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Devoicing of Word-Initial Stops

A Consequence of the Following Vowel?

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ABSTRACT

The aim of the current study is to investigate the contextual conditions of devoicing of phonologically voiced stops (bilabial and velar). Articulatory and acoustic data from four male speakers were recorded by means of EMMA and EPG. Devoicing was observed more frequently for the velar stops than for the bilabials. The highest occurrence of devoicing was observed when the voiced stop was followed by a low or mid-vowel. To test whether articulatory positions are affected by the identity of the following vowel ANOVAs were computed. All subjects showed significant effects on positional data varying with place of articulation of the stop. Percentage of devoicing was significantly correlated with vertical and horizontal tongue positions for the velar and with the vertical jaw position for both stops. Stepwise regression models were computed to achieve an objective measure of the relevance of the measured parameters. We assume that in German, movement economy, i.e., co-articulation is 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 for the voiceless stops.

INTRODUCTION

Devoicing of stops can be attributed to the fact that, due to the accumulation of air behind the oral closure, the transglottal pressure drop decreases and the vocal folds stop vibrating (see e.g., Ohala & Riordan, 1980).

Accordingly, devoicing of stops is generally a natural consequence of an oral closure, assuming the velar port is closed and the speaker does not produce an active or passive mechanism to overcome the transglottal pressure drop. A passive mechanism for this maintenance of voicing would be soft-tissue compliance, e.g., for the cheeks during the production of bilabials. A possible active strategy to counteract the effect of air accumulation behind the closure is to enlarge the intraoral cavity. This so-called cavity enlargement was investigated by Westbury (1983), who found that, depending on the place of articulation, tongue, jaw, larynx, and the soft palate can contribute to an increase in oral volume.

Thus there seems to be a trade-off between consequences of the physical properties of our speech apparatus, i.e., devoicing as a consequence of oral closure on the one hand and language-dependent demands related to the voicing contrast on the other: In Romance languages voicing is often found to be maintained throughout the complete stop closure, therefore mechanisms like cavity enlargement are necessary. In contrast, for Germanic languages the distinction between phonologically voiced and voiceless stops is mainly based on differences in aspiration, i.e., no additional strategy for the maintenance of voicing is required. This language contrast was experimentally examined by Shih, Möbius, and Narasimhan (1999) using "voicing profiles," which trace voicing status frame by frame from the beginning of stop closure until stop release. Shih et al. found a language-dependent contrast for Italian and Spanish vs. German with almost no devoicing for the former languages and lower devoicing probability for the latter. Fischer-Jørgensen (1968) found similar results examining the voicing patterns of French vs. Danish stops.

However, in both language families velar stops are more prone to devoicing in comparison with bilabial stops. This phenomenon can be attributed to aerodynamics: For velar stops the back cavity is rather small and probably allows only restricted use of enlargement strategies, whereas in bilabial stops such mechanisms could be applied rather easily. Maddieson (2003) provided evidence that the "missing /g/" patterns in the phoneme inventories of the sounds of the world's languages occur rather frequently; this he attributed to the morphology of the vocal tract in combination with aerodynamic factors.

Several factors have been found to influence devoicing of phonologically voiced stops:

1. *Place of articulation.* Ohala and Riordan (1980) found empirically that velar stops are more often subject to devoicing due to less volume behind the point of constriction. This limits their capacity for passive enlargement, which is necessary to keep the pharyngeal pressure low. Keating, Linker, and Huffman (1983) found that the duration of voicing into closure varies with

place of articulation in English and Swedish, with higher durations for bilabials and shorter durations for velars.

2. *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 that, from an aerodynamic point of view, a voiced stop is more likely to be produced in medial position. However, in utterance initial and final position aerodynamic demands are more likely to produce a voiceless stop.
3. *Voicing status of context*. Shih et al. (1999) found strong contextual influences on the devoicing patterns of stops in different languages, i.e., the devoicing of phonologically voiced German stops was dependent on whether the preceding context was voiced (vowels and sonorants) or voiceless (voiceless stops and voiceless fricatives), with lower percentage of devoicing if the preceding phone was voiced.
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.
5. *Stress.* Keating et al. (1983) found that stress increased the duration of closure voicing for Swedish.
6. *Duration of the stop.* The longer the stop closure the higher the probability that voicing will cease. Ohala (2003) found in a vented-valve experiment controlling the oral air pressure artificially that voicing during stop production could not be maintained for longer than about 60 ms. Kawahara (2004) examined Japanese singleton stops in comparison to geminates and found that voiced singleton stops showed voicing for almost 100 per cent of closure duration whereas voiced-geminate stops showed voicing for only 30–40 per cent of stop closure.

The general aim of the current investigation is to study the dependency of devoicing effects on 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 and acoustic 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.

In particular, we were interested in (1) whether the patterns of devoicing in German resembled the patterns in American English, (2) whether the articulatory configuration at the onset of the consonantal constriction is already influenced by the following vowel, and (3) whether the patterns of devoicing can be explained by these anticipatory effects.

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 four male subjects (CG, DF, JD, RW). Four sensors were attached mid-sagittally to the tongue spaced equally from 1 to 5 cm behind the tongue tip, one to the jaw (lower incisors) and one to the lower lip. Two sensors, one at the bridge of the nose and the other at the upper incisors, served as reference coils to compensate for helmet movements during the recording session. The audio signal was simultaneously recorded on DAT. The final sampling frequency for the articulatory data was 200 Hz (low-pass filtered with a cut-off frequency of 20 Hz) and 16 kHz for the acoustic data.

The speech material consisted of nonsense words /ɡVkə/ for the velars and /bVpə/ for the bilabials, where V consisted of the 14 German tense and lax stressed 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.” (/za:ɡə __ bɪtə/, “Say __ please.”). Since the devoicing of stops occurs only rarely in word-medial position we chose the word initial position to examine devoicing. Following Shih et al. (1999) a lower percentage of devoicing could be expected since the investigated stop was preceded by a vowel. Obviously a word boundary preceding the stop occurred and could introduce variation in stop duration. Each sentence was repeated 10 times in randomized order, except for speaker RW whose sensors came off after eight repetitions. Speakers were instructed to speak at a comfortable speaking rate and loudness.

Acoustic and Articulatory Measurements

For this study of vowel-specific influences on articulatory positions during the stop, we chose the acoustically defined onset of the stop closure as our reference point. The reasons for this choice were: (1) we assumed that if the patterns of devoicing can be explained by anticipation, then articulatory positions should differ before devoicing occurs and (2) it is guaranteed that for all tokens voicing is still maintained at this time point. The onset of stop closure is usually labelled as the offset of higher formants (Klatt, 1975), preferably the second formant.

Two problems occurred during labelling of the data: First, it was found that frequently the offset of the different higher formants did not occur at the same point in time, thereby introducing wide measurement variability. Secondly, even when concentrating on the offset of the second formant, one speaker showed strong nasalization during the preceding vowel, which was the speaker’s anticipatory strategy to maintain voicing throughout the following closure (this nasalization was clearly audible and confirmed by informal perceptual tests). This frequently resulted in a pronounced weakening of the second formant of the vowel to be measured, due to the interference of resonances of the nasal cavity (Stevens, 1998). The resulting increased variability led us to a different labelling technique in order to get a more reliable measurement: A relevant decrease of the sound intensity (intensity settings: 0.047 s Kaiser20 window) was operationally labelled as –6 dB, measured from the point of maximal intensity of the preceding vowel. Since there is no aerodynamic (or linguistic reason) to assume that at this acoustic landmark the speaker is actively decreasing the acoustic intensity of the glottal output, the –6 dB decrease of global intensity indicates the beginning of the stop closure and was in about 95 per cent of the cases identical with the offset of the second formant of the vowels. Figure 13.1 illustrates the procedure. The intensity decrease

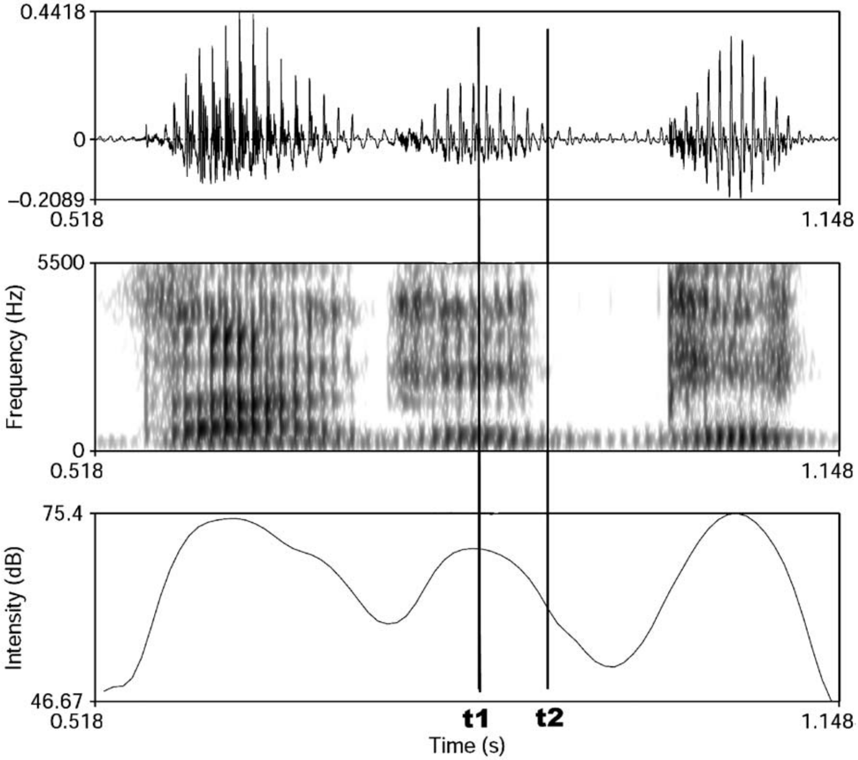

FIGURE 13.1. Procedure for acoustic labelling. Upper panel: the oscillogram; middle panel: the spectrogram; lower panel: the intensity contour. The left black bar (t1) indicates the landmark of the maximal intensity of the vowel. The right bar (t2) indicates the 6 dB intensity decrease measured from the point of maximal intensity.

was automatically measured using a script with the standard intensity settings (0.047 s Kaiser) of the software PRAAT (Boersma & Weenink, 1999).

At this acoustically defined landmark of closure onset, we measured the horizontal and vertical positions of the tongue dorsum (TDORS), tongue back (TBACK), jaw (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 formula given in Gibbon and Nicolaidis (1999):

$[COG=(0.5R8+1.5R7+2.5R6+3.5R5+4.5R4+5.5R3+6.5R2+7.5R1)/(R8+\ldots+R1)]$, where Rs are the number of activated contacts per row ($R8$: posterior row…$R1$: anterior row). POST is computed as the sum of the activated electrodes of the four posterior rows divided by the number of electrodes of the four posterior rows.

The stop was labelled as devoiced if there was no visible periodicity in the oscillogram for more than one glottal period (about 10 ms for male subjects, corresponding to one phonatory cycle at a fundamental frequency of 100 Hz) preceding the burst. The alternative method would be to measure the ratio of the devoiced part to the complete closure duration. This method was disfavoured because the aim of this investigation was to find the causal relationships between devoicing and articulatory configurations and not the temporal patterns. Therefore, we judged categorically the stop as voiced or devoiced by applying the criterion mentioned above. Closure duration (DurC) was measured as the temporal distance between the beginning of the stop closure (see above) and the stop release (burst).

RESULTS

Occurrence of Devoicing

Figure 13.2 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 per cent). 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. Also shown in Figure 13.2 is a tense-lax effect for mid- and high vowels, with lax vowels more likely to induce devoicing. This could be attributed to the fact that lax vowels are produced with a more open vocal tract compared to their tense counterparts (Hoole & Mooshammer, 2002) and therefore shows the same tendency as described above.

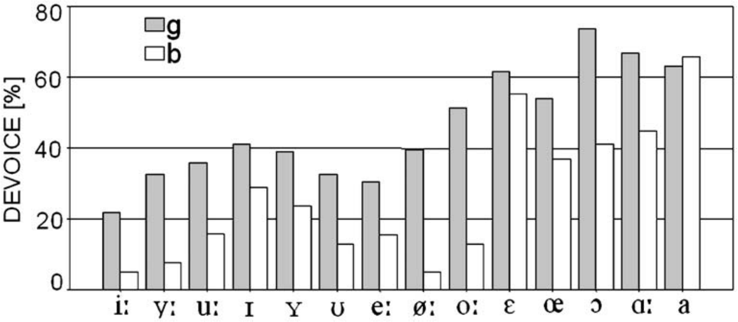

FIGURE 13.2. Percentage of devoicing, shown for each vowel and the contexts /b/ and /g/. The vowels are ordered by their phonological vowel height. Mean values are 46.3 per cent for the velar and 26.4 per cent for the bilabial.

Table 13.1 shows the percentage of stop devoicing for each vowel, split by speaker and stop. Data for each speaker show similar relationships between devoicing and vowel height, but the overall amount of devoicing varies according to the speaker, e.g., speaker DF is more prone to devoice the bilabial than speaker CG. Speaker JD's devoicing pattern for the bilabial is exceptional, with almost no instances of devoicing. This speaker avoids devoicing by prenasalizing the bilabial but not the velar stop.

TABLE 13.1. Percentage of Stop Devoicing Split by Speaker and 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 Duration and Articulatory Positions at Consonantal Closure Onset

As mentioned in the introductory section, closure duration plays a major role for the devoicing of phonologically voiced stops. Therefore, in Table 13.2 the means and *SD*s of the closure durations and in Table 13.3 the significant effects are shown. For two speakers we found longer closure durations when the bilabial stop was followed by a lax vowel, but no consistent effects for the other two speakers. For all speakers the duration of the velar was either not affected or only slightly affected by the following vowel.

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 position of the articulators and EPG measures as dependent variables, split by speaker and consonant. The results are shown in Table 13.3. Since vowel identity is a factor with 14 levels we used the highly conservative Scheffé post-hoc test, which requires very large differences between means in order to detect different groups. Therefore in some cases, the ANOVA gives significant effects where the Scheffé test shows no significantly different groups. These cases are marked in Table 13.3 by brackets around the asterisks, whereas when both the ANOVA and the Scheffé test yielded significant effects and groups, the *F* values are

TABLE 13.2. Mean Closure Durations for the Bilabial and Velar Stop, Split by Speaker and Following Vowel

	Bilabial stop				Velar stop			
Vowel	CG	DF	JD	RW	CG	DF	JD	RW
iː	106 (11)	102 (08)	124 (17)	87 (24)	76 (31)	78 (09)	136 (50)	106 (24)
yː	95 (16)	104 (20)	108 (12)	121 (28)	104 (14)	85 (10)	145 (18)	132 (22)
uː	93 (13)	74 (23)	107 (19)	112 (17)	97 (16)	98 (22)	108 (29)	124 (13)
ɪ	93 (10)	125 (10)	161 (24)	110 (16)	89 (16)	112 (24)	132 (21)	122 (14)
ʏ	88 (7)	125 (17)	135 (13)	110 (14)	85 (21)	107 (17)	130 (20)	135 (13)
ʊ	92 (11)	112 (23)	129 (14)	105 (15)	84 (17)	110 (28)	108 (23)	134 (29)
eː	100 (09)	116 (15)	127 (21)	102 (31)	89 (24)	85 (12)	121 (37)	116 (15)
øː	80 (12)	106 (23)	112 (17)	114 (32)	95 (13)	92 (17)	124 (19)	115 (35)
oː	93 (12)	99 (14)	123 (11)	122 (39)	87 (22)	92 (09)	90 (32)	108 (37)
ɛ	99 (17)	141 (34)	144 (15)	129 (23)	81 (19)	104 (31)	110 (20)	121 (29)
œ	82 (12)	125 (09)	136 (19)	127 (22)	83 (16)	119 (16)	118 (26)	129 (24)
ɔ	95 (10)	124 (18)	136 (8)	119 (28)	68 (15)	105 (23)	119 (22)	112 (35)
ɑː	102 (08)	108 (18)	116 (12)	110 (17)	74 (18)	79 (13)	78 (19)	95 (21)
a	95 (07)	110 (12)	136 (10)	127 (27)	69 (12)	99 (19)	114 (12)	108 (25)

Note. The corresponding standard deviations are given within parentheses.

TABLE 13.3. ANOVAs Showing the *F* Values, the Degrees of Freedom, and the Significance Levels

	Bilabial stop							
	CG *F*(13, 126)		DF *F*(13, 123)		JD *F*(13, 126)		RW *F*(13, 98)	
POST	**6.8**	***	**17.6**	***	**5.0**	***	**34.6**	***
COG	0.4		0.6		3.7	(***)	2.3	(**)
TBACKX	5.1	(***)	**8.5**	***	**12.9**	***	**4.4**	***
TBACKY	**5.2**	***	**7.7**	***	2.0	(*)	3.1	(***)
TDORSX	**15.3**	***	**7.5**	***	**5.6**	***	**10.0**	***
TDORSY	**11.0**	***	**23.5**	***	**7.3**	***	**8.8**	***
JAWX	0.3		0.6		1.8		1.5	
JAWY	**4.1**	***	**5.2**	***	**10.0**	***	1.4	
LLIPX	3.3	(***)	1.5		**11.4**	***	1.6	
LLIPY	2.5	(***)	**6.1**	***	**9.8**	***	1.0	
DURC	**3.8**	***	**5.9**	***	**8.2**	***	1.5	

	Velar stop							
	CG *F*(13, 119)		DF *F*(13, 133)		JD *F*(13, 120)		RW *F*(13, 101)	
POST	**3.6**	***	**7.5**	***	**19.0**	***	**5.4**	***
COG	0.8		0.6		**12.7**	**	1.7	
TBACKX	1.7		0.8		2.0	(*)	0.8	
TBACKY	2.1	(*)	**6.1**	***	1.0		1.1	
TDORSX	**4.3**	***	1.9	(*)	1.0		2.3	(***)
TDORSY	**5.1**	***	**18.1**	***	**11.0**	***	3.2	(***)
JAWX	2.0	(*)	3.6	(***)	1.7		1.8	
JAWY	4.2	(***)	5.2	(***)	3.0	(***)	3.0	(***)
LLIPX	**47.2**	***	**27.2**	***	**37.1**	***	**13.7**	***
LLIPY	**13.3**	***	**31.9**	***	**4.3**	***	**10.4**	***
DURC	2.94	(**)	**4.6**	***	**4.1**	***	1.6	

Note. The significant levels are $^{***}p < .001$; $^{**}p < .01$; $^{*}p < .05$ for each speaker split by bilabial and velar context. The asterisks in parentheses indicate cases where the ANOVA yielded significant effects, but the more conservative Scheffé-post-hoc test could not separate groups. *F* values printed in bold indicate significantly different vowel groups obtained by Scheffé-post-hoc test.

printed in bold. In the following section, anticipatory effects will only be considered for articulators if the Scheffé test showed significant groups.

For the EPG measures, the COG was insensitive for vowel context (except for speaker JD) 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 (not significant for RW). Jaw positions for velars tended to be higher for following closed vowels for speaker CG and higher for rounded vowels for speaker DF (both almost significant).

In contrast to the velar, for the bilabial both tongue sensors varied significantly according to the following vowel in the expected direction (the TDORS sensor was affected more consistently). The jaw tended to be significantly more closed when the following vowel was rounded for speakers DF and JD (for speaker CG the jaw was influenced by vowel height but not by rounding). 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 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. As might have been expected of those articulators, which do not directly contribute to the production of the stop vary most consistently with vowel identity, e.g., lip position for the velars and tongue position for the bilabials. For the jaw, whose position during phonologically voiced bilabial and velar closures is highly influenced by vowel context (see, e.g., Keating, Lindblom, Lubker, & Kreiman, 1994), we assume a helping function, which is probably more pronounced in the bilabial stop. For both contexts, the vertical jaw position varied for all speakers (except RW) but no consistent pattern could be extracted: For speaker CG the jaw height is influenced by vowel height whereas for speaker DF the jaw is elevated for rounded vowels (only for the bilabials for speaker JD). The presumably active articulator, namely the lower lip for bilabials and both tongue sensors for the velars, also varied for three speakers but the effects were weaker and less consistent compared to the nonactive articulators.

Relationship Devoicing–Articulatory Positions

To analyse which of the articulators might have an influence on the occurrence of devoicing, we computed correlations between average positional data and the percentage of devoicing calculated over 10 repetitions of each item. Since it is well known that the occurrence of devoicing is also influenced by closure duration (see the Introduction section) we added this variable (DurC) to our analyses. Table 13.4 shows the correlation coefficients and the level of significance.

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. This is also captured by Figure 13.3 (in the left panels), which shows scatter plots of the percentage of devoicing and the averaged vertical jaw position, split by speaker and consonant. The jaw positions of speakers CG and DF also varied significantly with vowel height. Speakers JD and RW showed no significant

TABLE 13.4. Correlation Coefficients Between Devoicing and Articulatory Measurement Points

	Bilabial stop				Velar stop			
	CG(B)	DF(B)	JD(B)	RW(B)	CG(G)	DF(G)	JD(G)	RW(G)
TBACKX	.291	−.113	−.273	.173	−.577	.593	−.483	−.386
TDORSX	.354	−.050	−.345	.353	−.167	.544	−.664	.090
JAWX	.214	.276	−.096	−.258	.009	−.250	.610	−.017
LLIPX	.433	.156	.175	−.133	.053	−.234	.348	.366
TBACKY	−.399	−.129	−.168	−.499	−.425	−.638	−.571	−.292
TDORSY	−.478	−.071	−.075	−.533	−.465	−.665	.173	−.553
JAWY	**−.669**	**−.700**	−.401	−.469	**−.715**	−.038	−.647	−.639
LLIPY	.058	−.475	.313	−.165	−.388	.143	.109	−.551
COG	.201	−.183	.143	−.181	−.029	−.349	.024	−.632
POST	−.149	.073	−.088	−.489	−.642	−.570	.002	−.481
DurC	.176	**.738**	−.152	**.664**	−.586	.309	−.134	−.010

Note. Significant values ($p = .05$) are marked with a grey cell background. Highly significant values ($p = .01$) are in bold.

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 (DurC) was positively correlated for two speakers, i.e., the longer the stop the higher the likelihood for devoicing.

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 was significantly negatively correlated with 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 the velar articulator best, opposing patterns could be observed for speakers CG and JD on the one hand and speaker DF on the other. 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 the velar more frequently when the stop was followed by a back vowel which was not the case for speakers CG and JD. The latter two speakers showed no fronting of the velar with a following front vowel but significant negative correlations between horizontal tongue position and devoicing, i.e., the more fronted the tongue the more frequently devoicing occurred. No significant correlations between devoicing and horizontal tongue position could be found for speaker RW.

To achieve an objective measure of the relevance of the measured parameters for the occurrence of devoicing SPSS, stepwise regression models were

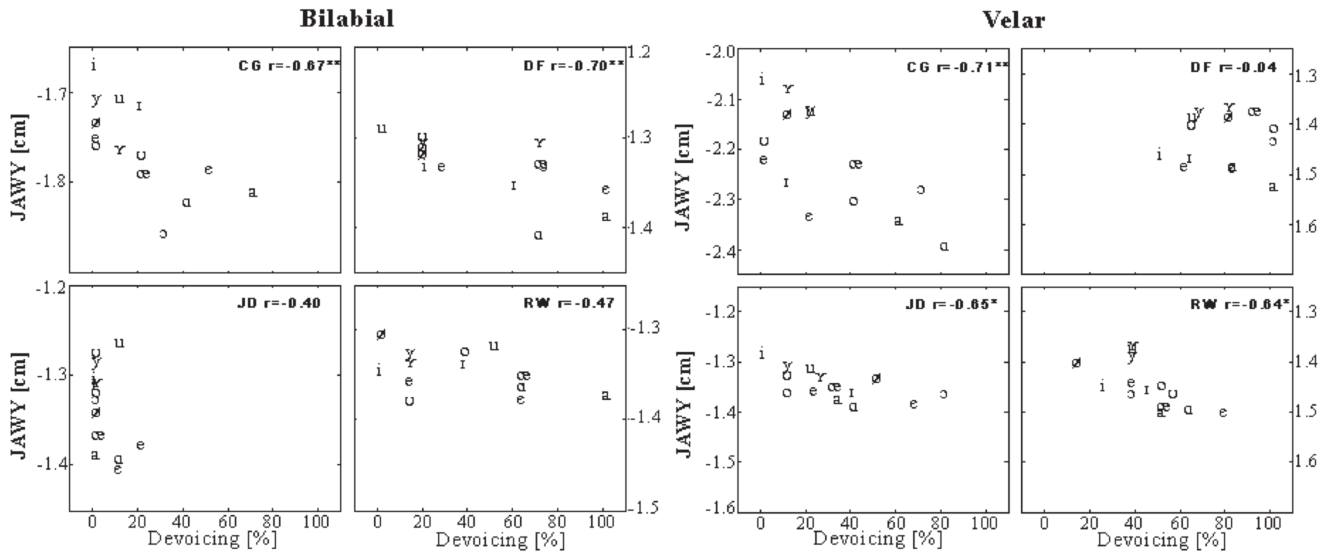

FIGURE 13.3. Scatter plots of the percentage of devoicing and the mean vertical jaw position at consonant onset for bilabials (left) and velars (right) for each speaker.

TABLE 13.5. Regression Models Computed by the SPSS Procedure Linear Stepwise Regression

CONS	VP	Model	R^2	F	Probability
Bilabial	CG	JAWY	.448	9.73	.0089
	DF	DurC	.545	14.37	.0026
		DurC, JAWY	.774	18.83	.0003
	RW	DurC	.442	9.51	.0095
		DurC, JAWY	.611	8.64	.0056
Velar	CG	JAWY	.511	12.53	.0041
		JAWY, JAWX	.767	18.12	.0003
	DF	TDORSY	.442	9.50	.0095
	JD	TDORSX	.441	9.46	.0096
		TDORSX, JAWX	.636	9.60	.0039
	RW	JAWY	.408	8.27	.0139

Note. 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.

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, COG, and stop duration as independent variables. Table 13.5 shows the extracted regression models with the predictors selected by stepwise regression models, explained variance (R2), *F* values, and probability. As can be seen no model could be extracted for speaker JD for the devoicing pattern of bilabials. Closure duration (DurC) only played 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 the vertical jaw position was actually the only variable that met the criterion for inclusion ($F > 3.84$) and explains about 45 per cent of the variance. The occurrence of devoicing of velar stops was best predicted by the vertical jaw position for speakers CG and RW. In two cases, the horizontal jaw position was included in the models. The inclusion for speaker CG can be attributed to a suppression effect of JAWX (Bortz, 1979) because it did not correlate with the criterion variable but significantly improved the model due to the high correlation between JAWX and JAWY ($r = -.586^*$). This was not the case for speaker JD whose pattern of devoicing significantly varied with jaw retraction (see Table 13.4). The main predictor variable for this speaker was the horizontal tongue dorsum position. Speaker DF, as can be seen in Figure 13.3, produced the velar stop with a higher jaw position when followed by a rounded vowel. Therefore, the jaw was not selected as a predictor variable for devoicing but the vertical tongue dorsum position was selected.

CONCLUSION AND DISCUSSION

In this study, we investigated the occurrence of devoicing in phonologically voiced stops and its dependence on the following vowel in German. We measured articulatory data (EMMA and EPG) at the acoustically defined closure onset. Depending on the place of articulation of the stop, devoicing was more frequently found for the velar with 46.3 per cent compared to the bilabial with 26.4 per cent. In accordance with earlier studies on American English (Ohala & Riordan, 1980), we found that the percentage of stop devoicing increases with increasing vowel openness. Ohala and Riordan attributed this devoicing pattern to the decreased pharyngeal volume in anticipation of following lower vowels. The presence of anticipatory effects at the onset of the stop closure was confirmed by ANOVAs and varied with place of articulation of the stop. However, one speaker showed no vowel effects in bilabial context because he used a different strategy to avoid devoicing, i.e., he prenasalized the stop. Another speaker-dependent pattern could exist due to the different palatal coronal shape of the speakers. In Mooshammer et al. (2004), the palatal shape of the speakers CG and DF is shown to be dome-shaped, whereas the palate of speaker JD is more flat. This morphologically different shape may influence the size of the oral cavity during a stop closure with a smaller cavity more prone to devoicing than a larger cavity. However, our speaker-dependent devoicing patterns (see Table 13.1) do not reflect this hypothesis.

Correlation between articulatory data and percentage of devoicing revealed significant correlations for the vertical jaw position for both stops. In the stepwise regression model, this articulator was selected as a predictor variable for all speakers who showed a devoicing pattern for the bilabial and two speakers for the velar. For the velar, significant correlations with vertical and horizontal tongue positions were found for three speakers. Closure duration showed a significant effect on the percentage of devoicing for the bilabial for only two of the four speakers. Since passive compliance of the walls plays a greater role for bilabials (see Ohala, 2003), 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.

Obviously not all relevant factors explaining devoicing patterns were captured by our experimental set-up, which can be seen in the low explained variances in the stepwise regression models. Aerodynamic factors such as the volume of the pharyngeal cavity, transglottal, and intraoral pressure were not captured nor were positions of articulatory structures such as larynx height or velum which contribute to the size of the oral cavity (see Westbury, 1983). Ohala and Riordan's hypothesis that pharyngeal volume plays the major role for vowel-specific devoicing patterns can only be tested indirectly with our data: As was found by Tiede (1996) tongue dorsum height and pharyngeal volume are highly positively correlated for English vowels. In our regression models tongue dorsum height was relevant only for one speaker in velar context whereas jaw height was one of the major factors. One possible explanation is that the jaw captures vowel height more consistently compared to the two tongue sensors, which are strongly influenced by vowel frontness (e.g., /i:/ is produced with a higher tongue dorsum position than /u:/ due to the shape of the palate). Since the jaw and the tongue are biomechanically linked and therefore highly correlated, an alternative possibility would be that one of these articulators is therefore more consistently selected in the regression analysis.

Another vowel-specific anticipatory effect, which also enlarges the cavity and therefore might be involved in maintenance of voicing, is larynx height, which has been shown to be significantly lower for rounded vowels (for German see, e.g., Hoole & Kroos, 1998). The hypothesis here would be that if larynx height is adjusted already at the beginning of the stop then stops followed by rounded vowels should be less frequently devoiced compared to unrounded vowels with the same vowel height. This pattern of devoicing was only found for one speaker (DF) in bilabial context (see Table 13.1) whose jaw position was also mainly dependent on rounding (see Figure 13.3). Since this pattern was only found for one speaker and one context larynx height does not seem to play a major role. The other possibility to control vocal tract length is lip rounding, but this strategy was not used by our speakers (i.e., no significant correlations between devoicing and lip position for the bilabials, as can be seen in Table 13.4).

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, requirements for economy of movement play a more important role than the maintenance of voicing in German.

ACKNOWLEDGMENTS

This work was supported by a grant from the German Research Council GWZ 4/8-1, P.1. We would like to thank Jörg Dreyer at the ZAS for technical setup and maintenance, especially for the realization of the synchronized recording of EMMA, EPG, and acoustic data. Thanks to Christian Geng for advice regarding the regression statistics.

REFERENCES

Boersma, P., & Weenink, D. (1999). *PRAAT, a system for doing phonetics by computer*, Report of the Institute of Phonetic Sciences of the University of Amsterdam (pp. 132–182).

Bortz, J. (1979). *Lehrbuch der statistik—für sozialwissenschaftler*. Berlin: Springer.

Fischer-Jørgensen, E. (1968). Voicing, tenseness and aspiration in stop consonants, with special reference to French and Danish. *ARIPUC*, *3*, 63–115.

Gibbon, F., & Nicolaidis, K. (1999). Palatography. In W. J. Hardcastle & N. Newlett (Eds.), *Coarticulation* (pp. 229–245). Cambridge: Cambridge University Press.

Hoole, P., & Kroos, C. (1998). Control of larynx height in vowel production. *Proceedings of the 5th international conference on spoken language processing* (Vol. 2, pp. 531–534).

Hoole, P., & Mooshammer, C. (2002). Articulatory analysis of the German vowel system. In P. Auer, P. Gilles, & H. Spiekermann (Eds.), *Silbenschnitt und tonakzente* (pp. 129–252). Tübingen: Niemeyer.

Jessen, M. (2001). Phonetic implementation of the distinctive auditory feature [voice] and [tense] in stop consonants. In T. A. Hall (Ed.), *Distinctive feature theory* (pp. 237–294). Berlin: Mouton De Gruyter.

Kawahara, S. (2004). *An acoustic and perceptual study of Japanese voiced geminates*. Manuscript for UMASS Mini-Conference.

Keating, P., Lindblom, J., Lubker, J., & Kreiman, J. (1994). Variability in jaw height for segments in English and Swedish VCVs. *Journal of Phonetics*, *22*, 407–422.

Keating, P., Linker, W., & Huffman, M. (1983). Patterns in allophone distribution for voiced and voiceless stops. *Journal of Phonetics*, *11*, 277–290.

Klatt, D. H. (1975). Voice onset time, frication, and aspiration in word-initial consonants clusters. *Journal of Speech and Hearing Research*, *18*, 686–706.

Maddieson, I. (2003). Phonological typology in geographical perspective. *Proceedings of the 15th ICPhS*, Barcelona, (Vol. 1, pp. 719–722).

Mooshammer, C., Perrier, P., Fuchs, S., Geng, C., & Pape, D. (2004). An EMMA and EPG study on token-to-token variability. *AIPUC*, *36*, 47–63.

Ohala, J. (2003). Effects on speech of introducing aerodynamic perturbations. *Proceedings of the 15th ICPhS*, Barcelona (Vol. 1, pp. 2913–2916).

Ohala, J., & Riordan, C. (1980). *Passive vocal tract enlargement during voiced stops*. Report of the Phonological Laboratory UC Berkeley (Vol. 5, pp. 78–87).

Shih, C., Möbius, B., & Narasimhan, B. (1999). Contextual effects on consonantal voicing profiles: A cross-linguistic study. *Proceedings of the 14th ICPhS*, San Francisco (Vol. 2, pp. 989–992).

Stevens, K. N. (1998). *Acoustic phonetics* (p. 512). Cambridge: The MIT Press.

Tiede, M. K. (1996). An MRI-based study of pharyngeal volume contrasts in Akan and English. *Journal of Phonetics*, *24*, 399–421.

Westbury, J. R. (1983). Enlargement of the supraglottal cavity and its relation to stop consonant voicing. *Journal of the Acoustical Society of America*, *73*, 1322–1336.

Westbury, J. R., & Keating, P. (1985). On the naturalness of stop consonant voicing. *Journal of Linguistics*, *22*, 145–166.