3. Results

3. Results

The aim of the present experiment was, first, to observe the direction and temporal extent of voicing assimilation in Catalan and English. The second objective was to see whether voicing assimilation co-varied with speaking rate or not. We wanted to determine the categorical or gradient nature of the process on the basis of speech rate effects. Finally, we also investigated how voicing assimilation varies with the degree of articulatory overlap of supraglottal gestures. These questions are addressed in sections 3.1, for voiced – voiceless stop sequences, 3.2, for voiceless – voiced stop sequences and 3.3 for fricative – stop sequences. Section 3.4 deals with sequences of nasals and obstruents and section 3.5 deals with sequences of laterals and obstruents.

3.0. Preliminary remarks

Before presenting the results, it is necessary to refer to two universal phonetic phenomena, namely voicing continuation in voiceless obstruents (Ladefoged and Maddieson 1996: 53) and mechanical devoicing in voiced obstruents (Ohala and Riordan 1979). As is well known, voicing continuation may take place in voiceless stops that follow voiced sounds. As shown in Figure 3.0 below, the consonant sequence /t#k/ in 'dret car' shows some vocal fold vibration in the initial portion of C1 in most tokens. Since both consonants in the sequence are underlyingly voiceless, vocal fold vibration during C1 is due to the presence of the preceding vowel and reflects the inertial effects of the previous sound: when the oral closure is reached the vocal folds have not separated widely enough (Ladefoged and Maddieson 1996: 52-53). In the present experiment, the range of values for voicing continuation in voiceless control sequences was observed in order to establish whether voicing in C1 was due to voicing continuation or to vocal fold vibration intended by the speaker.

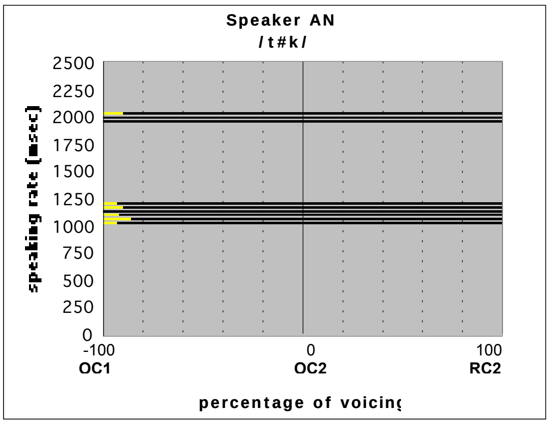


Figure 3.0. Percentage of voicing in the Catalan obstruent sequence 'dre**t c**ar' (/t#k/), uttered by speaker AN. The yellow lines represent vocal fold vibration and the black lines represent absence of vocal fold vibration. Speaking rate in milliseconds appears on the ordinate and the percentage of voicing in relation to supraglottal gestures appears on the abscissa. OC1 stands for onset of the constriction for C1, OC2 stands for onset of the constriction for C2 and RC2 stands for release of C2. Each line represents one observation.

Secondly, it is also well-known that the conditions under which voiced obstruents are produced make it difficult to maintain vocal fold vibration. This is a universal phonetic phenomenon that is even more pervasive in long obstruents and sequences of voiced obstruents. The difficulty in maintaining vocal fold vibration in voiced obstruent sequences may be accounted for in aerodynamic terms: oral pressure tends to increase once the closure for C1 is formed and vocal fold vibration can occur as long as the pressure drop across the glottis is greater than 2000 dyne/cm2 (Catford 1977). Figure 3.1 shows that the difference between P_s and P_o decreases with time, but it is greater than 2000 dymes/cm^2 for the first portion of the closure, during which voicing is present. Offset of voicing occurs when the pressure difference is below the 2000 dymes/cm^2 threshold, in the late portion of the closure.

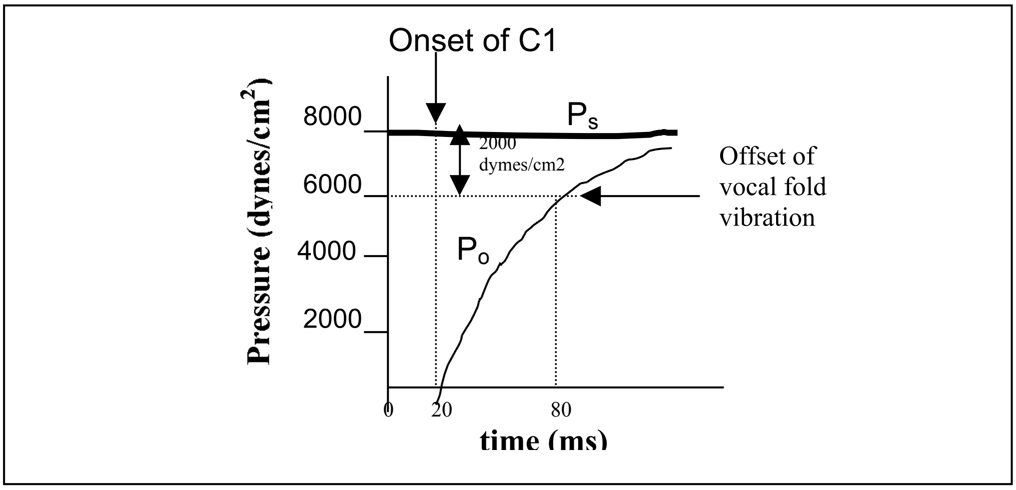


Figure 3.1. Diagrammatic subglottal (Ps) and oral (Po) air pressure traces following the closure for a sequence of obstruents, such as /d#k/. Adapted from Westbury and Keating (1986).

As Figure 3.2 shows, the voiced consonant sequence /d#g/ uttered by the English speaker AL displays vocal fold vibration which tends to die out during the constriction for C2. Yet both consonants in the sequence are underlyingly voiced, so absence of glottal vibration during the final portion of C2 is due to mechanical aerodynamic effects. The voiced control sequences for each speaker were used as a reference point to determine when voicing died out due to phonetic factors and when absence of voicing was intended by the speakers.

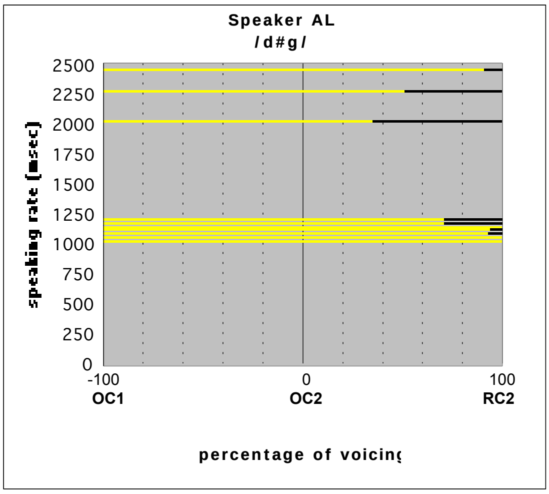


Figure 3.2. Percentage of voicing in the English sequence 'sa**d g**ap' (/d#g/), uttered by speaker AL. The yellow lines represent vocal fold vibration and the black lines represent absence of vocal fold vibration. Speaking rate in milliseconds appears on the ordinate and the percentage of voicing in relation to supraglottal gestures appears on the abscissa. OC1 stands for onset of C1 constriction, OC2 stands for onset of C2 constriction and RC2 stands for release of C2. Each line represents one observation.

3.1. Voiced – voiceless stop sequences

In this section, the amount of voicing during the consonant constriction in the sequence /d#k/ will be analyzed. Figure 3.3 presents the distribution of the percentage of voicing in the control sequences /t#k/, /d#g/ and the test sequence /d#k/ in Catalan. Both speakers showed absence of voicing during the constriction in the control voiceless sequence /t#k/, although there could be some voicing in the initial portion of C1 due to voicing continuation (see section 3.0 above). In the voiced control sequence /d#g/, Figure 3.3 shows that both C1 and C2 were fully voiced for speaker AN, although in two cases voicing died out during the second half of C2 due to aerodynamic effects. For speaker MJ voicing died out much earlier during the voiced obstruent sequence, but as can be observed in Figure 3.3 there was more voicing in this sequence than in the sequences /t#k/ and /d#k/.

As for the test sequence /d#k/, Figure 3.3 shows that the Catalan speakers followed slightly different patterns. Speaker AN, on the one hand, displayed significantly more voicing in C1 in the mixed sequence /d#k/ than in its voiceless counterpart /t#k/; the mean percentage of voicing during the constriction in C1 in /t#k/ was 6%, whereas in /d#k/ it was 34%. Speaker MJ, on the other hand, did not display a significant difference in the percentage of voicing between the test sequence /d#k/ and the control sequence /t#k/. The mean percentage of voicing in C1 was 4.5 in /t#k/ and 4 in /d#k/ for this speaker. Thus, speaker MJ produced both /t#k/ and /d#k/ with no voicing. Comparison of the mid and bottom panels in Figure 3.3 shows that the control sequence /d#g/ had significantly more voicing than the mixed sequence in both speakers.

One-way ANOVAs with sequence type as the independent variable with three levels (/t#k/ vs. /d#g/ vs. /d#k/) and percentage of voicing in the consonant sequence as the dependent variable were performed. Post-hoc tests were conducted to evaluate pairwise differences among means.

The results of one-way ANOVA and post-hoc tests as well as the means and standard deviations for the three types of sequences are reported in Table I below:

Table I. Results of ANOVA and post-hoc tests comparing the percentage of voicing in the mixed sequence /d#k/ and in the control sequences in Catalan. The asterisk shows that the result was significant at the .05 level; the double asterisk shows that the result was significant at the .01 level.

	Sequence type	Mean	SD	N	ANOVA	Sequences	*p* (Scheffé)	Sig.
AN	/t#k/	-94	4.9	9	F(2,30)=338,53 *p*=0.000<0.01	Voiced-vlss	0.000	**
	/d#g/	92	15.22	10		Mixed-voiceless	0.003	**
	/d#k/	-66	22.88	14		Mixed-voiced	0.000	**
MJ	/t#k/	-95.5	5	11	F(2,31)=7.48, *p*=0.002, p<0.01	Voiced-vlss	0.009	**
	/d#g/	-51	53.21	12		Mixed-voiceless	1.000	-
	/d#k/	-96	6.38	11		Mixed-voiced	0.009	**

The results of the tests show significant differences in the amount of voicing during the closure of voiced, voiceless and mixed sequences for speaker AN, but no significant differences between mixed and voiceless sequences for speaker MJ. Concerning the direction and extent of voicing assimilation, C1 was partially devoiced for speaker AN, so that there was partial regressive assimilation of the voicing feature of C2. For speaker MJ, C1 was totally devoiced in the mixed sequences so that there was complete regressive assimilation of the voicing feature of C2.

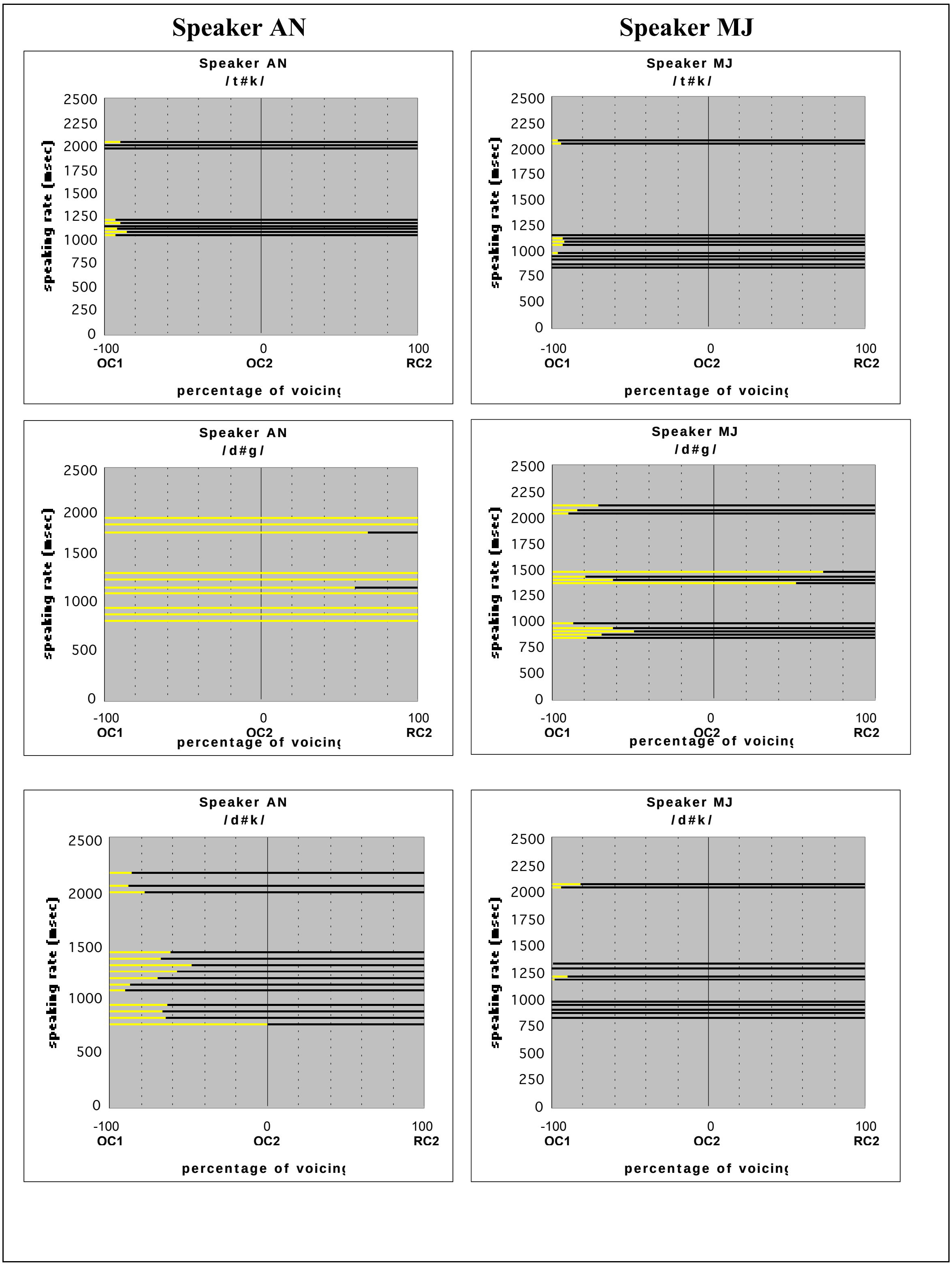


Figure 3.3. Vocal fold vibration in the obstruent sequences in 'dret car' (/t#k/), 'fred gal' (/d#g/) and 'fred car' (/d#k/) for the Catalan speakers AN and MJ. The yellow lines represent vocal fold vibration and the black lines represent absence of vocal fold vibration. Speaking rate in milliseconds appears on the ordinate and the percentage of voicing in relation to supraglottal gestures appears on the abscissa. OC1 stands for onset of C1, OC2 stands for onset of C2 and RC2 stands for release of C2. Each line represents one observation.

The English speakers showed a different pattern of organization of glottal and supraglottal gestures from Catalan speakers, as shown in Figure 3.4 below. Both speakers displayed complete absence of voicing in the control voiceless sequence /t#k/. In the voiced sequence /d#g/, they showed a fully voiced C1, and partial or complete voicing of C2. The mean percentage of voicing in this sequence was 80 for speaker AL and 51 for speaker ME.

In the test sequence /d#k/, both English speakers showed more voicing in C1 than in the voiceless control sequence /t#k/. The voicing timing pattern of the sequence /d#k/ differed significantly from that of the voiced control sequence /d#g/ for both speakers with significantly more voicing in C2 in the latter. Thus, both speakers seemed to implement C1 in the sequence /d#k/ as voiced, with slight differences as to the degree of voicing, and C2 as voiceless with some vocal fold vibration during the initial portion of C2.

The results of one-way ANOVA and post-hoc tests comparing the percentage of voicing in the control sequences /d#g/ and /t#k/ and in the test sequence /d#k/ are summarized in Table II below.

Table II. Results of ANOVA and post-hoc tests comparing the percentage of voicing in the mixed sequence /d#k/ and in the control sequences in English. The asterisk shows that the result was significant at the .05 level; the double asterisk shows that the result was significant at the .01 level.

	Sequence type	Mean	SD	N	ANOVA	Sequences	*p* (Scheffé)	Sig.
AL	/t#k/	-100	0	9	F(2,24)=350.26, *p*=0.000<0.01	Voiced-vlss	0.000	**
	/d#g/	80	22.8	10		Mixed-voiceless	0.000	**
	/d#k/	37	11.7	8		Mixed-voiced	0.000	**
ME	/t#k/	-100	0	13	F(2,33)=68.75, *p*=0.000<0.01	Voiced-vlss	0.000	**
	/d#g/	51	29.7	10		Mixed-voiceless	0.000	**
	/d#k/	-14	44.7	13		Mixed-voiced	0.000	**

To summarize, concerning the direction and extent of voicing assimilation in the English sequence /d#k/, it was found that, contrary to traditional descriptions, English speakers may not show regressive devoicing of a voiced stop preceding a voiceless stop. In fact, partial or complete devoicing of C1 in the sequence /d#k/ was only present in some tokens of speaker ME and never in speaker AL. In most occasions speakers showed vocal fold vibration during the whole constriction for C1.

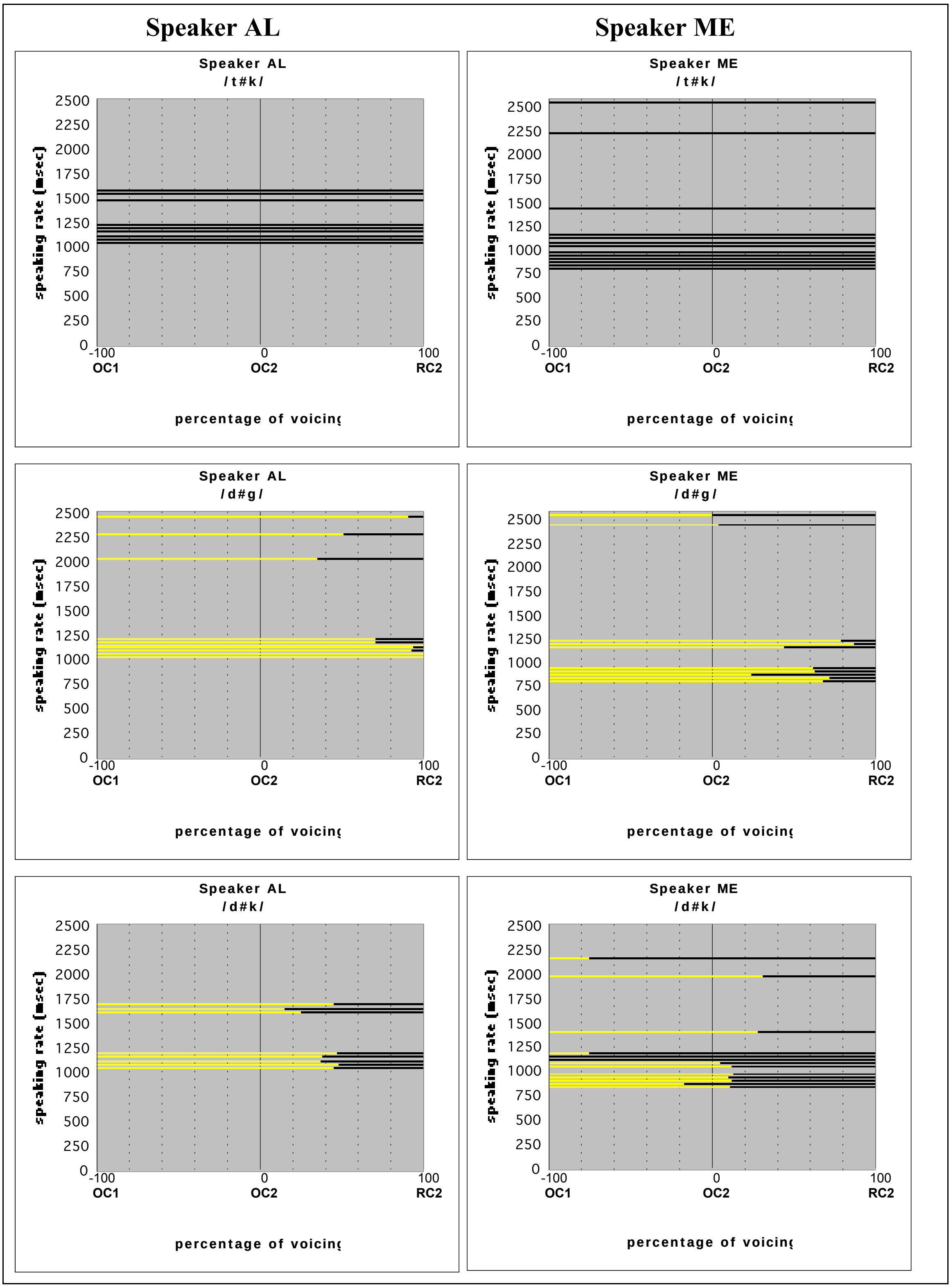
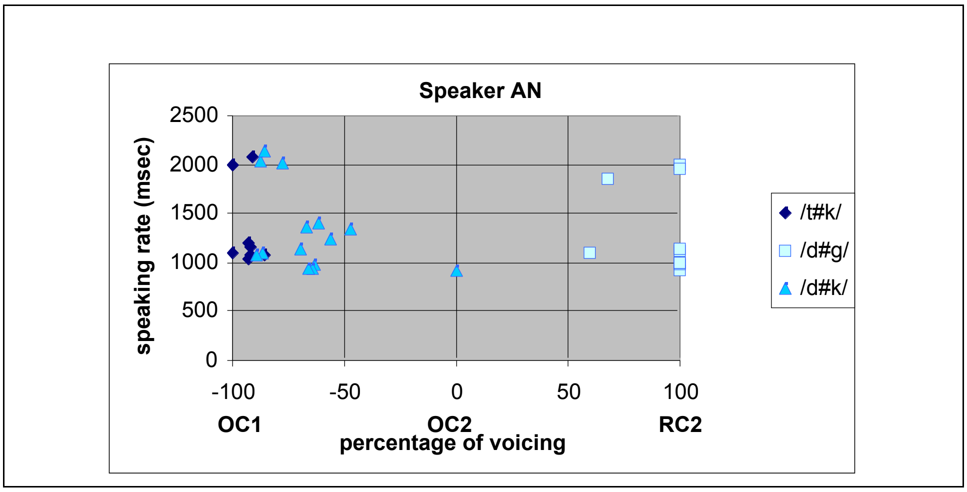


Figure 3.4. Vocal fold vibration in the obstruent sequences in 'fat cap' (/t#k/), 'sad gap' (/d#g/) and 'sad cap' (/d#k/) for the English speakers AL and ME. The yellow lines represent vocal fold vibration and the black lines represent absence of vocal fold vibration. Speaking rate in milliseconds appears on the ordinate and the percentage of voicing in relation to supraglottal gestures appears on the abscissa. OC1 stands for onset of C1, OC2 stands for onset of C2 and RC2 stands for release of C2. Each line represents one observation.

3.1.1. Speaking rate effects

In order to explore the relationship between degree of voicing assimilation and speaking rate, the percentage of voicing for each individual obstruent sequence was plotted as a function of rate of speech. Figure 3.5 below shows the results for the Catalan speakers. As Figure 3.5 shows, the voicing timing pattern for the sequence /d#k/ showed more variability than the control sequences /t#k/ and /d#g/, where the coordination of oral and glottal gestures was more stable across rates. For this speaker, some relationship was observed between voicing in C1 and speaking rate in the sequence /d#k/, with slower rates showing less voicing in C1 than faster rates; however, the correlation did not reach significance (r^2=0.22, p=0.111>0.05). In speaker MJ, the voicing timing pattern of the sequence /d#k/ clearly paralleled that of the voiceless control sequence /t#k/ across rates. No correlation was observed (r^2=0.08, p=0.830>0.05). Thus, for the sequence /d#k/, degree of voicing in C1 did not vary significantly with speaking rate for any of the two Catalan speakers.



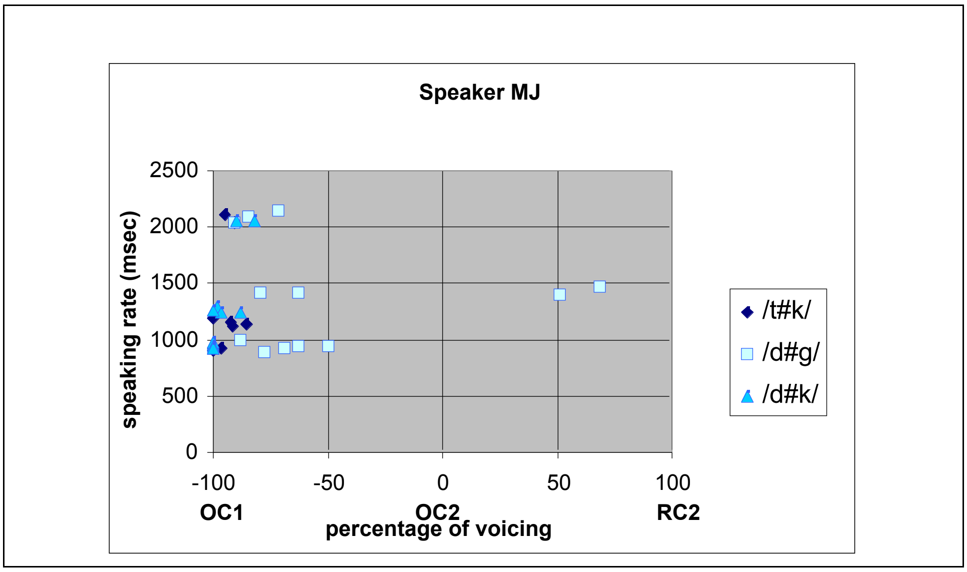


Figure 3.5. Scattergrams of percentage of voicing (horizontal axis) plotted as a function of speaking rate (vertical axis) in the Catalan sequences 'fred gal' (/d#g/), 'dret car' (/t#k/) and 'fred car' (/d#k/) with higher values indicating slower speaking rates. Each dot represents one observation.

Figure 3.6 below plots the values of the percentage of voicing for the individual tokens as a function of speaking rate in English. As can be observed, the voiceless control sequence /t#k/ was produced without voicing at all speaking rates by both speakers, whereas the voiced control sequence /d#g/ was produced with a voiced C1 and partial or complete voicing of C2, regardless of speaking rate. As for the test sequence /d#k/, speaker AL displayed a voiced C1 and partial voicing of C2 in all cases, regardless of speaking rate. The data from speaker ME, on the other hand, show slightly more variability in the voicing timing patterns but show no effect of speaking rate on voicing. The relationship between the two variables did not reach significance for any of the two English subjects (subject AL r^2=0.364, p=0.113, ME r^2=0.004, p=0.832>0.05).

All in all, the English data seem to show that the target for the offset of vocal fold vibration is around 0 – the onset of the oral constriction for C2 – with a wide time frame or window for the implementation of vocal fold abduction, which permits variability to take place.

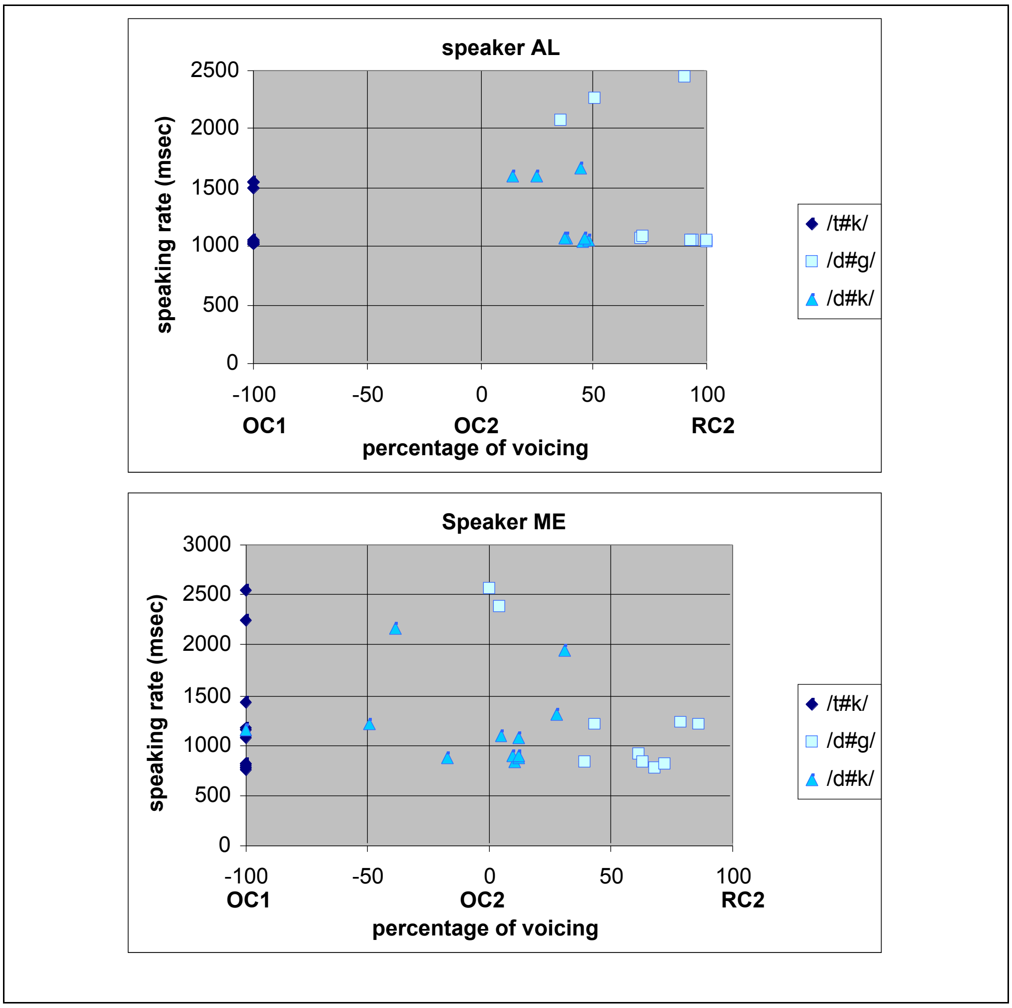


Figure 3.6. Scattergrams of percentage of voicing (horizontal axis) plotted as a function of speaking rate (vertical axis) in the English sequences 'sad gap' (/d#g/), 'fat cap' (/t#k/) and 'sad cap' (/d#k/), with higher values indicating slower speaking rates. Each dot represents one observation.

3.1.2. Degree of overlap

In order to explore the relationship between degree of voicing and degree of articulatory overlap of the two consonant gestures, the percentage of voicing for each individual token was plotted as a function of overlap indexes OIOC and OIACO. Early onset of the supraglottal gestures for C2 was expected to show anticipatory devoicing, given the expected coordination between glottal and supraglottal articulations. However, as Figure 3.7 below shows for Catalan, greater overlap of the supraglottal gestures did not correlate with a shorter extent of voicing in C1 for speaker AN (OIACO r^2=0.053, p=0.428; OIOC r^2=0.148, p=0.172) or for speaker MJ (OIACO r^2=0.005, p=0.842,

;OIOC r^2=0.003, p=0.856). Thus, degree of overlap did not affect the percentage of voicing in the consonant sequence /d#k/ in any of the two speakers.

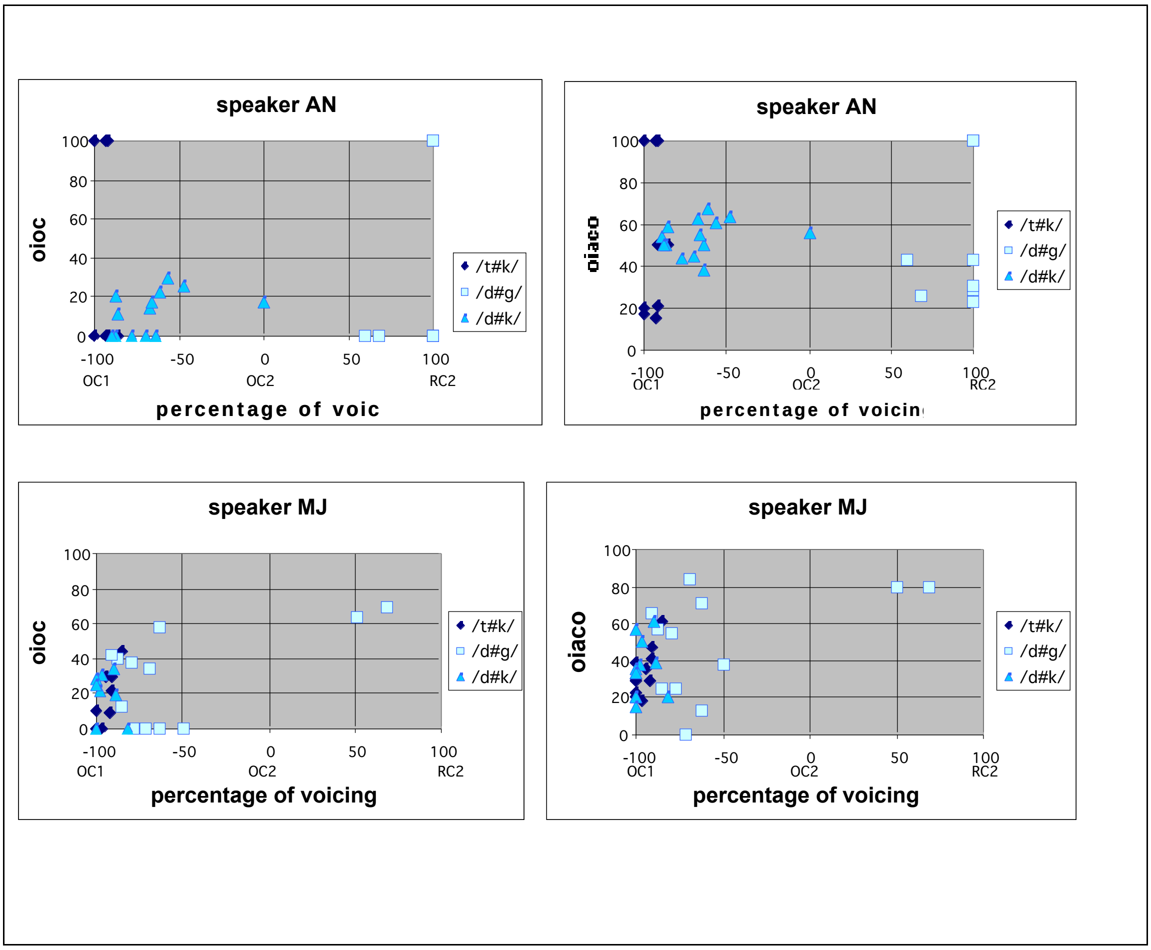


Figure 3.7. Scattergrams of percentage of voicing (horizontal axis) in the individual tokens plotted as a function of overlap indexes OIOC and OIACO (vertical axis) with higher values indicating larger overlap in the Catalan sequences 'fred gal' (/d#g/), 'dret car' (/t#k/) and 'fred car' (/d#k/). Each dot represents one observation.

Similarly, Figure 3.8 below shows that there was no correlation between articulatory overlap and the voicing timing pattern of the sequence /d#k/ for the English speaker AL (OIACO r^2=0.031, p=0.676>0.05; OIOC r^2=0.321, p=0.142>0.05) or for speaker ME (OIACO r^2=0.029, p=0.575>0.05; OIOC r^2=0.008, p=0.768>0.05).

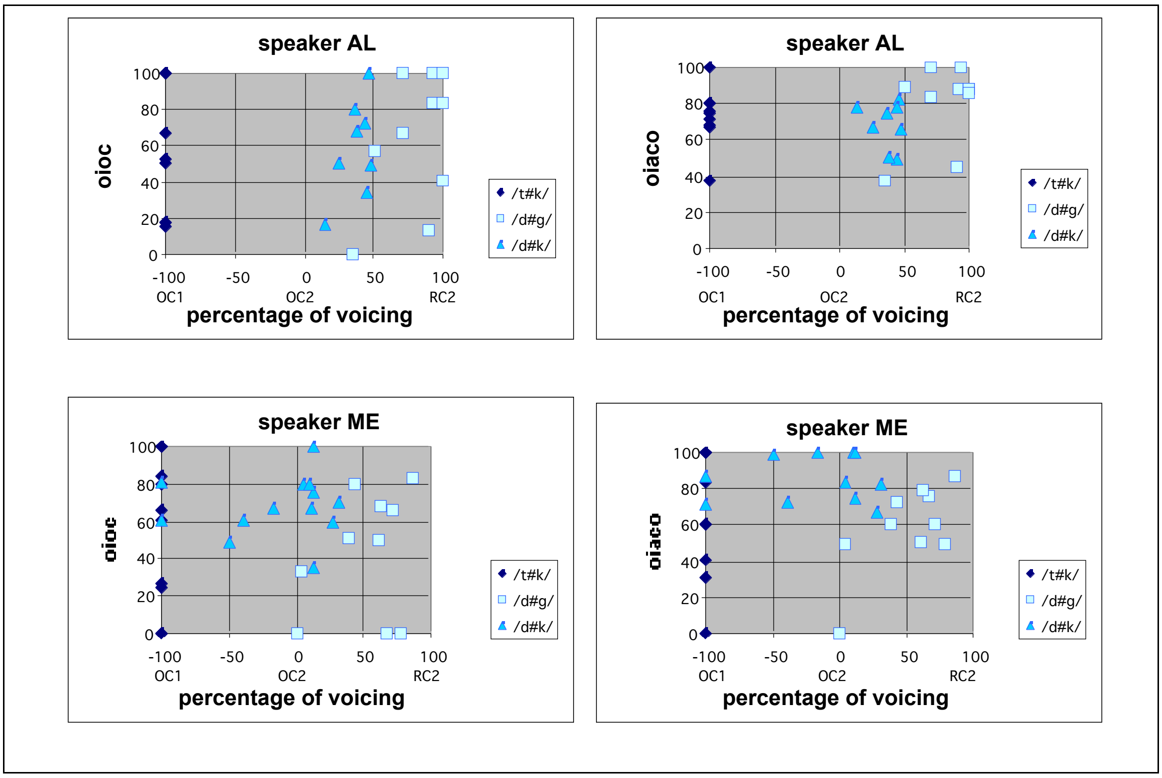


Figure 3.8. Scattergrams of percentage of voicing (horizontal axis) in the individual tokens plotted as a function of overlap indexes OIACO and OIOC (vertical axis) with higher values indicating larger overlap in the English sequences 'sad gap' (/d#g/), 'fat cap' (/t#k/) and 'sad cap' (/d#k/). Each dot represents one observation.

The results obtained in the Catalan and English voiceless – voiced stop sequence /d#k/ are summarized in Table III below.

Table III. Summary of the results obtained in the sequence /d#k/ in Catalan and English

Sequence		Subject	Coordination of glottal and supraglottal gestures	direction	extent	Effect of speaking rate	Effect of overlap	Neutralization	Approx. Phonetic Output
/d#k/	Catalan	AN	devoicing of C1	←	Between 0% and -90%	No	No	No	[dd6#k]
		MJ	devoicing of C1	←	Between -70% and -100%	No	No	Yes	[t#k]
	English	AL	voicing into C2	→	One third into C2	No	No		[d#gk]
		ME	voicing into C2	→	10%	No	No		[d#k]
			devoicing of C1	←	Between -39% and -100%	No	No		[dd8#k] or [d8#k]

In sum, the results show that the Catalan speaker AN exhibited different voicing timing patterns for the sequences /t#k/ and /d#k/, the latter being produced with more voicing in C1 than the former. Thus, for the sequence /d#k/, subject AN seems to target vocal fold vibration at the middle of the voiced consonant (C1). The Catalan speaker MJ, on the other hand, seems to target the voiced consonant as voiceless when followed by a voiceless consonant. Speaker MJ did not display any significant differences in the organization of oral and glottal gestures in the sequences /t#k/ and /d#k/ and both sequences appear to be planned as fully voiceless. Thus, speaker MJ displayed a categorical process where regressive voicing assimilation was complete, whereas speaker AN displayed a gradient process which resulted in partial assimilation. In addition, no effect of speaking rate or articulatory overlap was found in Catalan.

In English, it was found that the organization of oral and glottal gestures was different from Catalan. The English speakers tended to produce the sequence /d#k/ with a voiced C1 and a voiceless C2. Some differences were found between the English speakers, since speaker AL partial voicing into C2, whereas speaker ME also showed heavy devoicing of C1. Finally, no significant effect of speaking rate or articulatory overlap on the voicing timing pattern of the English sequence /d#k/ was found. It can be concluded from the data that, contrary to traditional descriptions, partial anticipatory devoicing is not the only pattern found in English, but full voicing of C1 is also common. The English data suggest that speakers target voicelessness at time 0 and that mechanical anticipatory movements are possible.

3.2. Voiceless – voiced stop sequences

This section focuses on the implementation of voicing in voiceless – voiced stop sequences. Figures 3.9 and 3.10 present the voicing timing patterns of the control sequences /t#k/, /d#g/ and the test sequence /t#g/ in Catalan and English, respectively.

Concerning direction and extent, the Catalan test sequence /t#g/ displayed a similar voicing timing pattern to that of the voiced control sequence /d#g/ for each individual speaker, as shown in Figure 3.9. It can be seen that in one case uttered by subject AN voicing died out during the initial portion of C1, yet it was considered that the sequences had been planned as voiced (and voicing died out due to mechanical devoicing, as explained in section 3.0 above) because the degree of voicing was greater than that in the voiceless control sequence /t#k/. The data for subject MJ in Figure 3.9 show that voicing in C1 in the sequence /t#g/ died out very early, as in the phonologically voiced sequence /d#g/, again due to mechanical aerodynamic factors. The degree of voicing in the test sequence was always greater than that in the voiceless control sequence and not significantly different, it was considered that the sequence was planned as voiced with vocal fold vibration dying out due to mechanical devoicing. One-way ANOVA showed a significant difference in degree of voicing of the obstruent sequences for both speakers. Post-hoc pairwise comparisons showed that the sequences /t#g/ and /d#g/ did not differ significantly for any of the two speakers, whereas /t#g/ differed significantly from the voiceless sequence /t#k/. This is compatible with the interpretation that Catalan shows complete regressive assimilation of voicing.

Table IV. Results of ANOVA and post-hoc tests comparing the percentage of voicing in the Catalan mixed sequence /t#g/ and in the control sequences in Catalan. The asterisk shows that the result was significant at the .05 level; the double asterisk shows that the result was significant at the .01 level.

	Sequence type	Mean	SD	N	ANOVA	Sequences	*p* (Scheffé)	Sig.
AN	/t#k/	100	0	9	$F(2,29)=22.179$, $p=0.0001<0.01$	Voiced-vlss	0.000	**
	/d#g/	-100	0	10		Mixed-voiceless	0.000	**
	/t#g/	-100	0	14		Mixed-voiced	0.285	-
MJ	/t#k/	100	0	11	$F(2,30)=6.120$, $p=0.006<0.01$	Voiced-vlss	0.001	**
	/d#g/	-100	0	12		Mixed-voiceless	0.024	*
	/t#g/	-100	0	10		Mixed-voiced	0.457	-

In the English sequence /t#g/, speaker AL showed vocal fold vibration throughout the sequence in most cases, as in the voiced control sequence, and partial or complete devoicing of C2 in other cases. Speaker ME showed a more commonly described pattern, namely absence of vocal fold vibration in C1 and partial or complete devoicing of C2. Thus, there were also important differences between the English speakers as to the voicing timing patterns observed in the sequence /t#g/.

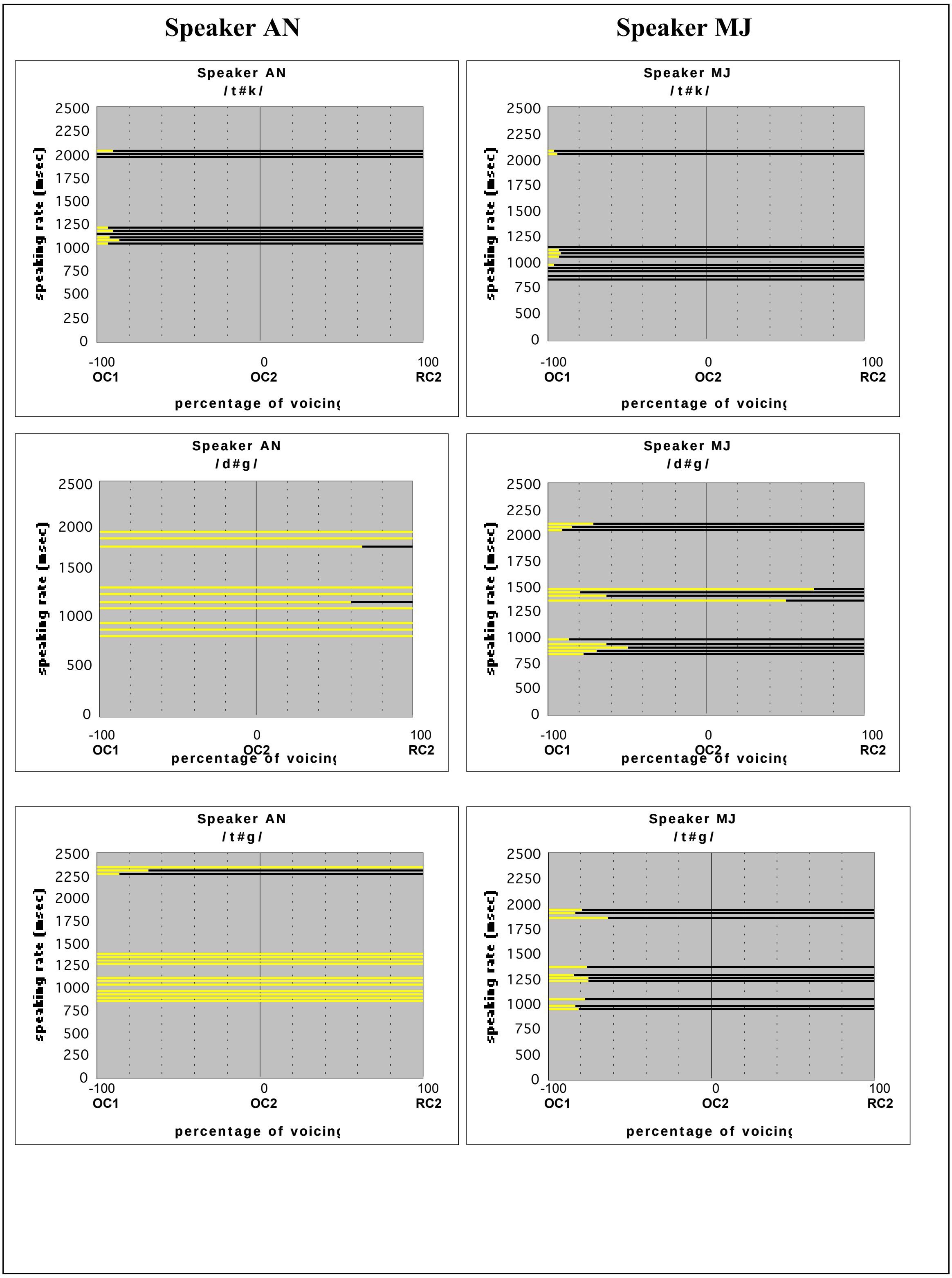


Figure 3.9. Vocal fold vibration in the obstruent sequences in 'dret car' (/t#k/), 'fred gal' (/d#g/) and 'dret gal' (/t#g/) for the Catalan speakers AN and MJ. The yellow lines represent vocal fold vibration and the black lines represent absence of vocal fold vibration. Speaking rate in milliseconds appears on the ordinate and the percentage of voicing in relation to supraglottal gestures appears on the abscissa. OC1 stands for onset of C1, OC2 stands for onset of C2 and RC2 stands for release of C2. Each line represents one observation.

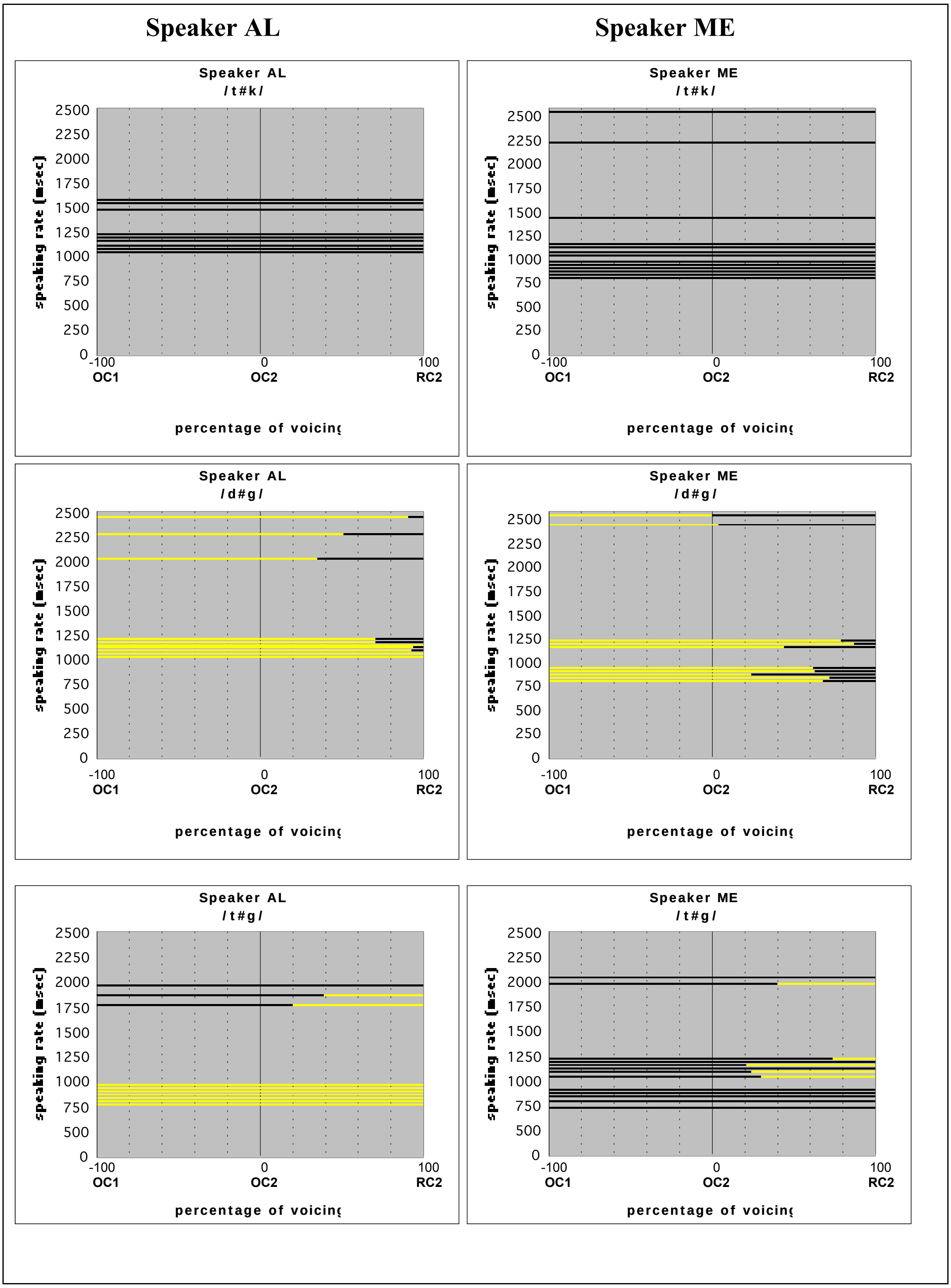


Figure 3.10. Vocal fold vibration in the obstruent sequences in 'fa**t c**ap' (/t#k/), 'sa**d g**ap' (/d#g/) and 'fa**t g**ap' (/t#g/) for the English speakers AL and ME. The yellow lines represent vocal fold vibration and the black lines represent absence of vocal fold vibration. Speaking rate in milliseconds appears on the ordinate and the percentage of voicing in relation to supraglottal gestures appears on the abscissa. OC1 stands for onset of C1, OC2 stands for onset of C2 and RC2 stands for release of C2. Each line represents one observation.

Comparison of the direction and extent of voicing assimilation in the Catalan sequence /t#g/ and the reverse sequence /d#k/ shows that the process was regressive and complete in Catalan. Unlike the reverse mixed sequence /d#k/, where one of the subjects displayed partial regressive assimilation, both speakers displayed complete assimilation. In English, both speakers displayed partial or complete progressive devoicing of C2, although one of the speakers also exhibited complete regressive assimilation of voicing into C1.

3.2.1. Speaking rate effects

Concerning the effect of rate of speech on voicing assimilation in Catalan, Figure 3.11 shows that C1 was categorically implemented as voiced regardless of speaking rate in /t#g/ sequences. No effect of articulatory overlap on voicing assimilation was observed, either, as shown in Figure 3.12.

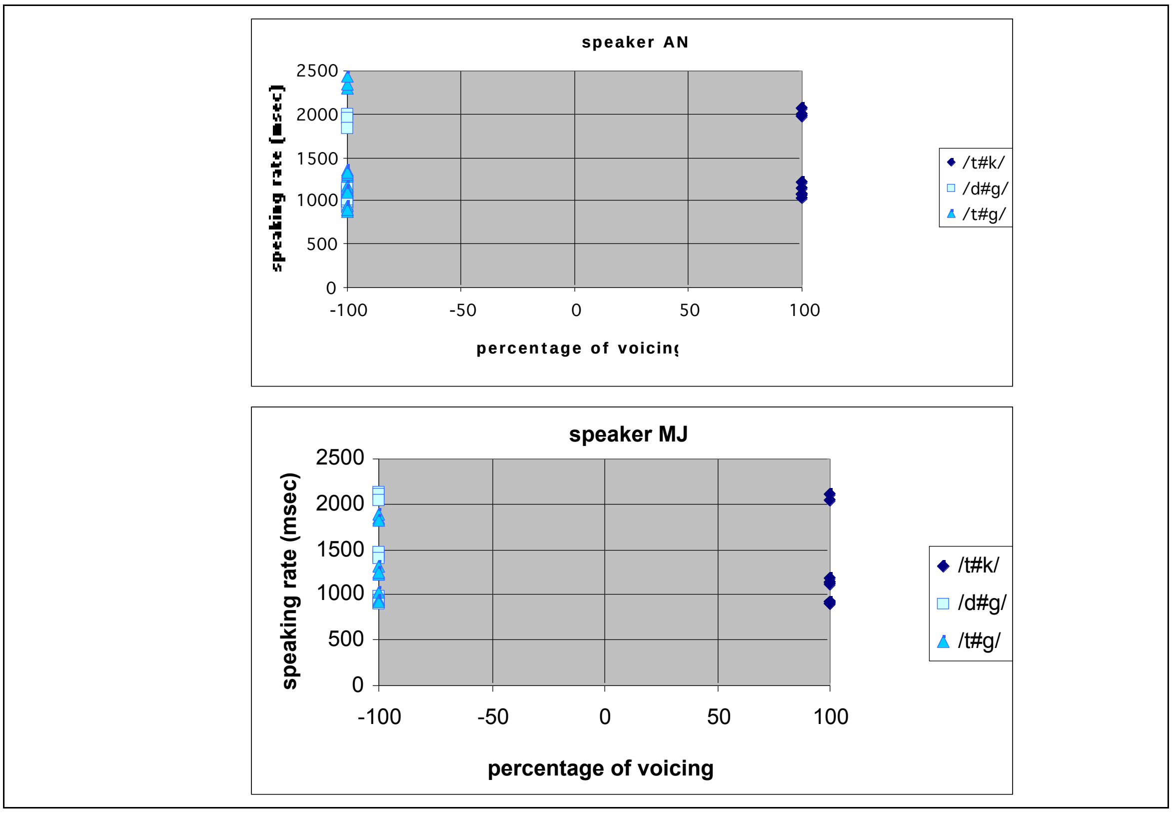


Figure 3.11. Scattergrams of variation in percentage of voicing (horizontal axis) plotted as a function of speaking rate (vertical axis) in the Catalan sequences ‘dret car’ (/t#k/), ‘fred gal’ (/d#g/), and ‘dret gal’ (/t#g/) uttered by speakers AN and MJ. Higher values indicate slower speaking rates. Each dot represents one observation.

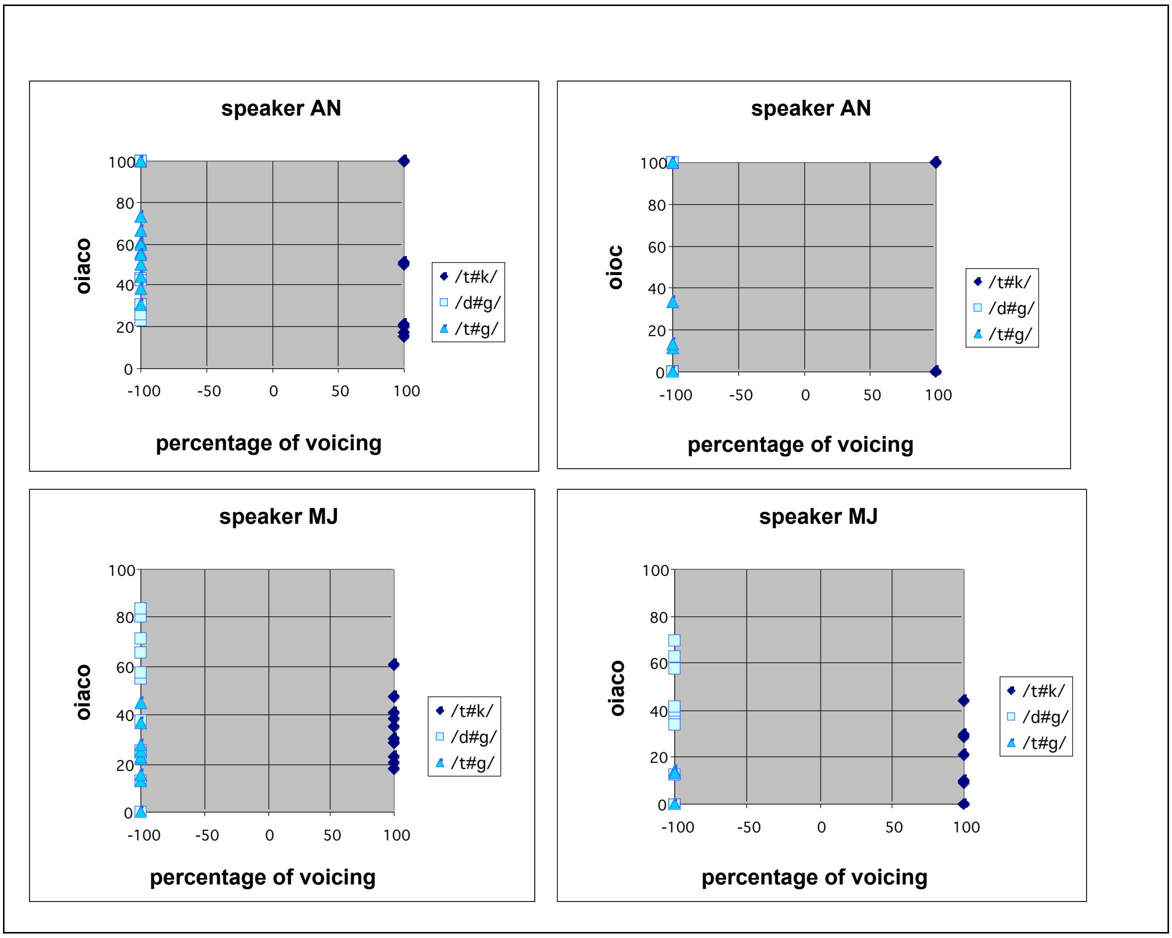


Figure 3.12. Scattergrams of variation in percentage of voicing (horizontal axis) plotted as a function of overlap indexes OIACO and OIOC (vertical axis) in the Catalan sequences ‘dret car’ (/t#k/), ‘fred gal’ (/d#g/) and ‘dret gal’ (/t#g/) uttered by speakers AN and MJ. Each dot represents one observation.

Speaking rate had an effect on the voicing timing pattern of the sequence /t#g/ for the English speaker AL: it was found that complete voicing during the consonant sequence occurred at faster speaking rates, whereas devoicing of C2 was present at slower speaking rates, as shown in Figure 3.13. Pearson’s correlation confirmed that there was a significant and strong correlation between rate of speech and percentage of voicing in the sequence /t#g/ (r^2=0.975, p=0.00001). Thus, speaker AL showed speaking rate-dependent voicing patterns. For the English speaker ME, no significant correlation was found between speaking rate and degree of C2 devoicing (r^2=0.083, p=0.337), although as can be observed in Figure 3.14, there seemed to be a tendency towards faster speaking rates showing complete devoicing of C2, whereas slower speaking rates showed more variability.

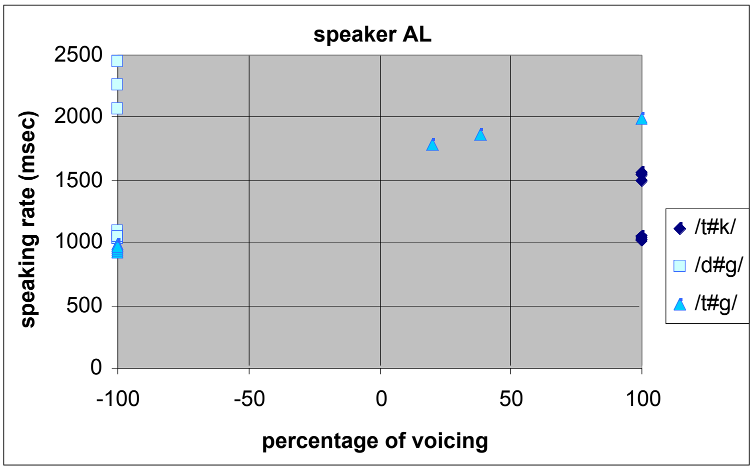


Figure 3.13. Scattergram of variation in percentage of voicing (horizontal axis) plotted as a function of speaking rate (vertical axis) in the English sequences ‘fat cap’ (/t#k/), ‘sad gap’ (/d#g/) and ‘fat gap’ (/t#g/) uttered by speaker AL, with higher values indicating slower speaking rates. Each dot represents one observation.

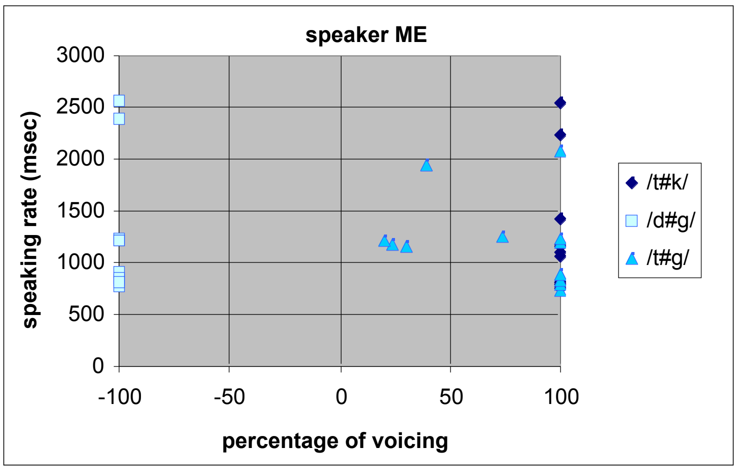


Figure 3.14. Scattergram of variation in percentage of voicing (horizontal axis) plotted as a function of speaking rate (vertical axis) in the English sequences ‘fat cap’ (/t#k/), ‘sad gap’ (/d#g/) and ‘fat gap’ (/t#g/) uttered by speaker ME, with higher values indicating slower speaking rates. Each dot represents one observation.

3.2.2. Degree of overlap

Concerning the effect of the degree of articulatory overlap on voicing assimilation, a significant and strong correlation was found between articulatory overlap and the percentage of voicing in the sequence /t#g/ for speaker AL (OIACO: r^2=0.838, p=0.0001; OIOC: $r2$=0.968, p=0.00001). As can be observed in Figure 3.15, vocal fold vibration during the whole consonant sequence occurred when there was complete overlap of the oral gestures for C1 and C2 (OIOCO, OIOC=100); otherwise, there was partial or complete devoicing of C2. For speaker ME, no significant correlation was found between articulatory overlap and percentage of voicing (OIACO r^2=0.014, p=0.849>0.05; OIOC: r^2=0.26, p=0.074>0.05). For this speaker, however, Figure 3.15 shows that when the degree of overlap of the articulators (OIOC) was higher than 50, there tended to be complete devoicing of C2, *i.e.*, the opposite tendency to that found for speaker AL. If the degree of articulatory overlap was smaller than 50, then the voicing timing patterns showed greater variability.

The results obtained in the Catalan and English sequence /t#g/ are summarized in Table V below.

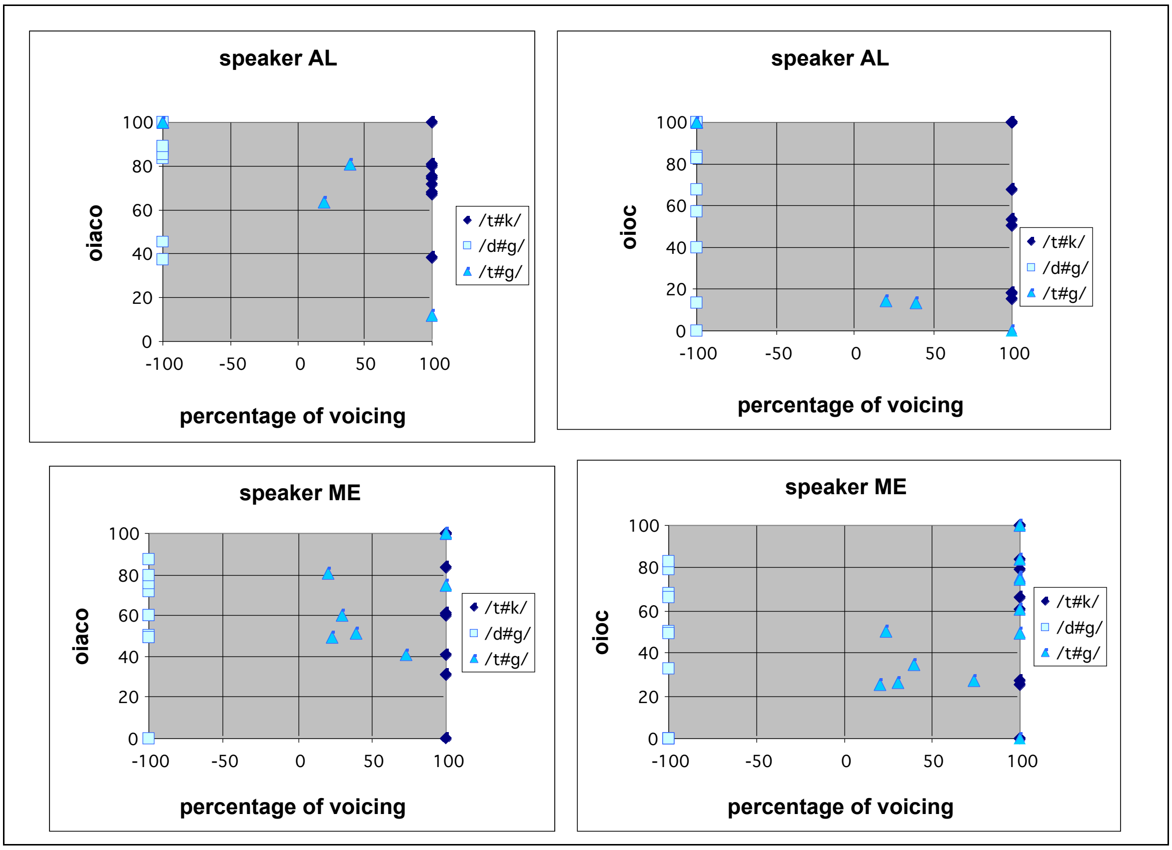


Figure 3.15. Scattergrams of variation in percentage of voicing (horizontal axis) plotted as a function of overlap indexes OIACO and OIOC (vertical axis) in the English sequences 'fat cap' (/t#k/), 'sad gap' (/d#g/) and 'fat gap' (/t#g/) uttered by speaker ME. Each dot represents one observation.

Table V. Summary of the results obtained in the sequence /t#g/ in Catalan and English

Sequence		Subject	Coordination of glottal and supraglottal gestures	direction	extent	Effect of speaking rate	Effect of overlap	Neutralization	Approx. Phonetic Output
/t#g/	Catalan	AN	C1 and C2 voiced	←	-100	None	None	Yes	[d#g]
		MJ	C1 and C2 voiced	←	-100	None	None	Yes	[d#g]
	English	AL	C1 and C2 voiced	←	-100	Yes: C2 devoiced at slow seaking rates	Yes		[d#g]
			Partial or complete devoicing of C2	→	between 20 and 100				[t#g]
		ME	Partial or complete devoicing of C2	→	Between 21 and 100	No	No		[t#g]or [t#k]

In sum, the Catalan sequence /t#g/ showed vocal fold vibration throughout C1 and C2 regardless of rate, which suggests complete regressive assimilation of voicing. The reverse sequence /d#k/, also showed complete regressive voicing assimilation for speaker MJ, but partial regressive assimilation for speaker AN. No effect of speaking rate or articulatory overlap was observed in this language.

In English, both speakers displayed partial or complete devoicing of C2 in the sequence /t#g/, and one of the subjects showed complete regressive assimilation of voicing at fast speaking rates and when there was complete overlap of the supraglottal gestures. Similarly to the sequence /d#k/, which showed partial voicing of C2 but also devoicing of C1, there was variability within and across speakers in the timing of oral and glottal gestures. Thus, there seems to be a wide time window for voicing during the oral constriction in consonant sequences in English.

3.3. Fricative – stop sequences

3.3.1. Voiced – voiceless sequences

Figure 3.18 below shows the voicing timing patterns of the fricative – stop control sequences /s#t/ (top panel) and /z#d/ (middle panel) and the test sequence /z#t/ (bottom panel) for the Catalan speakers. The voiceless control sequence /s#t/ was produced without vocal fold vibration by speaker AN whereas speaker MJ produced this sequence with some voicing in the initial portion of C1 due to voicing continuation (the mean percentage of voicing continuation in /s#t/ was 20). The voiced control sequence /z#d/ was mostly produced with full voicing during C1 and C2 by speaker AN, whereas speaker MJ showed more difficulty in maintaining vocal fold vibration in this sequence, so that in most cases voicing died out as early as the middle of C1.

Concerning the mixed test sequence /z#t/, Figure 3.18 shows that speaker AN produced it with complete absence of vocal fold vibration, as for /s#t/ sequences. Speaker MJ also showed a pattern similar to that of the voiceless control sequence: the mean percentage of voicing in C1 for this speaker was 14, reflecting voicing continuation. Analysis of variance and post-hoc tests showed that the sequences /z#t/ and /s#t/ did not differ significantly for any of the Catalan speakers, as shown in Table VI (mixed – voiceless) below.

In sum, the direction and extent of voicing assimilation in the sequence / z#t/ in Catalan was regressive and complete, so that the underlyingly voiced C1 was implemented as voiceless.

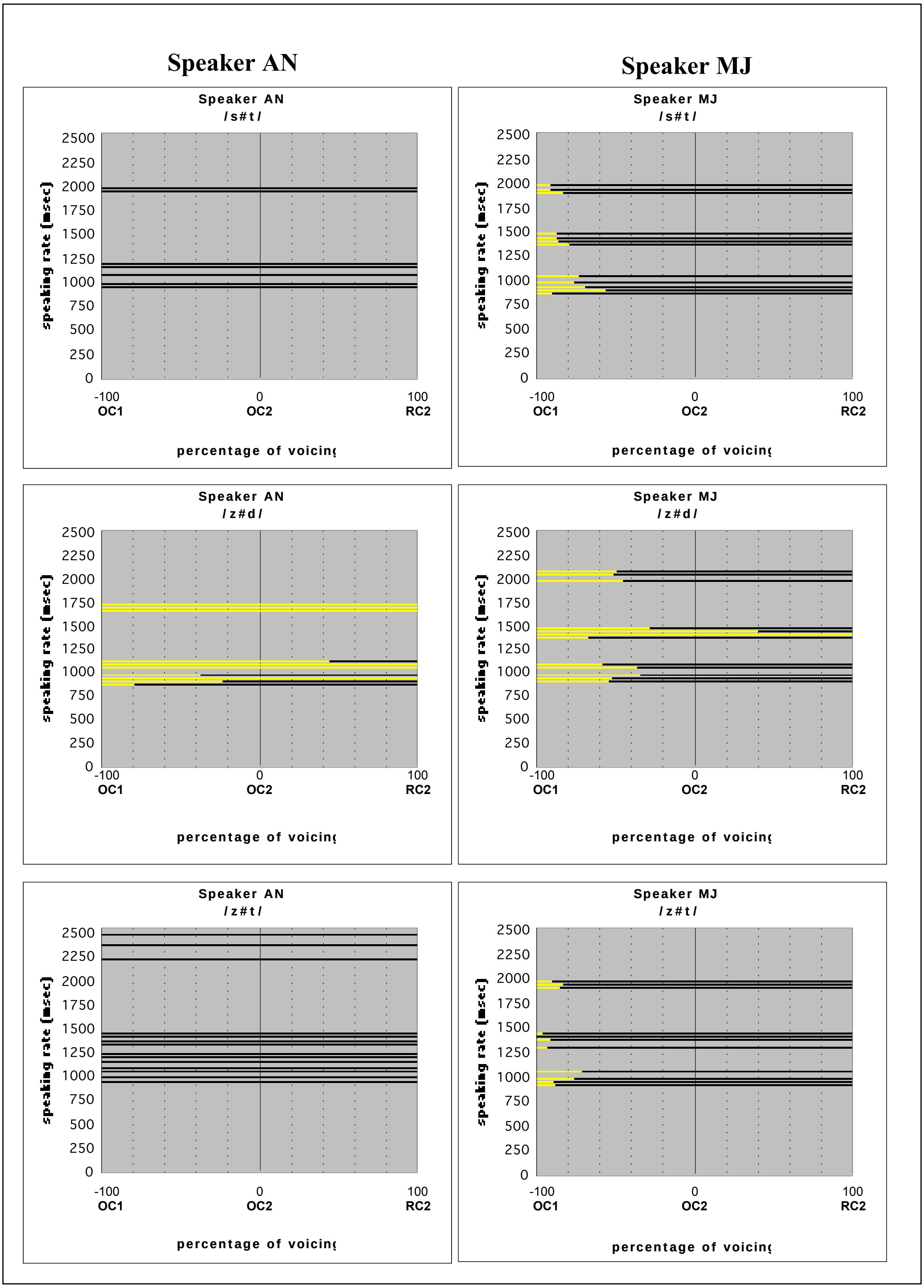


Figure 3.18. Vocal fold vibration in the obstruent sequences in 'pas turc' (/s#t/), 'gas dur' (/z#d/) and 'gas turc' (/z#t/) for the Catalan subjects AN and MJ. The yellow lines represent vocal fold vibration and the black lines represent absence of vocal fold vibration. Speaking rate in milliseconds appears on the ordinate and the percentage of voicing in relation to supraglottal gestures appears on the abscissa. OC1 stands for onset of C1, OC2 stands for onset of C2 and RC2 stands for release of C2. Each line represents one observation.

Table VI. Results of ANOVA and post-hoc tests comparing the percentage of voicing in the Catalan sequence /z#t/ and in the control sequences in Catalan. The asterisk shows that the result was significant at the .05 level; the double asterisk shows that the result was significant at the .01 level.

	Sequence type	Mean	SD	N	ANOVA	Sequences	*p* (Scheffé)	Sig.
AN	/s#t/	-100	0	7	F(2,28)=48.11, *p*=0.000<0.01	Voiced-vlss	0.000	**
	/z#d/	50	70.5	10		Mixed-voiceless	1.000	-
	/z#t/	-100	0	14		Mixed-voiced	0.000	**
MJ	/s#t/	-80	10.6	12	F(2,32)=13.37, *p*=0.000<0.01	Voiced-vlss	0.001	**
	/z#d/	-29.4	49.2	12		Mixed-voiceless	0.862	-
	/z#t/	-86	8.3	11		Mixed-voiced	0.000	**

The voicing timing patterns of the English sequences /s#t/, /z#d/ and /z#t/ are displayed in Figure 3.19 below. The voiceless control sequence was fully voiceless for speaker ME, whereas speaker AL could show some voicing continuation in the initial portion of C1. In the voiced control sequence /z#d/, speakers showed variability: the predominant pattern for speaker AL was full voicing of the consonant sequence, although in some cases voicing died out before the release of C2 due to mechanical devoicing. Speaker ME produced the voiced control sequence /z#d/ with voicing into the first half of C1.

Both speakers showed more voicing in /z#t/ than in /s#t/ sequences. They produced the test sequence with voicing into the first third (ME) or first half (AL) of C1; post-hoc tests showed that the sequence /z#t/ had significantly more voicing than the voiceless sequence /s#t/ for speaker ME but the difference did not reach significance for speaker AL suggesting almost complete devoicing of C1 for this speaker. In sum, concerning the direction and extent of voicing assimilation, the English sequence /z#t/ was produced with partial devoicing of C1 by both speakers. Table VII below displays the results of the ANOVAs and post-hoc tests comparing the percentage of voicing in the test and control sequences.

Table VII. Results of ANOVA and post-hoc tests comparing the percentage of voicing in the English mixed sequence /z#t/ and in the control sequences in English. The asterisk shows that the result was significant at the .05 level; the double asterisk shows that the result was significant at the .01 level.

	Sequence type	Mean	SD	N	ANOVA	Sequences	*p* (Scheffé)	Sig.
AL	/s#t/	-86.7	8.8	9	$F(2,26)=22.63$, $p=0.000<0.01$	Voiced-vlss	0.000	**
	/z#d/	31	67.7	10		Mixed-voiceless	0.708	-
	/z#t/	-71.4	21	9		Mixed-voiced	0.000	**
ME	/s#t/	-100	0	14	$F(2,36)=70.58$, $p=0.000<0.01$	Voiced-vlss	0.000	**
	/z#d/	-49.8	16.2	13		Mixed-voiceless	0.008	**
	/z#t/	-85	11	12		Mixed-voiced	0.000	**

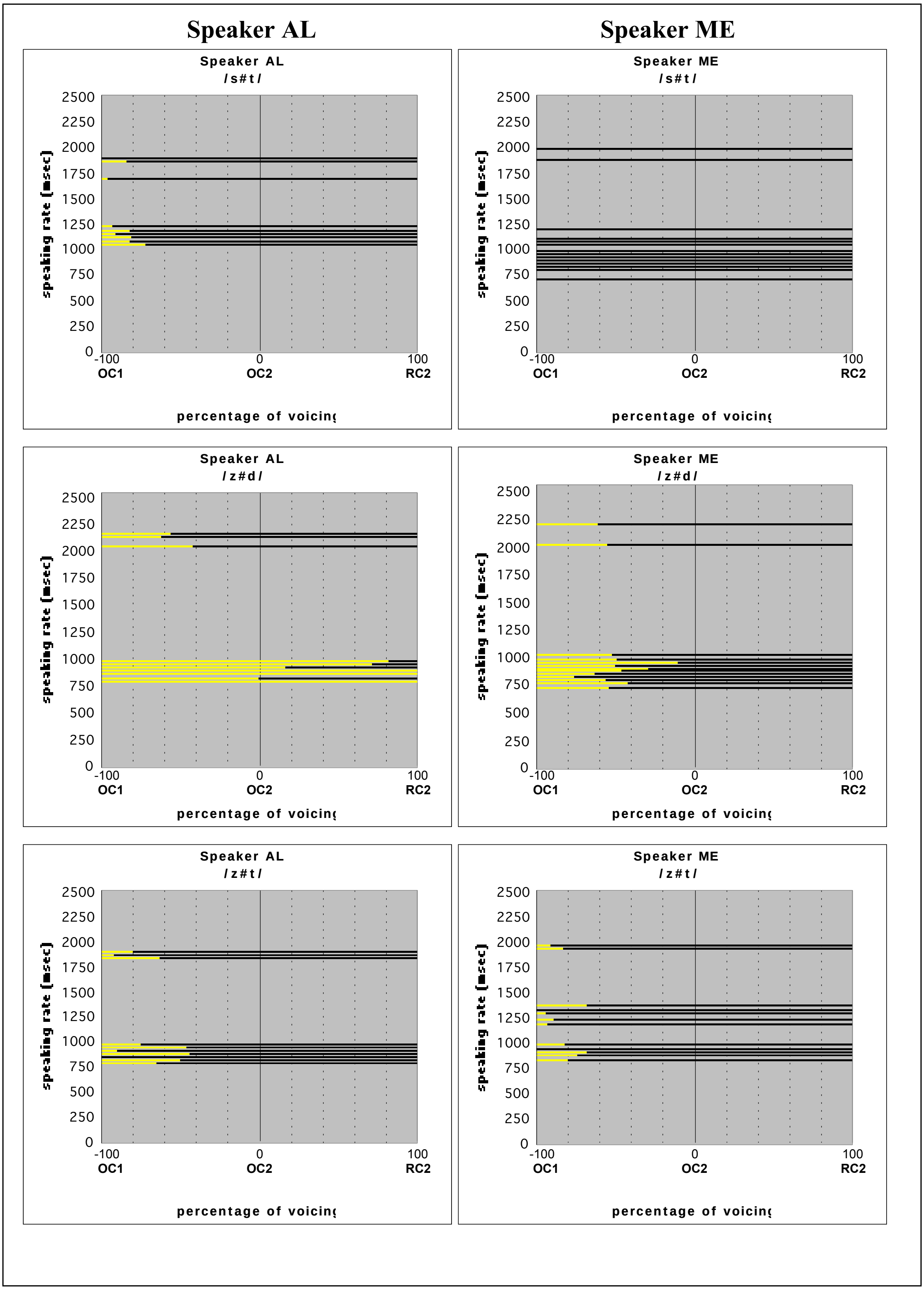


Figure 3.19. Vocal fold vibration in the obstruent sequences in ‘this toll’ (/s#t/), ‘his doll’ (/z#d/) and ‘his toll’ (/z#t/) for the English subjects AL and ME. The yellow lines represent vocal fold vibration and the black lines represent absence of vocal fold vibration. Speaking rate in milliseconds appears on the ordinate and the percentage of voicing in relation to supraglottal gestures appears on the abscissa. OC1 stands for onset of C1, OC2 stands for onset of C2 and RC2 stands for release of C2. Each line represents one observation.

3.3.2. Voiceless – voiced sequences

Let us next consider the voicing patterns of the sequence /s#d/ with reverse values for voicing vis-à-vis /z#t/, addressed above. Figure 3.20 presents the results for the Catalan test sequence /s#d/ and, again, the control sequences /z#d/ and /s#t/. As can be observed, both speakers displayed a similar amount of voicing in the test sequence /s#d/ and their respective voiced control sequence /z#d/. Post-hoc tests confirmed that the mean percentage of voicing did not differ significantly between these two sequences for any of the Catalan speakers, as shown in Table VIII (mixed – voiced) below. Thus, voicing assimilation in the sequence /s#d/ was regressive and complete in Catalan.

Table VIII. Results of ANOVA and post-hoc tests comparing the percentage of voicing in the Catalan mixed sequence /s#d/ and in the control sequences in English. The asterisk shows that the result was significant at the .05 level; the double asterisk shows that the result was significant at the .01 level.

	Sequence type	Mean	SD	N	ANOVA	Sequences	*p* (Scheffé)	Sig.
AN	/s#t/	100	0	7	F(2,28)=106.02, *p*=0.000<0.01	Voiced-vlss	0.000	**
	/z#d/	-100	0	10		Mixed-voiceless	0.000	**
	/s#d/	-100	0	14		Mixed-voiced	0.592	-
MJ	/s#t/	100	0	12	F(2,34)=42.11, *p*=0.000, <0.01	Voiced-vlss	0.000	**
	/z#d/	-66.6	78	12		Mixed-voiceless	0.000	**
	/s#d/	-84	55.4	13		Mixed-voiced	0.612	-

Figure 3.21 presents the results for English. As can be observed, the percentage of voicing in the test sequence /s#d/ was similar to that of the voiceless sequence /s#t/, whereas the voiced control sequence /z#d/ displayed a larger amount of voicing. ANOVAs and post-hoc pairwise comparisons showed that the mean percentage of voicing in the consonant sequences /s#t/ and /s#d/ did not differ significantly for any of the English speakers. In sum, concerning direction and extent of voicing assimilation, the sequence /s#d/ was produced with complete progressive devoicing of C2 by both speakers. The results of ANOVA and post-hoc tests are summarized in Table IX below.

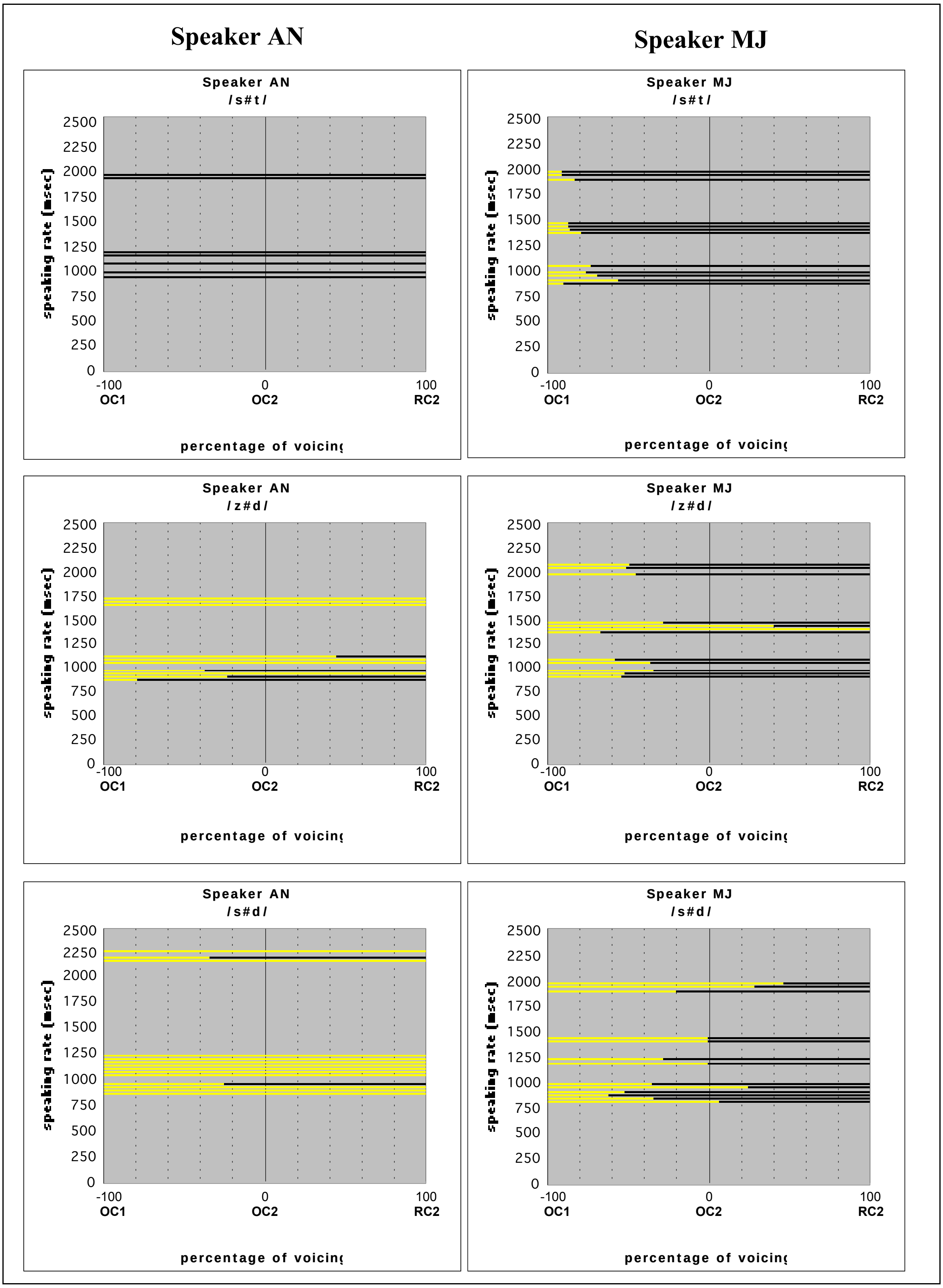


Figure 3.20. Vocal fold vibration in the obstruent sequences in 'pas turc' (/s#t/), 'gas dur' (/z#d/) and 'pas dur' (/s#d/) for the Catalan speakers AN and MJ. The yellow lines represent vocal fold vibration and the black lines represent absence of vocal fold vibration. Speaking rate in milliseconds appears on the ordinate and the percentage of voicing in relation to supraglottal gestures appears on the abscissa. OC1 stands for onset of C1, OC2 stands for onset of C2 and RC2 stands for release of C2. Each line represents one observation.

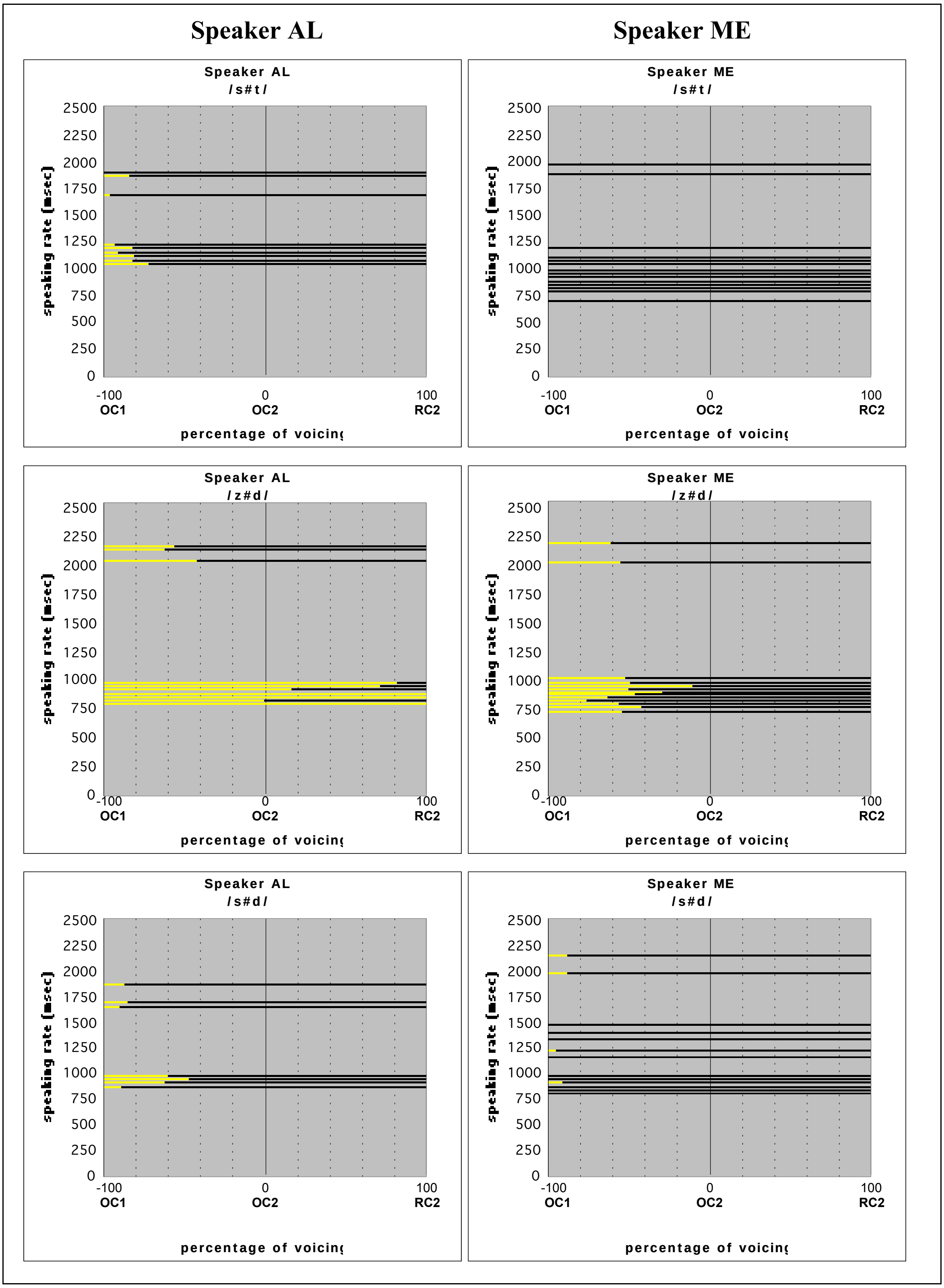


Figure 3.21. Vocal fold vibration in the obstruent sequences in 'this toll' (/s#t/), 'his doll' (/z#d/) and 'this doll' (/s#d/) for the English speakers AL and ME. The yellow lines represent vocal fold vibration and the black lines represent absence of vocal fold vibration. Speaking rate in milliseconds appears on the ordinate and the percentage of voicing in relation to supraglottal gestures appears on the abscissa. OC1 stands for onset of C1, OC2 stands for onset of C2 and RC2 stands for release of C2. Each line represents one observation.

Table IX. Results of ANOVA and post-hoc tests comparing the percentage of voicing in the English mixed sequence /s#d/ and in the control sequences in English. The asterisk shows that the result was significant at the .05 level; the double asterisk shows that the result was significant at the .01 level.

	Sequence type	Mean	SD	N	ANOVA	Sequences	*p* (Scheffé)	Sig.
AL	/s#t/	100	0	9	F(2,23)=35.62, *p*=0.000	Voiced-vlss	0.000	**
	/z#d/	-100	0	10		Mixed-voiceless	0.458	-
	/s#d/	100	0	7		Mixed-voiced	0.000	**
ME	/s#t/	100	0	14	F(2,37)=112.29, *p*=0.000	Voiced-vlss	0.000	**
	/z#d/	-100	0	13		Mixed-voiceless	0.733	-
	/s#d/	100	0	13		Mixed-voiced	0.000	**

3.3.3. Speaking rate effects

Figure 3.22 shows the effect of speaking rate on the voicing timing patterns of the sequences /z#d/, /s#t/ and /z#t/ in Catalan. For speaker AN regressive devoicing was complete in the sequence /z#t/ regardless of speaking rate (*i.e.* the percentage of voicing assimilation was always –100). As for speaker MJ, Pearson's correlation revealed that there was no significant relationship between speaking rate and percentage of voicing in this sequence (r^2=0.051, p=0.502>0.05). No significant correlation between speaking rate and percentage of voicing was observed in the control sequences for any of the two speakers, either. Finally, it can also be observed in Figure 3.22 that voiceless and mixed sequences showed a parallel behaviour across rates for both speakers, suggesting their common phonological status, whereas the voiced sequence /z#d/ always had more voicing than the other two sequences.

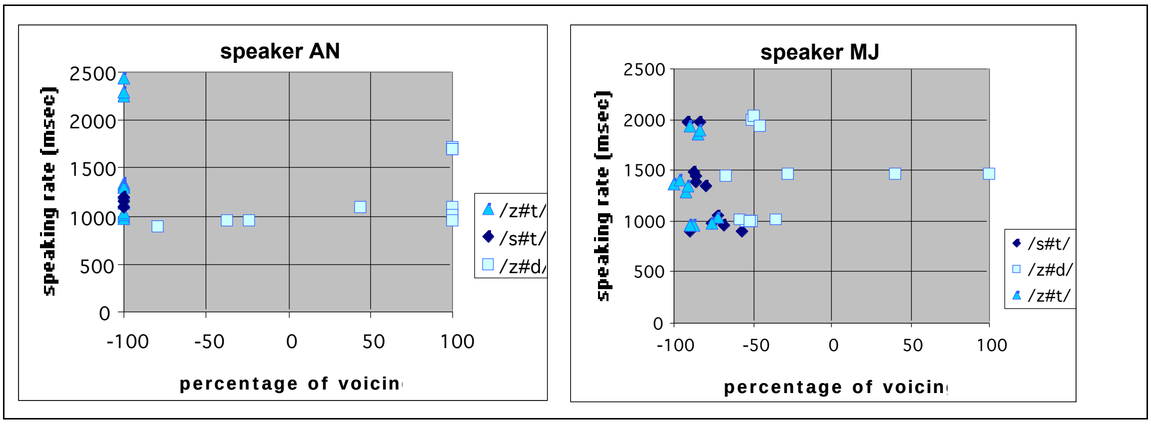


Figure 3.22 Scattergrams of percentage of voicing (horizontal axis) plotted as a function of speaking rate (vertical axis), with higher values indicating slower speaking rates. The percentage of voicing in the Catalan sequences 'gas dur' (/z#d/), 'pas turc' (/s#t/) and 'gas turc' (/z#t/) is plotted in the graphs. Each dot represents one observation.

The effect of speaking rate on the voicing timing patterns of the English sequences /s#t/ /z#d/ and /z#t/ is shown in Figure 3.23 below. No significant correlation was found between speaking rate and the voicing timing pattern of the sequence /z#t/ in English (speaker AL r^2 = 0.079, p=0.43>0.05; speaker ME r^2=0.043, p=0.515>0.05).

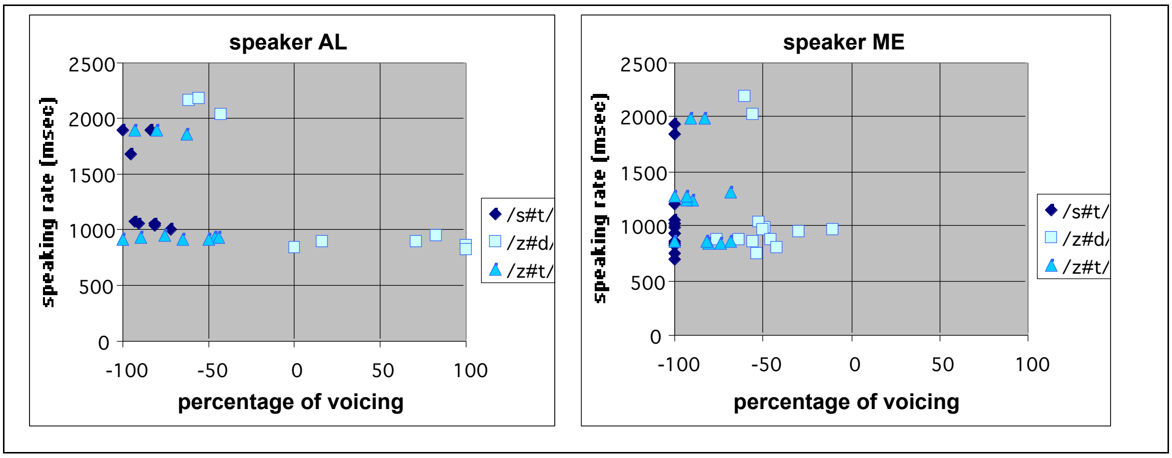


Figure 3.23. Scattergrams of percentage of voicing (horizontal axis) plotted as a function of speaking rate (vertical axis) in the English sequences 'his doll' (/z#d/), 'this toll' (/s#t/) and 'his toll' (/z#t/), with higher values indicating slower speaking rates. Each dot represents one observation.

Concerning the relationship between speaking rate and percentage of voicing in the reverse sequence /s#d/, Pearson's correlation did not show any significant correlation between the two variables for any of the two Catalan speakers (speaker MJ: r^2=0.068, p=0.387>0.05; for speaker AN, the correlation could not be calculated since the value was constant across rates) as can be observed in Figure 3.24.

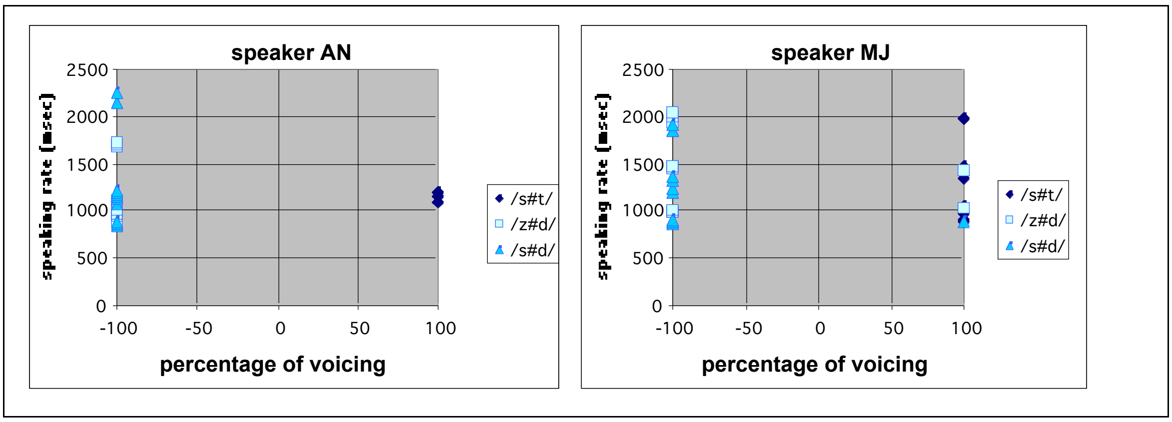


Figure 3.24. Scattergrams of percentage of voicing (horizontal axis) plotted as a function of speaking rate (vertical axis) in the Catalan sequences 'pas turc' (/s#t/), 'gas dur' (/z#d/) and 'pas dur' (/s#d/), with higher values indicating slower speaking rates. Each dot represents one observation.

No relationship between speaking rate and percentage of voicing for the English sequences /z#d/, /s#t/ and /s#d/, as shown in Figure 3.25 below. Pearson's correlation could not be calculated because the percentage of voicing was constant across rates for both speakers, that is, C2 in /s#d/ was always fully devoiced regardless of speaking rate.

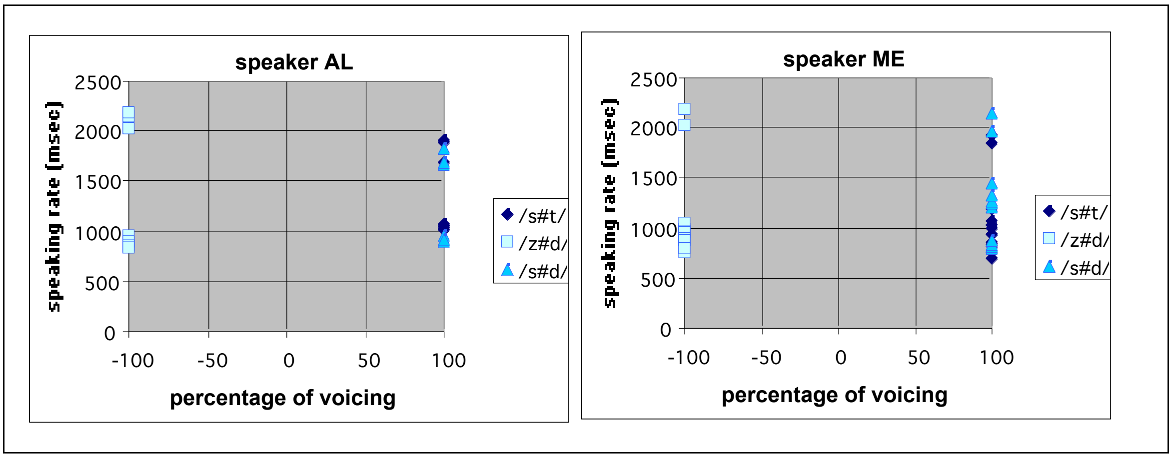


Figure 3.25. Scattergrams of percentage of voicing (horizontal axis) plotted as a function of speaking rate (vertical axis) in the English sequences 'this toll' (/s#t/), 'his doll' (/z#d/) and 'this doll' (/s#d/), with higher values indicating slower speaking rates. Each dot represents one observation.

3.3.4. Summary

The results obtained in the sequences of fricative and stop consonants in Catalan and English are summarized in Table X below.

Table X. Summary of the results obtained in the sequences /z#t/ and /s#d/ in Catalan and English

Sequence		Subject	Coordination of glottal and supraglottal gestures	direction	extent	Effect of speaking rate	Phonetic Output
/z#t/	Catalan	AN	Complete regressive devoicing of C1	←	-100	No	[s#t]
		MJ	Complete regressive devoicing of C1	←	-100	No	[s#t]
/s#d/		AN	Complete regressive voicing of C1	←	-100	No	[z#d]
		MJ	Complete regressive voicing of C1	←	-100	No	[z#d]
/z#t/	English	AL	Partial and complete regressive devoicing of C1	←	-25/-100	No	[zz8#t] [s#t]
		ME	Complete regressive devoicing of C1	←	Between - 68 and -94	No	[zz8#t] [s#t]
/s#d/		AL	Complete progressive devoicing of C2	→	100	No	[s#t]
		ME					