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Journal Title: Journal of Phonetics
Article Author: Slis, I.
Article Title: Assimilation of voice in Dutch as a function of stress, word boundaries, and sex of speaker and listener

Journal Vol: 14 Journal Issue:
Journal Month: Journal Year: 1986
Article Pages: 311-326

ILLiad Transaction Number: 685739
Transaction Date: 9/29/2011 5:38:34 PM

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Journal of Phonetics (1986) 14, 311–326

Assimilation of voice in Dutch as a function of stress, word boundaries, and sex of speaker and listener

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Received 1st November 1985, *and in revised form* 10*th January* 1986

The influence of stress and word boundary on assimilation of voice in Dutch were investigated in a production and a perception experiment. In both experiments it is shown that mainly regressive assimilation is found before stress. Compared to the pre-stress position relatively more progressive assimilation is observed after stress in both experiments; in the production experiment this increase in progressive assimilation leads to more progressive than regressive assimilation. Across syllable boundaries within words more assimilation is observed than across word boundaries; within words relatively more regressive assimilation occurs than across word boundaries. Comparison between produced and perceived assimilation shows that regressive assimilation is perceived more easily than can be expected on the basis of the articulatory/acoustic measurements.

1. Introduction

The topic of this paper is assimilation of voice before and after a stressed syllable, and assimilation of voice within words compared to assimilation across word boundaries. Two-consonant sequences (C1C2) will be selected, the elements of which (C1 and C2) are distributed across syllable boundaries within words or across word boundaries. Although some linguists prefer to reserve the term "cluster" for consonant sequences within one syllable, I use "cluster" for all sequences of two or more consonants.

The Dutch language sets a number of restrictions to the conditions that can be investigated. These led to experiments with all 12 combinations of the voiceless obstruents /p, t, k, f, s, x/ as the first consonant of the cluster (C1) with the voiced plosives /b, d/ as the second consonant of the cluster (C2), in three experimental conditions, viz. (1) across word boundary before stress, (2) across word boundary after stress, and (3) across syllable boundary within two-syllable compound words after stress.

Comparison between conditions 1 and 2 will yield the influence of the position of the cluster with respect to stress; comparison between conditions 2 and 3 will yield influences from boundary conditions.

Two experiments were performed. The first experiment was a production experiment in which we measured assimilation on an articulatory/acoustic basis. The sec

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experiment was a perceptual experiment in which the utterances of four speakers from the first experiment were used as stimuli. The responses were analysed to assess whether the subjects perceived regressive or progressive assimilation or no assimilation. Perceived assimilation was compared to produced assimilation.

Since sex of the speaker appears to affect assimilation of voice (Slis, 1982, 1984, 1985), both male and female speakers and listeners participated.

These investigations are part of a larger series of experiments on assimilation of voice in Dutch in two-obstruent clusters (Slis, 1982, 1983, 1984, 1985; van den Berg & Slis, 1985; van den Berg, in press).

1.1. *The influence of the position of stress*

It is a well-known fact that linguistic stress is effected by an increase in articulatory effort. As a consequence we expect that articulatory commands concerning the voice character of the consonant belonging to a stressed syllable dominate those for the voice character of the consonant belonging to an unstressed syllable in places where these consonants have to be produced with conflicting voice character. With respect to the influence of the position of a stressed syllable on assimilation in clusters across syllable boundaries this leads to the following expectations:

If the second syllable is stressed, the voiced C2 in a two-consonant cluster will dominate, and this will lead to predominantly voiced clusters. Therefore we expect more regressive assimilation before than after stress, both in production and perception.

If, on the other hand, the first syllable is stressed, voiceless C1 will dominate voiced C2 and the cluster will be voiceless. This will lead to progressive assimilation in clusters after a stressed syllable.

1.2. *The influence of the presence of a word boundary*

It is hypothesized that whenever a listener is confronted with a new word for the first time, he will probably not be able to analyse all speech sounds of the new word; as subsequent consonants overlap to a great extent within words, these will present relatively serious problems to the listener compared to a situation in which the features of the consonants are separately detectable to a high degree as e.g. in clusters without assimilation. It may be expected that the listener perceives the cluster as a whole. In reproducing the new word he will produce the best possible approximation of the perceived word. This includes programmed assimilation because he was not yet capable of making an appropriate perceptual analysis of the consonant clusters. In the light of this hypothesis it seems a sensible assumption that assimilated consonant clusters within words are part of a learned word pattern which is acquired during the speech development of the speaker. In other words, assimilation within words might be due to engrained motor patterns.

In clusters across word boundaries, however, the consonants forming the cluster belong to different words which are already known to the speaker. The consonants at issue belong to two different word patterns and have therefore motor programmes which do not contain built-in assimilations. In other words, clusters across word boundaries are new combinations and have therefore no engrained assimilations. For this reason, the motor programmes for these clusters are assumed to be less coherent than those for clusters within words. As a consequence we expect to find in the production experiment a higher frequency of assimilation within words than across word boundaries.

A second difference between "learned assimilation" within words and "newly formed assimilation" across word boundaries may manifest itself in a difference in direction of assimilation, viz. regressive vs. progressive. Because of the overlap between successive consonant articulations, the total cluster duration is considerably shorter than the sum of the separate durations of the consonant constrictions. In previous experiments on intervocalic obstruents in Dutch, we observed that a relatively short consonant duration leads to the perception of a voice consonant, even if the voice activity was interrupted (Slis & Cohen, 1969). On this basis we expect that some of the clusters with interrupted voicing will be perceived as completely voiced clusters. In other words, some of the clusters that are produced without assimilation or with progressive assimilation will be perceived as if they were regressively assimilated. Clusters in which voicing continues will always be perceived as voiced.

In word acquisition processes, the engrained word patterns will tend to more regressive assimilation than the words originally showed, because of the perceptual bias described above. We therefore expect more regressive assimilation within words than across word boundaries in production.

The difference between clusters across syllable boundaries within words and across word boundaries is not only a difference in degree of articulatory coherence or perceptual mix-up of acoustic features, but also one of strength of linguistic boundaries. Van Hoof & van den Broecke (1983) and Loots (1983) observed that boundaries of increasing strength in blocking assimilation of voice were morpheme boundaries, word boundaries and syntactic boundaries.

1.3. *Operational definition of assimilation of voice*

1.3.1. *Production*

In previous measurements of assimilation of voice we chose to base our criteria for assimilation on a definition given by Crystal (1980): "A general term in phonetics which refers to the influence exercised by one speech sound upon the articulation of another, so that the sounds become more alike, or identical". According to this definition, assimilation of voice occurs if it can be shown that the voice character of one consonant, measured on an articulatory basis, changed under the influence of an adjacent consonant. In order to be able to perform the necessary measurements, criteria for voicedness/voicelessness for both C1 and C2 have to be formulated. The articulatory events on which these criteria are based are defined directly on articulatory activity (viz. voice activity by electrolaryngography) and derived indirectly from the acoustic speech signal (viz. moments of oral closure and release from an oscillogram). By comparing the oscillograms of the electrolaryngograph and the acoustic signal we measured the timing of glottal activity in relation to oral closure and release. This articulatory feature represents a whole complex of other related articulatory features (cf. for example, Slis & Cohen, 1969). The timing of glottal activity was chosen as a criterion for assimilation of voice since it is easy to measure and since it gives reliable and reproduceable results.

Since for syllable final obstruents in Dutch a final devoicing rule holds (Trommelen & Zonneveld, 1979; Booij, 1981), the first consonants of the clusters at issue (C1) will have to be voiceless. This restriction implies that the second consonant in our clusters (C2) has to be a voiced obstruent; if it was voiceless the cluster would consist of two voiceless obstruents in which no assimilation of voice could be studied. Therefore we had

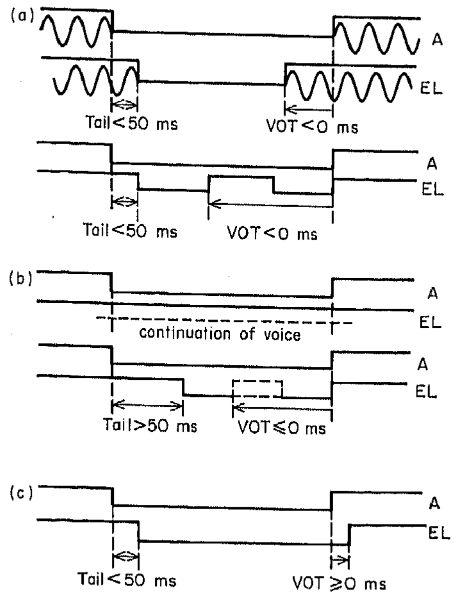


Figure 1. Schematic representation of the definitions of "no assimilation" (a), "regressive assimilation" (b) and "progressive assimilation" (c) demonstrated with laryngeal activity derived from an electrolaryngogram (EL) and with oral closure and opening phases derived from the audiosignal (A). VOT, voice onset time.

to define the limits of voicelessness in final obstruents and of voicedness in initial obstruents.

On the basis of measurements on intervocalic stops we labeled a final obstruent (C1) voiceless if voice activity terminates within an interval of 50 ms after oral closure; the continuation of voicing during the consonant closure (which we labelled "voice tail") amounts normally to about 25 ms (SD = 10 ms) in voiceless stops (Slis, 1970). The chance that the voice tail of a voiceless stop will be longer than 50 ms is less than 2.5% (mean voice tail plus 2 × SD). Final obstruents with a voice tail that was longer than 50 ms changed into voiced ones by assimilation.

In initial voiced obstruents (C2) we generally observed that voice activity started before the consonant constriction ended, in other words we found a "voice lead" or a "negative voice onset time (VOT)" (e.g. Slis & Cohen, 1969). In voiceless stops the voice onset occurs at or after the moment of oral release. Originally voiced initial obstruents changed into voiceless ones if VOT is equal or larger than zero.

As a result of these observations we arrive at the following definitions (Fig. 1).

(1) Clusters with a voice tail shorter than 50 ms and a negative VOT show "no assimilation".

(2) Clusters with a voice tail longer than 50 ms and a negative VOT show "regressive assimilation" (this includes clusters in which voicing is not interrupted).

(3) Clusters with a voice tail shorter than 50 ms and a VOT which is equal or larger than zero show "progressive assimilation".

1.3.2. *Perception*

As the experiments were done with the help of naïve subjects, we could not simply ask them to score regressive assimilation, progressive assimilation or no assimilation. Our operational definition of perceived assimilation was therefore based on identification responses to the two individual obstruents that constituted the clusters at stake. In case the subjects felt uncertain about the voicedness/voicelessness of a consonant, they were allowed to respond with an "in between" category. The subjects were asked to respond with one out of five response categories, presented in the form of a five point scale on the scoring form, for example

/zd/		/sd/		/st/
1	2	3	4	5

in which the numbers stand for the following categories:

(1) (voiced obstruent + voiced obstruent), e.g. /zd/; interpreted by the experimenters as fully regressive assimilation;

(2) between (voiced obstruent + voiced obstruent) and (voiceless obstruent + voiced obstruent); interpreted as partly regressive assimilation;

(3) (voiceless obstruent + voiced obstruent), e.g. /sd/; interpreted as no assimilation;

(4) between (voiceless obstruent + voiced obstruent) and (voiceless obstruent + voiceless obstruent); interpreted as partly progressive assimilation;

(5) (voiceless obstruent + voiceless obstruent), e.g. /st/; interpreted as fully progressive assimilation.

In the presentation and discussion of the results we will refer to our interpretation in terms of assimilation instead of to degree of voicing perceived by the listeners in order to make comparison between the two experiments (production vs. perception) easier.

1.4. *Considerations with respect to stimulus choice*

The obstruents in Dutch are

the voiceless plosives /p/, /t/ and /k/;
the voiced plosives /b/ and /d/; velar /g/ only occurs in loan words and as assimilated /k/;
the voiceless fricatives /f/, /s/ and /x/;
the voiced fricatives /v/ and /z/; velar /ɣ/ only occurs as assimilated /χ/.

In principle all combinations of these consonants should be considered candidates for the C1C2 clusters in our experiments. However, the experimental design was not fully crossed; a number of stimulus types were not included because of the following considerations.

(1) Due to the existence of a syllable-final devoicing rule (Trommelen & Zonneveld, 1979; Booij, 1981), the first obstruent C1 in our two-obstruent clusters will always be phonological voiceless. A study of assimilation of voice in Dutch will therefore concern clusters in which the first obstruent is voiceless and the second voiced.

(2) From previous experiments and from the literature we learned that if the second obstruent (C2) is a voiced fricative, assimilation will always be progressive. For this reason we don't expect interesting results from experiments on obstruent–fricative

clusters in a study on the influence of stress and boundaries on voaice assimilation; therefore we restricted the clusters in our study to combinations of voiceless stops (/p, 5, k/) or voiceless fricatives (/s, f, χ/) with voiced plosives (/b, d/).

(3) The results of a previous experiment showed that vowel length may influence assimilation in a following C1C2 cluster (Slis, 1984); clusters after long vowels tend to more regressive assimilation thatn those after short ones. In order to limit the number of stimuli we restricted our stimulus choice to intervocalic C1C2 clusters after short vowels.

(4) Two-syllable words with stress on the second syllable, containing a final obstruent in the first syllable and a voiced initial plosive in the second syllable, within the restrictions formulated above, hardly occur in Dutch. Our study of assimilation of voice within two-syllable words had therefore to be restricted to words with stress on the first syllable.

These restrictions led to experiments with all twelve combinations of the voiceless obstruents /p, t, k, f, s, χ/ as C1 with the voiced plosives /b, d/ as C2 in three experimental conditions, viz. (1) across word boundary before stress, (2) across word boundary after stress, and (3) across syllable boundary within two-syllable compound words after stress.

Since sex of the speaker appears to affect assimilation of voice (Slis, 1982, 1984, 1985) both male and female speakers participated.

2. Experiment I: production

2.1. *Method*

Ten male and 10 female subjects, members of the staff of the Institute of Phonetics and linguistics students at the University of Nijmegen, were asked to read aloud 21 sentences in which syllables that had to be stressed were underlined. The sentences contained six stop–stop (viz. /pb, tb, kb, pd, td, kd/) and six fricative–stop clusters (viz. /fb, sb, χb, fd, sd, χd/) in pre- and post-stress position across word boundaries, and in post-stress position across syllable boundaries within compound words. The experimental method has been described in detail in Slis (1982, 1983). Two signals were recorded on tape, viz. the speech signal and the output of an electrolaryngograph. Oscillograms were registered on photographic paper with a UV recorder (SE-oscillograph 6008), with a paper speed of 100 ms/cm.

On the basis of UV oscillograms of these two signals we scored assimilation of voice in the three categories defined above, viz. no assimilation, regressive assimilation or progressive assimilation. The moments of beginning and end of voice activity were observed by visual inspection of the electrolaryngograph oscillogram, the moments of oral closure and release were defined at the places of sudden amplitude drop and rise in the oscillogram of the acoustic signal. We also mentioned the consonant durations between the moments of oral closure and release from the oscillograms.

2.2. *Data analysis*

Since we wanted to know whether it was justified to average the data of male and female speakers, and those of stop–stop and fricative–stop clusters, we first performed a multidimensional χ^2 test (log linear model of Goodman, 1971); an extension of the normal χ^2 test for more than two variables). A correction was applied for small numbers by adding 0.5 to all observed frequencies. With this test it is possible to detect interactions between the independent variables, viz. sex of the speaker and cluster type, on the dependent variable, viz. assimilation of voice, for the different stress and boundary conditions separately. For comparisons of mean durations we used the t-test.

2.3. *Results*

An analysis of the results showed an interaction between cluster type and sex ($\chi^2 = 9.01$, df $= 2, p < 0.05$), and between cluster type and stress ($\chi^2 = 11.07$, df $= 2, p < 0.01$) as well as boundary condition ($\chi^2 = 6.81$, df $= 2, p < 0.05$). We concluded that cluster type was the variable that is responsible for these three interactions. Therefore stop–stop and fricative–stop clusters will be regarded separately. We observed that the influence of sex did not interact with other variables than cluster type. In the subsequent analysis of the results we therefore pooled the data of male and female speakers. All the main effects of cluster type, sex of the speaker, stress position, and word boundary were significant. The results are depicted in Fig. 2. The results of the measurements on cluster durations are given in Table I. Durations of clusters without assimilation are generally longer than clusters with assimilation and clusters with progressive assimilation are generally longer than clusters with regressive assimilation. Differences between clusters within words and across word boundaries are given.

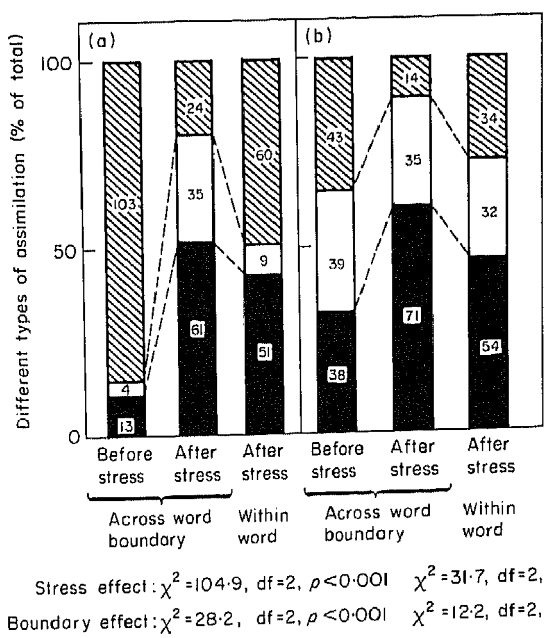


Figure 2. Frequency of assimilation as a function of stress and word boundary in stop–stop (a) and fricative–stop (b) clusters obtained in the production experiment. The data of 10 male and 10 female speakers were pooled. The actual frequencies are indicated within the histogram. Statistics are given below the figure. ▨, regressive assimilation; □, no assimilation; ■, progressive assimilation.

TABLE I. Mean cluster duration (ms) per assimilation category for stop–stop and fricative–stop clusters; differences between mean durations (ms) with regard to assimilation category are listed below and those with regard to the experimental condition are listed to the right of the respective mean durations. Only means based on five or more measurements are indicated.

	Across word boundaries		Within words	Stress: difference (a)–(b)	Boundary: difference (b)–(c)
	(a) Before stress	(b) After stress	(c) After stress		
Stop–stop					
No assimilation	—	177	137	—	40**
With assimilation	128	134	117	−6	17*
Difference between without and with assimilation	—	43**	20		
Regressive association	128	125	111	3	15**
Progressive association	130	138	125	−8	13**
Difference between regressive and progressive association	−2	−13*	−14**		
Fricative–stop					
No assimilation	175	208	165	−34**	43**
With assimilation	142	164	150	−22**	14**
Difference between without and with assimilation	33**	45**	15**		
Regressive association	142	133	136	9	−3
Progressive association	141	170	160	−29**	11
Difference between regressive and progressive association	1	−37**	−24**		

*$p < 0.05$ (t-test).
**$p < 0.01$ (t-test).

3. Experiment II: perception

3.1. *Method*

The speech material recorded on tape of two male and two female speakers of experiment I was used for a perception experiment in which the listeners were asked to judge the voice character of those clusters of which assimilation was measured in the first experiment. The speakers whose assimilations corresponded best with the average results of the 10 male and 10 female speakers respectively were selected for the purpose. The stimulus tape was played on a REVOX A_{77} tape recorder (19 cm/s), and the listeners were seated in a sound treated booth using high quality head phones.

Both male and female speech was used for the reason mentioned above (Section 1). As Gussenhoven (1981) has shown that male and female speakers have a different appreciation of assimilation of voice, we used male and female listeners. A different appreciation may result in a different identification of voicing. Assimilation of voice was scored as described in Section 1.3.2.

The complete stimulus sentence was printed on the scoring form. The cluster that was to be evaluated was underlined. At the right side of the stimulus sentence the response possibilities were indicated on the scoring form (Section 1.3.2). Each sentence was repeated three times with an interval of 3 s. Between different stimuli a scoring pause of 5 s was introduced.

All stop–stop and fricative–stop combinations of alveolar and labial obstruents (viz. /pb, tb, pd, td, fb, sb, fd, sd/) before and after stress across word boundaries, and after stress across syllable boundaries within words were used. Since /g/ and /ɣ/ have a very restricted occurrence in Dutch, clusters with /k/ and /χ/ were omitted from the stimulus tape in order to prevent scoring problems. The sentences were randomized for each speaker. In order to prevent order effects two tapes were made with a reverse order of the four speakers.

3.2. *Data analysis*

Analyses similar to those in experiment I were performed on the scores of the 20 listeners, the only difference being that five instead of three categories were used. We regarded the "five point scale" to consist of five discrete response steps since we asked our subjects to identify the stimuli. For that reason we feel justified in saying that the naïve subjects did not use a continuous voicing scale.

3.3. *Results*

Analyses of the results showed no significant interaction between the experimental variables on assimilation except between cluster type and word boundary ($\chi^2 = 30.43$, df $= 4, p < 0.001$). The results for stop–stop and fricative–stop clusters have therefore been analysed separately.

Main effects were found to be significant for stress position, word boundary, cluster type and sex of the listeners. No significant effect of sex of the speakers was observed. The results with respect to the frequencies of perceived assimilation under the different boundary and stress conditions for both cluster types are summarized in Fig. 3. In Fig. 4 we depict the results of comparisons between male and female listeners and male and female speakers. The results of the statistical analyses (chi-square) are indicated in the figure.

4. Comparison of experiments I and II

4.1. *Method*

In order to make the data of experiment II (five classes, viz. no assimilation, progressive assimilation) comparable to those of experiment I (three classes, viz. no assimilation, regressive assimilation, progressive assimilation) we pooled the data of partly and fully regressive assimilation, and of partly and fully progressive assimilation, thus obtaining three instead of five perceptual classes.

4.2. *Data analysis*

The same analysis as used in experiment I was used with one dependent variable (assimilation) and four independent variables, viz.

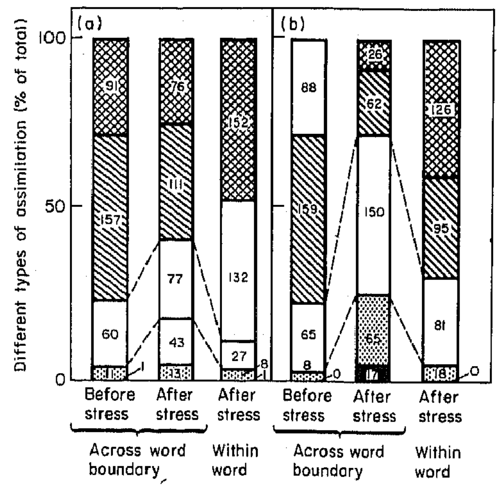


Figure 3. Frequency of perceived assimilation as a function of stress and word boundary in stop–stop and fricative–stop (b) clusters obtained in the perception experiment. The data obtained with 10 male and 10 female listeners were pooled. The actual frequencies are indicated in the histogram. Statistics are given below the figure. ■, Fully regressive assimilation; ▨, partly regressive assimilation; □, no assimilation; ▧, partly progressive association; ■, fully progressive assimilation.

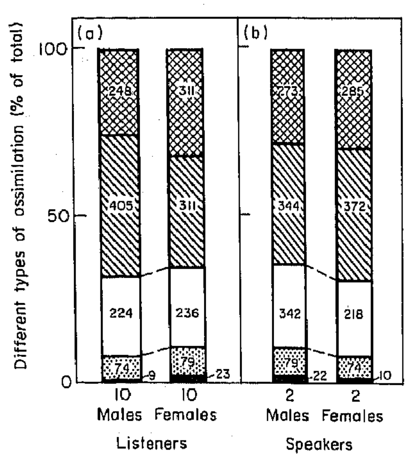
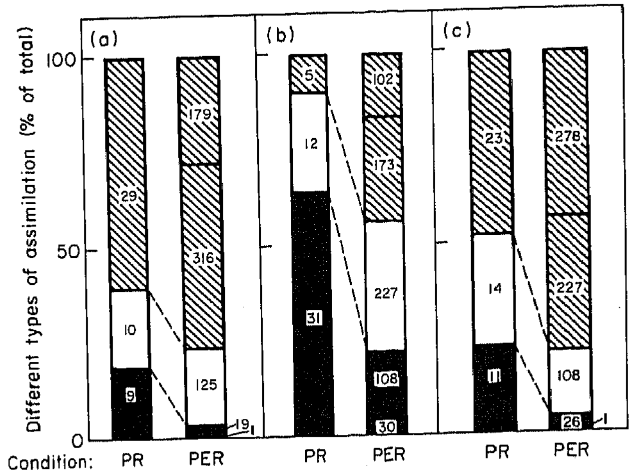


Figure 4. Comparison of the perceived frequencies of assimilation by respectively 10 male and 10 female listeners (a) and for all listeners pooled of the speech of 2 male and 2 female speakers (b). The statistics are given below the figure in terms of 5 and of 3 scoring categories. ■, Fully regressive assimilation; ▨, partly regressive assimilation; □, no assimilation; ▧, partly progressive association; ■, fully progressive assimilation.



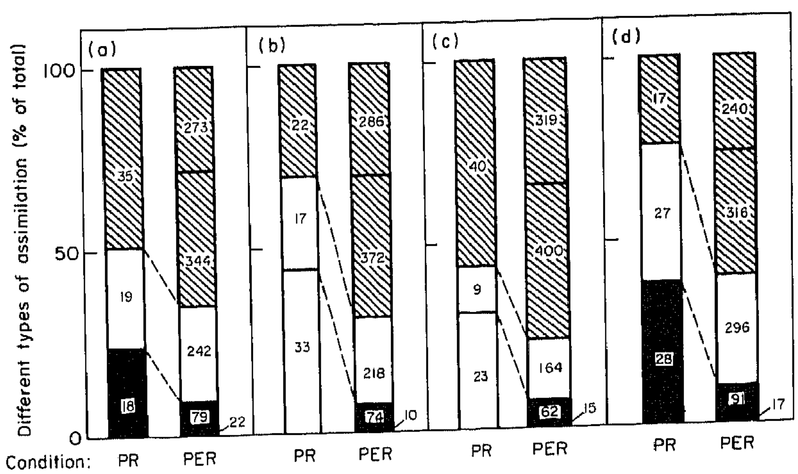
Difference between PR and PER experiments

(a) $\chi^2 = 27{\cdot}6$, df=2, $p<0{\cdot}001$

(b) $\chi^2 = 46{\cdot}7$, df=2, $p<0{\cdot}001$

(c) $\chi^2 = 37{\cdot}7$, df=2, $p<0{\cdot}001$

Figure 5. Comparison of the results of the production (PR) and the perception (PER) experiment for the three experimental conditions, separately: across word boundary before (a) and after (b) stress; and within word after stress (c). The statistics are given below the figure. ▨, regressive assimilation; □, no assimilation; ■, progressive assimilation.



Differences between PR and PER experiments

(a) χ^2=14·8, df=2, $p<0{\cdot}001$; (b) χ^2=95·9, df=2, $p<0{\cdot}001$

(c) χ^2=43·8, df=2, $p<0{\cdot}001$; (d) χ^2=54·0, df=2, $p<0{\cdot}001$

Figure 6. Comparison of the results of the production and the perception experiment for two male (a) and two female (b) speakers separately and for stop–stop (c) and fricative–stop (d) clusters separately. The statistics are given below the figure. ▨, fully and partly regressive assimilation; □, no assimilation; ■, partly and fully progressive assimilation.

(1) assimilation in three levels: regressive, no-assimilation, progressive;
(2) stress and boundary in two separate comparisons in 2 levels each: after stress vs. before stress, and across word boundary vs. across syllable boundary within word;
(3) cluster type in 2 levels: stop–stop, fricative–stop;
(4) sex of speaker in 2 levels: two men, two women;
(5) experiment in 2 levels: experiment I production, experiment II listening.

4.3. *Results*

A significant interaction between word boundary and cluster type ($\chi^2 = 27.58$, df = 2, $p < 0.001$) was found which was also the case in experiments I and II. Main effects were observed for stress position, word boundary, cluster type and "experiment"; sex of the speaker did not significantly influence assimilation as it did in experiment II. We depict the effect of experiment for the three experimental conditions (stress and boundary, Fig. 5) and sex of the speaker and cluster type (Fig. 6) separately.

5. Discussion

In this discussion we will first comment on the two main topics of this study, viz. the effect of position of stress and of word boundary on assimilation of voice. Since the results of the two experiments are on the whole in agreement with each other, we will not discuss the experiments separately. After discussion of these two topics, we will pay attention to other influences on assimilation, viz. cluster type, sex of the speaker and listeners, and, finally, we will compare production and perception.

5.1. *Position of stress*

In stop–stop clusters assimilation occurred less often after than before stress in both experiments. In a parallel, as yet unpublished, experiment we observed a strong tendency among our subjects to introduce pauses after a stressed syllable. Van Hooff & van den Broecke (1983) and Loots (1983) showed that the frequency of assimilation decreases with increasing strength of linguistic boundaries.

Although no difference in frequency of assimilation is observed in fricative–stop clusters before and after stress, the tendency to introduce pauses manifests itself in longer cluster durations after than before stress. Particularly in fricative–stop clusters a large difference in duration between the two stress conditions is found in the stimuli in which "no assimilation" is perceived (Table I). De Rooij (1979) observed that pauses, syllable lengthening, and pitch inflections contribute to the perception of prosodic boundaries. Coker, Umeda & Browman (1973) speak of pseudo-pauses in cases where a pause is perceived while no actual silence occurs.

We assume that both the high incidence of "no assimilation" after stress in stop–stop clusters and the longer duration of clusters with "no assimilation" in fricative–stop clusters in our material are signs of stronger syntactic boundaries after than before stress.

With respect to the direction of assimilation, the results of both experiments show considerably more regressive assimilation and less progressive assimilation before than after stress for both cluster types. This confirms our hypothesis: before stress the second syllable exerts a major influence on assimilation, while after stress the voiceless first consonant predominates. Fricative–stop clusters after stress proved to have significantly longer durations than before stress.

Although qualitatively similar results have been obtained with assimilation measurements on an acoustic/articulatory (experiment I) and a perceptual basis (experiment II), large quantitative differences between the results of the two experiments have been observed; more cases of regressive assimilation and fewer of progressive assimilation are perceived as compared to those measured with acoustic/articulatory voice timing criteria.

5.2. *Word boundary effects*

A comparison of the measurements in experiment I on clusters across word boundaries and those on clusters across syllable boundaries in compound words—both after stress—shows that assimilation occurs less frequently across word boundaries than within words in stop–stop clusters (Fig. 1). This also corroborates the results of van Hooff & van den Broecke (1983) and Loots (1983). Cluster duration within words was significantly shorter than across word boundaries; this difference shows in nearly all assimilation categories with stop–stop and fricative–stop clusters (compare columns b and c in Table I). We take it that this also indicates a stronger coherence of articulation within words which is effected by more overlap between the two successive consonants in the cluster. These results are fully in line with the prediction in Section 1.2; the linguistic boundary is weaker across syllable boundaries within words than across word boundaries.

The results of experiment I are, qualitatively, confirmed by those of the perceptual experiment as regards the influence of a syntactic boundary. In clusters within compound words more assimilation is perceived than in clusters across word boundaries, both after stress; moreover, less progressive assimilation and more regressive assimilation is observed in compound words than across word boundaries. Again, we find quantitative differences between the results of the two experiments in the sense that in perception more regressive assimilation was observed than in production.

5.3. *Cluster type*

Under all conditions more progressive assimilation and less regressive assimilation was measured in fricative–stop clusters than in stop–stop clusters. More cases of no-assimilation are measured in fricative–stop than in stop–stop clusters (significant in five out of six conditions). These results confirm previously obtained data (Slis, 1982, 1983, 1984, 1985). We see that in stop–stop clusters about 1.5 times more regressive than progressive assimilation occurs; on the other hand, in fricative–stop clusters nearly two times as much progressive as regressive assimilation is found.

The general phonological rule that obstruent–stop clusters show regressive assimilation (Trommelen & Zonneveld, 1979; Booij, 1981) is not confirmed by the measurements of experiment I. On the basis of these results we conclude that if any preference for regressive assimilation exists in obstruent–stop clusters, this preference cannot be generalized into a rule.

In the perceptual experiment (II) we find that under the condition before stress and across word boundaries, no significant differences are perceived between stop–stop and fricative–stop clusters. After stress both across word boundaries and across syllable boundaries within words, less regressive assimilation, more "no assimilation" and more progressive assimilation are scored on fricative–stop than on stop–stop clusters, which is in accordance with the results of experiment I. The different results obtained in the before stress and after stress conditions are reflected in the interaction between stress and boundary, and cluster type. We speculate that the identity of the first consonant of the cluster (stop or fricative) plays no significant role in the perception of voicing if it belongs to an unstressed syllable. The acoustic properties of the second (stressed) plosive will in that case determine the perceived voice character of the cluster as a whole. After stress, the first consonant belongs to the stressed syllable, and therefore attracts more attention. Particularly if C1 is a fricative, the voice character of C1 will be easily perceivable, leading to an extra increase in C1's perceived as voiceless, resulting in more cases of "no assimilation". The same quantitative differences are observed between the results of experiments I and II as were mentioned above.

5.4. *Sex of the speaker*

Under all conditions (before and after stress across word boundaries, and after stress within words, in both stop–stop and fricative–stop clusters) more regressive and less progressive assimilation is observed in the articulatory/acoustic data of male speech than of female speech (significant in five out of six conditions). These results confirm previously obtained data (Slis, 1982, 1983, 1984, 1985). In the speech of male speakers the frequency of regressive assimilation is nearly twice that of progressive assimilation, while, in contrast to this, in female speech the frequency of progressive assimilation is twice that of regressive assimilation.

If the data of the perception experiment are pooled across all independent variables except sex of the speaker, we find no significant differences between male and female speakers.

The differences in the timing of voice activity observed in experiment I, in which female speakers showed more progressive assimilation than male speakers, were not perceived by the listeners in experiment II. We conclude, therefore, that the listeners, instead of only using the moments of ending and beginning of voice activity as acoustical cues, also used other cues such as cluster duration, intonation and formant transitions; the relative contribution of these cues differ as a function of the sex of the speaker, thus compensating differences in assimilation measured with only one cue, viz. voice.

5.5. *Sex of the listeners*

A comparison of the judgements in five response categories (viz. totally and partly regressive assimilation, no assimilation, and totally and partly progressive assimilation) showed a significant difference between male and female listeners ($\chi^2 = 26.0$, df $= 4$, $p < 0.001$). If, however, we pool totally and partly regressive assimilation in one category and totally and partly progressive assimilation in another category, and compare the resulting judgements of male and female speakers using these three response categories, no significant differences occur ($\chi^2 = 3.0$, df $= 2$, $p > 0.2$). The differences between the two comparisons originate from the fact that women used the extreme response categories (totally regressive and totally progressive assimilation) more than did men. A similar effect was shown by Boves, Fagel & Van Herpt (1982) in a scaling experiment on "ideal voice quality" in which female listeners also scored in a more extreme way.

5.6. *Differences between production and perception*

Comparison between the results of the two experiments shows that more regressive assimilation and less progressive assimilation was perceived (under all conditions) in experiment II than could be measured in experiment I.

An explanation for the differences obtained under the two approaches may be found in the multi-dimensionality of the voiced–voiceless distinction; differences between voiced and voiceless consonants are found to be characterized by a number of concurrent features, such as voice activity, consonant duration, duration of the preceding vowel, duration and sweep of formant transitions, amplitude of fricative noise and intonation (Slis & Cohen, 1969; Lisker, 1978). Features that play a role in the voicing of single consonants, can be expected to play a role in consonant clusters as well. In our first experiment we selected a criterion which was based on one articulatory feature, viz. voice activity. This is a valid choice, since assimilation implies by definition "an influence exercised by one speech sound upon another so that the sounds become more alike" (Crystal, 1980); this implies that if one feature meets the definition, assimilation is found. In perception of natural speech however, unlike the measurement procedure on an articulatory basis, we cannot isolate one acoustical/perceptual aspect; all features play a role simultaneously. We know that voiced consonants can be perceived under conditions in which voice activity is absent; the other features are then interpreted by the listener in terms of voice. We assume that in two-consonant clusters these other features favour the perception of voice, thus leading to more regressive and less progressive assimilation in the perception experiment than the production experiment led us to expect. The role of separate acoustic parameters will be investigated in a series of perception experiments with synthetic speech (van den Berg & Slis, 1985; van den Berg, in press).

The fact that more regressive and less progressive assimilation is perceived than could be measured on an articulatory/acoustic basis supports our hypothesis that in speech development assimilation within words is perceived as regressive assimilation; an imitation of a cluster which is embedded in a word by a child will therefore show regressive assimilation. This may lead to engrained word patterns with regressively assimilated consonant clusters.

The shift towards more regressive judgements in perception as compared to production occurred in the speech of both male and female speakers. In female speech the shift was larger than in that of men; the production data of female speech showed more progressive assimilation than those of male speech, while this difference disappeared in the perceptual data. This finding may be explained in two different ways:

(1) the "voice" feature in men and women is effected by a different distribution of the acoustical aspects that are associated with this feature;

(2) listeners implicitly know that men and women assimilate differently and therefore perform a perceptual correction.

The fact that differences in assimilation between male and female speakers are not present in perception explains why this effect has remained largely unnoticed so far.

6. Conclusion

Summarizing, we found that position of stress and word boundaries played a role in assimilation. In previous studies, we primarily investigated speech of men in pre-stress position. An important conclusion from these former experiments was that in obstruent–stop clusters regressive assimilation predominates. If, however, we include data of post-stress clusters and data obtained with female speakers, we have to change this conclusion: on the average an equal amount of regressive and progressive assimilation of voice is found in the production of obstruent–stop clusters in Dutch.

The effects found in production were also found in perception, with an exception for sex differences of the speakers. A comparison of the data obtained by measurements on articulatory and acoustic features (experiment I) with the data obtained in a perceptual experiment (experiment II) shows that in listening more regressive and less progressive assimilation is perceived than is measured articulatorily/acoustically in the stimulus material. This shift towards regressive assimilation in perception explains the notion advanced repeatedly in the literature that assimilation is mainly regressive in Dutch.

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