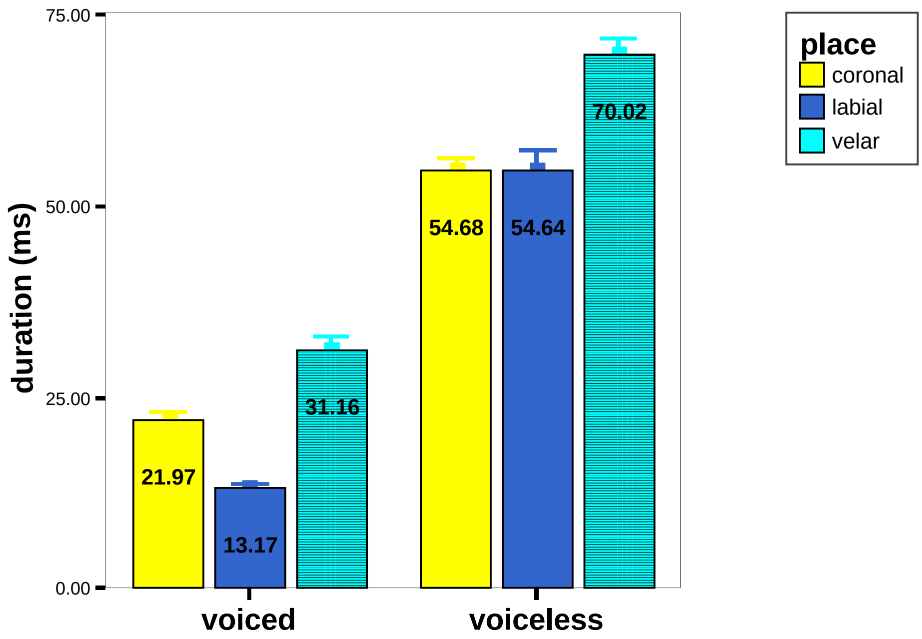

Figure 2: The average duration from stop release to the start of the following vowel (in ms) split according to voicing of the stops for all four speakers. Error bars indicate standard error.

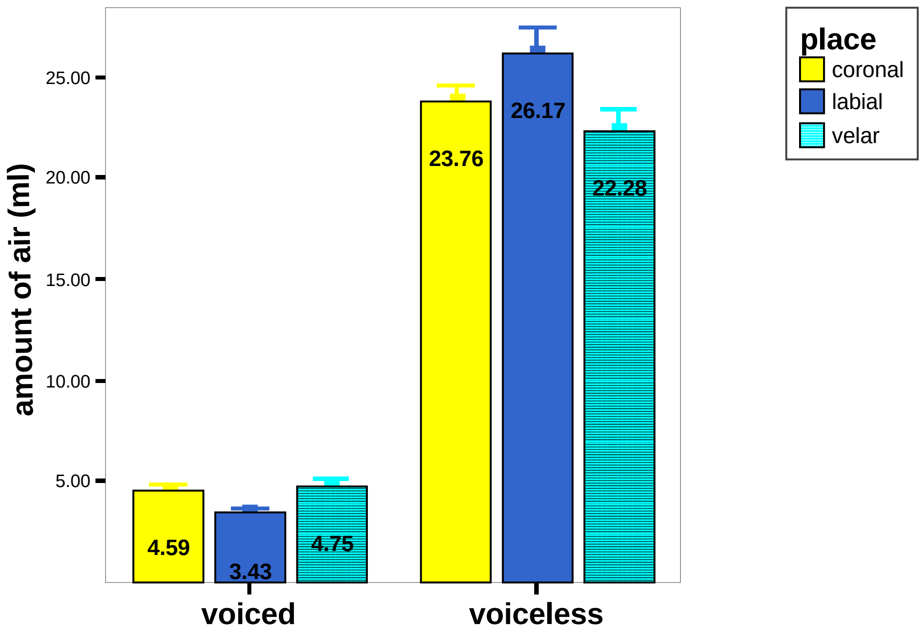

Figure 3: The average amount of air from stop release to the start of the following vowel (in ml) split according to voicing of the stops for all four speakers. Error bars indicate standard error.

A one-factorial ANOVA[2] with voicing as independent variable and the duration as dependent variable showed that the voicing had a significant influence, both for all places calculated together and for each place of articulation calculated separately (for all places of articulation together $F(1, 480) = 577.409$, $p < 0.001$; for coronals $F(1, 239) = 269.4$, $p < 0.001$; for labials $F(1, 119) = 207.682$, $p < 0.001$; for velars $F(1, 120) = 206.626$ $p < 0.001$). The analysis of the results in Figure 2 thus supports prediction (3a).

Similarly, the analysis of the results presented in Figure 3 supports prediction (3b), because the voiceless stops all result in a larger amount of airflow over the friction duration than the voiced stops, both calculated for all three places of articulation together and separately (for all together $F(1, 480) = 1018.969$; for coronals $F(1, 239) = 511.068$, $p < 0.001$; for labials $F(1, 119) = 333.705$ $p < 0.001$; for velars $F(1, 120) = 200.181$ $p < 0.001$).

These two results taken together give evidence in support of the assibilation hierarchy in (4).

3.2 Influence of the following vocoid

The influence of the following vowels /i̯, ɪ, ɛ, ʊ, a/ and the glide /j/ averaged over all four speakers are shown in the following two figures. The friction duration (in ms) is given in Figure 4 and the amount of air (in ml) over this duration in Figure 5. The vertical axes give the stops split according to the vocoid context.

A post-hoc Scheffé test showed that only the influence of the following glide on the duration of friction (as represented in Figure 4) is significantly different from the influence of all other contexts. The difference between the vowel /i:/ and /ʊ/ is almost significant ($p < 0.007$). The analysis of the amount of air split according to the vowel context, as represented in Figure 5, did not yield any statistically significant results.

It has to be pointed out that the investigation of the influence of the vowels /a, e, ʊ/ was restricted to coronals (cf. the item set in Table 1).

[2] All statistical calculations were made in SPSS 11.5.1.

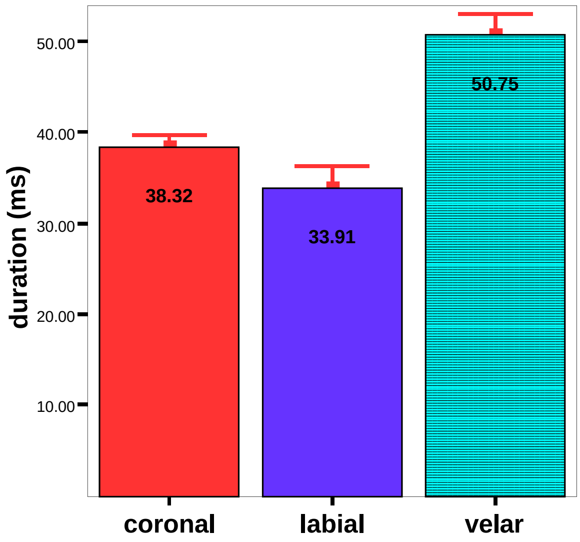

Figure 4: The duration from stop release to the start of the following vowel (in ms) split according to voicing of the stops for all four speakers. Error bars indicate standard error.

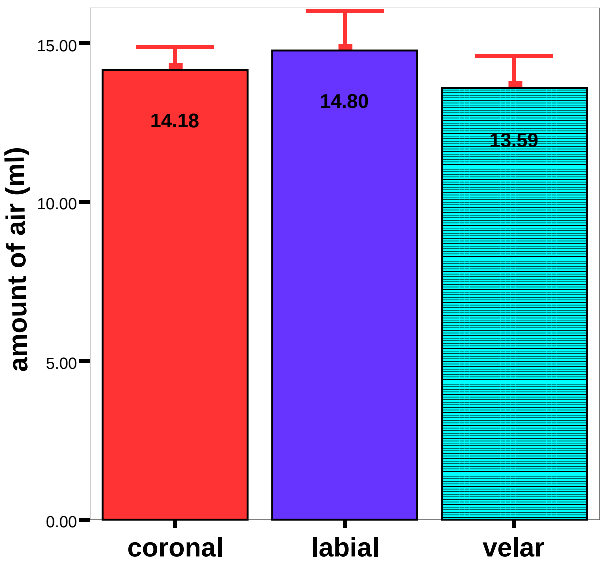

Figure 5: The average amount of air from stop release to the start of the following vowel (in ml) split according to voicing of the stops for all four speakers. Error bars indicate standard error.

3.3 Influence of the place of articulation

Figures 6 and 7 on the next page show the average duration (in ms) for the friction phase and the average amount of air (in ml) over this duration, respectively, for all places of articulation and all four speakers. The vertical axes show the stops split according to their place of articulation.

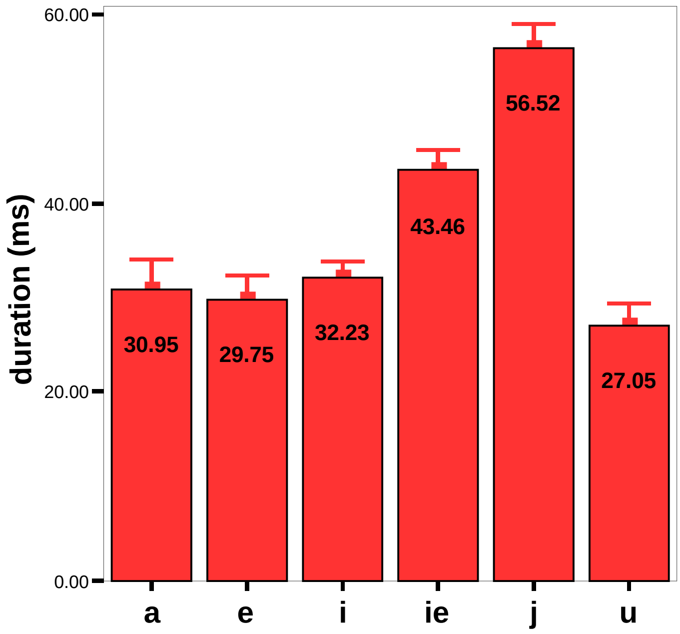

Figure 6: The duration from stop release to the start of the following vowel (in ms) split according to voicing of the stops for all four speakers. Error bars indicate standard error.

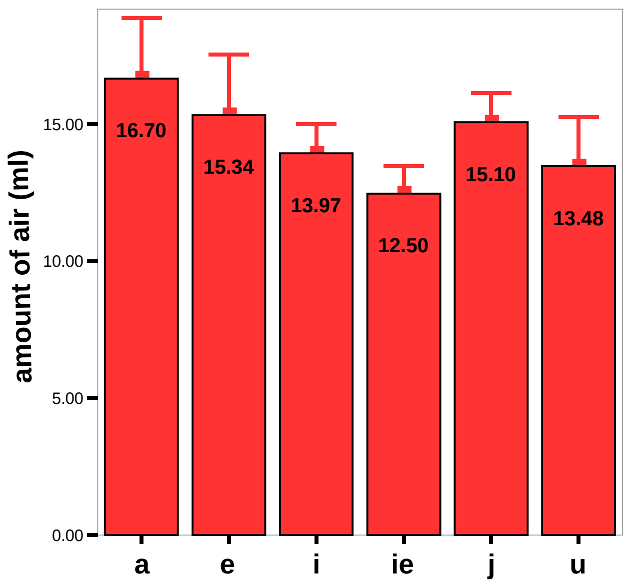

Figure 7: The average amount of air from stop release to the start of the following vowel (in ml) split according to voicing of the stops for all four speakers. Error bars indicate standard error.

The difference in duration (Figure 6) between coronal and velar place of articulation is statistically significant ($p < 0.001$) and so is the difference between labial and velar place of articulation ($p < 0.001$). The difference between coronals and labials is not significant (all results obtained by a post-hoc Scheffé test). None of the differences in amount of air (Figure 7) are significant.

4 Summary and discussion

The present study experimentally tested the influence of stop voicing, the following vowel and the place of articulation on the possible assibilation of a stop. We measured both the duration of airflow and the amount of air from release of a stop to the beginning of the following vowel in stop vowel-sequences of German.

Both in the duration measurement and the measurement of the amount of airflow a statistically significant difference was found between voiced and voiceless segments. The present study thus reproduced the findings by Hall et al. (2003), where the coronal voiceless segments showed a longer duration of the release phase than their voiced counterparts. In addition, the difference in duration and amount of air for the voicing condition could be established for the labial and velar places of articulation. This gives evidence for the partial hierarchies established in (4), repeated here in (7):

(7) p > b
t > d
k > g

The findings on the difference in release duration between voiced and voiceless stops are in accordance with the literature, see e.g. Isshiki & Ringel (1964), Klatt et al. (1968), and Warren (1996). It can be accounted for with the fact that the vocal fold vibration impedes the flow of air and consequently the duration and amount of air in the friction phase, see the discussion of Hall et al. (2003) in section 1.

For the influence of the following vocoid, only one context was significantly different from all others, namely that of the following glide /j/. This finding holds only for the duration of friction, the amount of air did not significantly differ between any of the vocoids. The assibilation hierarchy on the vocoid influence in (5) has to be changed accordingly to the one in (8).

(8) j > {iː, ɪ, ʊ, e, a}

This hierarchy is again in accordance with the findings by Hall et al. (2003). The fact that the quality of the other following vowels does not matter is not expected, see, however, similar results in Klatt et al. (1968: 45). The small number of tokens with the vowels /a, e, ʊ/ might be responsible for these findings.

The influence of the place of articulation was mainly not significant, only the duration measurement showed a significant difference between coronals or labials and velars. The assibilation hierarchy for place of articulation in (6) therefore has to be modified in the following way:

(6) velar > {coronal, labial}

Klatt (1975) and Keating, et al. (1980) found a difference in voice onset time (VOT) for voiceless plosives that is similar to the present durational hierarchy. The measure of friction duration employed in the present study is identical to VOT, but only for voiceless stops. According to Keating et al. the duration in VOT is "somewhat larger for alveolars than for labials and substantially larger for velars than for either" (p.93). Thus our present durational findings confirm those of previous studies. The hierarchy in (6) could not be attested with the measurements on the amount of air.

Summing up, there is durational evidence for the assibilation hierarchies established in Hall & Hamann (to appear), namely the difference in influence between voiced and voiceless stops and the difference in influence of the following glide and high front vowel on the likelihood of assibilation for the stop. We could not only confirm a difference for coronals (as in Hall et al.'s measurements) but also for velars and labials. And in addition to the durational differences, we found statistical differences in the amount of air depending on the place of articulation. For the special status of the glide /j/ in assibilation processes, our durational measurements attested this (again supporting Hall et al.'s study). The difference in the amount of air for glide versus non-glide context did not prove to be significant.

In general, the present study showed that the amount of air seems not to be a reliable predictor for assibilation processes, although this assumption has to be further tested with studies that involve larger samples.

Acknowledgements

We would like to thank Jana Brunner, Christian Geng and Daniel Pape for helpful comments, and Jörg Dreyer for technical support. We gratefully acknowledge funding by the German Science Foundation (DFG) grant GWZ 4/8-1-P2 to Silke Hamann.

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