DEVOICING OF WORD-INITIAL STOPS: A CONSEQUENCE OF THE FOLLOWING VOWEL?

Daniel Pape [1], Christine Mooshammer [2], Phil Hoole [3] &
Susanne Fuchs [14]

[1] ZAS Berlin, Germany
[2] Christian-Albrechts-Universität zu Kiel, Germany
[3] LMU München, Germany
[4] QMUC Edinburgh, U.K.

ABSTRACT: The aim of the current study is to investigate the contextual conditions of devoicing of phonologically voiced stops. Therefore articulatory and acoustical data of four male speakers were recorded by means of EMMA and EPG. Devoicing was observed more frequently for the velar stops with 46.3% than for the bilabial with 26.4%. The highest occurrence of devoicing was observed when followed by a low vowel. Analyses of variance were computed to test whether this distribution of devoicing was due to an anticipatory effect of the following vowel at the beginning of the stop closure. All subjects showed significant effects on positional data whereas the EPG measures varied only slightly. We assume that in German economical demands, i.e. coarticulation, are more important than the maintenance of voicing during the closure, which is in agreement with the view that the voicing distinction in German is primarily produced by a longer VOT of the voiceless stops.

1. INTRODUCTION

It is generally acknowledged that the main conditions for voicing are sufficient adduction and tension of the vocal folds, and a sufficient transglottal pressure drop. Devoicing of stops can be attributed to the fact that due to the accumulation of air behind the closure the transglottal pressure drop decreases and the vocal folds frequently stop vibrating (see e.g. Ohala and Riordan, 1980). The mechanism of passive devoicing seems to be exploited by speakers even for the production of voiceless stops in post-stressed word-medial position. Aspirated voiceless /t/ was quite frequently realized without a glottal abduction gesture as was found in a transillumination study by Fuchs (2003) (see also for an overview on earlier studies). A possible strategy to counteract the effect of air accumulation behind the closure is to actively enlarge the cavity which was extensively investigated by Westbury (1983). He found that depending on the place of articulation tongue, jaw, larynx and the soft palate can contribute to cavity enlargement. Several factors have been found to influence devoicing of phonologically voiced stops:

1) Position in utterance: to examine the likelihood of voiced and devoiced stops in different positions in an utterance, Westbury and Keating (1985) computed the different aerodynamic conditions given by different positions of a stop in an utterance. They found (1) from an aerodynamic point of view it is more likely to produce a voiced stop in intervocalic position and (2) voicing could be maintained due to tissue compliance for about 60 ms. However, in utterance initial and final position aerodynamic demands are more likely to produce a voiceless stop.

2) Voicing status of context: Shih and Möbius (1999) found strong contextual influences on the devoicing patterns of stops in different languages, i.e. the voicing of phonologically voiced German stops were strongly dependent on whether the preceding context was voiced or voiceless.

3) Place of articulation: Ohala and Riordan (1980) found that velar stops are more often subject to devoicing due to less surface area behind the point of constriction. This limits their capacity for passive enlargement which is necessary to keep the pharyngeal pressure low. Keating et al. (1983) found that the duration of voicing into closure varies with place of articulation in English and Swedish.

4) Vowel context: Ohala and Riordan (1980) observed that stops coarticulated with high vowels permitted voicing to continue longer than those coarticulated with low vowels, due to the enlarged pharyngeal cavity for high vowels.

The general aim of the current investigation is to study devoicing effects in dependency of the following vowel. Therefore we extend the work of Ohala and Riordan (1980) to a greater variety of vowel contexts, i.e. to the whole German vowel inventory. The second aim is to test their hypothesis that coarticulatory influences cause the vowel-specific distribution of devoicing occurrence by means of articulatory measurements. Therefore we conducted a combined EMMA, EPG and acoustic experiment to investigate the causes for devoicing of phonologically voiced word-initial stops in German.

METHOD

Experimental setup: We investigated tongue and jaw movements together with tongue-palate contact patterns by means of synchronized EPG (Reading EPG3), EMMA (AG100, Carstens Medizinelektronik) and acoustic recordings of our four subjects (CG,DF,JD,RW).. Four sensors were attached mid-sagittally to the tongue, one to the jaw (lower incisors) and one to the lower lip. The audio signal was recorded on DAT. We will focus on bilabial and velar stops. The speech material consisted of nonsense words /gVkə/ for the velars and /bVpə/ for the bilabials, where V consisted of the 14 German tense and lax vowels /iː yː uː ɪ ʏ ʊ eː øː oː ɛ œ ɔ ɑː a/. The target words were embedded in the carrier phrase “Sage __ bitte.” (“Say __ please.”). Each sentence was repeated 10 times except for speaker RW whose sensors came off after 8 repetitions.

Acoustic and articulatory measurements: Following our goal, our intention was to measure articulatory positions with respect to a reference, the onset of stop closure. The onset of a stop closure following a vowel is usually labeled as the offset of higher formants. Since in our data a word boundary occurs before the relevant stop, we chose another measurement criterion. After looking carefully at the data we observed that formant offset was highly variable. In order to get a more reliable measurement, a relevant decrease of intensity was operationally labelled as –6dB, measured from the maximal intensity of the preceding vowel. At this acoustically defined landmark of closure onset we measured the horizontal and vertical positions of the tongue dorsum (Tdors), tongue back (Tback), jaw and lower lip (Llip) sensors. From the EPG data the centre of gravity index (COG) and the percentage of contacts in the posterior palatal region (POST) were calculated by using the formulae given in Gibbon and Nicolaidis (1999).

RESULTS

Occurrence of Devoicing: Figure 1 shows the percentages of devoicing for all speakers split by place of articulation and following vowel. As was expected the velar stop is more often subject to devoicing than the bilabial stop (46.3% vs. 26.4%). The percentage of devoicing clearly increases with decreasing vowel height, e.g. the bilabial stop was more often devoiced when followed by the mid and low vowels /ɑː, a, ɛ, ɔ/ compared to the high vowel /iː, yː, uː, eː/. These findings are generally in agreement with previous studies. Furthermore a slight tendency can be observed for bilabials preceding rounded vowels to be less often devoiced than their unrounded counterparts (exception: high tense vowels).

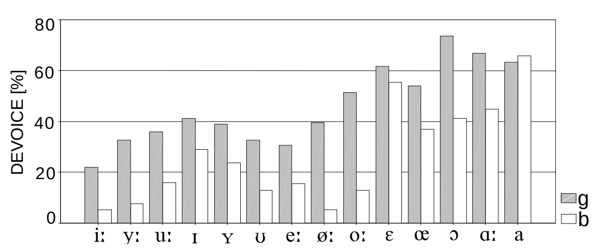

Figure 1. Percentage of devoicing, shown for each vowel and the contexts /b/ and /g/. The vowels are ordered by their phonological vowel height.

Table 1 shows the percentage of stop devoicing for each vowel, split by speaker and stop. Data of each speaker show similar relationships between devoicing and vowel height, but the overall amount of devoicing varies speaker-dependently, e.g. speaker DF is more prone to devoicing the bilabial than speaker CG. Speaker JD’s devoicing pattern for the bilabial is exceptional, with almost no instances of devoicing. This speaker uses a strategy to avoid devoicing by prenasalizing the bilabial but not the velar stop which was visible in the spectrogram.

Table 1. Percentage of stop devoicing split by speaker and place of articulation depending on the following vowel

	Bilabial stop				Velar stop			
Vowel	CG	DF	JD	RW	CG	DF	JD	RW
iː	0.00	20.00	0.00	0.00	0.00	50.00	0.00	25.00
yː	0.00	18.18	0.00	12.50	20.00	66.67	10.00	37.50
uː	10.00	0.00	10.00	50.00	20.00	63.64	20.00	37.50
ɪ	20.00	60.00	0.00	37.50	11.11	63.64	40.00	44.44
ʏ	10.00	70.00	0.00	12.50	10.00	80.00	25.00	37.50
ʊ	20.00	18.18	0.00	12.50	0.00	63.64	10.00	55.56
eː	0.00	27.27	20.00	12.50	0.00	60.00	22.22	37.50
øː	0.00	18.18	0.00	0.00	10.00	80.00	50.00	12.50
oː	0.00	18.18	0.00	37.50	40.00	100.00	10.00	50.00
ɛ	50.00	100.00	10.00	62.50	20.00	81.82	66.67	77.78
œ	20.00	70.00	0.00	62.50	40.00	90.91	30.00	50.00
ɔ	30.00	72.73	0.00	62.50	70.00	100.00	80.00	37.50
ɑː	40.00	70.00	10.00	62.50	80.00	81.82	40.00	62.50
a	70.00	100.00	0.00	100.00	60.00	100.00	33.33	50.00

Anticipatory effects on articulatory positions at consonantal closure onset: The vowel-specific distribution of devoicing suggests that the following vowel influences the volume of the oral cavity during occlusion. To test whether tongue, jaw and lip positions are also affected by the identity of the following vowel at the moment of the acoustically defined consonant onset ANOVAs were calculated with vowel identity as independent variable and positions of the articulators and EPG-measures as dependent variables split by speaker and consonant. For the EPG measures the COG was insensitive for vowel context but the POST increased significantly for all speakers and both consonants comparing front high vowels with low back vowels. At the onset of the velar the position of the most posterior tongue sensor (TBACK) was not affected by the vowel but the vertical positions of the more fronted sensor (TDORS) varied significantly with vowel height for three speakers (n.s. for RW). Jaw positions for velars were not influenced by the following vowel. In contrast for the bilabial both tongue sensors varied significantly according to the following vowel in the expected direction. The jaw tended to be significantly more closed when the following vowel was rounded for speakers DF and JD. The horizontal lip position at the onset of the bilabial was affected by rounding for three speakers but significant only for speaker JD, the speaker who maintained voicing most effectively for the bilabials. This speaker also showed a peculiar pattern for the vertical lip position, with lower values for following rounded vowels, whereas the other speakers tended to lower the lower lip for unrounded vowels (not significant).

To summarize the results so far, significant vowel effects could be detected at the onset of the consonant. The affected articulators vary with place of articulation, e.g. jaw and tongue back positions do not vary for the velar but for the bilabial whereas lip protrusion is significant at the onset of the velar but not of the bilabial except for speaker JD.

Relationship Devoicing-Positions: To analyse which of the articulators might have an influence on the occurrence of devoicing we computed correlations between positional data and the percentage of devoicing calculated over 10 repetitions of each item. Table 2 shows the correlation coefficients and the level of significance.

Table 2. Correlation coefficients between devoicing and articulatory measurement points. Significant values (p=.05) are marked with a grey cell background. Highly significant values (p=.01) are bold printed.

	CG(B)	DF(B)	JD(B)	RW(B)	CG(G)	DF(G)	JD(G)	RW(G)
TbackX	0.291	-0.113	-0.273	0.173	-0.577	0.593	-0.483	-0.386
TdorsX	0.354	-0.050	-0.345	0.353	-0.167	0.544	-0.664	0.090

JawX	0.214	0.276	-0.096	-0.258	0.009	-0.250	0.610	-0.017
LlipX	0.433	0.156	0.175	-0.133	0.053	-0.234	0.348	0.366
TbackY	-0.399	-0.129	-0.168	-0.499	-0.425	-0.638	-0.571	-0.292
TdorsY	-0.478	-0.071	-0.075	-0.533	-0.465	-0.665	0.173	-0.553
JawY	**-0.669**	**-0.700**	-0.401	-0.469	**-0.715**	-0.038	-0.647	-0.639
LlipY	0.058	-0.475	0.313	-0.165	-0.388	0.143	0.109	-0.551
COG	0.201	-0.183	0.143	-0.181	-0.029	-0.349	0.024	-0.632
POS1	-0.149	0.073	-0.088	-0.489	-0.642	-0.570	0.002	-0.481
DurC	0.176	**0.738**	-0.152	**0.664**	-0.586	0.309	-0.134	-0.010

For the bilabial stop the devoicing pattern can only be related to the vertical jaw position for two speakers with a highly significant negative correlation, i.e. the lower the jaw position the higher the percentage of devoicing (see also figure 2, left panels). The jaw positions of speakers CG and DF also varied significantly with vowel height. Speakers JD and RW showed no significant correlations at all for the bilabial. For speaker JD obviously this can be attributed to the very rare instances of devoicing. Lip rounding (LlipX) was never significantly related to the percentage of devoicing. The duration of the bilabial was positively correlated for two speakers, i.e. the longer the stop the higher the likelihood for devoicing.

Bilabials: Velars:

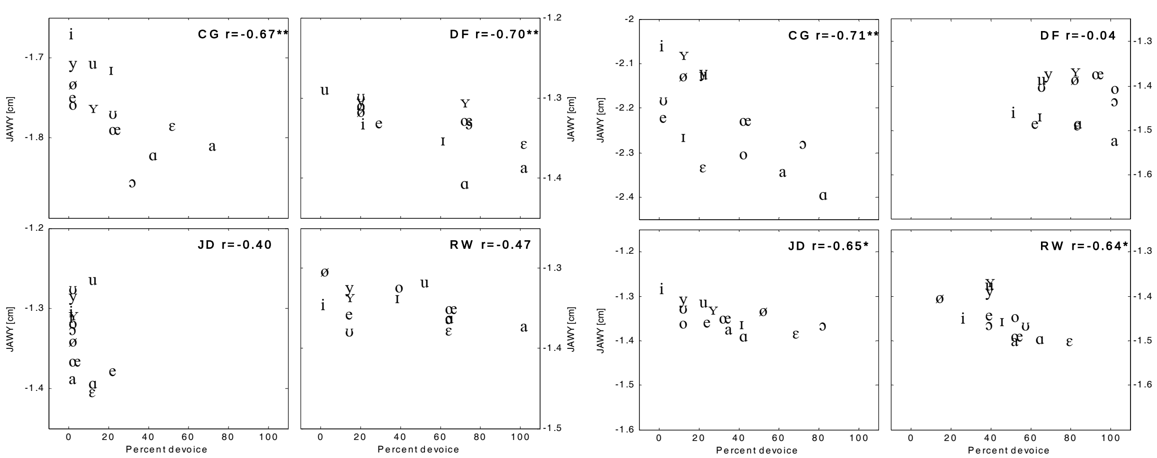

Figure 2. Scatterplots of the percentage of devoicing and the vertical jaw position at consonant onset of bilabials (left) and velars (right) for means of each speaker.

For the velar stop the devoicing pattern is also related to the vertical jaw position for three speakers, for CG with a highly significant correlation. For two speakers the POST and for speaker RW the COG were significantly negatively correlated to the percentage of devoicing. The vertical tongue sensors showed a negative correlation, i.e. the lower the tongue, the higher the percentage of devoicing (not significant for speaker CG). For the two posterior tongue sensors, which are assumed to capture best the velar articulator, oppositional patterns could be observed for speakers CG and JD on the one hand and speaker DF on the other hand. The latter fronted the place of articulation before front vowels. Because of the curved shape of the palate the tongue was also higher before front vowels. Furthermore speaker DF tended to devoice /g/ more frequently when the stop was followed by a back vowel which was not the case for speakers CG and JD. These two speakers showed no fronting of the velar with a following front vowel but significant negative correlations between horizontal tongue positions and devoicing, i.e. the more fronted the tongue the more frequently devoicing occurred which is rather surprising in view of the back cavity volume. No significant correlations between devoicing and horizontal tongue positions could be found for speaker RW. Figure 2 shows scatterplots of the percentage of devoicing and the averaged vertical jaw position split by speaker and consonant.

To achieve an objective measure of the relevance of the measured parameters for the occurrence of devoicing SPSS stepwise regression models were computed with percentage of devoicing as dependent variable and articulatory positions of tongue back, tongue dorsum, jaw and lower lip sensors, the EPG measures POST and COG as well as the stop duration as independent variables. Table 3 shows the extracted regression models with the predictors selected by stepwise regression models, explained variance (R^2), the F values and the probability. As can be seen no model could be extracted for speaker JD for the devoicing pattern of bilabials. Closure duration does only play a significant role for the bilabials (speakers DF and RW) but not for the velars. The inclusion of the vertical jaw component improved the prediction considerably for speakers DF and RW whereas for speaker CG only the vertical jaw position met the criterion for inclusion (F>3.84) and explains about 45% of the variance. The occurrence of devoicing of velar stops is best predicted by the vertical jaw position for speakers CG and RW. Surprisingly in two cases the horizontal jaw position is included in the models. The inclusion for speaker CG can be attributed to a suppression effect of JAWX because it does not correlate with the criterion variable but significantly improves the model due to the high correlation between JAWX and JAWY (Bortz 1979). This is not the case for speaker JD whose pattern of devoicing significantly varies with jaw retraction. The main predictor variable for this speaker is the horizontal tongue dorsum position. As can be seen in figure 3 speaker DF produces the velar stop with a higher jaw position when followed by a rounded vowel. Therefore the jaw is not selected as a predictor variable for devoicing but the vertical tongue dorsum position.

Table 3. Regression models computed by the SPSS procedure linear stepwise regression. Degrees of freedom are always 1,13. The dependent variable is percentage of devoicing and the independent variables are articulatory positions and EPG measures at the onset of the stop as well as stop duration.

CONS	VP	Model	R^2	F	prob
Bilabial	CG	JAWY	0.448	9.73	0.0089
	DF	DUR	0.545	14.37	0.0026
		DUR,JAWY	0.774	18.83	0.0003
	RW	DUR	0.442	9.51	0.0095
		DUR,JAWY	0.611	8.64	0.0056
Velar	CG	JAWY	0.511	12.53	0.0041
		JAWY, JAWX	0.767	18.12	0.0003
	DF	TDORSY	0.442	9.50	0.0095
	JD	TDORSX	0.441	9.46	0.0096
		TDORSX, JAWX	0.636	9.60	0.0039
	RW	JAWY	0.408	8.27	0.0139

CONCLUSION AND DISCUSSION

In this study, we investigated the occurrence of devoicing in phonologically voiced stops and its dependency on the following vowel. We measured articulatory data (EMMA and EPG) at the acoustically defined closure onset. Dependent on the place of articulation of the stop, devoicing was more frequently found for the velar with 46.3% compared to the bilabial with 26.4%. In accordance with earlier studies (Ohala and Riordan, 1980), we found that the percentage of stop devoicing increases when followed by a low vowel.

Additional evidence was provided by articulatory data, where significant vowel effects were found. The affected articulators vary with place of articulation of the stop. Correlation between articulatory data and percentage of devoicing revealed significant correlations for the vertical jaw position for both stops. For the velar significant correlations with vertical and horizontal tongue positions were found. Closure duration shows only a significant effect on the percentage of devoicing for the bilabial for two of the four speakers. Since passive compliance of the walls plays a greater role for bilabials (see Keating 1983) occurrences of devoicing might be more strongly affected by closure duration, i.e. the cavity enlargement due to lax cheeks provides a sufficient pressure drop only for shorter closure durations. This possibility of cavity enlargement does not exist for velars.

One shortcoming of our experiment is that aerodynamic factors such as the volume of pharyngeal cavity, transglottal and intraoral pressure are not captured as well as positions of articulatory structures such as larynx height or velum which contribute to the size of the oral cavity (see Westbury 1983). However, even with our limited data set we are tempted to conclude that cavity enlargement does not seem to play a major role in the production of German stops. Our results are in accordance with the results of Jessen (2001) and others who stated that in Germanic languages other features for voiced/voiceless stop distinction, mainly aspiration duration, are of greater importance than the maintenance of voicing throughout the complete stop closure. Even though anticipatory effects of the following vowel on the occurrence of stop devoicing vary speaker-dependently, economical requirements play a more important role than the maintenance of voicing in German.

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