ZASPiL Nr. 39 – February 2005

Supralaryngeal mechanisms of the voicing contrast in velars

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Abstract

This study investigates supralaryngeal mechanisms of the two way voicing contrast among German velar stops and the three way contrast among Korean velar stops, both in intervocalic position. Articulatory data won via electromagnetic articulography of three Korean speakers and acoustic recordings of three Korean and three German speakers are analysed. It was found that in both languages the voicing contrast is created by more than one mechanism. However, one can say that for Korean velar stops in intervocalic position stop closure duration is the most important parameter. For German it is closure voicing. The results support the phonological description proposed by Kohler (1984).

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Acknowledgements

The present paper is a slightly modified version of an MA thesis which was written at the Humboldt-University of Berlin. Most of the support came from the Phonetics section of the Zentrum für Allgemeine Sprachwissenschaft Berlin. First of all I would therefore like to thank Susanne Fuchs who proposed the topic of this work to me and supported and encouraged me consistently throughout the whole six months with many useful suggestions and fruitful discussions. Furthermore, I would like to thank my supervisors Bernd Pompino-Marschall and Hans-Georg Piroth for their support and many encouraging comments on the work. Thanks also to Phil Hoole for doing corrections so quickly and Silke Hamann for giving a phonologist's opinion on the work.

For the Korean data I would like to acknowledge Hyeon-Zoo Kim and Pascal Perrier; Hyeon-Zoo Kim also for the English translation of the Korean corpus and Pascal for a Matlab-script for calculating ensemble averages as well as for introducing me to digital signal processing. For the German data I thank Christine Mooshammer. I am also very happy that I could use her ARTMAT programme in order to carry out the articulatory segmentation.

Furthermore, many thanks to Anke Busler for acoustic segmentation and to Jörg Dreyer and Daniel Pape for technical support. Thanks to Christian Geng for having assisted me during my first insecure steps in MATLAB. I have benefited enormously from being allowed to use the locations of the Phonetics section in the Zentrum für Allgemeine Sprachwissenschaft in Berlin, and I would also like to thank Anke Busler and Johanna Creutzburg who shared a room with me.

1 INTRODUCTION

This work investigates phonetic mechanisms of producing the voicing contrast in German and Korean velar stops in intervocalic position. The data which are analysed in this study have been recorded previously for other purposes. For Korean articulatory and acoustic data were available, for German only acoustic data could be analysed. The Korean articulatory and acoustic data have been recorded at the Institut de la Communication Parlée, Grenoble by Pascal Perrier and Hyeon-Zoo Kim during the post-doc programme of Hyeon-Zoo Kim. The acoustic data for German were recorded for the studies presented in Mooshammer (1992) and Mooshammer et al. (1995) at the Institut für Phonetik und Sprachliche Kommunikation of the Ludwig-Maximilians University Munich. These two studies also dealt with articulatory recordings but only the acoustic data were used for the work presented here. In order to compare the articulation of German and Korean the results presented in Mooshammer (1992) and Mooshammer et al. (1995) will be discussed.

The first chapter of this study gives some theoretical background about the production of voicing in general, it discusses previous work in the field of voicing and phonological descriptions of the voicing contrast. Furthermore, a number of questions about the voicing contrast in the two languages will be developed. In the first part of the second chapter the two experiments carried out at the Institut de la Communication Parlée and the Institut für Phonetik und Sprachliche Kommunikation will be described. To capture the articulatory data electromagnetic articulography was carried out. The second part of this chapter describes the analysis carried out for the present study. In the third chapter the results will be presented. Chapter 4 will compare the mechanisms contrasting the stops in the two languages. The comparison of the acoustic mechanisms will be based on the experimental data from both languages. The comparison of the articulatory data, on the other hand, will be based on the experimental data of Korean and the results of Mooshammer (1992) and Mooshammer et al. (1995). Finally, an attempt to answer the questions developed in chapter 1 will be made.

1.1 Voicing and voicelessness

The voicing contrast is primarily seen as the result of laryngeal activities, i.e. vocal fold vibration for voiced sounds and lack of it for voiceless sounds. In stops voicelessness often occurs together with aspiration. The following two sections explain how the contrast is produced physically. Since this study deals with stops it will focus on this manner of articulation.

1.1.1 The physics of voicing

Vocal fold vibration is the result of a complex process (Fry 1982: 62f). At first the vocal folds which are in a position apart from each other during normal breathing have to be brought together by the laryngeal muscles (cf. figure 1.1) so that they are touching each other.

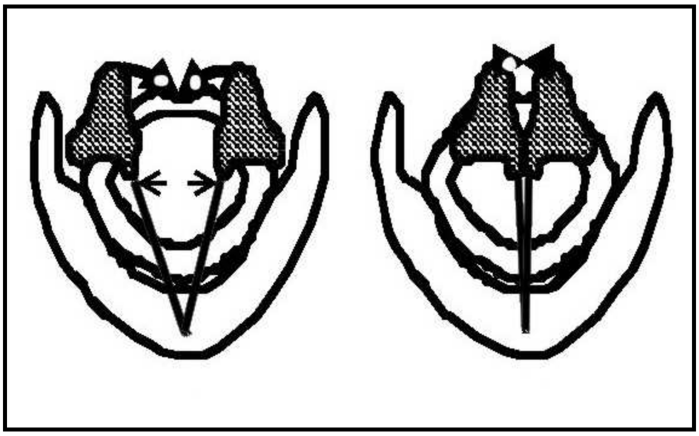


Figure 1.1 (based on Pompino-Marschall, B. Einführung in die Phonetik, 1995: 35. With kind permission by Walter de Gruyter GmbH & Co. KG): Larynx with open glottis (left side) and vocal folds touching each other while vibrating (right side). The arrows symbolise the activity of the larynx muscles.

Then the air coming from the lungs moves towards the adducted vocal folds and pushes against them from below the glottis with a certain pressure which increases with more and more air coming. If the air pressure below the glottis reaches a level sufficiently higher than the pressure above the glottis, the vocal folds break apart and the air moves through the glottis just until the pressure difference has fallen to a level low enough so that the vocal folds move towards each other again until they are touching each other. This effect, the suction after the pressure drop which lets the vocal folds move towards each other is called the Bernoulli effect. The successive opening and closing of the glottis results in periodic movements of air molecules which are perceived as voicing.

In order for this process to work three conditions must be fulfilled:

- The vocal folds have to be adducted to each other.
- They need to have a certain tension.
- There needs to be a pressure difference between subglottal and supraglottal pressure.

In more detail this means that if the vocal folds are not adducted to each other it is not possible to build up a sufficiently high pressure below the glottis. The vocal folds will not break apart and there will be no Bernoulli effect causing them to move towards each other again. Consequently there will be no periodic movements of air molecules. Furthermore, in order to move periodically the vocal folds need to have a certain elasticity. This means that they need to be sufficiently tensed in order to allow for a pressure build-up below the glottis. However, they must not be too stiff because this would result in aperiodic movements. Finally, the supraglottal pressure has to be lower than the pressure below the glottis because otherwise the vocal folds will not break apart.

For stops this third precondition of pressure difference is especially difficult to fulfil, since the mouth cavity is closed at some point so that the air stream is blocked and the pressure behind the closure increases with more and more air coming from the glottis. This will cause the vocal folds to stop vibrating and there will be no voicing anymore. Velar stops are affected in particular because the closure is situated in the back of the mouth so that the cavity behind the closure is quite small and the pressure in this small cavity increases quickly (Ohala 1983).

To summarise the main points of this section, voicing in stops is difficult to sustain since there is a closure in the mouth cavity and with more and more air coming from the glottis and no possibilities of releasing air from the mouth the supraglottal pressure will reach the level of the subglottal pressure at some time and the vocal folds will stop vibrating. When exactly this will be depends on the size of the cavity behind the closure. If this cavity is big as in bilabial stops this process will take longer than if it is smaller as in velar stops.

1.1.2 The physics of voicelessness

In order to produce a voiceless stop the vocal folds must not vibrate. Preventing vibration can be done by keeping the vocal folds stiff and apart from each other so that the air can move through the glottis unhindered. Consequently, there will be no Bernoulli effect which means that there will be no suction which lets the vocal folds move towards each other. For an aspirated stop the glottis needs to be wide open at the time of oral release so that aspiration noise can be produced (Fuchs 2003: 2.3.1). The aspiration airstream needs to have a high velocity in order to produce turbulences and consequently friction.

1.1.3 Stop inventories in the languages of the world

Following Maddieson (1984: 25) stops can be classified according to "manner of articulation"[1], for example *plain voiced, plain voiceless, aspirated voiceless, breathy voiced*, *laryngealized voiceless*, and they can be classified according to place of articulation, for example *bilabial, alveolar, palatal, velar, uvular*. Looking at the languages of the world, however, not all the manners and places of articulation occur with the same frequency. There are some manners and places of articulation which are clearly favoured over others. Furthermore, languages differ in the number of manners and places of articulation they exhibit.

With regard to the number of manners of articulation a two way contrast is most common. Maddieson (1984), who investigated 317 languages from typologically diverse language families, found that 51.1% of the languages in the sample had only two manners of articulation in stops. Next most common is to have a three way contrast. This was true for 24% of the languages investigated (Maddieson 1984: 26). Plain voiceless stops are most common, succeeded by plain voiced and aspirated voiceless stops (Maddieson 1984: 27). Linking the numbers for manner and place of articulation one can say that nearly all the languages which have a two way contrast in stops either have a distinction between plain voiceless and plain voiced or plain voiceless and aspirated voiceless stops. In languages with a three way contrast this is not as clear. The most common type (25% of the languages with a three way distinction in Maddieson's sample) exhibits a distinction among aspirated voiceless, plain voiceless and voiced stops. What is common as well in a three way distinction is to differentiate between two stops via voice onset time (VOT) and between those two and the third stop via a glottalic element[2] (Maddieson 1984: 28f).

Something very interesting in Maddieson's results is that there are a number of asymmetries and gaps in the systems. Thus, there are some manners of articulation which occur more often in a certain position than others. Additionally, even if a language exhibits three places of articulation and two manners this does not necessarily mean that there are two stops differing in manner of articulation in every place. Of the 317 languages investigated by Maddieson 283 had a plain voiceless velar stop, but only 175 a plain voiced velar stop (Maddieson 1984: 35). This means that voiceless velar stops seem to

[1] "Manner of articulation" here means "different kinds of stops". It should not be confused with the traditional terminology where it is used to classify consonants, for example fricatives versus stops.
[2] "glottalic element" means either ejective or implosive.

be more frequent in the languages of the world than voiced velar stops. In Maddieson (2003) the investigation was deepened and the inventories of 565 languages were investigated. In 37 of them a pattern was found that was called *missing /g/*. Languages with this pattern exhibit a very common two way contrast in manner of articulation, i.e. plain voiced vs. plain voiceless in two of three positions, i.e. bilabial and alveolar, but they lack a voiced velar stop.

Furthermore, Maddieson found that the missing /g/-pattern occurs widely dispersed over the whole world. This suggests that this pattern is not limited to a couple of language families because if it were it would be a more local phenomenon, as it is the case for example in the *missing /p/*-pattern which is very common in the northern half of Africa but cannot be found on North- and South America (cf. Maddieson 2003 for details). If missing /g/ cannot be explained by language relatedness, however, there should be ‘universal phonetic principles” (Maddieson 2003: 719) resulting in this pattern.

A possible explanation for the rarer occurrence of voiced velar stops as opposed to voiceless velar stops and for the missing /g/-pattern is based on the difficulty in keeping sounds apart from each other. As supposed by the quantal theory (Stevens 1989) the mapping between articulation and acoustics is nonlinear so that there are certain stable regions where the articulation can change without changing the acoustic output a lot. On the other hand, there are other regions where small changes in the articulation result in huge changes in the acoustic output. This can be seen in the transition from an approximant to a fricative. The tongue may raise a considerable amount without causing friction, but there is one point where the friction suddenly starts and the acoustic output changes enormously without a huge change in the position of the tongue.

Another approach to the same phenomenon is the theory of adaptive dispersion (Liljencrants & Lindblom 1972, Lindblom 1990). This theory claims that maximally distinct elements will be the most common elements because they are easy to keep apart from each other. For example, a dental and an alveolar stop are more difficult to keep apart than a bilabial and a velar one, simply because the articulatory and also the acoustic space between them is greater.

Both theories reach the conclusion that there are contrasts which are more easily kept and contrasts which are less easily kept. Applied to velar stops this means that in order to keep a voiced and a voiceless stop apart perceptually the acoustic output needs to be distinctive enough. If, however, voicing is difficult to sustain in velar stops the articulation might more easily reach a state where the acoustic output is more or less the same for both stops, the voiceless one and the voiced one, and the distinctiveness is not guaranteed any more. There are two possible consequences. Either the speakers try to enlarge the difference. They could for example stop producing a closure so that the voiced velar stop becomes a fricative. Another possibility is that the stops become more and more similar and finally merge so that only one stop, the voiceless one, is left (Maddieson 1984: 36). In both cases the voiced stop is lost.

The remarks above can explain the missing /g/-pattern. Since voicing is more difficult to sustain in velar than in alveolar or bilabial stops the voicing contrast is lost more easily in velar than in bilabial or alveolar stops. Consequently, it is more common in the languages of the world to have a two way distinction among stops in the alveolar or bilabial than in the velar place of articulation.

Coming back to the comparison of missing /g/, which occurs all over the world, and missing /p/, which is a local phenomenon, one can say that the first one is the result of a "universal phonetic principle". Missing /g/ is not a result of the relatedness of languages but one of pure physics and therefore universal whereas missing /p/ is probably a language family specific phenomenon[3].

1.1.4 The "voicing" contrast in Korean velar stops

Korean belongs to one of the rarer language types in that it exhibits a three way contrast among stops. The handbook of the IPA assigns the symbols /g/, /k/ and /k^h/ to the three velar stops and describes the contrast as being built on voicing, aspiration and laryngeal characteristics. /g/ is described as a "voiceless unaspirated (or slightly aspirated) lenis" stop which is voiced in intervocalic position (Handbook of the IPA 1999: 122). /k/, on the other hand, is a voiceless unaspirated fortis stop which is produced with a partially constricted glottis and additional subglottal pressure. The third stop, /k^h/ is voiceless and strongly aspirated.

The symbols used in the Handbook of the IPA for /g/ and /k^h/ will be adapted in this study. In order to avoid confusion, however, the forced stop will be written /k'/. The symbols used in this study mirror the voicing characteristics of the stops in intervocalic position. Since, however, /g/ is voiced only in this position most grammars and studies about Korean velar stops use other symbols. Martin (1992), for example, calls the IPA-lenis stop "lax" and assigns the symbol /k/ to it. He describes it as "lightly voiced in rapid speech" in "between typically voiced sounds" (Martin 1992: 27). Next to the aspirated /k^h/ which is, following Martin, never voiced, he distinguishes the "reinforced" stop /kk/ which is produced with great muscular tension. Furthermore, he states that the vowel following the reinforced stop is often laryngealized and similar to the tense unaspirated stop of French. For Martin the reinforced stop is never voiced.

[3] although it could be explained by universal aerodynamic constraints: Voicing is sustained in /p/ because the cavity is large.

Chang (1996) uses yet other symbols, /k/, /k'/ and /k^h/, to describe his "plain", "tense" and "aspirated" stops. Following his description all the stops are voiceless phonemically but the plain stop is voiced in intervocalic position. He stresses that neither the aspirated nor the tense stop are geminates or compound sounds.

Kim (1996) uses the same symbols but a different terminology. She calls the stops "lenis", "fortis" and "aspirated" which stresses her view that consonant voicing is not contrastive in Korean and that voiced stops are allophones of lenis stops in intervocalic position.

Lee (1998) finds another term for the so far called lax or lenis stop: neutral stop. This stop, which is produced with the vocal cords in a neutral state, is "slightly aspirated". There may be voicing depending on the "surrounding energy level" (Lee 1998: 38). Aspirated and "tensed" stops are fully voiceless. The tensed stop is furthermore characterised by a great tension of the vocal cords and fortis articulation.

Sohn (1999) describes the "lax" stop as generally voiceless but lightly voiced in between voiced sounds with a minor degree of aspiration and no tenseness. According to him, the phonetic quality of the lax stops is not shared by any English stop. The aspirated and tensed stops are described as never being voiced and exhibiting a minimum of allophonic variation. The tensed stop is furthermore produced with the glottis constricted and by building up air pressure behind the closure. It is comparable to the quality of the English voiceless stop that occurs after s in *ski* (Sohn 1999: 153f).

Generally, the parameters by which the stops are distinguished in the grammars seem to be voicing, aspiration and tension of the vocal folds.

1.1.5 The "voicing" contrast in German velar stops

As opposed to Korean, German belongs to the most common language type, one with a two way contrast in stops. According to the *Großes Wörterbuch der deutschen Aussprache* (1982) German has two velar stops. One of them is voiceless, and aspirated if it precedes a stressed vowel. The other one is voiced except if it follows a voiceless sound. Voicing can be lost in utterance-initial position.

The *Duden Aussprachewörterbuch* (1990[3]) also distinguishes two stop series. One of them is aspirated, and the aspiration is especially strong word initially or if the following vowel is stressed. Here *Duden* contradicts the *Wörterbuch der deutschen Aussprache*, which requires both conditions for aspiration. Intervocalically the degree of aspiration is weaker. The other stop Duden mentions is voiced intervocalically and word initially but weakly voiced or almost voiceless after voiceless sounds.

Siebs. Deutsche Aussprache (1969[19]) mentions one stop which is always aspirated and a voiced stop which is always voiced except for final devoicing contexts. In contrast to the other two dictionaries of pronunciation Siebs does not mention stress as a factor influencing aspiration. Furthermore, it does not state a difference in degree of aspiration comparing word-initial and intervocalic position. In moderate standard German the voiced stops are voiceless if they are in word-initial position or follow voiceless sounds.

As can be seen from these descriptions, voicing and aspiration seem to be the most important mechanisms of distinguishing the two stops. These two mechanisms, however, seem to be somewhat weaker in intervocalic than in other positions. So the question is whether there are other mechanisms distinguishing the stops in this position.

1.2 State of the art

A result from the discussion in section 1.1.1 was that sustaining voicing in velar stops can be problematic and a two way contrast is easily lost. Looking at Korean, a question immediately arising is therefore how this three way contrast can be maintained. One could think of two strategies. Either speakers try to make better use of the voicing distinction by finding mechanisms for prolonging voicing during closure. Another strategy could be to develop mechanisms not in order to sustain voicing but in order to keep the stops apart otherwise. Section 1.2.1 describes a mechanism which has been proposed as designed for prolonging voicing but later found as not in fact doing so. The rest of this section is dedicated to studies investigating the voicing contrast in Korean (section 1.2.2) and German (section 1.2.3) which aim at finding out in how far voicing is relevant in the distinction between /g/, /k'/ and /k^h/ or /g/ and /k/, and at finding other mechanisms which are used to distinguish the stops and which have nothing to do with voicing in its pure sense.

1.2.1 Looping patterns in velar stops

Houde (1968) discovered for intervocalic velar stops that the tongue moves forwards during closure so that the complete trajectory from the middle of the first vowel to the middle of the second vowel is elliptical. The movement was therefore called *loop*. He interpreted this movement as a strategy in order to enlarge the cavity behind the closure and thus reduce the pressure so that voicing can be sustained for a longer period. Ohala (1983) supported this.

Other studies, however, contradict this view in saying that those looping movements are not performed in order to sustain voicing but have other reasons. Mooshammer et al. (1995) for example found for German that the loops are larger for /k/ than for /g/. Kent & Moll (1972) propose airstream mechanisms as a reason for looping patterns, Perrier et al. (2003) suggest biomechanical reasons. Löfqvist & Gracco (2002) propose cost minimisation principles as a reason for looping patterns in that they regard the whole movement as being planned from the beginning of the first vowel to the end of the second vowel.

A question which will be dealt with in this study is what the trajectories of the three Korean stops are like and whether one of the approaches mentioned above can be supported by the Korean data.

1.2.2 Previous investigations of Korean velar stops

Apart from the descriptions in grammars of Korean there are a number of studies which investigate the phonetic properties of the three way contrast in the stops in more detail.

Kim (1965) states that there are two parameters according to which the three way contrast in Korean is created: tension of the articulation and aspiration. The first one sets the lenis stop, which has a lower tension, apart from the other stops. The aspiration distinguishes between fortis and lenis on the one hand and the aspirated stop on the other. Tension is described as involving a higher f_0 after the burst, a higher and faster pressure build-up, a longer duration during which a high pressure is kept and more contact between tongue and palate.

Kim (1970) adds that the glottal opening for word initial stops is larger for aspirated stops than for lenis stops, and the opening for lenis stops is larger than for fortis stops. This means that there is a correlation between glottal opening and aspiration, the aspirated stop with the longest aspiration also has the greatest opening, and the stop with the shortest aspiration, the fortis stop, also has the smallest opening.

Han & Weitzman (1970) support Kim (1965) in that the f_0 of the vowel following the stop serves to distinguish the stops. They found that the f_0 after aspirated and fortis stops is higher than after lenis stops. Furthermore, they found that it takes longer until the full glottal intensity is reached after a lenis or aspirated stop than after a fortis stop.

Kagaya (1974) again investigated laryngeal movements in word initial and medial stops and found that the glottis is open a long time before oral release in fortis stops. For lenis stops the glottis is open at release even if not as wide as for aspirated stops.

Dart (1987) measured intraoral pressure and air flow in fortis and lenis stops and found that the intraoral pressure before release is higher in fortis than in lenis stops even if the air flow after the release is lower.

Silva (1992) found yet another characteristic distinguishing the stops, i.e. stop closure duration. The closure duration is shortest for the lenis stop, longer for the aspirated stop and longest for the fortis stop.

Cho & Keating (2001) contradict Silva (1992). In their study they did not find significant differences between the closure durations of aspirated and fortis stops. However, they found support for Kim (1965) in that there is more contact between tongue and palate in aspirated and fortis stops than in lenis stops.

Cho et al. (2002) investigated a number of mechanisms, i.e. VOT, burst energy, fundamental frequency, voice quality, intraoral pressure and intraoral airflow. They found that VOT is longest for the aspirated stop, intermediate for the lenis and shortest for the fortis stop. Burst energy is higher for the aspirated than for the other stops. Fundamental frequency of the following vowel is lower for the lenis stop than for the others. The vowel following a lenis stop is breathier than the vowel following the fortis stop. Furthermore, the intraoral pressure of the lenis stop is lower than the one of the other stops. With regard to intraoral airflow, however, the tense stop has the lowest measurement results. The authors state that this is rather counterintuitive since the consequence of high intraoral pressure should be a lot of intraoral airflow. Here, however, the degree of opening of the glottis has to be taken into account. If the glottis is not wide open the airflow will be minimal.

Choi (2002) investigated two characteristics of the distinction in Seoul and Chonnam Korean, fundamental frequency and VOT and found that there is a two way contrast in fundamental frequency in Chonnam Korean with the aspirated stop having a lower fundamental frequency than the other two stops. In Seoul Korean there is a three way contrast in fundamental frequency. The aspirated stop has the lowest frequency, the forced stop an intermediate and the lenis stop the highest frequency. With regard to VOT there is a three way contrast in Chonnam Korean (/k’/</g/</k^{h}/) and a two way contrast in Seoul Korean (/k’/</g/ and /k^{h}/).

Most of those studies restrict themselves to stops in initial position. Furthermore, although there are lots of acoustic studies of Korean velars there are not very many on articulation (e.g. Sawashima & Park (1979) for laryngeal adjustment in final stops, Silverman & Jun (1994), dealing with consonant clusters). The present study therefore fills a gap in dealing with supralaryngeal characteristics of Korean velar stops in VCV-position.

1.2.3 Previous investigations of German velar stops

As for Korean, most studies about German stops investigate acoustic mechanisms rather than articulatory ones. They all concentrate on four mechanisms: VOT, voicing, length of the preceding vowel and stop closure duration. What differs are the experimental devices and the definitions of VOT. Because there are plenty of studies on German stops this section will restrict itself to investigations of velar stops in intervocalic position.

Haag (1975) measured VOT as the time from rapid rise in oral airflow to the voicing onset, which was found via an electroglottographic signal, and found that /g/ in intervocalic position has a significantly shorter VOT than /k/. Voicing was found in /g/ and /k/, but the voicing of /g/ was significantly longer measured on the basis of the electroglottographic signal. Vowels preceding /g/ were found to be longer than vowels preceding /k/ and stop closure duration was longer for /k/ than for /g/.

Fischer-Jørgensen (1976) measured the "open interval" of the glottis after the burst, which should be identical with Lisker & Abramson VOT (cf. section 2.5.1.1 for definition). Her results are not as clear as the ones of Haag (1975). She found that there is only a tendency to distinguish /g/ and /k/ intervocalically in terms of aspiration. For /g/ she found that it is often fully voiced; in some subjects and specific vowel contexts, however, /g/ is almost voiceless. Closure duration was found to be longer for /k/ than for /g/.

Mansell (1979) measured the open interval acoustically and found a longer open interval for /k/ than for /g/. Furthermore, great variation across speakers was found in voicing. The difference in voicing between /g/ and /k/ is smaller than between other stop pairs. With regard to length of the preceding vowel it was found that it is longer before /g/ than before /k/.

Piroth et al. (1991) measured "release" which is the duration of the burst together with the duration of the aspiration. This segment was found to be longer for /k/ than for /g/. They also found a significant difference in closure duration. The duration of the first vowel was longer if it preceded /g/ than if it preceded /k/.

Mitleb (1981) found a difference between /g/ and /k/ by measuring closure voicing acoustically. The closure voicing of /g/ was found to be longer than the one of /k/. In this study Mitleb also found that closure duration was shorter for /g/ than for /k/ and the duration of the preceding vowel was longer for /g/ than for /k/.

Inozuka (1991) found a longer aspiration for /k/ than for /g/ which turned out to be statistically significant. Voicing and the duration of the preceding vowel was found to be longer for /g/ than for /k/. Closure duration is longer for /k/ than for /g/.

Braunschweiler (1994) found that /g/ has a significantly shorter VOT than /k/. This, however, was not true for one speaker. The reason for that could be a southern German dialectal pronunciation of this one speaker. The difference in duration of the preceding vowel and closure duration, on the other hand was significant for all speakers.

Although many different measuring techniques were used the authors arrived at similar results. It seems to be well proved that German /g/ and /k/ in intervocalic position can be distinguished by VOT, voicing, closure duration and duration of the preceding vowel. Apart from these acoustic studies there are a couple of articulatory ones. Butcher (1977) investigated the amount of glottal opening in voiceless aspirated and unaspirated stops and found that the glottis is opened widest in voiceless aspirated and least in voiceless unaspirated stops.

Mooshammer et al. (1995) investigated supralaryngeal characteristics of velar consonants by means of electromagnetic articulography and found that the tongue is moving during closure and that there is more movement during /k/ than during /g/.

Jessen (1995 and 1998) found support for Butcher (1977) in that there is a significant difference between /g/ and /k/ in the amplitude and duration of glottal opening. There is less and shorter glottal opening for /g/ than for /k/. However, glottal opening is still common in /g/, especially in intervocalic post-stressed position.

1.3 Phonological descriptions and phonetic correlates

As has become clear so far, the voicing contrast is built up by a number of phonetically measurable parameters. Phonological descriptions, however, regard voicing as an abstract feature which combines all the phonetically measurable parameters. From now on the phonetically measurable parameters will be called "parameters", "characteristics" or "correlates of a feature" whereas the abstract phonological items will be designated "features". The notion of a "feature" describing the voicing contrast implies that there should be a parameter which is a sort of common denominator in that it distinguishes all the stops in all contexts. Phonetically, however, it seems to be hard to find this parameter. In this section three proposals for this feature (or those features) and the respective parameter(s) will be described. The first one by Kohler is rather phonetic than phonological in its assumptions and suggests one pair of features, [fortis] and [lenis], to distinguish all possible stop series. The second one by Chomsky & Halle uses four features, [tense], [heightened subglottal pressure], [voiced] and [constricted glottis]. The third approach by Jessen has two features for every language i.e. [checked] and either [tense] or [voiced]. Chomsky & Halle as well as Jessen assume that there are phonological features and phonetic correlates which are always present even if Jessen states that the basic correlates can be concealed and substitute correlates take their function. Compared to Kohler they are less concerned with various phonetic correlates but more interested in describing the phonemic contrast.

1.3.1 Kohler (1984)

Kohler describes the voicing contrast as being built on mainly two components, i.e. articulatory timing and laryngeal power. According to him these are the two correlates of the features [fortis] and [lenis]. The components can be involved in the distinction between [fortis] and [lenis] up to different degrees. In initial position laryngeal power is more important than articulatory timing, in medial position they have approximately the same importance and in final position articulatory timing is involved to a higher degree than laryngeal power (cf. figure 1.2).

The two components, laryngeal power and articulatory timing manifest themselves in a number of measurable parameters. Those parameters are gradual, which means that there are two ends of a scale with many positions in between.

The first component, articulatory timing, is expressed by the length of the preceding vowel, the duration of the stop closure and the degree of the oral stricture. Thus, a short vowel marks the stop as [fortis], whereas a long vowel marks it as [lenis]. If the stop closure is short the stop is [lenis], if it is long, it is [fortis]. If the stricture is very small, as in a stop, the sound is [fortis], if it is bigger as in an approximant it is [lenis]. Laryngeal power, on the other hand, is expressed by aspiration, voicing and glottalization. Long aspiration, short voicing during closure and glottalization mark a [fortis] stop, short aspiration, long voicing into closure and no glottalization mark a [lenis] stop.

Applied to German, this means that in inital position laryngeal power is more important than articulatory timing, [fortis] and [lenis] stops in this position are distinguished by one or more of the following: aspiration, voicing or glottalization. German takes aspiration to mark the contrast. In medial position, on the other hand, articulatory timing becomes more important, that is why medial stops in German can be distinguished by voicing, duration of the preceding vowel and stop closure duration. In final position German does not distinguish different stop categories.

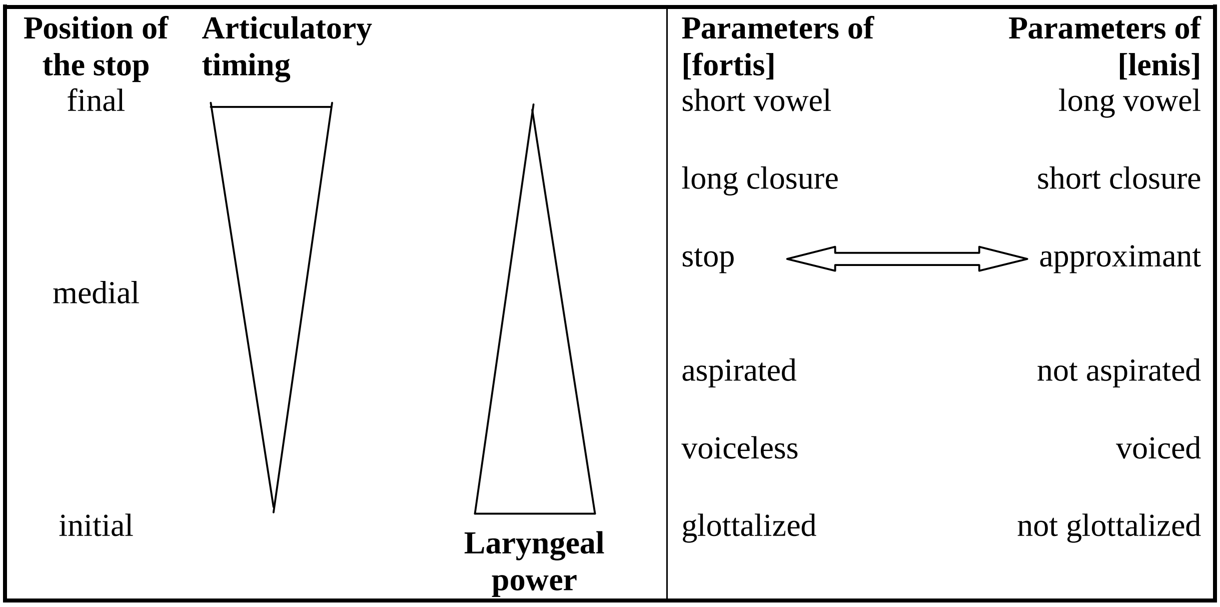


Figure 1.2: There are two components of the pair of features [fortis] and [lenis]. In final position the first one, articulatory timing, which is manifested in the parameters vowel length, closure duration and degree of stricture (parameters can be seen in the right part of the figure), is more important. In initial position the second component, laryngeal power, which is manifested in the parameters aspiration, voicing and glottalization creates the contrast. In medial position both components carry the same weight. The parameters are gradual which is expressed by the horizontal arrow.

Korean, on the other hand, uses different characteristics to mark the contrast. In initial position voice quality plays a higher role, in medial position the stops are distinguished by two parameters from the laryngeal power component, voicing during closure and aspiration and one parameter from the articulatory timing component, stop closure duration.

To summarise, for Kohler it is not possible to find something like a phonetic common denominator in the voicing contrast. The pair of features [fortis] and [lenis] is realised by a number of gradual parameters. This feature, however, is expressed on a number of scales. According to the position of the stop in the word different parameters and different positions on the scale of each parameter are chosen. By describing [fortis] and [lenis] as being built of a number of gradual parameters Kohler manages to get along with only one pair of features. Following from that a stop cannot simply be [fortis] or [lenis], but it should be "more fortis" or "less fortis". This is especially true for a three way contrast like the one in Korean. A question deriving from that is whether a three way contrast can be sufficiently described by the feature [fortis]. Which of the two voiceless Korean stops /k'/ and $/k^h/$ is "more fortis" than the other?

1.3.2 Chomsky & Halle (1968)

The main difference between Kohler and Chomsky & Halle is that Kohler uses one pair of gradual features to describe the voicing contrast whereas Chomsky & Halle use four features which are not gradual, but binary. These are the features [tense], [heightened subglottal pressure], [voice] and [glottal constriction]. The features belong to two different groups of features. The first feature, [tense], belongs to the group of *manner of articulation features* whereas the others belong to the group of *source features*. The manner of articulation features distinguish for example continuants from noncontinuants and different kinds of releases. The [tense] feature actually combines two different parameters: tension of the muscles and duration of the segment:

> "Tense sounds are produced with a deliberate, accurate, maximally distinct gesture that involves considerable muscular effort; nontense sounds are produced rapidly and somewhat indistinctly. In tense sounds, both vowels and consonants, the period during which the articulatory organs maintain the appropriate configuration is relatively long, while in nontense sounds the entire gesture is executed in a somewhat superficial manner." (Chomsky & Halle 1968: 324)

The three source features, [heightened subglottal pressure], [voiced] and [constricted glottis] describe characteristics of the source of the sound, in this case of the vocal folds. Stops which are [+heightened subglottal pressure] are produced with greater subglottal pressure which can result in aspiration. Chomsky & Halle claim that aspirated stops are usually produced with a higher subglottal pressure than unaspirated stops. As Jessen (1998: 135) notes, this has been rejected by several studies.

Chomsky & Halle draw the connection between tenseness and voicelessness as follows: In order to sustain voicing during closure cavity enlargement is necessary (cf. section 1.1). Cavity enlargement, however, is not possible if "the walls of the tract are rigid as a result of muscular tension" (Chomsky & Halle 1968: 325). Therefore, tense stops will be voiceless. If, however, the muscles are lax, cavity enlargement can take place and voicing can be sustained. Chomsky & Halle support this by referring to an X-ray motion pictures investigation by Perkell (1965) which shows an increase in pharynx width during lax stops.

Relating this approach to the different stops dealt with in this study, an aspirated stop does not only have to be [+heightened subglottal pressure], it needs to be [-constricted glottis] at the same time because a precondition for aspiration is an open glottis. A stop is [+voiced] if the glottis is not wide open. However, it does not necessarily have to be closed or constricted although it can be if there is "an air flow of sufficient magnitude or the vocal cords are not held so tight as to prevent vibrating" (Chomsky & Halle 1969: 327). So [-voiced] sounds are exclusively sounds with a spread glottis so that vibration of the vocal cords is not possible. According to Jessen (1998: 129) Chomsky & Halle's definition of [voice] "has shifted from the actual occurrence of voicing ... to the articulatory configurations leading to or inhibiting voicing".

For Korean Chomsky & Halle give the following feature matrices:

Table 1.1: Feature matrices for the Korean velar stops adapted from Chomsky & Halle (1968: 328)

	/k'/	/g/	/k^h/
tense	+	-	+
voice	+	-	-
heightened subglottal pressure	+/-	-	+
glottal constriction	+	-	-

The Korean stop /k'/ is produced with great muscular tension, the vocal folds are in a position that allows for voicing and glottal constriction. The subglottal pressure can be high or low. Since the glottis is constricted there can be no aspiration and no voicing. /g/ is counterintuitive: It is according to Chomsky & Halle [-voiced] although it is the only one of the three stops that can have vocal fold vibration. [-voiced] here only means that the glottis is not closed. Vocal fold vibration, however, is possible even if the glottis is not exactly closed, but not wide open. In order to sustain voicing /g/ is not tense. There is no aspiration because the subglottal pressure is not high enough. /k^h/ is tense and the vocal folds are not in the voicing position. The subglottal pressure is high and the glottis is not constricted so that aspiration can occur.

German /k/ is presumably [+tense], [-voice], [+heightened subglottal pressure] and [-glottal constriction] so that voicing is prevented and aspiration is possible. /g/ is [-tense], so that voicing can be sustained, [-voice], [-heightened subglottal pressure] and [-glottal constriction] (cf. table 1.2).

Table 1.2: Feature matrices for the German velar stops following Chomsky & Halle (1968)

	/k/	/g/
tense	+	-
voice	-	-
heightened subglottal pressure	+	-
glottal constriction	-	-

In order to account for the different realisations of the stops in different environments, Chomsky & Halle propose a set of phonological rules. The notation of those rules is as follows:

> "A → B / X_Y
> where A and B represent single units of the phonological system (or the null element); the arrow stands for "is actualized as"; the diagonal line means "in the context"; and X and Y represent, respectively, the left- and right-hand environments in which A appears." (Chomsky & Halle 1968: 332).

The variables represent features or feature complexes. For German final stops the following rule could be developed:

[-tense] → [+tense] / _ #

expressing final devoicing: A [-tense] stop becomes tensed in word final position. The rule which makes German and Korean /g/ voiced in intervocalic position could be:

[-voiced] → [+voiced] / [+vocalic] _ [+vocalic].

In contrast to Kohler, who proposes one feature Chomsky & Halle need four "phonetic features" to describe the contrast between different stop series. This means that there is a certain redundancy in the system of Chomsky & Halle since only two binary features are needed in order to contrast three sounds and only one is needed in order to contrast two sounds. Another difference is that the features proposed by Chomsky & Halle are binary whereas the one proposed by Kohler is gradual. A question arising from the classification by Chomsky & Halle is what is exactly the difference between the features [+voiced] and [+constricted glottis] since phonetically they seem to describe the same mechanisms?

1.3.3 Jessen (1998)

For two way contrasts Jessen proposes only one feature per language to distinguish stop series, however, as in Kohler's description this feature is not basic but consists of several correlates. In contrast to Kohler the correlates have different degrees of importance. In order to create a three way contrast Jessen introduces a second feature, the feature [checked].

Following Jessen, there are basically two possibilities of setting up a voicing contrast, either by the features [tense] or by the feature [voice]. Each language selects one of those two possibilities. Both features manifest themselves in a number of correlates, one *basic correlate* which differs for the two features and a number of *non-basic correlates* which are shared by the two features (cf. figure 1.3).

There are two kinds of non-basic correlates, namely *substitute correlates* and *concomitant correlates.* Substitute correlates are contextually more limited than the basic correlates. However, in some contexts they can take the place of the basic correlate. Concomitant correlates are bound to the basic correlate in that they co-occur with them for physical reasons. They cannot be controlled, they are just a consequence of the basic correlate (Jessen 1998: 263f).

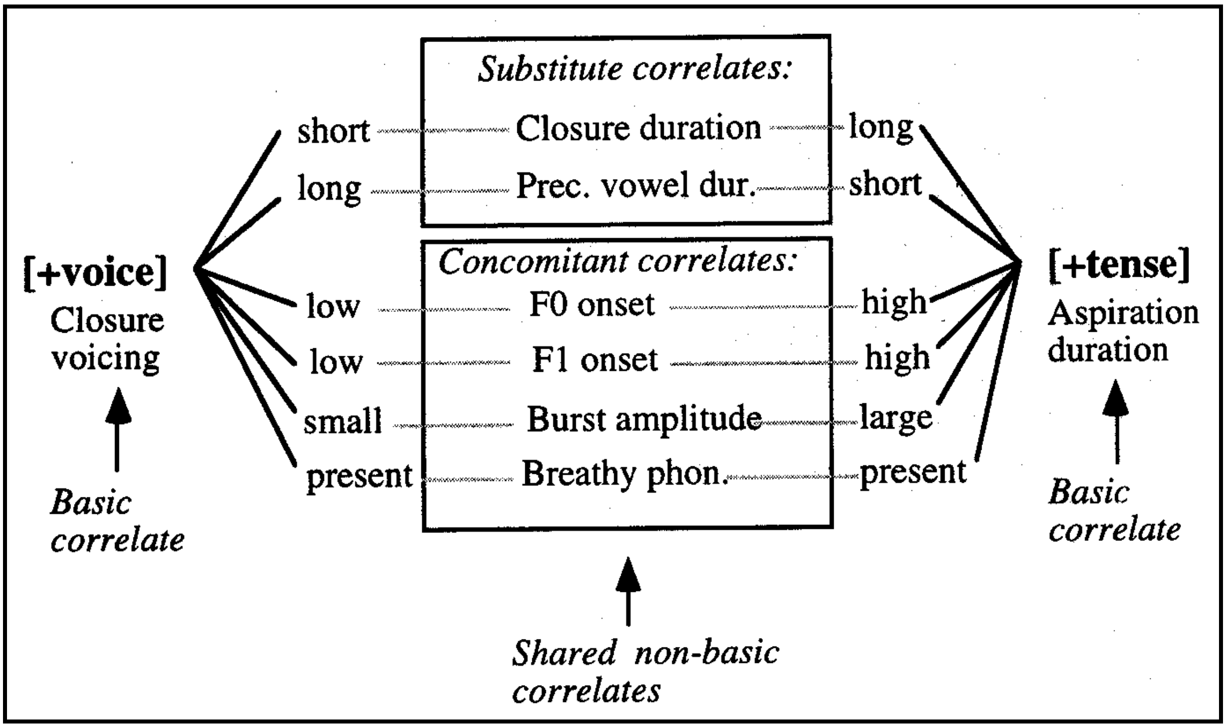


Figure 1.3: The features [voice] and [tense] and their correlates. From Jessen, M.: Phonetics and Phonology of Tense and Lax Obstruents in German, 1998: 270. With kind permission by John Benjamins Publishing Company, Amsterdam/Philadelphia. Each language chooses either [voice] or [tense] to mark the voicing contrast. The basic correlate of [tense] is aspiration, the basic correlate of [voice] is closure voicing. In some contexts the basic correlates are replaced by one or both of the substitute correlates. The concomitant correlates occur together with the basic correlates for physical reasons. The concomitant correlate "breathy phonation" does not actually create a contrast because it is present for both [voice] and [tense].

The basic correlate of [tense] is aspiration. This is because crosslinguistically "aspiration is the most common way [tense] is expressed"

(Jessen 1998: 261). The basic correlate of the feature [voice] is closure voicing. The substitute correlates are closure duration and preceding vowel duration. What is most important in those duration features is the relative length of the stop in comparison to the surroundings:

> "Obstruents with the feature specification [+tense] are characterized by a duration that is longer relative to obstruents with the feature specification [-tense] and relative to segments occurring in the immediate context." (Jessen 1998: 122)

This means that if a stop has a long closure and is preceded by a short vowel, this stop is [+tense], whereas a stop with a short closure which is preceded by a long vowel is [-tense]. Closure duration and vowel duration therefore have to be looked at together (Jessen 1998: 123). Aspiration actually supports the duration characteristics in that an increased aspiration contributes to a longer overall duration of the tense stop relative to the corresponding lax stop (Jessen 1998: 124). Jessen does not distinguish aspirated sounds from geminates. For him, both sounds are [+tense], the difference lies in the correlates by which the feature is expressed. In the aspirated stop it is expressed by the basic correlate, in the geminate by a substitute correlate, namely closure duration. Jessen supports this by referring to the small number of languages which exhibit both, aspiration and gemination (Jessen 1998:122).

The concomitant correlates are the frequency of f_0 onset and F1 onset, burst amplitude and breathy phonation. Fundamental frequency and the first formant are higher after an aspirated stop than after an unaspirated stop. This is because the transition which results from lowering the articulators, occurs during the aspiration in aspirated stops so that when f_0 and F1 become visible it is already high whereas the transition is visible in unaspirated stops so that f_0 and F1 are still lower when they become visible. The burst amplitude is higher for aspirated than for unaspirated stops. This is because the glottis is open in aspirated stops and there is a higher transglottal airflow than in unaspirated stops. This creates an intense turbulence noise during the burst (Jessen 1998: 263).

The fourth concomitant correlate, breathy phonation, is a correlate of both basic correlates. For aspirated stops "breathy phonation in the following vowel reflects the end of the glottal opening phase" (Jessen 1998: 272). Looking at Asian and African languages, however, breathy phonation also seems to be a correlate of [voice]. Jessen therefore decides to present breathy phonation as a concomitant of both, [voice] and [aspiration] and refers to Denning (1998) for an explanation (Jessen 1998: 272). The question remains in how far this concomitant then can be used to create the voicing contrast.

Jessen analyses German as a language selecting aspiration as the basic correlate. The unaspirated /g/ is therefore [-tense], the aspirated /k/ is [+tense]. The phonetic common denominator of the feature [tense], however, is, following Jessen the substitute correlate duration. German does not employ [voice] as a feature to distinguish /g/ and /k/. (Jessen 1998: 163)

Korean /k^h/ is analysed as [+tense] because of its aspiration. The other two stops are analysed as [-tense] because they are not aspirated. In order to distinguish /k'/ and /g/ Jessen uses the feature [checked] introduced by Jakobson, Fant & Halle (1952). If a sound is [+checked] it is produced with a compressed or closed glottis. Following from that /k'/ is [+checked] whereas /g/ is [-checked]. Jessen also notes the differences in duration in the stops. However, he rejects the proposal to analyse /k'/ as a geminate since this difference in duration occurs only word-medially whereas differences in voice quality occur in all positions (Jessen 1998: 126-128). So the distinction between /k'/ and /k^h/ is not classified as a voicing contrast by Jessen.

Table 1.3: Feature matrices for the Korean velar stops following Jessen (1998)

	/k'/	/g/	/k^h/
tense	-	-	+
checked	+	-	-

In conclusion, Korean aspirated stops are analysed as [+tense, -checked], lax stops as [-tense, -checked], and reinforced stops [-tense, +checked] (Jessen 1998: 128, cf. table 1.3). What is not entirely clear is why the durational parameters are "only" substitute correlates although Jessen states that they are the common denominator in the voicing distinction.

1.4 Aims and structure of the study

As one can see, the analyses especially of /k'/ differ in the three approaches. Whereas Jessen assigns the feature [-tense] to it Chomsky & Halle and Kohler assign [+tense] or [fortis] and state that no stop is more tense or fortis than this one. Normally, Korean /k^h/ and German /k/ are analysed similarly. The same is true for Korean and German /g/. Korean /k'/ on the other hand is analysed differently by all the authors. Furthermore, there is no agreement as to which parameter is the most important one or even the common denominator, although this seems to be an important question in all the descriptions. For Kohler all the parameters mentioned have the same importance, for Chomsky and Halle it seems to be tension of the muscles and for Jessen it is segment duration.

However, none of the description is very specific about the reasons for choosing one or the other parameter as most important and none has tried to compare the differences between the stops created by the parameters. In this study a method for doing this is developed (cf. section 2.7.1).

Apart from trying to find the common denominator or the most important parameter for the voicing distinction in intervocalic position in Korean and German this study aims at answering the following questions:

- Looking at Kohler's theory, which of the Korean stops is "most fortis"?
- Are German and Korean /g/ on the one hand and Korean /k^h/ and German /k/ on the other hand really as similar as suggested by Kohler, Chomsky & Halle and Jessen or is the acoustic and articulatory space divided differently among the three segments in Korean than between the two segments in German?
- Since all the theories put their focus on laryngeal characteristics, are there important supralaryngeal mechanisms which have not been taken into account in those descriptions? What role do for example the looping patterns play? Hypotheses about that will be developed and tested in the course of the study.
- To what extent is the choice of the parameters influenced by the surrounding vowel context?

2 METHODS

As described at the beginning of the previous chapter the data used in this study were originally recorded for other purposes. The present study analyses acoustic recordings of VCV-sequences for both languages and articulatory recordings of Korean. The information about German articulation will be taken from Mooshammer (1992) and Mooshammer et al. (1998). The first part of this chapter describes the recording procedure carried out for the other studies (sections 2.1-2.3). The second part deals with the analysis of the data performed in the course of the present study (sections 2.4-2.7). Section 2.1 deals with the subjects involved in the experiments. The second section describes the word material used in the recordings. In the third section electromagnetic articulography and the acoustic recording procedure are described. The fourth and fifth section deal with the segmentation of the signal and with calculations which were carried out. The sixth section explains a way of developing hypotheses (called *suppositions* here) about characteristics of movement trajectories. The last section of this chapter is dedicated to the procedure of testing the suppositions i.e. by weighting parameters and by statistical analyses.

2.1 Subjects

The data of six subjects, three Korean speaking, three German speaking were involved in the present study. The Korean speaking subjects, HS, SH and HZ had been recorded via electromagnetic articulography as well as acoustically. The German speakers, KL, TI and TO had been recorded articulatorily and acoustically as well, however only the acoustic data could be analysed in the present study. The Korean speakers HS and HZ were female, while SH was male. Because the synchronization of the acoustic and articulatory signal of HZ had failed, the acoustic and articulatory signal of this speaker had to be treated separately so that certain calculations, for example determining Euclidean distance from acoustic closure onset to offset, could not be carried out for this speaker. The articulatory data of HS were of limited quality since the tongue back coil was attached too far at the front and the speaker did not produce the closure with the part of the tongue to which the coil had been attached but with a part more in the back. The German speakers were all male.

2.2 Word material

2.2.1 Korean

The word material for the Korean corpus consisted of 26 Korean words and one nonsense word (cf. table A1 in the appendix). There was one word for each possible VCV-sequence where V is either /a/, /i/ or /u/ and C one of the three velar stops. The nonsense word was chosen because there is no word with the sequence /uk^{h}u/ in Korean. All the words consisted of three or four syllables. The speakers stressed the words differently, since there is no fixed stress in Korean. There were two randomised sessions, and each of the 27 words was repeated five times in succession in each session. For technical reasons, there was a time limit for the experiment. That is why carrier sentences could not be used.

2.2.2 German

The German corpus consists of two subcorpora which were designed in order to contrast the velar stops (first subcorpus) but also in order to find out in how far the stops are influenced by the vowel context (second subcorpus). The first subcorpus consists of nonsense words with the structure /bVC❶/ where V is either /a/, /✋/ or /✞/ and C either /g/ or /k/ following a stressed syllable. Those nonsense words were produced in the carrier sentence ‘Sage /bVC ❶/ bitte.”.

The second subcorpus consists of nonsense words with the structure /bVgV/ in the same carrier sentence where V was /a/, /i/ or /u/ and the first syllable was stressed. The sentences were repeated 8 times by subject KL, 10 times by subject TI and 12 times by subject TO.

2.3 Experimental procedure

2.3.1 Acoustic recording

The acoustic recordings of the Korean and German data were carried out via a DAT recorder onto two channels, one carrying the acoustic signal, the other one the synchronisation impulse of the parallel EMA recording. The sampling rate was 48 kHz. The signal was downsampled to 16 kHz.

2.3.2 Articulatory recording: Electromagnetic articulography

2.3.2.1 Configuration

During the recording the subject wears a helmet made of plexiglass onto which three transmitter coils are attached midsagittally. There is one transmitter coil behind the neck, one near the chin and a third one near the forehead (cf. figure 2.1). The three transmitter coils form an equilateral triangle. Furthermore, there are three receiver coils (sensors) adhered to the tongue, one just behind the tongue tip (tt), a second one at the tongue dorsum (td) and the third one at the tongue back (tb). The sensors were located at equal distance from about 1cm to about 5 cm from the tongue tip. Furthermore, there is one sensor at the lower incisors. A further sensor is used as reference coil (cf. section 2.3.2.2 for details) one at the upper incisors.

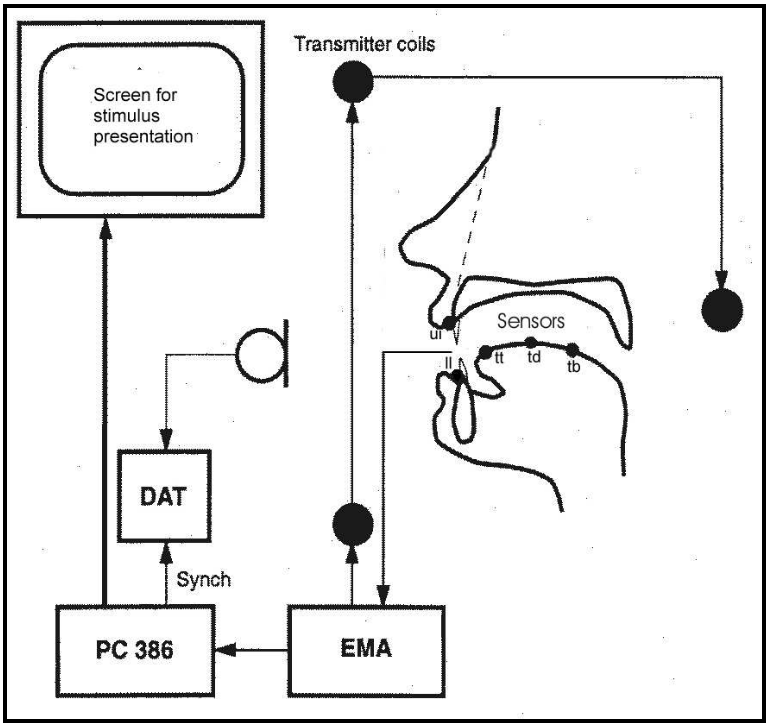


Figure 2.1: Schematic experimental set-up

2.3.2.2 How the system works

Electromagnetic articulography is based on measuring the induced current within a magnetic field, which is generated by the three transmitter coils. The transmitter coils are operated with different frequencies. When the five sensors are placed within the magnetic field a current is induced within them. The signal of the current which is induced in the sensors is the sum of the sinusoidal oscillations of each of the transmitter coils and is led to the system over small cables coming from the sensors. The amplitude of the induced current depends on the position of the sensor within the magnetic field: The closer the sensor is to one of the transmitter coils the higher is the amplitude of the induced current with the respective frequency of the transmitter coil.

The induced current is sampled with a frequency of 500 Hz and the position of the coils is calculated from the amplitude of each of the three sinusoidal oscillations of the signal. Because the resulting data are rather noisy they are filtered with a 20 Hz lowpass filter.

The coils on the tongue supply fleshpoint information about the position of the tongue at a certain time. For the purposes of this study only the data from the tongue back coil have been analysed. The coil at the upper incisors is used as reference coil to compensate for head movements.

Two kinds of velocities, the one in vertical direction (y-velocity) and one in horizontal direction (x-velocity) have been calculated as the first derivative of the movement data. As can be seen in the fifth line of figure 2.2 there is a positive velocity peak in the y-velocity if the tongue is moving upwards and a negative peak if the tongue is moving downwards. With regard to the x-velocity (fourth line) there is a positive peak if the tongue is moving backwards and a negative one if the tongue is moving forwards.

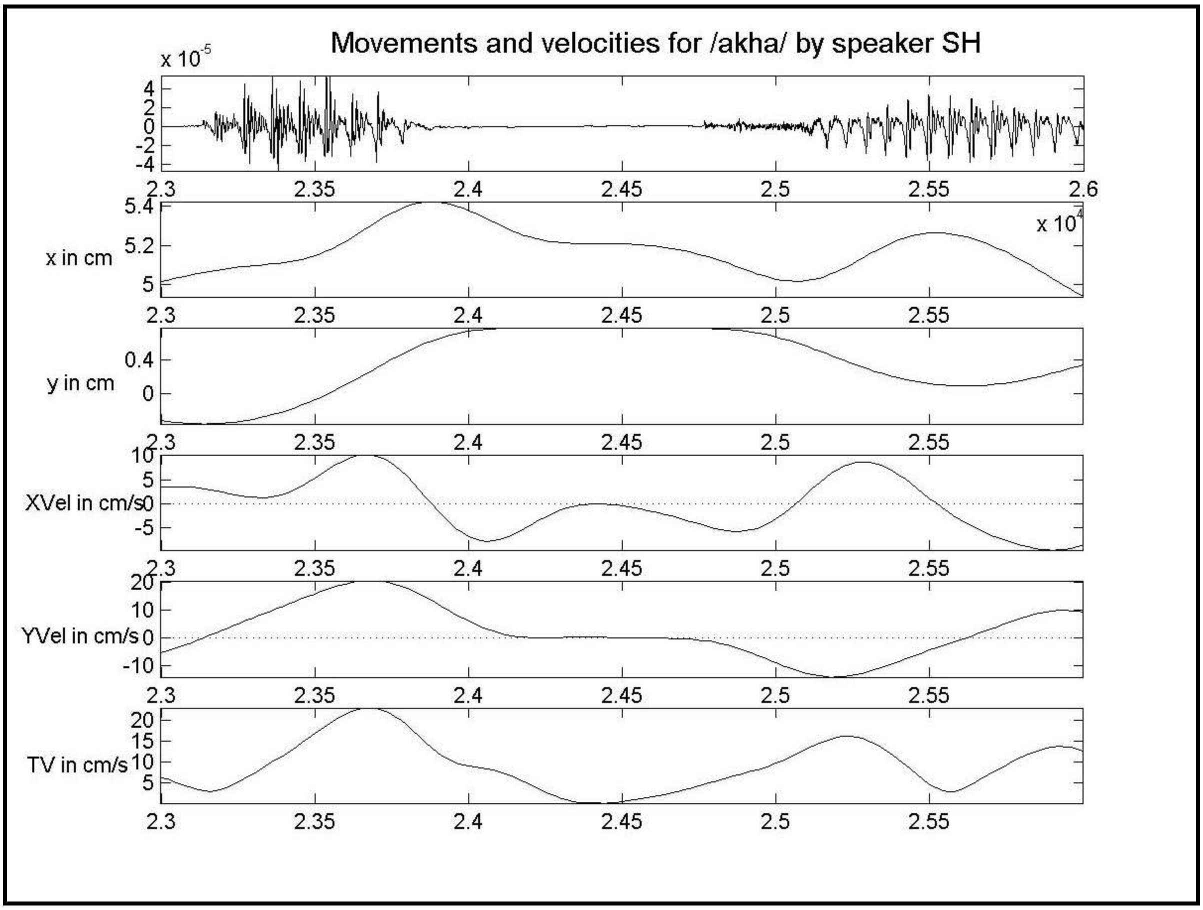


Figure 2.2: Movements and velocities: first line: oscillogram, second line: x-positions of the tongue back coil, third line: y-positions of the tongue back coil, fourth line: x-velocity, fifth line: y-velocity, last line: tangential velocity

From those two velocities the tangential velocity which includes movements in both directions has been calculated via the following formula:

$$v_t=\sqrt{(v_x^2+v_y^2)}$$

where v_t is the tangential velocity, v_x the velocity in horizontal direction and v_y the velocity in vertical direction. Because the two velocities are squared the tangential velocity is always positive.

In addition the acceleration was calculated as the second derivative of the movement. Tangential acceleration is again a combination of x and y acceleration and calculated via the respective formula:

$$a_t=\sqrt{(a_x^2+a_y^2)}$$

where a_t is the tangential acceleration, a_x the acceleration of the movement in horizontal direction and a_y the acceleration of the movement in vertical direction. Again all the values are positive due to the squaring down. This results in the fact that there are actually two kinds of peaks: acceleration and deceleration peaks.

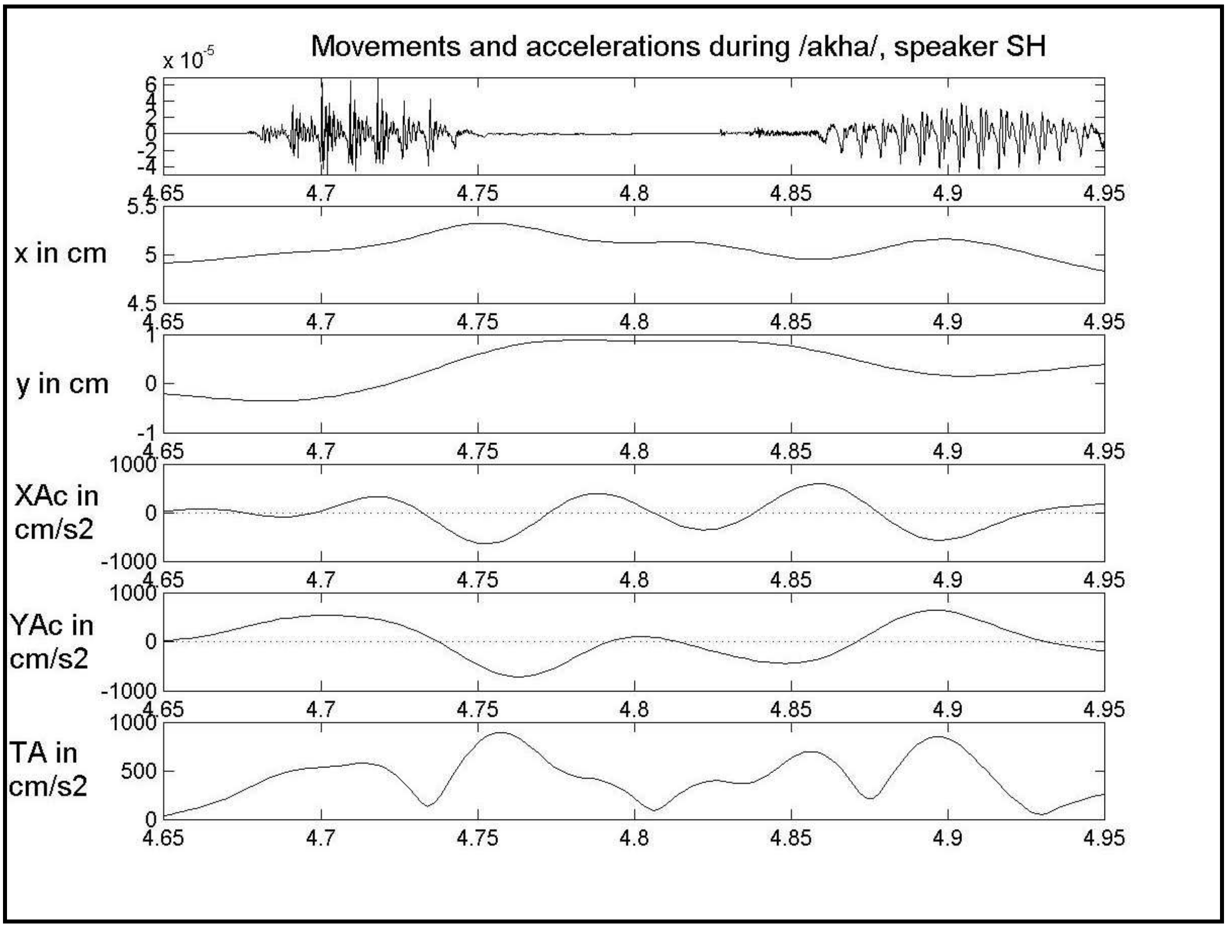


Figure 2.3: Movements and accelerations: first line: oscillogram, second line: x-positions of the tongue back coil, third line: y-positions of the tongue back coil, fourth line: x-acceleration, fifth line: y-acceleration, last line: tangential acceleration

Comparing tangential velocity and tangential acceleration one can see that there is one peak in acceleration before the velocity peak and one after the velocity peak (cf. figure 2.6). The one before is an acceleration peak, the one after a deceleration peak. This can be seen by looking at x and y acceleration (cf. figure 2.3). Whereas the values are above 0 at the moment of the acceleration peak in tangential acceleration, at least one of them is below 0 in the moment of the deceleration peak.

To summarise, the articulatory signal of a VCV sequence where C is a velar stop normally shows a vertical movement from a lower vowel position up to the consonant and down to the second vowel and a horizontal from back to front during the closure. There are two velocity peaks, one during the movement from the vowel up to the palate and one during the movement down from the palate to the second vowel. There are four acceleration peaks, one before and one after each velocity peak, the ones after the velocity peaks, however, could also be called deceleration peaks.

2.4 Segmentation and labelling

2.4.1 Acoustic segmentation and labelling

Acoustic labelling marks specific events in the signal and thus divides it into segments. For the current study six events were of interest (cf. figure 2.4):

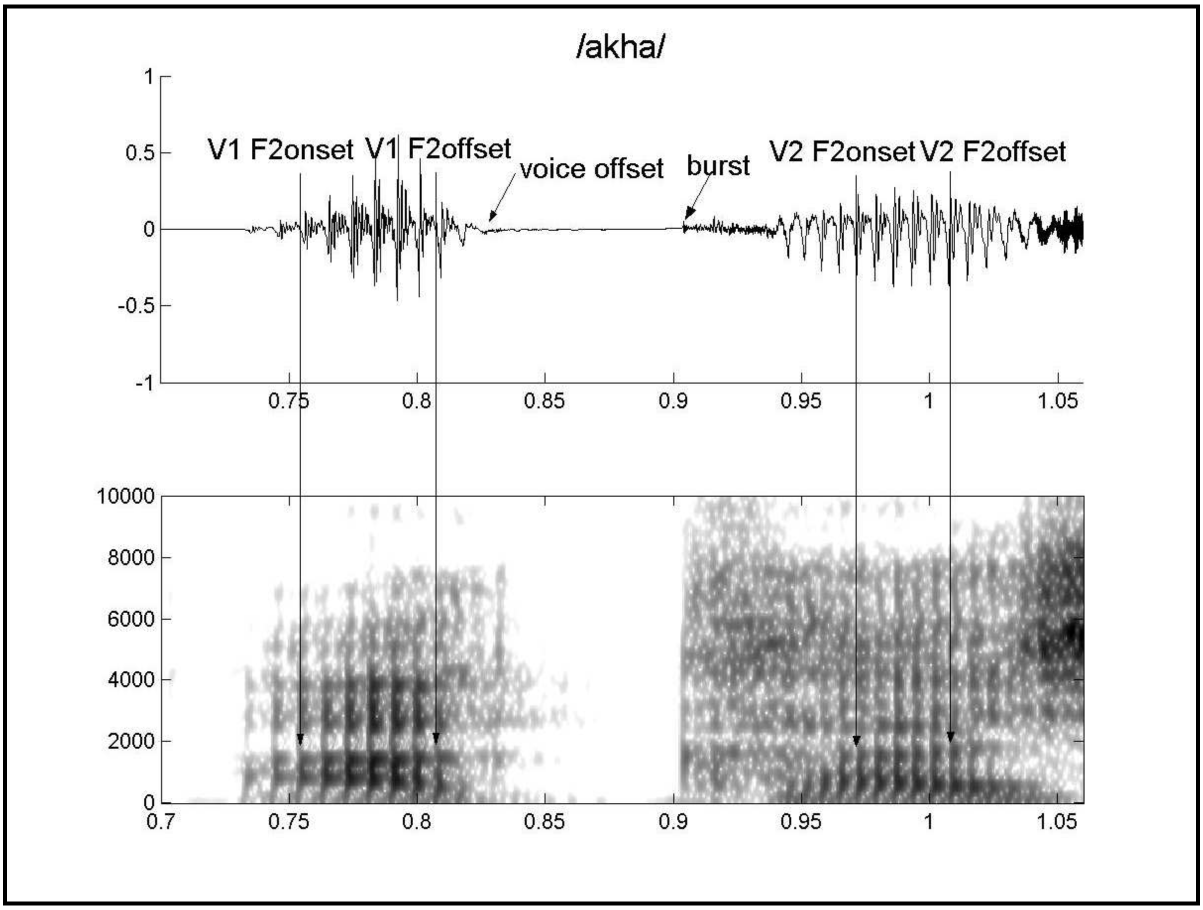


Figure 2.4: Oscillogram and spectrogramm for /ak^{h}a/ for speaker SH

- the beginning of V1: onset of the second formant of V1,

- the end of V1 and beginning of closure: offset of the second formant of V1,
- voice offset: the end of vibration of the glottis, in the oscillogram this is the end of clear periodic movement,
- the end of closure and beginning of aspiration: the burst,
- the end of aspiration and beginning of V2: onset of the second formant of V2,
- the end of V2: offset of the second formant of V2.

Onset and offset of F2 were defined not as the point in time where the formant becomes visible or disappears completely from the spectrogram but where its intensity becomes characteristic for a vowel.

Acoustic labelling involved a number of problems which will be mentioned briefly. Especially for the Korean speakers SH and HZ and the German speakers KL and TI, there was often no closure for /g/, the tongue only approximated the palate without producing a closure. Consequently, it was impossible to measure a burst (cf. figure 2.5).

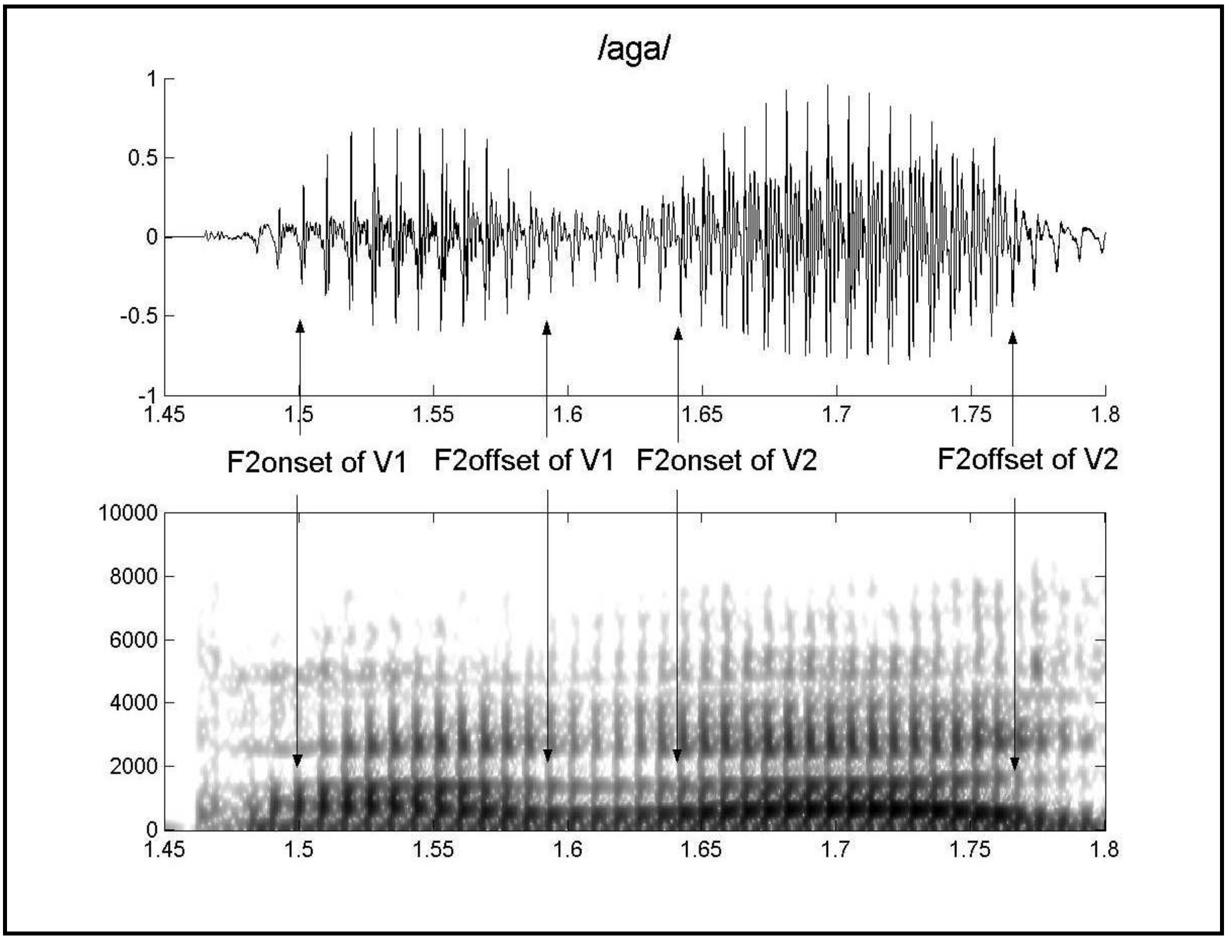


Figure 2.5: Oscillogram and spectrogramm for /aga/ for speaker SH

On the other hand, especially for the Korean /k'/ often multiple bursts were detected. In those cases the first one was considered as end of closure for following calculations. Furthermore, the Korean speaker HS pronounced the nonsense word "suk^{h}uli" without the first /u/: /sk^{h}uli/. In this case F2 onset and offset of V1 could not be labelled. Additionally, because of technical problems with the first recording of /aga/ for speaker HS this recording could not be analysed. So there are only five repetitions of /aga/ for this speaker.

2.4.2 Articulatory segmentation and labelling

Articulatory segmentation involves marking certain points in time according to characteristics of the movement of the tongue back, for example when the tongue changes direction or when it has a certain velocity. Articulatory segmentation and labelling was done with the help of the programme ARTMAT written in MATLAB by C. Mooshammer. This programme enables the user to view the acoustic signal together with certain articulatory parameters. For the purposes of the present study for example the movement of the tongue back sensor in vertical direction, y-velocity, tangential velocity and tangential acceleration had to be viewed at the same time in order to label certain points in time (cf. figure 2.6).

As can be seen in the second line in figure 2.6 for the sequence /ak^{h}a/, the tongue has at first a rather low position for V1, it then moves up for the stop and down again for V2. Below this second line showing the movement in vertical direction one can see the y-velocity. There is a velocity peak when the tongue is approximately in the middle of its way from the position in the middle of V1 up to the palate and a negative peak during the movement from the palate down to V2. In the fourth line one can see the tangential velocity. This value combines the velocity in x and y direction. It has two peaks, one during the movement up to the palate and the other one during the movement down to V2. The tangential acceleration has four peaks, acceleration and deceleration peaks alternatively.

In a first step the middle of V1, the turning point and the middle of V2 were defined (cf. section 2.4.2.1). Afterwards, acceleration peaks, velocity and deceleration peaks were labelled for sequences with V1=/a/ (cf. section 2.4.2.2).

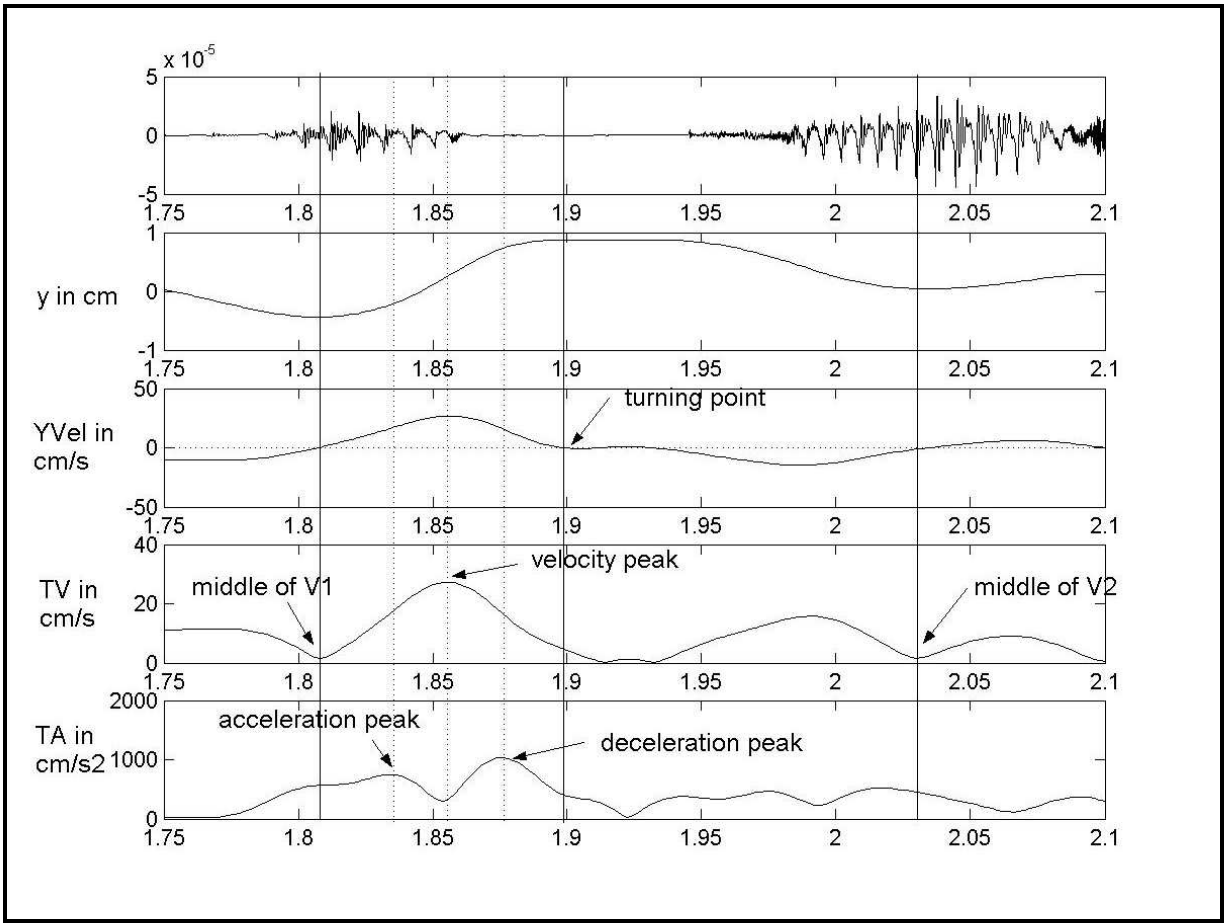


Figure 2.6: Articulatory segmentation of /akʰa/: first line: oscillogram, second line: movement of the tongue back coil in vertical direction, third line: y-velocity, fourth line: tangential velocity, fifth line: tangential acceleration. Solid vertical lines show segmentation points of middle of V1, turning point at the palate and middle of V2 (cf. 2.4.2.1). Dashed vertical lines show segmentation points of acceleration peak, velocity peak and deceleation peak (cf. section 2.4.2.2).

2.4.2.1 Middle of V1, turning point, middle of V2

Following Mooshammer (1992), the following three points in time were labelled:

- the middle of V1
- the turning point at the palate
- the middle of V2.

The middles of V1 and V2 are characterised by a minimum in y-position and a minimum in tangential velocity. If the movements are large, as is the case for all a-contexts, those points are rather easy to find (cf. figure 2.6). If the movements are smaller, as for example in the sequence /igi/ especially the middle of V2 is difficult to find (cf. figure 2.7).

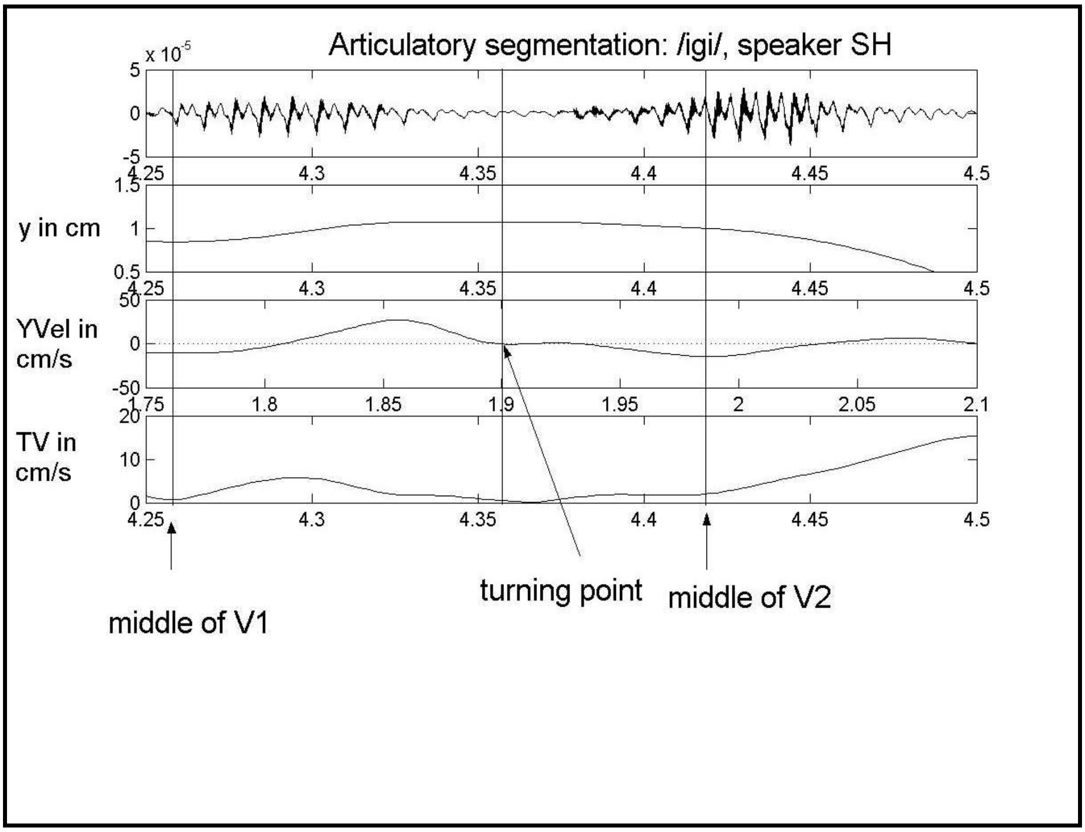


Figure 2.7: Articulatory segmentation of /igi/: first line: oscillogram, second line: movement of the tongue back coil in vertical direction ,third line: y-velocity, fourth line: tangential velocity

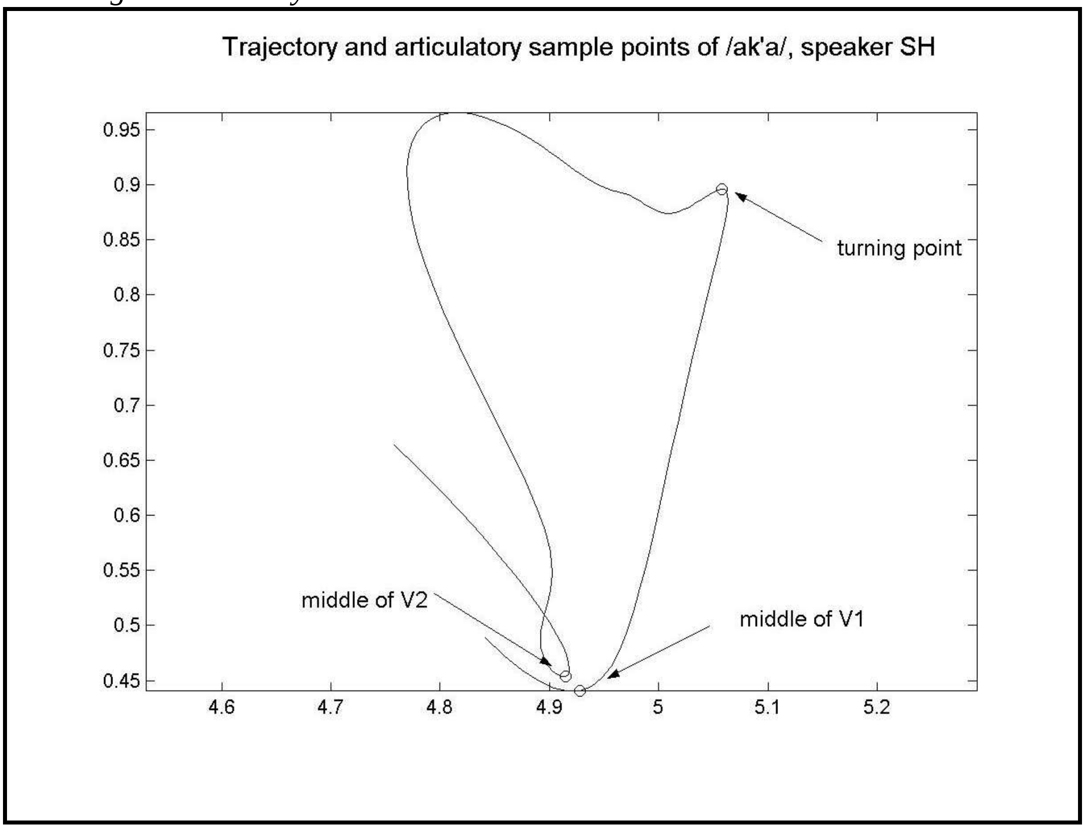


Figure 2.8: Trajectory of the tongue back sensor with labelled points. The turning point is normally close to the acoustically measured closure onset.

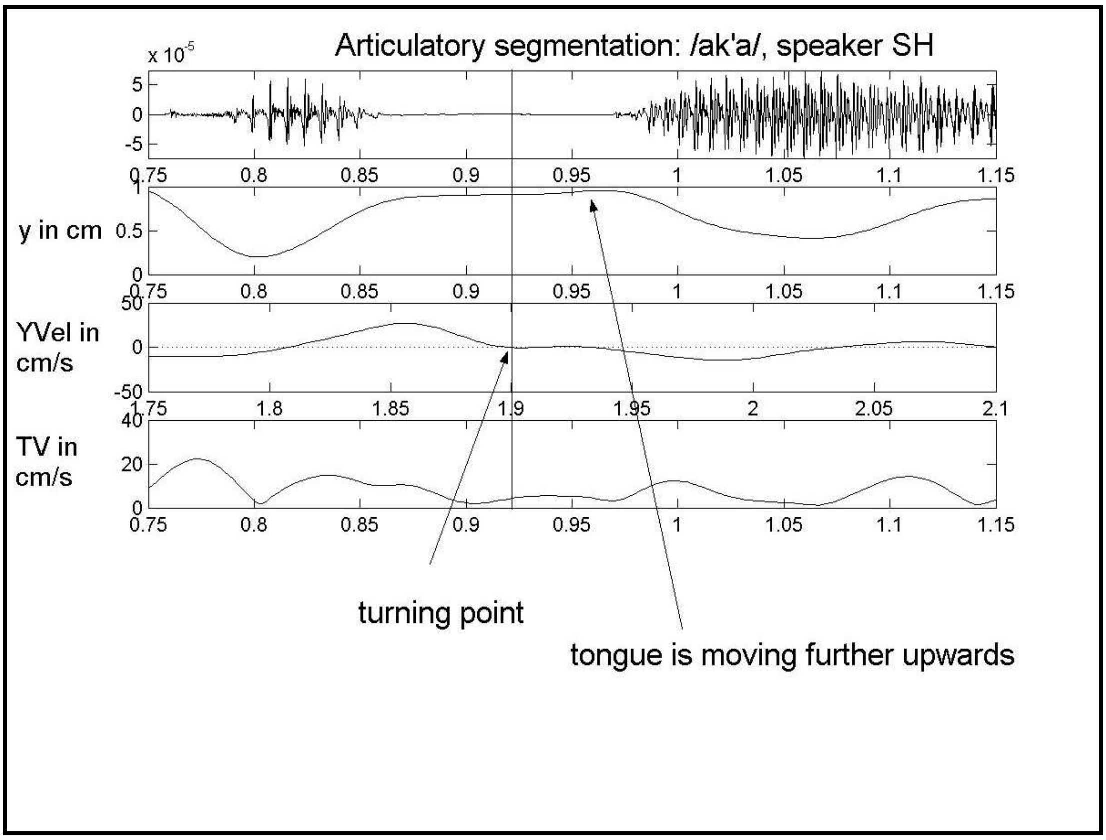


Figure 2.9: Especially if the closure is very long the turning point is not necessarily the point where the tongue has the highest position.

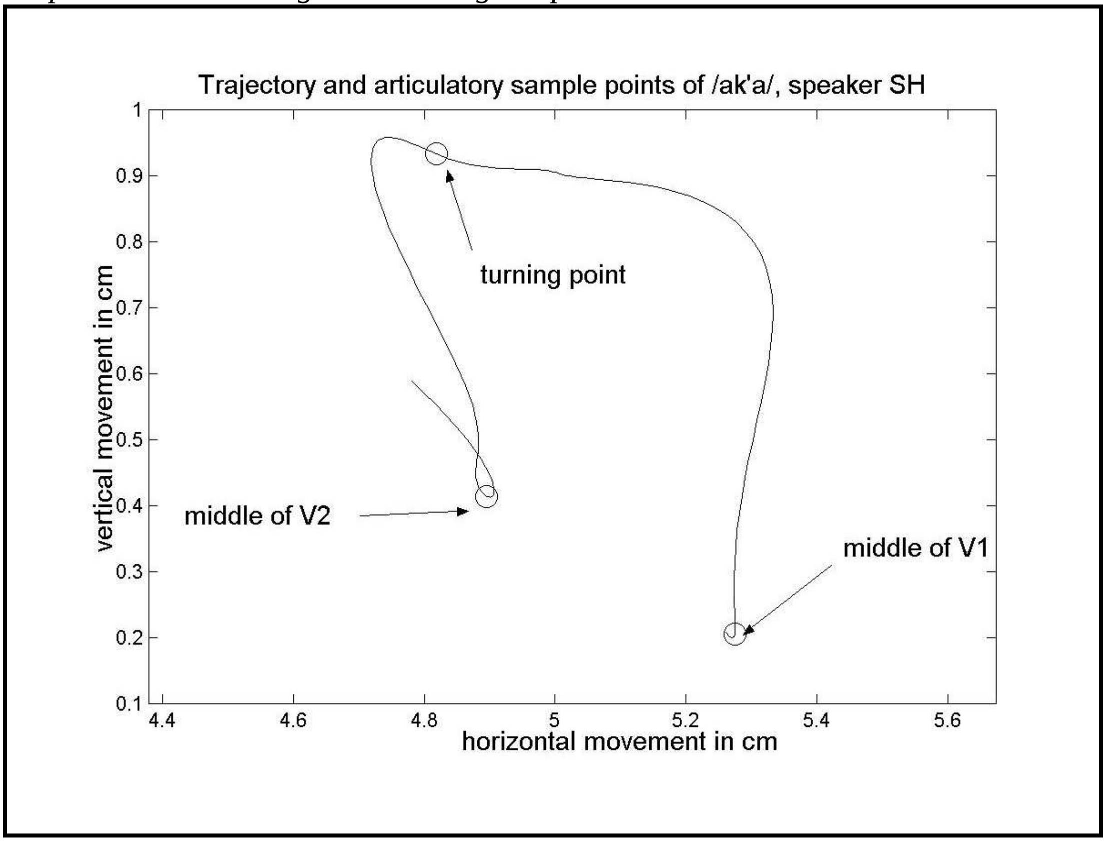


Figure 2.10: Trajectory of the tongue back coil with the three articulatorily sampled points. The turning point is in this case not the point with the highest y-value.

The turning point at the palate is often close to the acoustically measured closure onset (cf. figure 2.8). It has been defined as the first zero point of the y-velocity. It is the highest position of the tongue if the closure is very short or if there is no closure at all. If the closure is longer, as in /ak'a/ it does not necessarily have to be the highest point since the tongue might move up further during closure. Consequently, the point cannot be found where the line for y-velocity crosses the zero-line but where it first "touches" it (cf. figure 2.9).

Looking at the trajectory of /ak'a/ (cf. figure 2.10) one can see that the turning point can be very far away from closure onset if the closure is very long.

2.4.2.2 Acceleration peak, velocity peak and deceleration peak

For sequences with V1=/a/ three further points during the closing gesture were measured (cf. figure 2.6):

- acceleration peak (of tangential acceleration)
- velocity peak (of tangential velocity)
- deceleration peak (of tangential acceleration)

For sequences with V1=/i/ or /u/ those points were not labelled because there were normally lots of peaks in velocity and acceleration so that the result would have been rather inconsistent.

2.5 Calculations

The calculations based on acoustic measurements were carried out for both languages, the calculations based on articulatory measurements or both, acoustic and articulatory measurements were carried out for Korean only.

In order to constitute a set of parameters that can be used to distinguish the stops from each other the following calculations, which will be explained in detail immediately, were carried out:

- segmental durations (acoustic and articulatory segments)
- percentages of segment durations
- movement amplitudes
- Euclidean distances
- velocities, accelerations, decelerations
- tongue position at closure

2.5.1 Segmental durations

Phoneme realisations can often be distinguished by the duration of certain acoustic segments, either belonging to the sound itself or preceding or following the particular sound. A voiced stop, for example, normally has a longer voicing into closure than a voiceless stop. Therefore the durations of acoustically and articulatorily defined segments have been calculated.

2.5.1.1 Acoustically defined segments

From the points in time labelled acoustically the segments below could be defined. They will be explained immediately:

- V1
- V2
- closure
- V2-V1
- voicing into closure
- Klatt VOT
- duration of the complete VCV-sequence

The duration of the vowels is the time from F2 onset to F2 offset of the vowels. The closure is the time from F2 offset of V1 to the burst. As discussed above, there was often no closure for /g/. This results in the problem that for a lot of sequences it is not possible to define closure duration. Since, however, closure duration is one of the most important characteristics of the stops, another segment comparable to it had to be found. This is the time in between the stops (V2-V1), which is the period from F2 offset of V1 until F2 onset of V2. It includes VOT. Voicing into closure is the voicing that still takes place after closure onset.

There are two ways of measuring the aspiration duration after the burst, the VOT. Both ways of measuring VOT start with the burst. The end of the aspiration phase, however, can be defined as either the beginning of periodic oscillation (Lisker & Abramson 1964) or the beginning of a well defined formant structure (Klatt 1975: 686-706). For this study it was decided to measure Klatt VOT, the time from the burst to F2 onset of V2, because it includes information about the opening gesture of the vocal tract (P. Perrier, pers. comm.).

2.5.1.2 Articulatorily defined segments

The movement from the articulatorily measured middle of V1 to the turning point was defined as the closing gesture. The opening gesture is the movement from the turning point to the middle of V2. The time in between the two points, the duration of the closing or opening gesture, was calculated.

2.5.2 Percentages of segmental durations

As was pointed out by Luce & Charles-Luce (1985) in English CV productions there are relations between segment durations. For example, if the closure is short, the V2 is longer so that closure and V2 together are constant. Although this could not be found in this study it is possible that there are relationships among durations so that segment durations should not only be seen as absolute numbers but also in relation to the other segments.

With regard to voicing, another problem of absolute durations is that voicing into closure cannot be calculated in milliseconds if the stop is fully voiced and a burst cannot be measured because it is not possible to say where the voicing into closure stops and the voicing of the second vowel begins.

In order to deal with both problems, the following percentages of segmental durations were calculated:

- percentage of duration of V1 and V2 in relation to the VCV-duration,
- percentage of closure duration in relation to the VCV-duration,
- percentage of voicing in relation to closure duration.

In the case of the fully voiced stop where the burst cannot be measured one can simply set the percentage of voicing to 100%.

2.5.3 Movement amplitudes

The movement amplitude is the distance the tongue is travelling during a given interval. It was calculated as the integral of the tangential velocity with the following formula:

movement amplitude = sum(tangential velocity/sampling rate)

The following movement amplitudes were calculated:

- movement amplitude during V1,
- movement amplitude during closure,
- movement amplitude during V2,
- movement amplitude during the VCV-sequence.

2.5.4 Euclidean distances

The Euclidean distance is the straight line distance between two points. It differs from movement amplitude in that it is not the length of the path the tongue actually moves along but the way it should move if it was taking the shortest path.

The Euclidean distance was calculated via the following formula:

$$euc = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

with x_1 and y_1 being the coordinates of the starting point and x_2 and y_2 being the coordinates of the endpoint.

The following Euclidean distances have been calculated:

- Euclidean distance during V1,
- Euclidean distance during closure,
- Euclidean distance during V2,
- Euclidean distance during the VCV-sequence.

2.5.5 Velocities

Velocities at the previously labelled acceleration peak, the velocity peak and the deceleration peak of sequences with V1=/a/ were calculated.

2.5.6 Tongue position at closure

Velar stops are produced in the velar region, however, they can differ in the exact place where the stop is produced. In German, for example, the aspirated velar stop is produced more fronted in an /i/-context than in other contexts (Geng et al. 2003). Therefore the x-coordinates of the turning point at the palate were determined.

2.6 Developing suppositions

In order to enable an organised analysis of the three way distinction in Korean and the two way contrast in German a number of hypotheses, called suppositions here were developed and later checked. This was done by creating ensemble averages of the tongue back coil movements following a proposal in Hoole (1996: 120ff). It was suggested that the distinction of the stops is highly influenced by the different vowel contexts. Therefore, ensemble averages, which are a kind of averaged trajectories (cf. sections 2.6.1-2.6.2), were calculated for one speaker, for each stop in each context separately[4]. Afterwards, the movements were plotted. This was done for the Korean data only.

2.6.1 Typical productions

In order to come up with suppositions about characteristics of a stop in a certain context, more or less "typical productions" had to be found. Because speaker SH seemed to have the most consistent pattern, he was chosen for this step. Of

[4] Ensemble averages were calculated for one speaker only because they were a means of developing hypotheses and should not be seen as part of the investigation.

course, even this speaker had a number of productions that deviated from his other productions. As can be seen in figure 2.11, of the ten repetitions of /ak^{h}u/ there is one that is considerably more at the front.

An explanation for this repetition to be so much different from the others is that it was the last one in a row. As is well known, for prosodic reasons first and last repetitions are likely to deviate from the more typical ones in the middle. Building ensemble averages of all the ten productions shown in figure 2.10 would result in a misleading graph because all the productions of /ak^{h}u/ would move further to the front, although the "typical way" to produce /ak^{h}u/ seems to be to produce it further in the back.

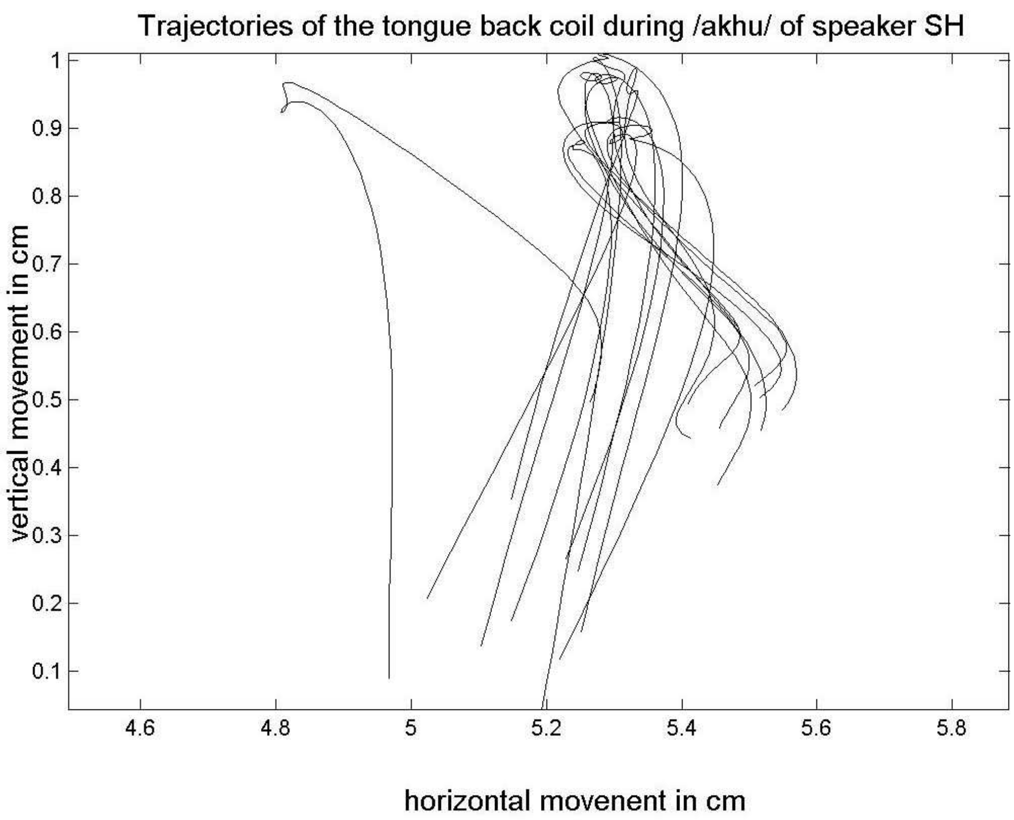


Figure 2.11: Trajectories during /ak^{h}u/: There is one untypical production which is more fronted than the other nine.

In order to catch the "typical production", which means the /ak^{h}u/ production which has the most similarities with all real productions, untypical productions like the one in figure 2.11 where ignored. Apart from repetition 10 of /ak^{h}u/, the one discussed above, repetitions 1, 6 and 7 of /ik^{h}a/ and 1, 2 and 6 of /uk'i/ were taken out. As can be seen, those repetitions are mainly first and last ones in a row (1 and 6 are first ones, 5 and 10 are last ones).

2.6.2 Ensemble averages

In order to create ensemble averages of the movements, the beginning of V1 and the end of V2 were measured acoustically (cf. section 2.4.1). Of course, the number of x/y pairs for the tongue positions in between those two points in time differed with the duration. If the duration from V1 onset to V2 offset was 30 ms longer for one repetition than for another one, there were, with a sampling rate of 500, 13 pairs of values more for the first repetition than for the second. To count averages of these vectors as they are would not be reasonable because even if the beginnings of the vectors fall together, the ends do not since the numbers of x/y pairs differ. In order to solve this problem the duration of the trajectory from beginning to end was regarded as being the same for all the measurements, a sort of reference duration. Then 20 temporally equally spaced points on the trajectory were chosen for each trajectory. In other words, the trajectory was now sampled with a sampling frequency of 20 per reference duration. For each of the 20 sample points the average x and y values for the (maximal) 10 repetitions were calculated. Finally, the graphs were plotted (cf. figures A1-A9). In order to see the influences of the vowels, all the graphs of different consonants but the same surroundings were plotted together in one figure.

2.7 Testing the suppositions

There were two main methods of testing the suppositions set up after the step described in the last section. The first method was developed in order to find the most important characteristic, a sort of common denominator which is independent of the vowel context. This method involved taking all parameters of which values have been calculated together and weighting them according to their importance in setting up the contrast between the three velar stops. The second method which was carried out afterwards is to calculate analyses of variance for the parameters that turned out as being important in the weighting procedure.

2.7.1 Weighting parameters

Characteristics like voicing into closure, horizontal tongue position at closure, velocity at certain points in time, vowel duration and VOT have previously been found as being involved in the voicing contrast. Together with the parameters found by calculating ensemble averages they created a set of parameters that could possibly influence the voicing distinction in Korean or German.

Consequently, the 26 parameters in table 2.1 were set up as candidates for voicing characteristics.

It is important to note that there are acoustic (e.g. VOT, vowel duration) as well as articulatory parameters (movement amplitude, Euclidean distance) involved. For the German data only the acoustic parameters could be measured.

*Table 2.1: Parameters grouped according to the segment they refer to. The parameters with a * could not be determined for speaker HZ. The parameters with a + could not be determined for the German data.*

a) VCV-movement
1. overall duration
2. movement amplitude*+
3. Euclidean distance*+
b) V1
4. duration of V1
5. movement amplitude of V1*+
6. Euclidean distance of V1*+
7. percentage of VCV-duration
8. duration of articulatorily measured closing gesture+
9. peak acceleration+
10. peak velocity+
11. peak deceleration+
c) V2
12. duration of V2
13. movement amplitude of V2*+
14. Euclidean distance of V2*+
15. percentage of VCV-duration
16. duration of articulatorily measured opening gesture+
d) stop closure
17. closure duration
18. movement amplitude of closure*+
19. Euclidean distance of closure*+
20. percentage of whole duration
21. V2-V1
22. percentage of complete duration for V2-V1
23. voicing into closure
24. percentage of voicing into closure
25. VOT
26. x-value of tongue position at closure+

If one aims at finding out which of these parameters are useful for distinguishing the stops and which ones are not one has to compare them with each other. In order to do this, one has to make the parameters comparable. For example, to find out whether voicing into closure or movement amplitude during V1 is more important to characterise /k’/ and to set it apart from /k^{h}/, one has to develop a scale which is independent from value and measuring unit.

In order to do this, the minimal and maximal values of each parameter, independently of the consonant were set to 0 and 100, respectively, and the values in between were converted into values on this scale. This was done separately for each speaker. To reduce the influence of outliers, the means of the three highest and the three lowest values for one parameter and all the stops were taken as maximal and minimal values for each parameter. For example, the three highest values of velocity for SH for all measurements regardless of the stop are 19.74, 19.32 and 19.07 cm/s, the minimal values are 0.27, 0.42, 1.76 cm/s. The mean value for the maxima, 19.38, was set to 100, the mean for the minima, 0.82 was set to 0.

For all the values in between the two a place on the scale was calculated. For /k’/ in /ak’a/ in the third repetition, which was 15.75 cm/s, this meant that it now was 80.46 on the scale. This procedure can be seen in table 2.2:

Table 2.2: Conversion of measured values into scale values

measured values:	0.82 cm/s	15.75 cm/s	19.38 cm/s
scale values:	0	80.46	100

After all the measured values had been converted into values on this neutral scale they were grouped according to consonants. For each parameter and consonant the arithmetic mean was calculated. Now the importance of a single parameter for the characterisation of a consonant could be estimated. Parameters that have a very high or very low scale value, which is, following from that, close to the calculated maximum or minimum are characteristic for the consonant, whereas parameters that have an average value are less important.

To find out how important a parameter is for marking the contrast between two consonants, the difference between the arithmetic means of scale values of two consonants was calculated. To give an example, if one looks at closure duration of speaker HS, the mean value on the scale for /g/ is 20.77, the one for /k’/ is 70.91. The contrast between the two is the difference, 50. 14.

After an analysis of variance the parameters that did not produce a significant difference were excluded since they are not useful to distinguish among the stops. For the remaining parameters a hierarchy was set up according to the scale value contrast the parameters produced.

2.7.2 Analyses of variance

Weighting the parameters did already produce very important results, i.e. the parameter that is most important in the voicing contrast. However, as discussed earlier, it is very likely that this parameter does not have the same importance in every vowel context. Therefore, in order to find out in how far the voicing contrast is influenced by vowel context, the data were split according to the vowel context and analyses of variance were carried out for the parameters listed in table 2.1. The statistical analyses were performed as multivariate one way analyses according to the General Linear Model with the program SPSS Version 11.5. They included a post-hoc test after Scheffé.

The difference between this analysis of variance and the one used in the weighting procedure is that the measurement results are split according to vowel context now whereas the influence of the vowel context was neglected in the weighting procedure.

2.8 Summary of the methods

This study uses data gained by an EMA recording for Korean and acoustic recordings of German and Korean. Six subjects, three Koreans and three Germans were involved in the experiments. The word material consisted of VCV-sequences where V is either /a/, /i/ or /u/ and C=/g/, /k'/ or /k^{h}/ for the recordings of Korean and C=/g/ or /k/ for the recordings of German. The articulatory and acoustic data were segmented and a number of calculations including segment durations, movement amplitudes, Euclidean distances and velocities were carried out. Hypotheses (called suppositions here) about Korean articulation were won by calculating ensemble averages. In order to find general characteristics of the stops a set of parameters was composed and weighted according to the degree of the difference between the stops. Finally, the parameters have been looked at in more detail by carrying out statistical analyses for all the parameters, separately for each vowel context.

3 RESULTS

In this section the results of the analyses will be presented. Section 3.1 lists the suppositions won from two sources, on the one hand from previous studies and on the other hand from the ensemble averages. In section 3.2 the most important parameters for the voicing contrast in velar stops in intervocalic position will be presented as a result of weighting the parameters. The succeeding section (section 3.3) will present the results of a deeper analysis of the data which includes context specific characteristics of the stops. The section is subdivided into an acoustic and an articulatory part. The acoustic part will present results for both languages, Korean and German, whereas the articulatory part will present results for Korean only. The comparision between Korean and German articulatory parameters will be carried out in chapter 4 and will be based on the results of previous studies.

3.1 Suppositions

3.1.1 Korean

There are a number of parameters which have been shown to be involved in the voicing contrast in previous studies (cf. section 1.2), namely voicing into closure, VOT, vowel duration and closure duration. Those parameters were suggested to be involved in the Korean voicing distinction as well. /g/ is predicted to have the longest voicing into closure, /k^h/ will have the longest VOT, /g/ will have a longer V1 and /k'/ and /k^h/ will have a longer closure duration than /g/.

Furthermore, by looking at the plots of the ensemble averages (cf. figures A1-A9) a number of further observations were made which were consequently also looked at in greater detail in the present study:

- Movement during closure
  During the closure the tongue is sliding along the palate. It moves either forwards or backwards. The direction of the movement and its movement amplitude depend on the vowel context. There seems to be more movement during closure for forward movement than for backward movement.
- Tongue position at closure
  The tongue position during closure seems to depend on the first vowel. If the first vowel is /i/ the tongue position is more fronted than if it is /a/ or /u/.
- Smoothness
  The trajectories of /g/ seem to be smoother. Probably they have a lower velocity peak and a smaller difference between acceleration and

deceleration peak than /k'/ and maybe even /k^h/. In contrast to /g/, /k'/ has sharp edges in its trajectory. High acceleration and deceleration peaks can be expected. Furthermore, it seems as if especially /k'/, but also /k^h/ produce a greater impact at the palate which should be the result of a higher velocity during the closing gesture.

- Closure
  /k'/ seems to have the longest closure and /g/ the shortest. Furthermore, the amplitude and Euclidean distance of the movement during closure are probably greater for /k'/ than for the other stops. /g/ appears to have the smallest movement amplitude and Euclidean distance during the sliding movement along the palate.
- Similar trajectories
  The trajectories of /igi/, /ik'i/ and /ik^{h}i/ (cf. figure A5) are very similar, as are the ones of /igu/, /ik'u/ and /ik^{h}u/ (cf. figure A6). There are probably hardly any differences in articulatory parameters and the stops in those contexts can only be distinguished by acoustic characteristics, e.g. differences in voicing into closure or VOT.
- Influence of vowel height on closing and opening gesture
  /i/ and /u/ are produced with a higher tongue position than /a/. The closing gesture duration should therefore be shorter for sequences with V1=/i/ or /u/ than for sequences with V1=/a/. Similarly, the opening gesture duration should be shorter for sequences with V2=/i/ or /u/ than for sequences with V2=/a/.

3.1.2 German

For German only acoustic parameters could be investigated. Following the literature (cf. section 1.2), the parameters VOT, voicing into closure, vowel length and closure duration are expected to distinguish /g/ and /k/. A long VOT and a longer closure duration should be characteristic for /k/, a long voicing into closure and a long V1 should be found in /g/.

3.2 Weighting parameters

As described in section 2, the weighting procedure assigned a value on a neutral scale to every calculated value and thus made it possible to compare different units with each other. Parameters that showed a statistically significant difference between the stops for all speakers were regarded as distinguishing the stops and weighted according to the contrast they produced on the neutral scale. This section presents the results of this procedure, first for Korean and afterwards for German.

3.2.1 Korean

The parameters that set up a three way distinction are listed in section 3.2.1.1. The parameters that distinguish two stops will be discussed in sections 3.2.1.2-3.2.1.4.

3.2.1.1 Three way distinction

There are four parameters that create a three way distinction among the stops (cf. table 3.1). All those parameters are acoustic ones. There were no articulatory parameters which showed a three way contrast. The two most important parameters are closure duration and the related percentage of complete duration of V2-V1. /k’/ has the longest closure, /g/ the shortest and the closure duration of /k^h/ is in between. Those two parameters are very significant for all the speakers. This result is supported by a high difference on the weighting scale (cf. tables 3.2-3.4). Furthermore, the length of V2 seems to play an important role. It is longest for /g/ and shortest for /k^h/.

Table 3.1: Parameters which show a three way distinction. The asterisks show the level of significance (: $p<0.05$, **: $p<0.01$, ***: $p<0.001$).*

	Level of significance		
Parameter	**Speaker HZ**	**Speaker HS**	**Speaker SH**
closure duration ($g<k^h<k'$)	***	***	***
percentage of complete duration V2-V1 ($g<k<k^h$)	***	***	***
percentage of complete duration for V2 ($k^h<k<g$)	***	**/k' / vs. /k^h/, *** /g/ vs. /k' / and /k^h/	***
duration of V2-V1 ($g<k<k^h$)	***/g/ vs. /k/ and /k^h/, **/k' / vs. /k^h/	***	***/g/ vs. /k' / and /k^h/, ** /k' / vs. /k^h/

3.2.1.2 Distinction of /g/ vs. /k’/

Tables 3.2 to 3.4 show the hierarchy of parameters for each speaker set up by the weighting procedure. It is easy to see that closure duration and the related parameters (V2-V1 and the percentages of closure duration and V2-V1) have on the whole the highest importance in distinguishing /g/ and /k’/. The percentage of voicing into closure is also very important. Furthermore, vowel durations and the related parameters play an important role in distinguishing /g/ and /k’/, for /g/ the vowels are longer than for /k’/. Also, /k’/ has a higher acceleration than

/g/. Generally, the articulatory parameters show less clear results and the acoustic parameters play a more important role.

The parameter voicing into closure does not appear in the list since absolute values of voicing into closure could often not be measured (cf. section 2.5.2). The relative durations of voicing into closure still show its importance.

Table 3.2: Parameters which distinguish /g/ and /k'/ for speaker HZ. The asterisks show the level of significance (: p<0.05, **: p<0.01, ***: p<0.001). The right column gives the contrast on the neutral scale. Euclidean distance of V2 could not be calculated (cf. 2.1 for an explanation).*

HZ	*Contrast*
percentage of complete duration for closure (g<k')***	93.93
closure duration (g<k')***	87.89
percentage of voicing into closure (g>k)***	85.85
duration of V2-V1 (g<k')***	48.84
percentage of complete duration for V2-V1 (g<k')***	39.44
percentage of complete duration for V1 (g>k')***	33.15
duration of the VCV-sequence (g<k')***	29.74
peak acceleration (g<k')***	25.96
duration of V1 (g>k')***	23.01
percentage of complete duration for V2 (g>k')***	21.77
duration of V2 (g>k')*	8.09
Euclidean distance of V2 (g>k')	not calculated

Table 3.3: as 3.2, but for speaker HS

HS	*Contrast*
closure duration (g<k')***	50.14
percentage of complete duration for closure (g<k')***	47.48
percentage of voicing into closure (g>k)***	44.36
percentage of complete duration for V2-V1 (g<k')***	38.39
duration of V2-V1 (g<k')***	37.50
percentage of complete duration for V1 (g>k')***	26.30
Euclidean distance of V2 (g>k')***	21.76
percentage of complete duration for V2 (g>k')**	21.49
duration of V1 (g>k')***	21.42
peak acceleration (g<k')**	20.24
duration of the VCV-sequence (g<k')***	16.36
duration of V2 (g>k')*	10.00

Table 3.4: as 3.2, but for speaker SH

SH	*Contrast*
percentage of voicing into closure (g>k)***	80.5808
closure duration (g<k')***	42.3974
percentage of complete duration for V2-V1 (g<k')***	38.5713
duration of V2-V1 (g<k')***	38.3319
percentage of complete duration for closure (g<k')***	34.5840
percentage of complete duration for V1 (g>k')***	29.4541
duration of V1 (g>k')***	27.3979
peak acceleration (g<k')***	25.6976
percentage of complete duration for V2 (g>k')***	22.1403
duration of V2 (g>k’)***	12.4352
Euclidean distance of V2 (g>k')**	12.4347
duration of the VCV-sequence (g<k')**	12.1177

3.2.1.3 Two way distinction /g/ vs. /k^h/

As in the distinction /g/ vs. /k’/ the closure duration and the relative duration of voicing into closure play an important role in distinguishing /g/ and /k^h/. The third important characteristic in this distinction is VOT. /g/ and /k^h/ cannot be distinguished by velocity parameters.

Table 3.5: Parameters which distinguish /g/ and /k^h/ for speaker HZ. The asterisks show the level of significance (: p<0.05, **: p<0.01, ***: p<0.001). The right column gives the contrast on the neutral scale.*

HZ	*Contrast*
percentage of voicing into closure (g>k^h)**	79.55
closure duration (g<k^h)***	60.07
duration of V2-V1 (g<k^h)***	55.34
percentage of complete duration V2-V1 (g<k^h)***	52.47
VOT (g<k^h)***	44.42
percentage of complete duration for V1 (g>k^h)***	37.32
duration of the VCV-sequence (g<k^h)***	17.89
movement amplitude of V1	not calculated
Euclidean distance of V2	not calculated

Table 3.6: as 3.5, but for speaker HS

HS	*Contrast*
percentage of complete duration V2-V1 (g<k^h)***	50.34
duration of V2-V1 (g<k^h)***	44.59

closure duration ($g<k^h$)***	40.28
VOT ($g<k^h$) ***	36.13
percentage of voicing into closure ($g>k^h$)***	34.73
percentage of complete duration for V1 ($g>k^h$) ***	30.45
Euclidean distance of V2 ($g>k^h$)***	24.65
movement amplitude of V1 ($g>k^h$)***	18.14
duration of the VCV-sequence ($g<k^h$)**	7.92

Table 3.7: as 3.5, but for speaker SH

SH	*Contrast*
percentage of voicing into closure ($g>k^h$)***	82.48
percentage of complete duration V2-V1 ($g<k^h$)***	57.31
duration of V2-V1 ($g<k^h$)***	52.14
VOT ($g<k^h$)***	51.26
percentage of complete duration for V1($g>k^h$)***	35.21
Euclidean distance of V2 ($g>k^h$)***	24.10
closure duration ($g<k^h$)***	21.94
movement amplitude of V1($g>k^h$)**	10.90
duration of the VCV-sequence ($g<k^h$)*	8.43

3.2.1.4 Two way distinction /k’/ vs. /k^h/

The most important parameter in this distinction is VOT. Closure duration is involved in the distinction as well, same as peak acceleration and V2-parameters.

Table 3.8: Parameters which distinguish /k’/ and /k^h/ for speaker HZ. The asterisks show the level of significance (: $p<0.05$, **: $p<0.01$, ***: $p<0.001$). The right column gives the contrast on the neutral scale.*

HZ	*Contrast*
VOT ($k’<k^h$)**	35.10
percentage of complete duration for closure ($k’>k^h$)***	28.27
closure duration ($k’>k^h$)***	27.82
duration of V2 ($k’>k^h$)***	18.14
peak acceleration ($k’>k^h$)***	16.13
percentage of complete duration for V2-V1 ($k’<k^h$)***	13.02
percentage of complete duration for V2 ($k’>k^h$)***	11.64
duration of V2-V1 ($k’<k^h$)**	6.51
movement amplitude of V2	not calculated

Table 3.9: as 3.8, but for speaker HS

HS	*Contrast*
VOT (k’<k^{h}) ***	28.93
peak acceleration (k’>k^{h})**	17.83
duration of V2 (k’>k^{h}) ***	14.41
percentage of complete duration for V2-V1 (k’<k^{h})***	11.96
movement amplitude of V2 (k’>k^{h})*	11.28
percentage of complete duration for V2 (k’>k^{h}) **	10.47
closure duration (k’>k^{h}) ***	9.86
percentage of complete duration for closure (k’>k^{h})**	7.75
duration of V2-V1 (k’<k^{h})***	7.08

Table 3.10: as 3.8, but for speaker SH

SH	*Contrast*
VOT (k’<k^{h})***	43.58
peak acceleration (k’>k^{h})**	23.51
closure duration (k’>k^{h}) ***	20.46
percentage of complete duration for closure (k’>k^{h}) ***	19.95
percentage of complete duration for V2-V1 (k’<k^{h})***	18.74
percentage of complete duration for V2 (k’>k^{h}) ***	18.66
duration of V2 (k’>k^{h}) ***	16.46
duration of V2-V1 (k’<k^{h})**	13.81
movement amplitude of V2 (k’>k^{h})**	13.21

To summarise, the results for Korean suggest that closure duration is the common denominator for velar stops in intervocalic position since it creates a three way contrast and has the highest difference on the scale. Thus the voicing contrast in Korean is not a simple voicing contrast but a contrast built primarily on a supralaryngeal mechanism. Furthermore, VOT sets /k^{h}/ apart from the other stops and a high percentage of voicing into closure is characteristic for /g/. Articulatorily measured parameters provide less evidence for the distinction than acoustically measured parameters. Length of closing or opening gesture, for example, is not significant at all. A reason for that could be that the articulatory parameters are highly dependent on the context. This question will be dealt with in section 3.3.

3.2.2 German

The parameters that distinguish the German velar stops are the same as the ones that distinguish the Korean velar stops: closure duration, VOT, voicing into closure and duration of vowels. The hierarchy for each speaker can be seen in tables 3.11-3.13. In contrast to Korean, the duration of the VCV-sequence is not significant in German.

Table 3.11: Parameters which distinguish /g/ and /k/ for speaker KL. The asterisks show the level of significance (: p<0.05, **: p<0.01, ***: p<0.001). The right column gives the contrast on the neutral scale.*

KL	*Contrast*
percentage of voicing into closure (g>k)***	88.17
percentage of complete duration for V2-V1 (g<k)***	71.38
duration of V2-V1 (g<k)***	66.11
percentage of complete duration for V2 (g>k)***	57.07
closure duration (g<k)***	53.10
percentage of complete duration for closure (g<k)***	51.69
percentage of complete duration for V1 (g>k)***	47.28
duration fo V2 (g>k)*	43.01
duration of V1 (g>k)***	39.05
VOT (g<k)***	36.44

Table 3.12: as 3.11, but for speaker TI

TI	*Contrast*
percentage of voicing into closure (g>k)***	72.67
percentage of complete duration for V2-V1 (g<k)***	42.02
percentage of complete duration for closure (g<k)***	39.49
duration of V2-V1 (g<k)***	36.55
closure duration (g<k)***	29.88
percentage of complete duration for V1 (g>k)***	25.76
percentage of complete duration for V2 (g>k)***	25.42
duration of V1 (g>k)***	24.17
VOT (g<k)**	24.00
duration fo V2 (g>k)**	20.46

Table 3.13: as 3.11, but for speaker TO

TO	*Contrast*
percentage of voicing into closure(g>k)***	61.50
duration of V2-V1 (g<k)***	42.82
VOT (g<k)***	40.34
percentage of complete duration for V2-V1 (g<k)***	35.82
closure duration (g<k)***	35.40
percentage of complete duration for V1 (g>k)***	34.74
percentage of complete duration for closure (g<k)***	30.95
duration of V1 (g>k)***	30.62
percentage of complete duration for V2 (g>k)***	19.95
duration for V2 (g>k)**	13.59

Voicing seems to be the common denominator in the voicing contrast of stops in intervocalic position in German. It has the highest contrast on the neutral scale for all the speakers. Here Korean and German differ. Furthermore, as in Korean, closure duration and of course V2-V1, which correlates with closure duration, are also very important. Except for speaker TO VOT is relatively unimportant.

3.3 Deeper analysis of parameters

So far the stops have been treated independently of the context in which they occurred. By doing this candidates for a common denominator, closure duration for Korean and voicing into closure (represented by the percentage of voicing into closure) for German could be found. Furthermore, other important parameters like VOT and vowel duration could be found. However, as suggested earlier, not every parameter needs to be distinctive in every context. Consequently, it is necessary to look at each vowel context separately. This will be done in this section. All the parameters except for the absolute voicing into closure will be dealt with. This one parameter is taken out because, since the burst was very often missing, good results cannot be expected. The section is subdivided into two parts. The first one is dedicated to the articulatory parameters, the second one to the acoustic ones.

3.3.1 Articulatory parameters for Korean

Since there were no articulatory data for German this section will discuss Korean data only.

3.3.1.1 Movement during closure

As has been noted previously for other languages (e.g. Houde 1968, Mooshammer 1992, Mooshammer et al. 1995, Perrier 2003) the tongue is sliding along the palate during closure when a velar stop is produced. There are two possible directions, i.e. forward movement, which means movement towards the lips and backward movement, which is movement towards the pharynx. The direction of the movement during closure is dependent on the vowel context.

For Korean it could be found that not all the stops behave alike in the same vowel context. Sometimes the tongue is moving forwards in one stop and backwards in another one although the vowel context is the same. There is forward movement during /a_a/, /a_i/, /agu/, /ak'u/, /uga/, /uk^{h}a/, /u_i/, /u_u/, and backward movement during /ak^{h}u/, /i_a/, /i_i/, /i_u/ and /uk'a/. The general tendency seems to be that the direction of the movement is dependent on the first vowel: There is normally forward movement after /a/ and /u/ and backward movement after /i/.

The direction of the movement has important consequences on the Euclidean distance and the movement amplitude of the closure in that it prolongs them for forward movement (cf. table 3.14 and 3.15). This difference, however, is only significant for /k'/ and in some cases /k^h/. In order to catch the differences between forward and backward movement the data were in this case not grouped according to vowel context but according to direction of movement during closure for the analysis of variance. Vowel context was treated as second factor in order to compensate for its influences. For speaker HZ movement amplitude during closure could not be determined (for an explanation see section 2.1).

Table 3.14: Analysis of variance for movement amplitude of movement during closure, forward movement vs. backward movement

Speaker	*Consonant*	*Standard error*	*Significance*
HS	g	.485	.666
	k'	.420	.000
	k^h	.427	.037
SH	g	1.202	.605
	k'	.438	.000
	k^h	.580	.053

Table 3.15: Analysis of variance for Euclidean distance of movement during closure

Speaker	*Consonant*	*Standard error*	*Significance*
HS	g	.481	.981
	k’	.431	.006
	k^h	.399	.455
SH	g	1.174	.456
	k’	.400	.000
	k^h	.469	.096

3.3.1.2 Tongue position at oral closure

One of the suppositions in section 3.1 was that the contact with the palate is more fronted for sequences with V1=/i/ than for sequences with V1=/a/ or /u/. In order to find out about this the x-value of the position of the tongue at the turning point at the palate was determined and the positions of sequences with V1=/i/ were compared with the positions of other sequences.

It turned out that for all speakers the x-value was significantly lower if V1 was /i/ than if V1 was /u/ or /a/ (cf. figure A10, table A2). For speaker HS, for example, the x-values for V1=/a/ were between 3.68 and 3.82 cm, the ones for V1=/u/ were between 3.86 and 3.94 cm, for V1=/i/, however, they were between 3.48 and 3.82 cm. This means that the closure of sequences with V1=/i/ is more fronted than the closure of sequences with a different first vowel. All the differences were significant, and except for two cases they were even highly significant. This result is consistent with Mooshammer et al. (1995) and Geng (2003).

3.3.1.3 Closing gesture duration

As discussed in section 3.1 a sequence with a low first vowel should have a longer closing gesture than one with a high first vowel since the Euclidean distance from a low position up to the palate is longer than the Euclidean distance from an /i/-position to the same point and Euclidean distance and movement duration correlate. For the Korean data it turned out that although the closing gesture of a sequence with V1=/a/ is longer than one with V1=/i/, it is not longer than the gesture of a sequence with V1=/u/. Since /u/ is a high vowel the duration should be shorter than for V1=/a/ and about the same as V1=/i/. However, the values of /u/ are more similar to the ones of V1=/a/ than for V1=/i/ and for SH they even exceed V1=/a/. The average durations of the closing gestures for all speakers can be seen in the table 3.16.

On the whole the tongue closing gesture is shorter if V1=/i/ than if V1 is one of the other vowels. The analysis of variance (cf. table A3) shows that the distinction between V1=/i/ and V1=/a/ is significant for C=/g/ ($p<.001$, except for HS where $p=.005$) or C=/k^h/ ($p<.001$), except for C=/k^h/ of speaker HS (p=.095). An exception to this general pattern is /k^h/ of HS where the closing gesture of V1=/u/ (113 ms) is shorter than the one of V1=/i/ (122.27 ms). For HS and HZ it is longest if V1=/a/ (136.33 ms and 106.82 ms, respectively) . For SH it is longest for V1=/u/.

An explanation for that could be that the Korean /u/ is produced very much in the back so that the Euclidean distance and consequently the duration of the closing gesture increase. This seems to be true. There is in fact a tendency for the Euclidean distance of the closing gesture to be longer if the first vowel is /u/ than if it is /i/. The difference is even greater if one looks at movement amplitude (cf. tables A4 and A5).

Another observation that could be made is that the closing gesture is longer for /g/ than for the other stops except if V1=/i/. This has certainly to be seen in connection to the long V1 preceding /g/.

Table 3.16: Durations of the closing gesture in ms

Speaker	*V1*	*Consonant*	*Mean duration (ms)*	*Standard deviation*	*N*
HS	a	g	143.12	39	25
		k’	129.05	14	30
		k^h	138.02	20	29
			136.33	**26**	**84**
	i	g	110.33	40	30
		k’	125.45	26	30
		k^h	122.27	35	30
			119.35	**34**	**90**
	u	g	150.33	22	30
		k’	138.13	27	30
		k^h	113.00	25	30
			133.82	**29**	**90**
HZ	a	g	119.87	18	30
		k’	89.33	29	30
		k^h	111.27	12	30
			106.82	**24**	**90**
	i	g	74.95	18	30
		k’	75.68	16	25
		k^h	79.77	21	30
			76.86	**18**	**85**
	u	g	101.53	23	30
		k’	79.53	19	30
		k^h	90.83	22	29
			90.63	**23**	**89**

SH	a	g	106.87	14	30
		k’	83.47	15	30
		k^h	102.57	11	30
			97.63	**17**	**90**
	i	g	70.93	14	30
		k’	82.53	26	30
		k^h	69.07	19	30
			74.18	**21**	**90**
	u	g	116.40	35	30
		k’	115.87	45	30
		k^h	106.88	36	30
			113.05	**39**	**90**

3.3.1.4 Opening gesture duration

The durations of the opening gesture are on the whole longer than the ones for the closing gesture. An explanation could be that the beginning of the opening gesture, the turning point, is often the point where the closure begins (but see restrictions described in section 2.4.2), so that the closure is counted as part of the opening gesture. Especially for /k’/, which has an extremely long closure, this might be misleading. The alternative to take the burst as the beginning of the opening gesture was rejected because, as described in the previous chapter, there was often no burst in the productions of /g/. Furthermore, one could not have measured the duration of the opening gesture for speaker HZ because there would have been problems with the synchronization of the acoustically measured value burst and the articulatorily measured value middle of V2.

Table 3.17: Durations of the opening gesture in ms

Speaker	*V2*	*Consonant*	*Mean duration (ms)*	*Standard deviation*	*N*
HS	a	g	143.84	32.336	25
		k’	174.47	24.583	30
		k^h	151.03	36.188	29
			157.26	**33.617**	**84**
	i	g	123.43	34.384	35
		k’	165.04	41.921	25
		k^h	181.27	23.986	30
			154.27	**42.016**	**90**
	u	g	107.12	23.044	25
		k’	166.80	39.138	35
		k^h	185.33	40.810	30
			156.40	**47.728**	**90**

HZ	a	g	169.53	31.125	30
		k’	219.36	31.127	25
		k^h	210.73	45.192	30
			198.73	**42.414**	**85**
	i	g	157.20	40.461	30
		k’	195.93	30.520	30
		k^h	176.53	19.312	30
			176.56	**34.804**	**90**
	u	g	173.07	60.462	30
		k’	205.53	55.043	30
		k^h	198.21	50.462	29
			192.20	**56.663**	**89**
SH	a	g	123.80	23.950	30
		k’	181.07	34.996	30
		k^h	164.53	46.565	30
			156.47	**43.337**	**90**
	i	g	86.00	26.177	30
		k’	119.67	36.979	30
		k^h	134.07	18.274	30
			113.24	**34.466**	**90**
	u	g	122.93	26.407	30
		k’	149.53	34.783	30
		k^h	168.00	30.062	30
			146.82	**35.524**	**90**

In general, the results for the opening gesture meet the expectations formulated in 3.1 even less than the ones for the closing gesture (cf. table 3.17). The opening gesture is shorter for V2=/i/ than for V2=/a/ but not shorter than for V2=/u/. Moreover, the statistical analysis (cf. table A6) shows that the distinction between V2=/a/ and V2=/i/ is only significant for C=/kʼ/ for speakers HS and SH (p=.001) and C=/k^h/ for speakers HS (p=.026) and HZ (p=.010).

As for the closing gesture, the duration of the opening gesture of sequences with V2=/u/ is longer than for V2=/i/. This can again be explained with a more retracted position of /u/ so that the Euclidean distance is longer for the opening gesture of sequences with V2=/u/ than for sequences with V2=/i/.

A further observation is that the opening gesture is shorter for /g/ than for the other two stops although, as seen in section 3.2, the vowels surrounding the stops tend to be longer for /g/ than for the other stops and the opening gesture should consequently be longer for /g/. This contradiction can again be explained with the turning point, which was often at the beginning of the closure. So the closure duration, which is longer for /k'/ and /k^h/ than for /g/ is included in the opening gesture and prolongs it.

3.3.1.5 Velocity parameters

In section 3.1 it was stated that the trajectories of the three stops differ in smoothness. Furthermore, it was said that /k'/ is probably produced with a greater impact at the palate than /g/. The reasons for that could lie in differences in velocity. A smooth trajectory can only be produced if the tongue reduces velocity (or does not even reach high velocities) before it collides with the palate. A greater impact, on the other hand, can only be produced if the velocity is rather high. Thus, to specify the expectations towards acceleration, velocity and deceleration peak one can say:

- /k'/ is most forced and therefore expected to have the highest velocity peaks, acceleration peaks and deceleration peaks.
- /g/ has a smooth trajectory and will therefore have the lowest velocity peaks, acceleration peaks and deceleration peaks.
- The position of the velocity peak on the trajectory should be closer in time to closure onset for /k'/ than for /g/ since the tongue has to use the whole trajectory from the middle of the first vowel up to the palate in order to develop the high velocity needed.
- The deceleration peak of /k'/ should be later in comparison to closure onset than for /g/ since if the tongue produces a great impact it should move against the palate and therefore not decelerate before closure onset. For /g/ the tongue should decelerate much earlier so that the impact is not as strong.

3.3.1.5.1 Peak velocity and peak deceleration

Looking at the averages of peak velocity (cf. figure A11) the statements above do not seem to be true. Peak velocity seems to be quite inconsistent. The expectations can only be fulfilled in the /a_i/-context where peak velocity for /g/ is 19, 17 and 19 cm/s, for /k'/ 23, 20 and 24 cm/s and for /k^h/ 20, 20 and 21 cm/s for HS, HZ and SH respectively. A similar pattern emerges for the deceleration peaks (cf. figure A12, table A8).

3.3.1.5.2 Peak acceleration

Peak acceleration, on the other hand, shows the expected pattern at least in part. The acceleration is higher for /k'/ than for /g/ and /k^h/ if the tongue is moving forwards. In /ak'u/, where the tongue is moving backwards during closure, speaker SH does not show the expected pattern (756 mm/s^2 for /g/, 698 for /k'/ and 634 for /k^h/). Furthermore, /k^h/ has a tendency to have a higher acceleration peak than /g/. The differences are significant for HZ and SH, but not for HS who does not make a significant difference between /k'/ and /kʰ/ although she makes a difference between /g/ and /k'/ as long as /k'/ is moving forwards (cf. table A9).

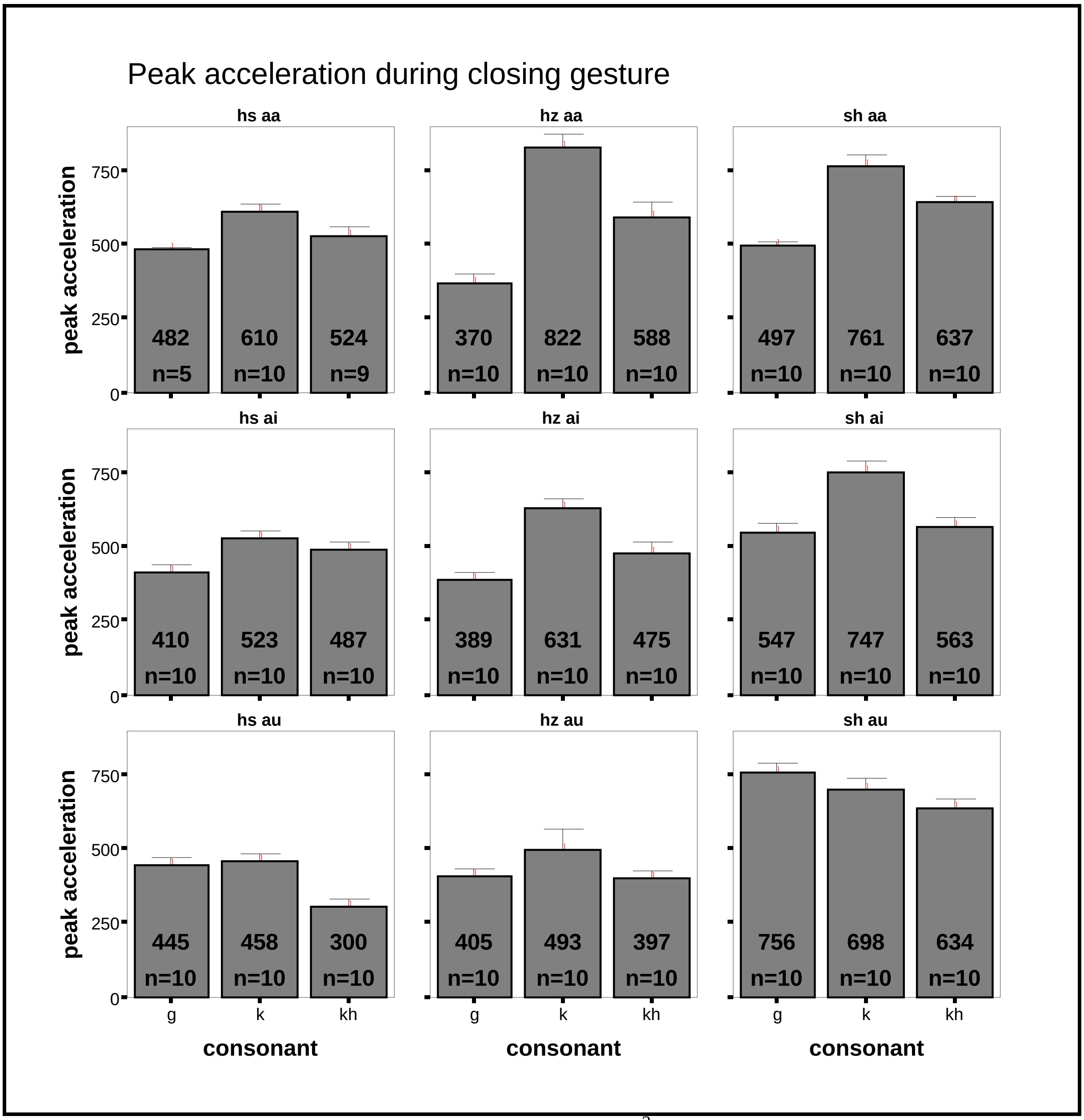


Figure 3.1: Bar plots with peak acceleration in mm/s² for speakers HS (first column), HZ (second column) and SH (third column). Error bars show the standard error.

3.3.1.5.3 Point in time of the velocity peak

In order to produce a lot of force the velocity peak should be close in time to closure onset, so that the difference in time between velocity peak and closure onset is greater for /g/ than for /k'/ or /kʰ/, since they are produced with more force.

This turned out to be true. The velocity peak of /k'/ was significantly nearer to closure onset than for /g/. The average distances between velocity peak and closure onset for /g/ were between 14 and 18 ms for speaker HS and 15 and 23 ms for speaker SH. For /k'/ the numbers are 3-6 ms for HS and 4-9 for SH, for /k^h/ the distance is 10-16 ms for HS and 1-7 ms for SH. Except for the /a_u/ context of HS the velocity peak of /k^h/ was also nearer to the closure onset than the one of /g/. The exception can be explained by the backward movement of /k^h/ in this context which probably reduces the velocity. The difference between /k'/ and /k^h/ is on the whole not significant (cf. figure A13, table A10). The calculation could not be carried out for speaker HZ.

3.3.1.5.4 Point in time of the deceleration peak

The deceleration peak is in the majority of cases situated after closure onset. This can be seen in the negative difference between closure onset and deceleration peak. For /k'/ (-13 to -17 ms) and /k^h/ (-12 to -20 ms) it is later than for /g/ (-5 to -11 ms). This difference is significant, except for the distinctions /aga/ vs. /ak^{h}a/ and /agi/ vs. /ak'i/ and /ak^{h}i/ of speaker HS. (cf. figure A14, table A11). Again only results for speakers SH and HS could be calculated.

3.3.1.6 Summary of the articulatory parameters for Korean

There is movement during closure in all Korean velar stops. The direction of the movement depends on the vowel context. As a general rule one can say that there is forward movement during closure if the vowel preceding the stop is a back vowel and backward movement if the vowel preceding the stop is a front vowel. There are a number of exceptions to this rule. Furthermore, it was found that the closure (turning point at the palate, cf. section 2.4.2) is more fronted and the closing gesture is shorter if the first vowel is /i/. /k'/ is characterised by a high acceleration peak and late velocity and deceleration peaks.

3.3.2 Acoustic parameters

3.3.2.1 Korean

In this section the acoustic parameters discussed in section 3.1 will be looked at in greater detail. Closure duration, VOT, voicing into closure and vowel duration were found as the most important parameters in the distinction of the stops. However, it is likely that they do not have the same importance in every vowel context.

3.3.2.1.1 Closure duration

The closure is the most important part for the identification of the stop. In word internal position it is possible to distinguish the stops simply by closure duration: /g/ is shorter than in /k'/ and /k^h/, and /k'/ is longer than /k^h/. Since HZ and SH often did not produce a burst for /g/, it was hard to measure closure duration as burst-V1F2offset. Therefore, in addition V2F2onset-V1F2offset (V2-V1) was measured, which for the aspirated stops included aspiration and is therefore not entirely comparable to closure duration, but made it possible to say something about the closure of /g/.

3.3.2.1.1.1 Closure duration (burst-V1F2offset)

Looking at the analysis of variance (figure 3.2, tables A12-A13), the following things are remarkable:

- A number of values, normally the ones involving /g/, could not be calculated. This is because there was either no burst that could be measured or no closure onset or neither the one nor the other. As can be seen this occurs only in contexts with at least one high vowel.
- The hierarchy /g/</k^h/</k’/ is not always significant. For HS the difference is not significant for /ik’a/ vs. /ik^{h}a/, for /ik’i/ vs. /ik^{h}i/, /ik’u/ vs. /ik^{h}u/, /uk’a/ vs. /uk^{h}a/ and /uk’i/ vs. /uk^{h}i/. For HZ the difference is not significant for /ik’a/ vs. /ik^{h}a/. For SH it is not significant for /ik’a/ vs. /ik^{h}a/, /igi/ vs. /ik^{h}i/, /ugi/ vs. /uk^{h}i/ and all the distinctions in the /u_u/-context.
- In one case, /i_a/ for speaker SH, the closure duration of /k^h/ is even longer than the one of /k’/.

To generalize, in high vowel contexts the distinction between /k’/ and /k^h/ is not very robust. The results for closure duration as percentage of the duration of the VCV-sequence support this (cf. figure A15, tables A14 and A15).

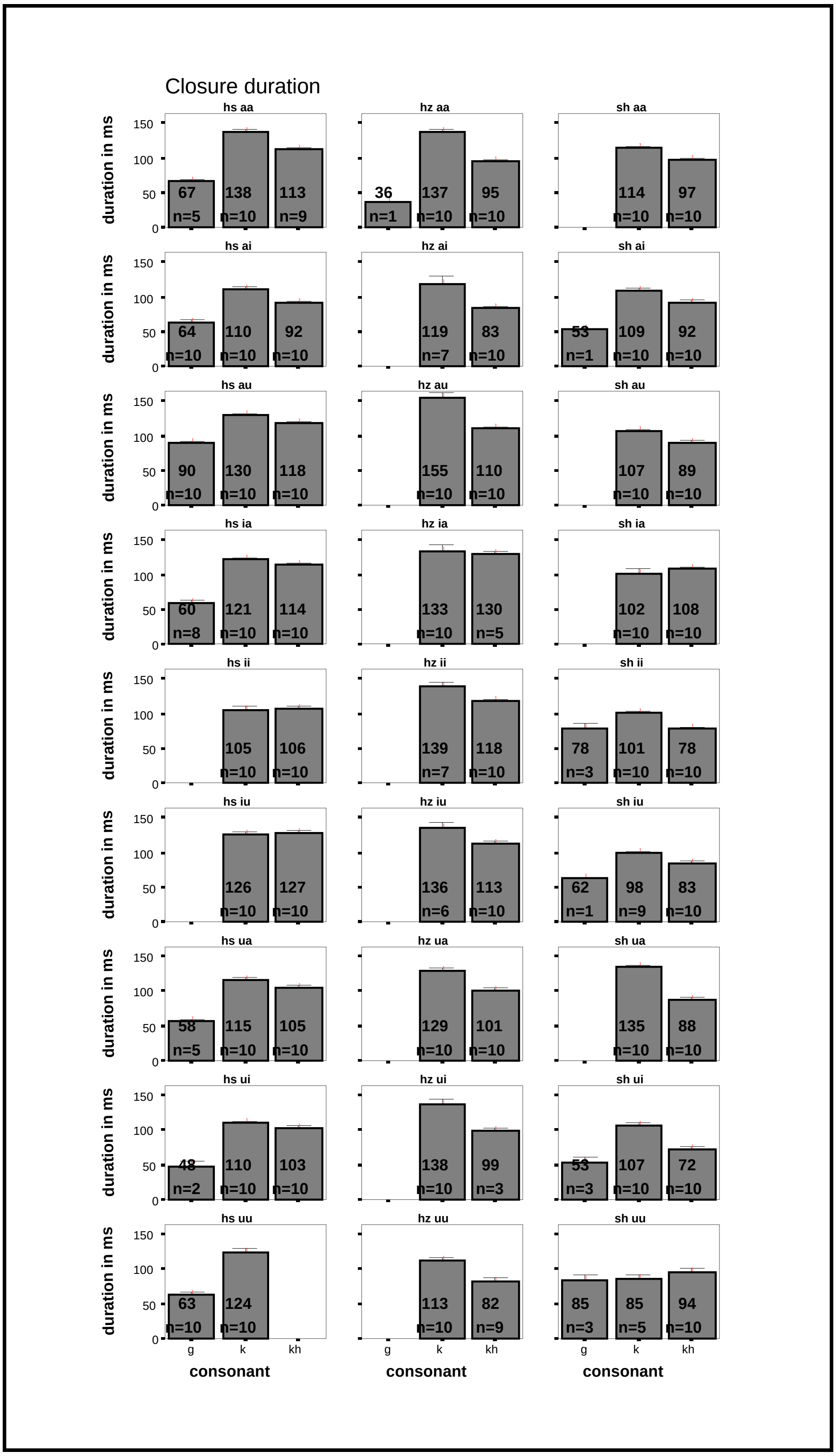


Figure 3.2.: Bar plots of average closure durations for HS (first column), HZ (second column) and SH (third column) in different vowel contexts. Error bars show standard error. The gaps for /g/ are due to the missing bursts. There is no result for $/uk^hu/$ of speaker HS because the speaker did not produce the sequence correctly (cf. section 2.4.1).

3.3.2.1.1.2 V2-V1

V2-V1 is significant for all distinctions between /g/ and /k'/, except for one case, /i_i/ for HS, where significance cannot be determined because there is only one measurement for /igi/. In all the other measurements for /g/ in this context it was not possible to determine an offset of V1 or an onset of V2 because there was only a reduction in intensity but no end of the second formant (cf. figure 3.3).

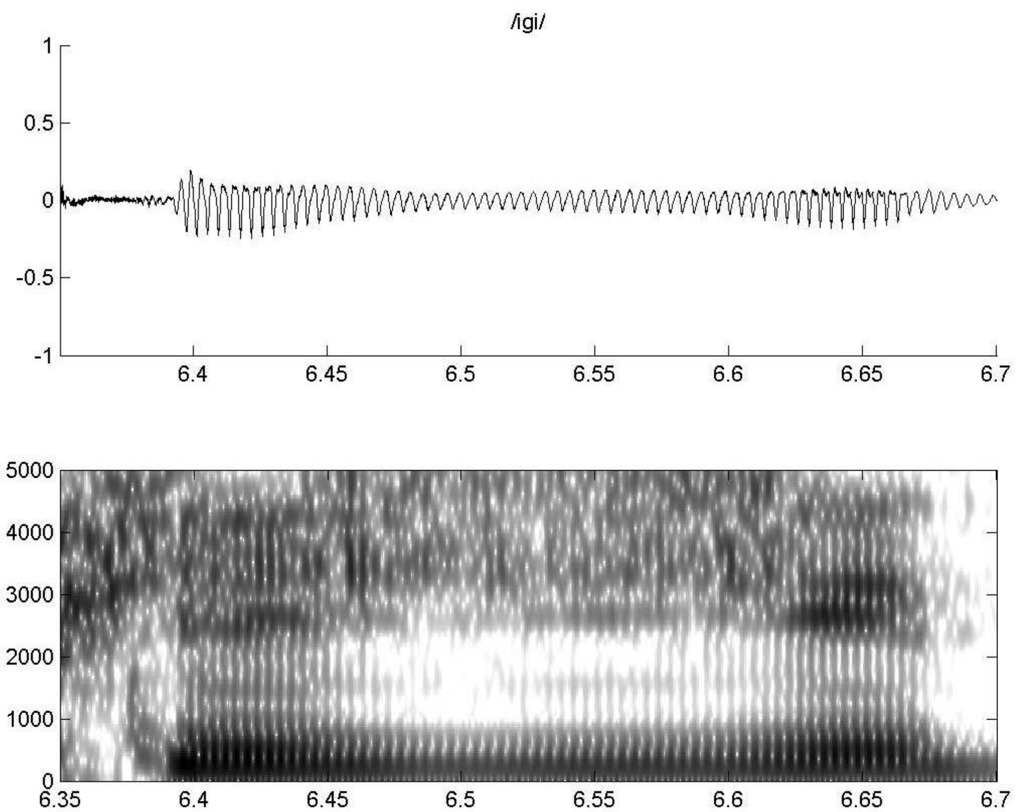


Figure 3.3: Oscillogram and spectrogram of the fifth repetition of /igi/ of speaker HS

The results of the statistical analysis (cf. figure A16, table A16) for the parameter V2-V1 show that /g/ (between 59 and 124 ms) can be distinguished from /k'/ (125 -182 ms) in all vowel contexts. Although the distinction /g/ vs. /k^h/ is also significant in all vowel contexts, this cannot show how far closure duration separates /g/ and /k^h/ because /k^h/ has a long VOT which is included in V2-V1.

Summarising the results from closure duration and V2-V1 one can say that /g/ can normally be kept apart from the other two stops very easily, whereas the distinction between /k'/ and /k^h/ is sometimes not possible in high vowel contexts.

3.3.2.1.2 VOT

VOT was defined as the time from the burst to the F2 onset of V2. Here one is again faced with the problem that VOT cannot be calculated if there is no burst. This was the case in /agi/, /agu/, /iga/, /igi/, /igu/, /uga/, /ugi/, /ugu/ for speaker HZ, /igi/, /igu/ for speaker HS and /aga/, /agu/, /iga/, /uga/ for SH. Furthermore, there are two cases with only one measurement out of the ten possible measurements which was also not taken into consideration in the analysis of variance: /agi/ and /igu/ for speaker SH.

The analysis of variance (cf. figure A17 and tables A17-A18) shows that VOT is always significant in distinguishing /k'/ (16-61 ms) and /k^h/ (36-120 ms), except for two cases, i.e. the /i_i/-context of speaker HS and the /u_u/ context of speaker SH. In cases where VOT could be measured for /g/ the contrast between /g/ (14-36 ms) and /k^h/ was also significant.

3.3.2.1.3 Percentage of voicing into closure

As expected, /g/ has a higher percentage of voicing (22-100%) as compared to /k'/ (9-67%) and /k^h/ (13-28%). The only exception is /ugu/ by speaker HS (cf. figure 3.4) where the voicing into closure of /g/ is about equally long as the one of /k'/. The analysis of variance confirms this (cf. table A19-A20). An explanation for /k'/ often having a lower percentage as compared to /k^h/ could be that even if the absolute values are the same they will be lower if the closure is long. Since /k'/ has a longer closure the percentages of voicing into closure can be expected to be lower.

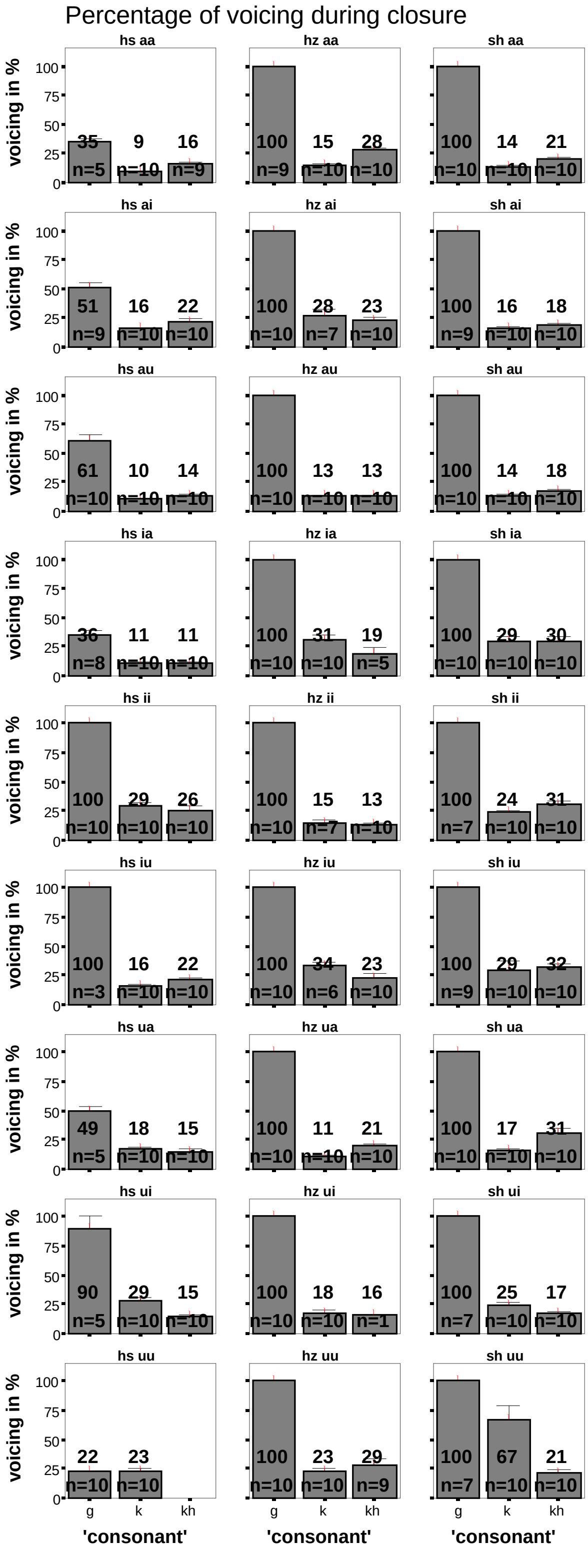


Figure 3.4: Average percentage of voicing into closure for HS (first column), HZ (second column) and SH (third column) in different vowel contexts. Error bars show standard error.

3.3.2.1.4 Duration of V1

In general, V1 is longer if it precedes /g/ (35-123 ms) than if it precedes one of the other stops (26-73 ms for /k’/, 20-74 ms for /k^{h}/). This difference is significant in all contexts except for the distinction /aga/ vs. /ak^{h}a/, /uga/ vs. /uk’a/ for speaker HS, /aga/ vs. /ak’a/, /agi/ vs. /ak’i/, /uga/ vs. /uk^{h}a/ for speaker HZ and /agi/ vs. /ak’i/, /ugu/ vs. /uk’u/ for speaker SH (cf. figure A18, tables A21-A22).

Because the duration of V1 could again depend on the duration of the other segments, the percentage of the duration of V1 in relation to the duration of the complete movement was calculated (cf. figure A19, tables A23-A24). Here the result is even clearer: There are only three cases in which a vowel preceding /g/ is not longer than a vowel preceding another stop (/agi/ vs. ak’i/ for speakers SH and HS and /aga/ vs. /ak^{h}a/ for speaker HS). The percentages lie between 18 and 42% for C=/g/, 10 and 23% for C=/k’/ and 6 and 24% for C=/k^{h}/.

3.3.2.1.5 Duration of V2

In the parameter hierarchy the duration of V2 was discussed as distinguishing between the three stops (/g/>/k’/>/k^{h}/). Looking at the different vowel contexts, however, one can see that the durations vary too much to say something about the distinction between /k’/ and /k^{h}/ (cf. figure A20, tables A25-A26). However, one can still remark a tendency of V2 to be longer following /g/ (53-145 ms) than following /k’/ (40-139 ms) or /k^{h}/ (35-125 ms). The distinction between /g/ and the other stops is still not significant in a number of contexts: /ugi/ vs. /uk’i/ and /uk^{h}i/, /ugu/ vs. /uk^{h}u/ (speaker HS), /iga/ vs. /ik’a/ and /ik^{h}a/, /igu/ vs. /ik’u/ and /ik^{h}u/, /uga/ vs. /uk’a/, /ugi/ vs. /uk’i/ and /uk^{h}i/, /ugu/ vs. /uk’u/ (speaker HZ), /igi/ vs. /ik’i/, /ugi/ vs. /uk’i/ and /ugu/ vs. /uk’u/ (speaker SH).

Looking at the percentages again gives a clearer picture (cf. figure A21). Except for the contexts /a_a/, /u_a/, /u_u/ for speaker HS and /u_i/ for speakers HS and HZ /g/ (where V2 is between 27 and 49% of the complete movement) is longer than /k’/ (18-41%) and /k’/ is longer than /k^{h}/ (15-38%). However, the differences are very small and not always significant (cf. tables A27-A28).

3.3.2.1.6 Duration of the VCV-sequence

In the weighting procedure it was found that sequences with C=/g/ are shorter than sequences with other stops. Again, looking at the vowel contexts this has to be specified. For the relationship /g/ vs. /k’/ one can say that sequences with /k’/ are longer if the tongue is moving forwards (231-338 ms for C=/k’/ vs. 214-314 ms for C=/g/). If the tongue is moving backwards as in all contexts with V1=/i/ and /uk’a/ the duration of the sequence is shortened. There is one exception,

/ak'u/. With regard to the distinction of /g/ vs. /k^{h}/ the difference seems to be too small to say something about it (cf. figure A22, table A29).

3.3.2.1.7 Summary of the acoustic parameters for Korean

To summarise, one can say that all the stops in nearly all the vowel contexts are distinguished by closure duration. Furthermore, VOT is an important characteristic of /k^{h}/ and a high percentage of voicing into closure one of /g/. The first vowel is longer for /g/ than for the other stops. Closure duration, VOT and the vowel durations seem to be less distinctive in backward movement and high vowel contexts. Voicing, on the other hand is distinctive even in those contexts.

3.3.2.2 German

Because the data are structured differently, the analysis of the German data will be different in comparison to the one of the Korean data. At first /g/ and /k/ will be compared in sequences with different V1 but the same V2 (first subcorpus, cf. section 2.2.2). Afterwards the influence of the vowel context will be discussed. Therefore, /g/ in different environments will be looked at (second subcorpus).

The parameter duration of the VCV-sequence will not be looked at in this section since it did not produce a significant result in the parameter catalogue.

3.3.2.2.1 Closure duration and V2-V1

In sequences with V2=/❶/ and different V1 the closure duration of /g/ is always shorter than the one of /k/ (cf. figure A23). The averages for /g/ lie between 47 and 77 ms, whereas for /k/ they are between 81 and 93 ms. Those differences are significant except for the sequence /i_❶/ for speaker TI (cf. table A30). Looking at the influence of the vowel context, closure duration is shortest for V2=/a/ and longest for V2=/u/ (cf. figure A24). However, this difference is hardly ever significant (cf. table A31).

V2-V1 was calculated for the Korean speakers in order to avoid the problem of missing bursts in /g/ and be able to compare /g/ and /k'/. For German measuring the burst was not as problematic as for Korean so that the parameter V2-V1 does not have to be considered in order to say something about the German voicing distinction. Furthermore, as stated earlier, it does not make sense to include aspirated stops like the German /k/ in the comparison because of the VOT which prolongs V2-V1. So the only reason for calculating V2-V1 is to be able to compare the two languages. As expected, /k/ has a longer V2-V1 duration than /g/. The averages are between 63 and 113 ms for /g/ and 120 and 140 for /k/. The difference is significant in all the vowel contexts (cf. figure A25, table A32).

V2-V1 is shortest if V2=/a/ and longest if V2=/u/. This, however, is hardly ever significant. If it is significant, V1 is /a/ or /u/ (cf. figure A26, table A33).

3.3.2.2.2 VOT

/k/ has a longer VOT than /g/ in all the vowel contexts (cf. figure A27). The difference is not significant for one speaker (cf. table A34) but this is clearly a speaker dependent characteristic. The averages are between 15-42 ms for /g/ and 33-57 ms for /k/. The differences caused by vowel context are not significant (cf. figure A28).

3.3.2.2.3 Voicing into closure

/g/ has a longer voicing into closure than /k/ in all vowel contexts (43-73 ms for /g/, 30-38 ms for /k/), but this difference is not significant for speakers KL and TO if V1=/a/ (cf. figure A29, table A35). Again the result is clearer if one looks at percentages of voicing into closure. Here the difference is always significant (cf. figure A30, table A36). The averages lie between 82 and 100 ms for /g/ and 31 and 45 ms for /k/.

There is a tendency for voicing into closure to be longer for V2= /i/ than for V2=/a/ (cf. figure A31). This, however, is only significant when V1=/a/ for TI and TO and for V1=/u/ for speaker TO (cf. table A37). This can also be seen in the results for the percentage of voicing into closure (cf. figure A32). If the voicing of sequences with V1=/a/ is not 100%, it is lower than the voicing into closure for V1=/i/.

3.3.2.2.4 Duration of V1

V1 is longer if it precedes /g/ than if it precedes /k/ (45-86 ms for /g/, 30-65 ms for /k/). This difference is significant in all the contexts (cf. figure A33, table A38). The result is confirmed by the calculations for percentages of the complete duration (cf. figure A34, table A39). The differences caused by vowel context were not significant.

3.3.2.2.5 Duration of V2

The duration for /g/ (65-132 ms) is longer than for /k/ (60-119 ms), however, this distinction is not significant for TI when V1=/i/ and for TO when V1=/a/ or /u/ (cf. figure A35, table A40). The percentages support this, V2 is longer for /g/ (26-45%) than for /k/ (24-39%). In three cases this is not significant: if V1=/a/ for TI and TO or /i/ for TI. The differences caused by vowel context were not significant (cf. figure A36, tables A41-A42).

3.3.2.2.6 Summary of the acoustic parameters for German

/k/ has a longer closure duration than /g/. Furthermore, the two stops can be distinguished by VOT, percentage of voicing into closure and length of V1.

3.4 Summary of the results

In the first part of this chapter the suppositions won from the ensemble averages were presented. What is most important here is that the tongue is moving during closure, either forwards or backwards. Furthermore, /k'/ seems to be produced with a lot of force and consequently has a trajectory with lots of edges. /g/ on the other hand, has a smooth trajectory. Whereas in low vowel contexts the trajectories of the different stops can be distinguished easily they look very much alike in high vowel contexts.

Section 3.2 presented the results of the weighting procedure. Closure duration was found as a candidate for the common denominator in Korean and percentage of voicing into closure for German. Further important parameters are VOT and vowel length.

Section 3.3 dealt with the results of the statistical analyses of the data split according to vowel context. The main results are that articulatory parameters do not show as clear results as acoustic ones. Peak acceleration turned out to set /k'/ apart from the other stops. Closure duration was found not to be distinctive in some vowel contexts in Korean and voicing into closure was not distinctive in one case in German. Consequently, they cannot be seen as common denominators.

4 DISCUSSION

Up to now a set of parameters which create the voicing distinction in velar stops in intervocalic position has been set up, the parameters have been weighted and the influence of the vowel context has been investigated. This has been done separately for each language. Now the results for German and Korean will be compared (section 4.1). Furthermore, the suppositions set up in chapter 2 will be checked (section 4.2.). Sections 4.3 - 4.6 will answer the questions developed in the introduction. Section 4.7 summarises the main results of the study.

4.1 Comparison of German and Korean velar stops

4.1.1 Comparison based on the weighting procedure

Korean /g/ is often no real stop because it is frequently produced without closure. However, it does not sound like a fricative but like a stop. This means that the constriction is probably rather wide so that friction cannot develop. If there is a closure, it is very short, shorter than for the other two consonants. Consequently, the percentage of closure is also very low. The second important characteristic of /g/ is its high percentage of voicing during closure. Often the consonant is fully voiced. In the remaining cases, the VOT is shorter than the ones for the other two consonants. The vowels surrounding it are longer than the vowels surrounding the other stops.

German /g/ is similar in having a short closure, a high percentage of voicing into closure, a short VOT and long vowels surrounding it. However, the importance of the parameters differs. Whereas the high percentage of voicing into closure is the most important characteristic for German /g/ in intervocalic position, closure duration is ranked higher than voicing into closure for Korean.

Korean /k^h/ is an aspirated stop, and this is also its most important characteristic. Its VOT is the longest of all the consonants. Its second important characteristic is the short duration for both vowels, the duration of V1 sets it apart from /g/, the one of V2 from /k'/. Its closure duration is shorter than the one of /k'/ but longer than for /g/.

The most important characteristic of Korean /k'/ is its long closure. The vowels surrounding /k'/ are shorter than the ones surrounding /g/, even if they are longer than for /k^h/. The VOT of /k'/ is considerably shorter than the one for /k^h/, but longer than for /g/. The duration of voicing into closure of /k'/ is considerably shorter than the one of /g/.

German /k/ has more similarities with Korean /k^h/ than with Korean /k'/ in that it has a long VOT. Furthermore, its closure duration is longer than the one of German /g/, and only a little shorter than the one of Korean /k^h/ (around 100 ms for Korean /k^h/ and 86 ms for German /k/). The closure duration of Korean

/k'/ (around 120 ms) on the other hand, is much longer than the one of German /k/. Even if German /k/ and Korean /k^h/ are similar, there are differences in the ranking of the parameters. In the distinction of German /g/ vs. /k/ VOT is ranked very low for two speakers and higher, but not very high for one speaker. In the Korean distinction /g/ vs. /k'/ VOT is ranked in the middle, in the distinction /k'/ vs. /k^h/ it is ranked highest for all the speakers.

Two conclusions can be drawn from that. Firstly, in both languages the "voicing contrast" is a contrast not only built on voicing but on a conglomer ate of parameters of which voicing is one. Secondly, although voicing is most important in the distinction of German /g/ and /k/, this is not true for Korean, where the contrast is built primarily on closure duration.

4.1.2 Comparison of German and Korean articulatory characteristics

This section is based on the results of the articulatory measurements for Korean of this study and the results of articulatory measurements for German by Mooshammer (1992) and Mooshammer et al. (1995).

4.1.2.1 The trajectories as a whole

This section will compare the trajectories of ensemble averages for German (cf. figures A37 and A38) and Korean (cf. figures A1-A9). Comparing the trajectories of /g/ in both languages one can say that German /g/ is more like a real stop whereas Korean /g/ looks like a flap. German /g/ has a true looping pattern with a long sliding movement along the palate whereas in Korean /g/ the tongue only touches the palate very shortly without much movement (compare e.g. the movements for /aga/, figure A1 for Korean and the corresponding figure A37 (first line) for German). The trajectory of German /g/ has more similarities with Korean /k'/ or /k^h/ than with Korean /g/, for example the trajectory of German /uga/ is similar to Korean /uk^ha/, in that it has a long sliding movement whereas Korean /g/ has none. The same is true for German /ugu/ which looks similar to Korean /uk^hu/ or even /uk'u/, but not to /ugu/ which has a much shorter closure. For /agu/ one can say that German /g/ is similar to Korean /g/ or /k^h/, but not /k'/. An exception are the trajectories for /agi/, which look the same for both languages, the tongue slides along the palate.

Furthermore, if V1=/i/ the trajectories of all the stops look very similar. This is the same for both languages. In both languages there is hardly any movement during closure and there are hardly any differences related to manner of articulation in the trajectory.

For both languages the loops are smaller for /g/ than for any other velar stop. Furthermore, they are very small if V1=/i/. This is consistent with Houde (1967) for English.

4.1.2.2 Direction of movement during closure

For German there is forward movement after /a/ and /u/ and no movement after /i/ (Mooshammer 1995: 13). For Korean, the rule for German can be seen as a general tendency although there are a few exceptions. There is forward movement after /a/ and /u/, except for /ak^hu/ and /uk'a/ which are moving backwards. There is backward movement after /i/ and in /ak^hu/ and /uk'a/.

4.1.2.3 Movement amplitude of movement during closure

There are no differences in movement amplitude between the consonants for V1=/i/. For V1=/u/ or /a/, on the other hand, there are differences. For German, there is more movement during closure for /k/ than for /g/ (cf. figure A38). For Korean the results are not as clear. For speaker HS the movement amplitude of /g/ is shorter than the ones of /k^h/ and /k'/ if the tongue is moving forwards. Backward movement as in /uk'a/ reduces the movement amplitude. Furthermore, there is a tendency for the movement amplitude of /k'/ to be longer than the one of /k^h/. For speaker SH the results are very inconsistent. For German there is generally more movement during closure for V1=/u/ than for V1=/a/ (Mooshammer 1995: 13f) whereas for Korean it is the other way around.

4.1.2.4 Euclidean distance of movement during closure

For German the Euclidean distance for the movement during closure is greater for /k/ than for /g/ for long vowels. In lax vowel contexts this is only true for one speaker. The distance is smaller if the first vowel is /i/ (Mooshammer 1992: 71). There is the same tendency in Korean. In general, the Euclidean distance is shorter for /g/ than for /k'/ or /k^h/. Again the Euclidean distance is shortened if the tongue is moving backwards as in /ak^hu/ and /uk'a/ and, same as in German, if the first vowel is /i/.

4.1.2.5 Position of the closure

For both languages the closure is produced more advanced for sequences with V1=/i/ than for sequences with V1=/u/ or /a/ (Mooshammer 1995: 9). The identity of the consonant has no consistent influence on the position of the closure.

4.1.2.6 Velocity parameters

For German, as for Korean it was found that there is no difference in peak velocity between the stops. Since there are no data for the acceleration and deceleration peaks it is not possible to set up a comparison of those parameters between Korean and German. However, it is possible to find an explanation for the inconsistent results for the velocity data.

The low values of velocity and deceleration in /ak'a/ could be explained by the high position of V1=/a/ in this context in comparison to /g/ or /k^h/ (cf. figure A1). Thus, Euclidean distance, peak velocity and peak deceleration should correlate. Furthermore, there should be no correlation between peak acceleration and the other parameters. The results of the correlation calculation can be seen in table 4.1. To make the contents of the table easier to grasp, the relations are visualised in figure 4.1. where the correlations are signalled by dotted lines (correlation coefficient of 0.500-0.699) or solid lines (correlation coefficient higher than 0.699). Speaker HZ was excluded from the figure since the correlations for movement amplitude and Euclidean distance could not be calculated.

Table 4.1: Correlation coefficients for movement amplitude of V1 (mov. ampl.), Euclidean distance of V1 (euc. dist.) peak deceleration (deceleration), peak acceleration (acceleration) and peak velocity (velocity). The results for HZ do not include Euclidean distance and movement amplitude since these parameters could not be calculated. The results represented in figure 4.1 are printed in bold.

Speaker	*Parameter*	*ma*	*dec*	*acc*	*vel*	*euc*
HS	mov. ampl.	1	.482	.213	**.703**	**.989**
	deceleration	.482	1	**.544**	.791	.474
	acceleration	.213	**.544**	1	**.694**	.196
	velocity	**.703**	**.791**	**.694**	1	**.688**
	euc. dist.	.989	.474	.196	.688	1
HZ	deceleration	-	1	.433	.938	-
	acceleration	-	.433	1	.306	-
	velocity	-	.938	.306	1	-
SH	mov. ampl.	1	.238	-.097	**.537**	**.981**
	deceleration	.238	1	.351	**.774**	.291
	acceleraton	-.097	.351	1	.150	-.186
	velocity	**.537**	**.774**	.150	1	**.622**
	euc. dist.	**.981**	.291	-.186	**.622**	1

As can be seen, the movement amplitude correlates strongest with Euclidean distance, which should be expected since Euclidean distance and movement amplitude are equal if the movement is straight. Furthermore, Euclidean distance correlates also very strongly with peak velocity. Moreover, there is a strong correlation between peak velocity and peak deceleration although peak deceleration does not correlate with movement amplitude. Peak acceleration, on the other hand, stands quite alone and has only weak correlations for one speaker with peak velocity and peak deceleration. This means that peak acceleration seems to be rather independent of all the other parameters.

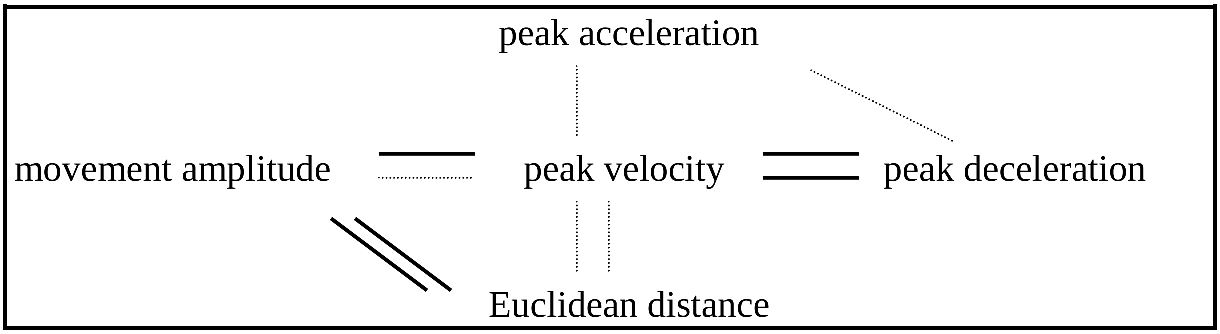


Figure 4.1: Relations among the velocity paramters, Euclidean distance and movement amplitude during V1 for speakers HS and SH. Solid lines show a correlation r>0.699, dotted lines show a correlation 0.500<r<0.699.

If one regards movement amplitude as more or less given by Euclidean distance and as influencing velocity and deceleration, the acceleration is the only parameter that is rather independent and might therefore be used to characterise each stop. That is why only in the acceleration diagrams does the expected result turn up in that /k’/ as the most forced stop has the highest value.

Looking at movement amplitudes (cf. figure A1-A3) one can notice that the “basic requirement” for /k’/ to develop high velocities and a high deceleration peak, namely a high movement amplitude, is not given in the /a_a/ context. The movement amplitudes for /k’/ are so small that the other parameters which correlate with the movement amplitude cannot be larger than the ones for /k^h/ and /g/. In the /a_i/ context, on the other hand, the movement amplitude of /k’/ is large enough so that /k’/ can develop highe r velocities.

4.1.2.7 Closing and opening gesture

For Korean it was found that the closing gestures were shorter for V1=/i/ than for V1=/u/ or /a/. There was no difference between V1=/a/ and /u/. For German this is less consistent. Whereas the results are the same as for Korean for one speaker, the other speaker has a closing gesture for V1=/i/ which is longer than the one of V1=/u/ or /a/ (Mooshammer 1992: 75, 94) for both subcorpora.

For the opening gesture the result was less clear for Korean and there were no data for German because in Mooshammer (1992) the data were split according to the first vowel. Since, however, the data split according to V1 led to clearer results, it is very likely that the identity of the first vowel influences the opening gesture to a higher degree than the one of the second. For German long vowels the opening gesture is significantly shorter if V1=/i/ than if V1=/u/ or /a/ (Mooshammer 1992: 94f). For short vowels this is only true for one speaker (Mooshammer 1992: 75). For Korean the opening gesture was shorter for V2=/i/ than for different V2, this difference, however, was often not significant.

To make a very broad generalisation, one could say that there seems to be a tendency for closing and opening gestures in /i/-contexts to be shorter than the gestures in other contexts. The length of the gestures does in any case not only depend on the height of the vowels surrounding the stop. This has to be investigated further. An explanation for this phenomenon could be the longer closure in /u/- and /a/-contexts as compared to /i/-context. In the segmentation process the whole trajectory is divided into two gestures by the turning point at the palate, and if the closure is longer the gestures become longer. This was also suggested by Mooshammer (1992).

4.1.3 Comparison of German and Korean acoustic characteristics

In this section the acoustic results won from the data of the two experiments will be compared.

4.1.3.1 Closure duration

Closure duration is in both languages an extremely important characteristic in distinguishing among the stops. For Korean, /g/ has a shorter closure duration than /k^h/, and /k^h/ has a shorter closure duration than /k'/. For German, the closure duration of /g/ is shorter than the one of /k/. This means that in both languages the voiced stop has a shorter closure duration than the voiceless or less voiced stops. This could be explained with the difficulty of sustaining voicing in velars (cf. section 1.1). In order to keep the stops fully voiced as they normally are, the closure duration has to be short. If the closure duration was longer, the supralaryngeal pressure would increase and the vocal cords would stop vibrating.

There are more exceptions to this rule for the Korean data than for the German data (cf. sections 3.3.2.1.1 and 3.3.2.2.1). One reason for that could be that the corpora differed. Whereas for German the second vowel was kept constant, it varied in the Korean corpus. Consequently, there is more dispersion in the measurements for Korean than in the ones for German resulting in less distinctive categories in Korean than in German. A second reason could be that the temporal distances in closure duration between the stops are shorter for three stops than for only two. This is comparable to local distances for example in the vowel systems of the languages of the world. A contrast between /i/, /e/ and /ɛ/ is more easily lost than one between /i/ and /ɛ/ because there is more space between the two (cf. section 1.1.2 for the theory of adaptive dispersion). Adapting this concept to velar stops this means that if there exists a certain maximum in closure duration for all languages, the differences between three stops necessarily have to be smaller than the one between only two stops. However, the comparison with the vowel system is problematic since there is a biologically defined maximum in vowel space but there does not have to be one in closure duration. Furthermore, looking at the averages for closure duration (cf. figure 3.2 for Korean, figure A23 for German) shows that something like a maximal value in closure duration for all languages does not exist. Whereas the longest closure duration for German is only 93 ms the respective value for Korean is 138 ms.

4.1.2.4 Duration of V1

In both languages the first vowel tends to be longer before /g/ than before one of the other stops.

4.1.2.5 Duration of V2

V2 has no consistent influence on the distinction between the stops, neither in Korean nor in German.

4.1.2.6 VOT

In both languages VOT serves to set the aspirated stops apart from the other velars. For German the difference is significant except for one speaker whereas for Korean it is not significant in many high vowel contexts.

4.1.2.7 Voicing into closure

In both languages the percentage of voicing during closure is characteristic for /g/. There is a tendency for the percentage to be higher in high vowel contexts than in lower ones.

4.2 Looking back at the suppositions

In this section the suppositions developed at the beginning of chapter 3 will be looked at again.

It was suggested that the movement during closure is longer for forward than for backward movement (cf. section 3.3.1.1) This turned out to be true. With regard to the position of the closure it was found that it depends on the first vowel. If the first vowel is /i/ the closure is produced more fronted than if it is another vowel (cf. section 3.3.1.2). Furthermore, the trajectory of /g/ was judged to be smoother than the ones of /k'/ and /k^h/. As a reason for that a lower velocity peak for /g/ was supposed. For /k'/ which has sharp edges in its trajectory high acceleration and deceleration peaks were expected. This did not turn out to be true. Only the acceleration peak is higher for /k'/ than for /g/. It was also suggested that /k’/ has the longest closure and the greatest movements during closure. This turned out to be true. With regard to the trajectories of the /i_i/ and the /i_u/ context it turned out that the stops in this context are more easily distinguished by acoustic parameters than by articulatory ones. With regard to the opening and closing gesture durations the result was unclear. For the closing gesture duration it turned out that it is shorter after /i/ than after /a/ and /u/. So the height of the vowel is not the only factor influencing this parameter. For the opening gesture it was found that V1 is probably more influential than V2. Again the influence of /u/ was contrary to the expectation.

4.3 Influence of the vowel context on the choice of the parameters

If one reads the second part of the third chapter one can see that not all the parameters that are involved in the voicing distinction are significant in all the contexts. Comparing the trajectories of Korean /aga/, /ak’a/ and /ak^{h}a/ (figure A1) with the ones of /igi/, /ik’i/ and /ik^{h}i/ (figure A5) for example one can see that the trajectories in the /i/-context are very similar whereas there are obvious differences between the three trajectories in the /a/-context. Looking at the German trajectories supports this view (figures A37-A38). This means that articulatory parameters cannot be expected to create significant differences in this context.

The difference in the articulatory parameter voicing into closure on the other hand is for German greater in the /i/-context than for the /a/-context (figure A29). For Korean a similar effect can be seen for the percentage of voicing during closure of HS (figure 3.4). In the /a/ context it is generally lower than in the /i/-context.

This shows that the voicing contrast is a contrast which is built on a number of parameters of which voicing can be one. Not all the parameters need to be distinctive in all the vowel contexts. There is no common denominator which is present in all the contexts even if there are more important and less important parameters. To give an example, the trajectories of /igi/, /ik’i/ and /ik^{h}i/ look very much alike. This is a consequence of the low impact of the tongue at the palate of /k’/ and /k^h/ which is again a consequence of the short movement amplitudes which are a result of the vowel context. This means that the contrast between the stops is hard to produce by articulatory parameters as for example closure duration or velocity parameters. However, it is possible in this context to create the difference by voicing. Therefore, the contrast produced by the acoustic parameter voicing into closure is enlarged.

Furthermore, /g/ which is normally characterised by the acoustic parameter voicing into closure has very many different trajectories in the different contexts whereas /k’/ and /k^h/ show something typical in every trajectory, for example the sharp edges in /k'/. An explanation could be that /g/ is sufficiently characterised by voicing and therefore rather free in the development of its trajectory.

4.4 Articulatory vs. acoustic parameters

As stated in section 4.1.2.1 the trajectories of German /g/ often look like the ones of Korean /k^h/ or even /k'/. Looking at the acoustics, however, shows that German /g/ shares the two most important acoustic characteristics of Korean /g/, namely the long voicing into closure and the short VOT. This shows that there is a discrepancy between the articulation of a stop and its acoustic output.

A second fact that is remarkable is that the acoustic results are clearer and more often significant than the articulatory ones. For example, the most important parameters are the acoustically measured voicing into closure, VOT and closure duration. Articulatorily measured parameters as for example the duration of gestures or the acceleration show less clear results. There are also more speaker dependent differences in articulatorily measured parameters than in acoustically measured ones.

A conclusion that can be drawn from that is that many different articulations seem to be able to produce a similar acoustic signal. Even if the German speakers articulate differently the acoustic output of /g/ is similar to the one of Korean /g/. Furthermore, it is likely that articulation depends on the architecture of each speaker's vocal tract. If all the speakers would articulate similarly although their vocal tracts are differently the acoustic output would be different for each speaker. However, since in communication the important thing is what reaches the hearer (the acoustics) and not how it is produced, speakers are likely to adapt their articulation so that the acoustic output is similar to the one of other speakers (cf. Perkell (2000)).

4.5 Explanations for looping patterns

Even if an explanation for the looping patterns cannot be found it has become clear that looping patterns are not produced in order to sustain voicing. The study therefore supports the conclusions of Mooshammer et al. (1995) for German and Munhall, Ostry & Flanagan (1991) for English. There is more movement during closure during voiceless stops than during voiced stops, although, if the loops were produced in order to sustain voicing, they should be bigger for voiced stops. Furthermore, as has become clear there is a tendency to have more voicing in high vowel contexts, although here the movements during closure are very small and moreover in backward direction so that the pressure behind the closure should be enhanced by that movement.

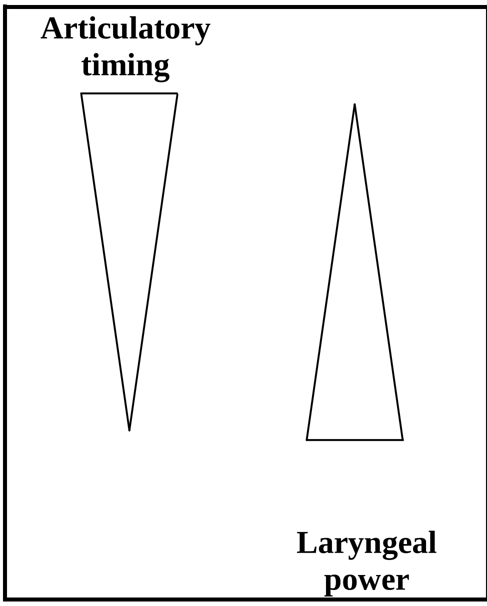
As was suggested by Mooshammer (1995: 11) a reason for the looping patterns could be that the target of the velar stops is simply nearer to /i/ than to /u/ so that loops are a result of coarticulation. This also explains the fact that there is hardly any movement if V1=/i/. Here the tongue is already in the correct position.

4.6 Features

A common denominator for contrasting all the stops in intervocalic position in all contexts which could serve as a phonetic basis for a phonological feature does not exist. However, for each language a "most important parameter" can be found which can be substituted in some contexts. For German velar stops in intervocalic position this is voicing into closure whereas for Korean it is closure duration. This means that whatever feature is used to classify the stops, the correlates should involve those two characteristics. Therefore, the proposal made by Chomsky & Halle is not adequate to describe the Korean voicing contrast. Jessen, on the other hand, includes the important duration features. However, he describes the contrast as one involving two features, [tense] and [checked] although the stops can be kept apart from each other by only one characteristic, namely closure duration in most contexts. This one parameter should therefore be expressed in one feature. Consequently, binary features which can describe two categories only are not adequate to describe the Korean voicing contrast in velars in intervocalic position.

Kohler's approach, which involves gradual features, is therefore most adequate for describing a three way contrast. Figure 4.2 is a revised version of figure 1.2. for Korean velar stops in intervocalic position. One can see that not every stop shows all the correlates up to a maximal degree, but one can say that /g/ is [lenis], /k^h/ is "more fortis" than /g/ and "less fortis" than /k'/, and /k'/ is "most fortis" since its features show most often the maximal fortis characteristics.

A result of this study is that the voicing contrast cannot be described by binary features, at least if the feature is meant to be universal and therefore should also be able to describe three way contrasts. Moreover, a common denominator does not exist, consequently the voicing contrast is always a conglomerate of several parameters. Furthermore, supralaryngeal parameters seem to be as important as laryngeal ones in the distinction of the stops. This can be seen in the parameters set up by Kohler (cf. figure 4.2) of which only two are laryngeal, voicing and aspiration. Jessen's basic correlate for German, aspiration, cannot be supported by this study since voicing turned out to be more important in German than aspiration. For one speaker VOT differences were not significant at all.



Parameters of [fortis]			**Parameters of [lenis]**
short vowel	/k'/ /k^h/	/g/	long vowel
long closure	/k'/ /k^h/	/g/	short closure
stop	/k'/ /k^h/	/g/	approximant
aspirated	/k^h/	/g/ /k'/	not aspirated
voiceless	/k'/ /k^h/	/g/	voiced
glottalized	/k'/	/k^h/ /g/	not glottalized

Figure 4.2: Adaption from figure 1.2. Both components of the feature [fortis] are used to describe the three way contrast in Korean stops in medial position. The stops have different positions on the scales of the parameters.

4.7 Conclusion

This study has investigated acoustic and supralaryngeal articulatory parameters of Korean velar stops and acoustic parameters of German velar stops in intervocalic position. The main phonological difference between the two languages is that there is a two way contrast in German, but a three way contrast in Korean. In order to find the phonetic concomitants of the contrast a set of phonetically measurable parameters which are potentially involved in the contrast has been set up. To find the most important characteristics these parameters have been weighted by displaying them on a neutral scale. Afterwards, the influence of the vowel context on the involvement of the parameters in the voicing contrast has been investigated. The results show that phonetically the contrast in Korean is mainly built on closure duration whereas in German the most important parameter is voicing into closure although a common denominator, a parameter that creates the voicing contrast in all the contexts, does not exist. German and Korean /g/ are different with regard to articulation but very similar with regard to their acoustic characteristics. German /k/ and Korean /k^h/ are similar both in acoustics and articulation. Korean /k'/ on the other hand, is not similar to any German stop. The theory of adaptive dispersion cannot be applied to the stop distinction of German vs. Korean because then no German stop should be similar to a Korean one because the acoustic space should be used differently in having "more space" between the stops in German than in Korean stops. Both voicing contrasts, the one in Korean intervocalic stops and the one in German intervocalic stops can be described phonologically with the approach by Kohler (1984).

APPENDIX

1. Word material for Korean

Table A1: Stimuli used in the recording procedure of the Korean data

Word	**VCV-sequence**	**English translation**
pagaci	/aga/	gourd
kak'ai	/ak'a/	near
ak^{h}asia	/a k^h a/	acacia
sagilo	/agi/	made of chinaware
ak'ita	/ak'i/	to save money
sak^{h}ita	/ak^{h}i/	to grow
paguni	/agu/	basket
pak'uta	/ak'u/	to change
sak^{h}ula	/ak^{h}u/	cherry flower
kigahata	/iga/	to raise one's family
cik'aci	/ik'a/	you too
mik^{h}ael	/ik^{h}a/	-name-
pigita	/igi/	to be equal
pik'ita	/ik'i/	to illuminate obliquely
pik^{h}ita	/ik^{h}i/	to line up
piguni	/igu/	buddhist nun
mik'ulaci	/ik'u/	the loach
mik^{h}ulaci	/ik^{h}u/	the loach
pugahata	/uga/	to add
acuk'ali	/uk'a/	ricinus
uk^{h}ano	/uk^{h}a/	how to do?
ugida	/ugi/	to insist
uk'ita	/uk'i/	it is funny
chuk^{h}ita	/uk^{h}i/	to compliment
suguhata	/ugu/	to be conservative
puk'umi	/uk'u/	wheat pancake
suk^{h}uli	/uk^{h}u/	-nonsense word-

2. Plots of ensemble averages of the trajectories of speaker SH

There is one figure for each vowel context and one plot for each stop. The solid lines show the trajectories of the forced stop, the dotted lines the ones of the voiced stop and the dash-dotted lines the trajectories of the aspirated stop.

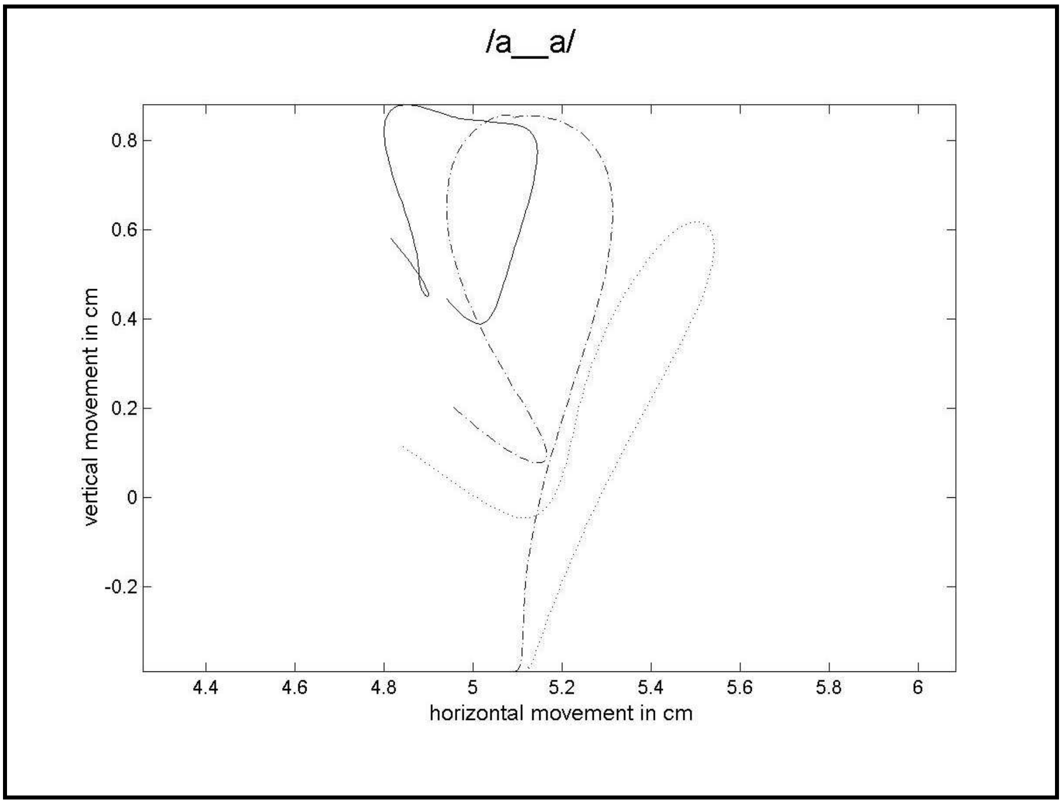


Figure A1: Trajectories during /a_a/

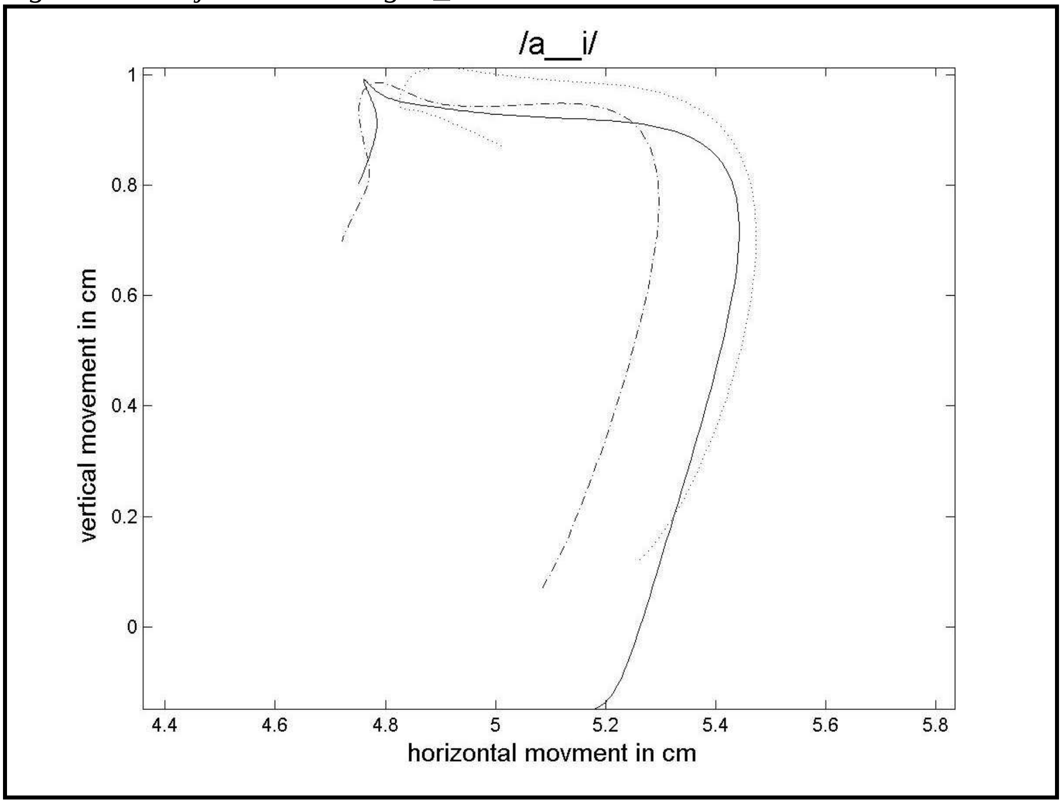


Figure A2: Trajectories during /a_i/

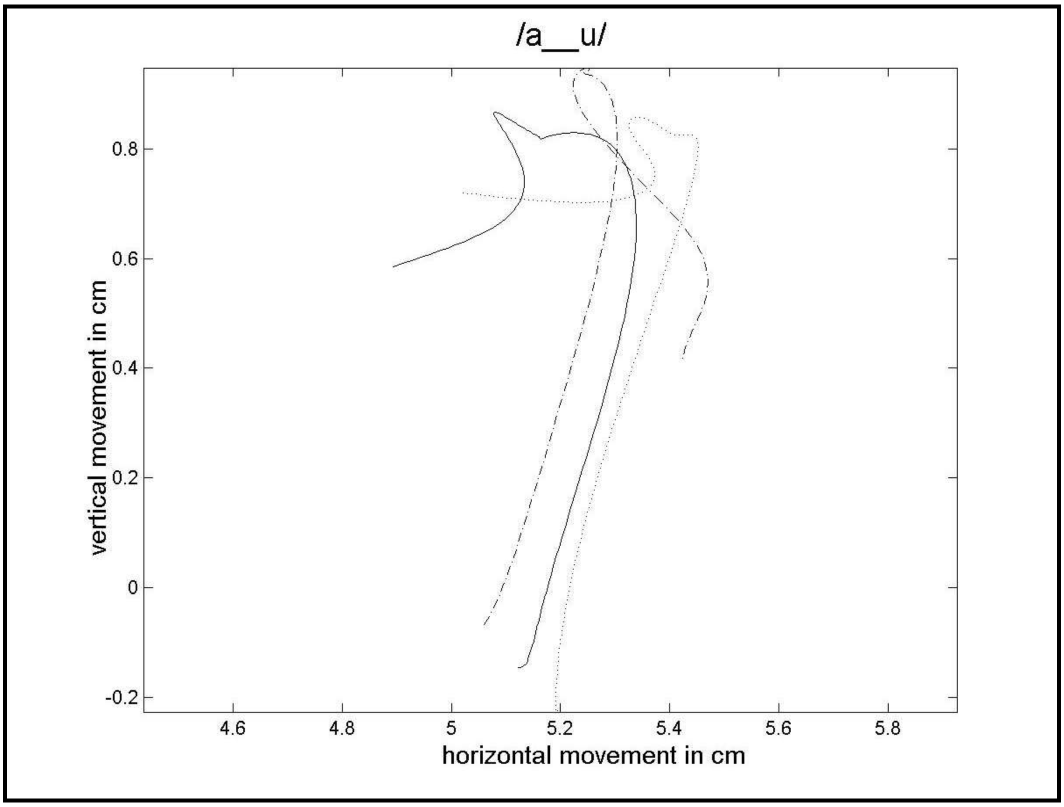


Figure A3: Trajectories during /a_u/

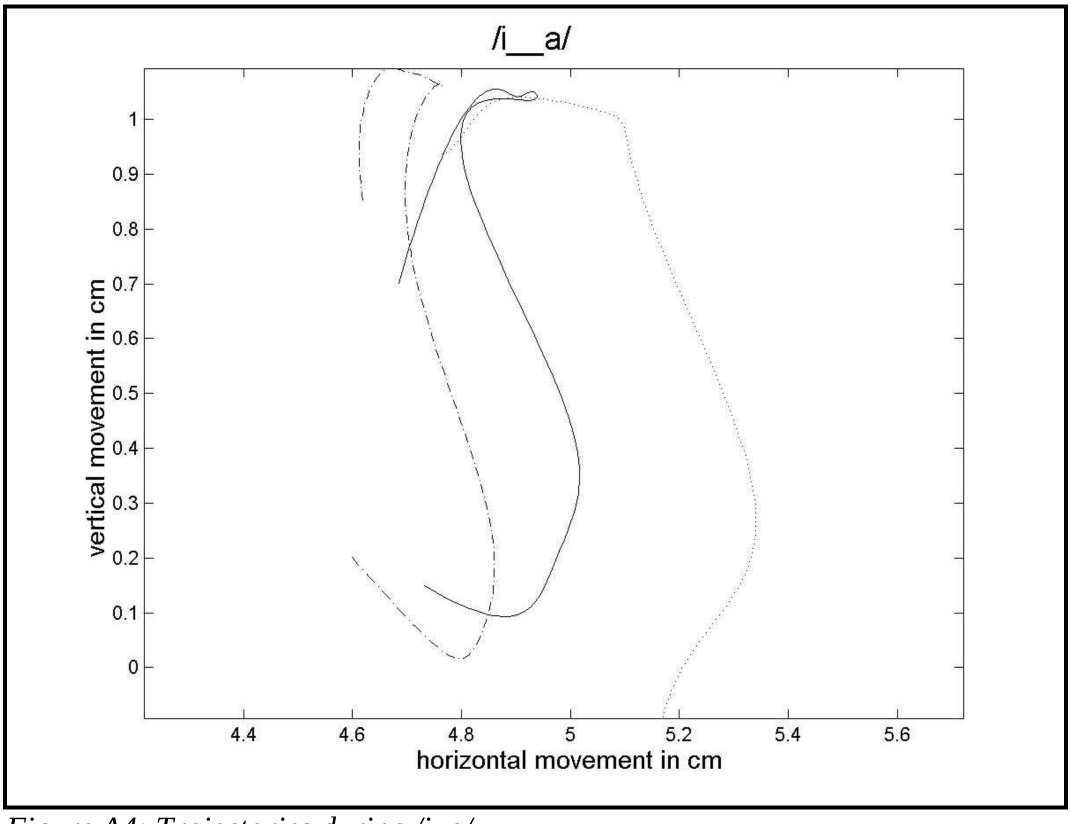


Figure A4: Trajectories during /i_a/

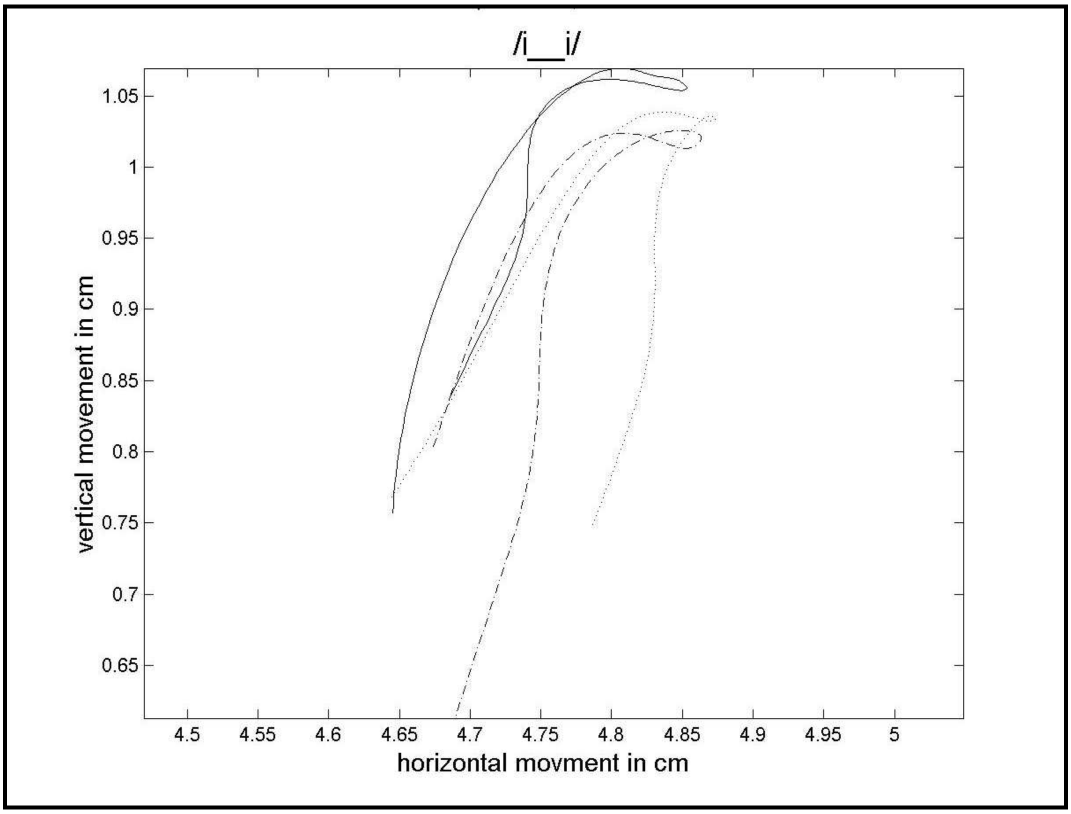


Figure A5: Trajectories during /i_i/

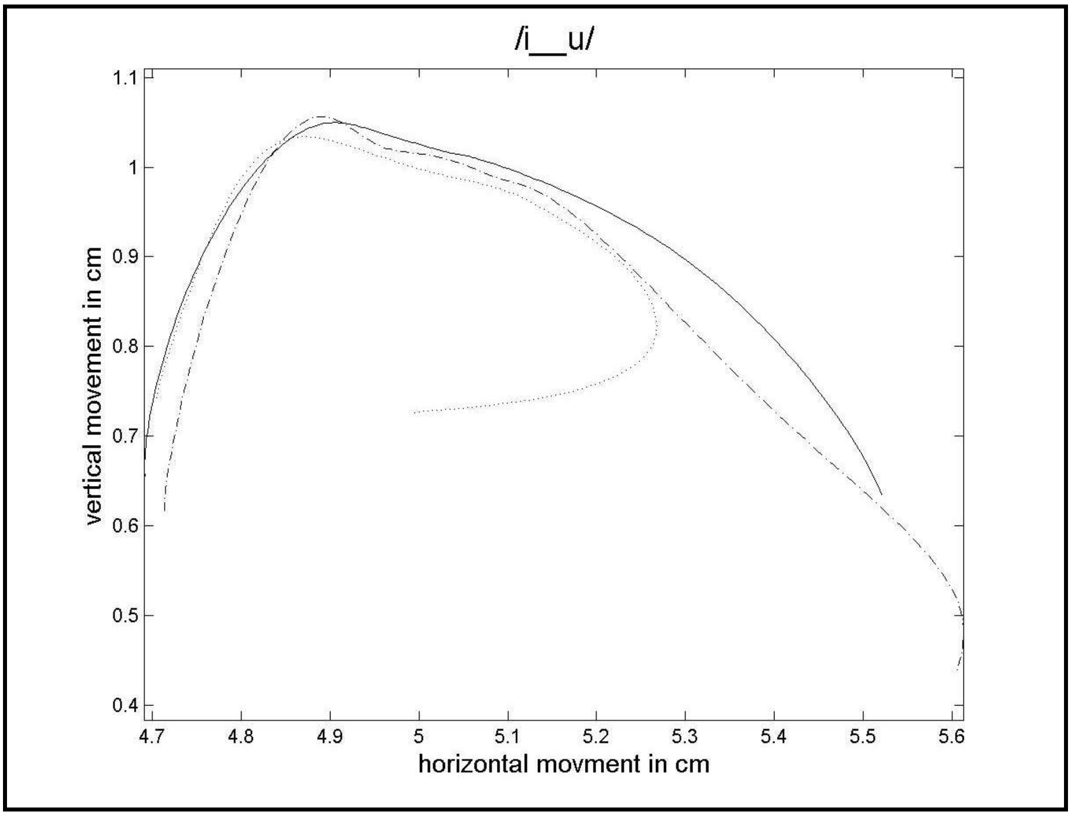


Figure A6: Trajectories during /i_u/

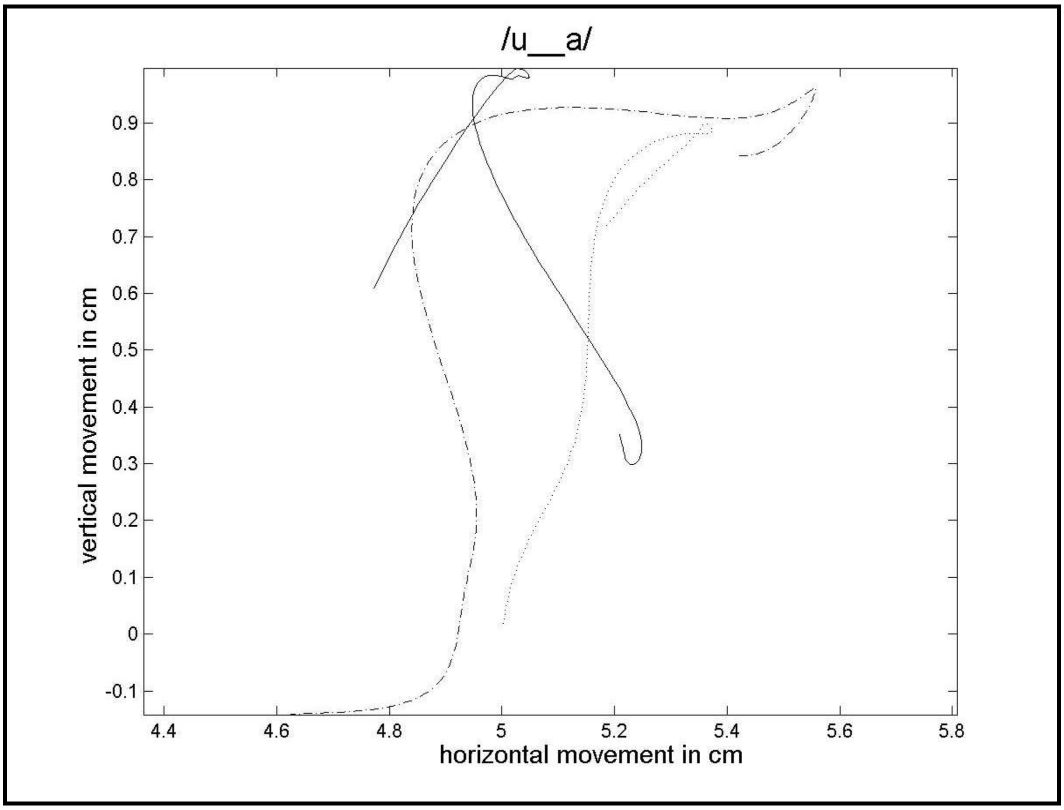


Figure A7: Trajectories during /u_a/

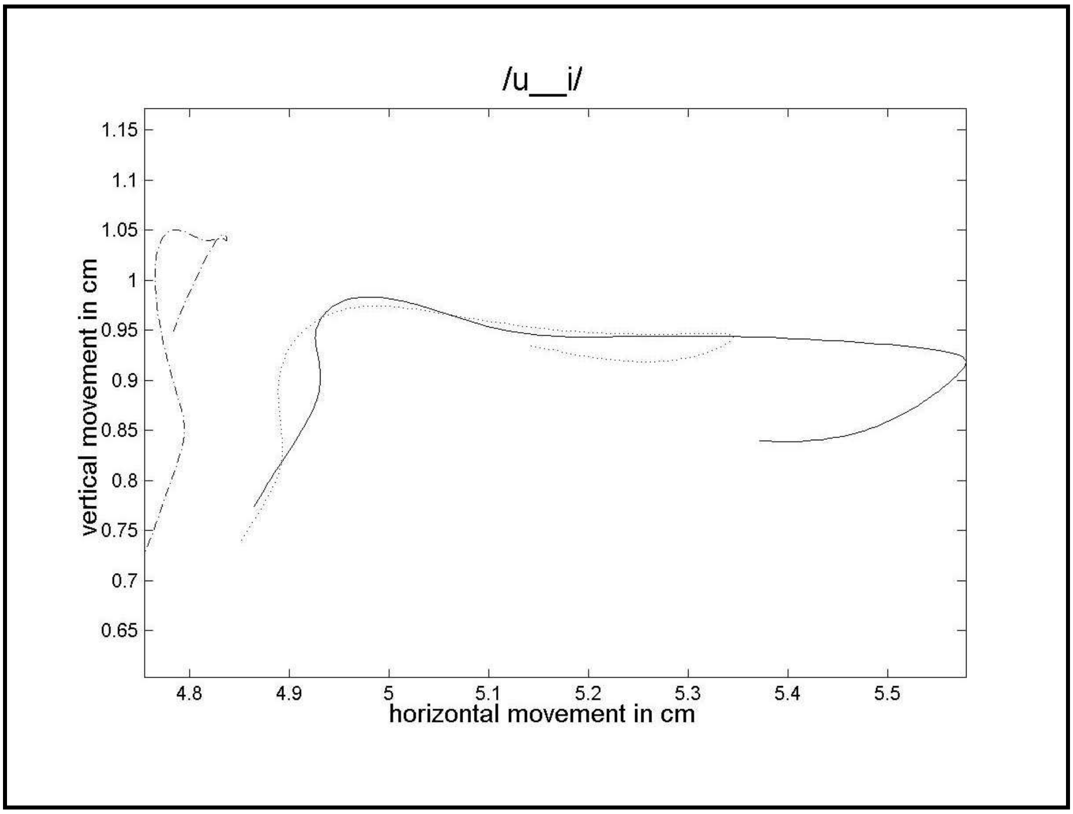


Figure A8: Trajectories during /u_i/

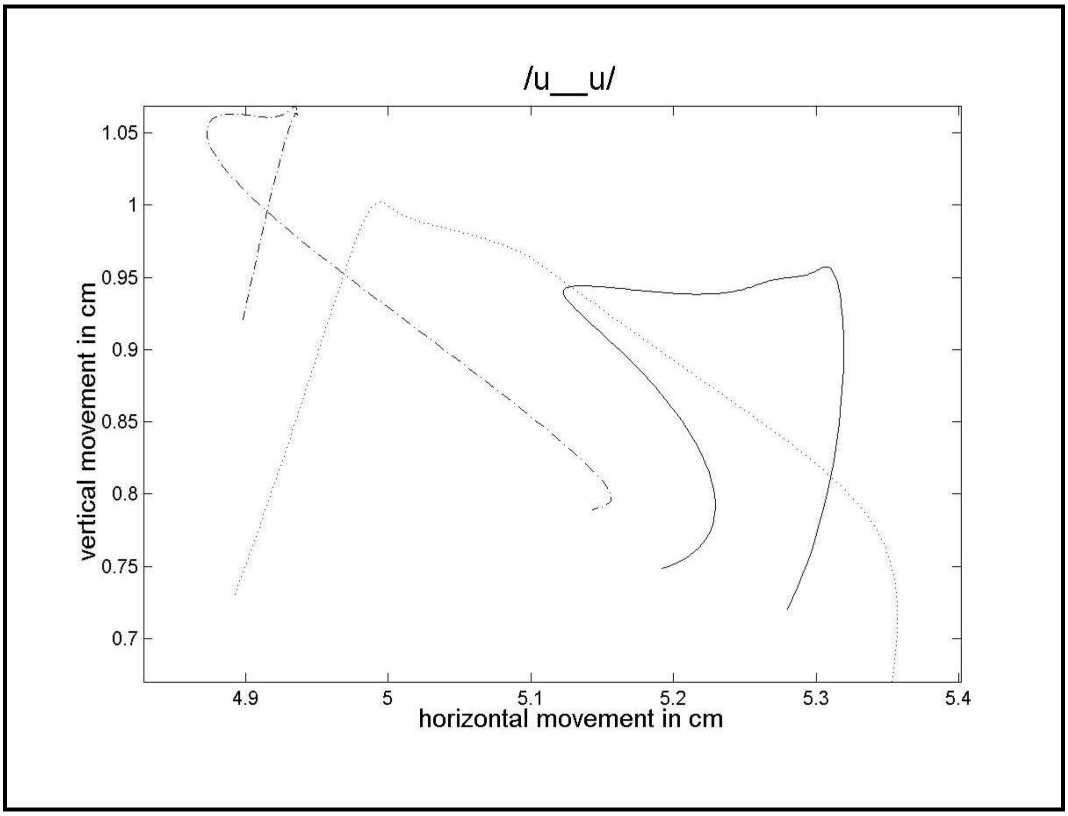


Figure A9: Trajectories during /u_u/

3. Results of statistical analyses

For most statistical analyses which have been carried out there is one diagram and at least one table giving the significances. In some cases there are two tables for one analysis. In these cases the first table shows the results of the analysis of variance for three groups (e.g. /g/ vs. /k’/ vs. /k^h/) and the second table the one of two groups (e.g. /k’/ vs. /k^h/ for Korean if one group is missing due to the lack of measurements). The error bars in the diagrams show standard error.

Table A2: Analysis of variance for the x-value of the turning point

Speaker	*Consonant*	*V1*	*V1*	*Standard error*	*Significance*
HS	g	a	i	.052	.017
		u	i	.049	.000
	k’	a	i	.062	.015
		u	i	.062	.000
	k^h	a	i	.055	.000
		u	i	.054	.000
HZ	g	a	i	.053	.000
		u	i	.053	.000
	k’	a	i	.048	.000
		u	i	.048	.000
	k^h	a	i	.054	.000
		u	i	.054	.000
SH	g	a	i	.046	.000
		u	i	.046	.000
	k’	a	i	.036	.000

		u	i	.036	.000
	k^h	a	i	.053	.000
		u	I	.053	.000

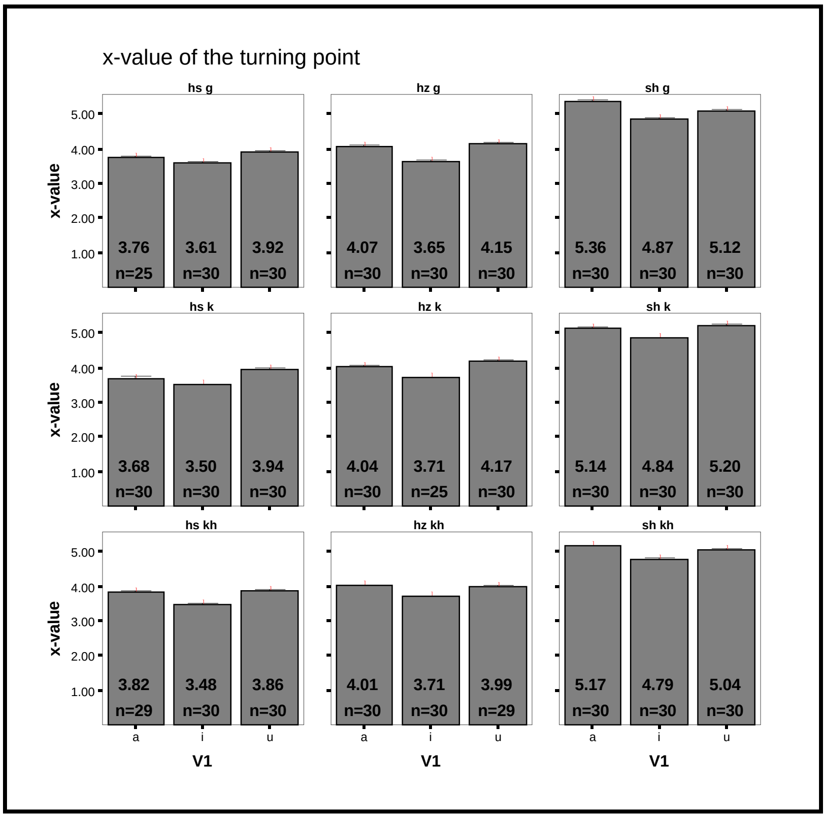


Figure A10: x-value of the turning point at the palate for different V1

Table A3: Analysis of variance for the duration of the closing gesture

Speaker	*Consonant*	*V1*	*V1*	*Standard error*	*Significance*
HS	g	a	i	8.390	.005
			u	8.390	.368
	k’	a	i	5.895	.830
			u	5.895	.310
	k^h	a	i	7.154	.095
			u	7.154	.003
HZ	g	a	i	5.018	.000
			u	5.018	.002
	k’	a	i	5.964	.079
			u	5.686	.232
	k^h	a	i	4.832	.000
			u	4.873	.000
SH	g	a	i	6.040	.000
			u	6.040	.293
	k’	a	i	8.072	.993
			u	8.072	.001
	k^h	a	i	6.391	.000
			u	6.391	.797

Table A4: Analysis of variance of Euclidean distance during closing gesture: The Euclidean distance tends to be higher for V1=/u/ than for V1=/i/. This can be seen in the positive values in the fifth column "Average difference". Those values are calculated as the average value for /u/ minus the average value for /i/ .

Speaker	*Consonant*	*V1*	*V1*	*Average difference*	*Standard error*	*Significance*
HS	g	u	i	3.1	.35	.000
	k'	u	i	2.4	.52	.000
	k^h	u	i	2.4	.40	.000
HZ	g	u	i	2.1	.61	.005
	k'	u	i	0.2	.67	.951
	k^h	u	i	2.4	.56	.000
SH	g	u	i	0.0	.33	.998
	k'	u	i	0.0	.77	.999
	k^h	u	i	1.8	.48	.001

Table A5: Analysis of variance for movement amplitude during closing gesture: The movement amplitude tends to be higher for V1=/u/ than for V1=/i/. This can be seen in the positive values in the fifth column "Average difference". This value is calculated as the average value for /u/ minus the avaerage value for /i/.

Speaker	*Consonant*	*V1*	*V1*	*Average difference*	*Standard error*	*Significance*
HS	g	u	i	3.3	.42	.000
	k'	u	i	2.3	.60	.001
	k^h	u	i	2.5	.48	.000
HZ	g	u	i	2.2	.64	.003
	k'	u	i	0.3	.70	.891
	k^h	u	i	2.3	.57	.000
SH	g	u	i	1.8	.42	.000
	k'	u	i	1.5	.85	.226
	k^h	u	i	2.3	.47	.000

Table A6: Analysis of variance for duration of opening gesture

Speaker	*Consonant*	*V1*	*V1*	*Standard error*	*Significance*
HS	g	a	i	10.047	.835
			u	10.047	.289
	k'	a	i	8.095	.000
			u	8.095	.473
	k^h	a	i	10.210	.026
			u	10.210	.646
HZ	g	a	i	11.615	.342
			u	11.615	.009
	k'	a	i	13.340	.649
			u	12.720	.916
	k^h	a	i	9.667	.010
			u	9.750	.375
SH	g	a	i	5.626	.248
			u	5.626	.000
	k'	a	i	8.547	.000
			u	8.547	.000
	k^h	a	i	8.171	.122
			u	8.171	.000

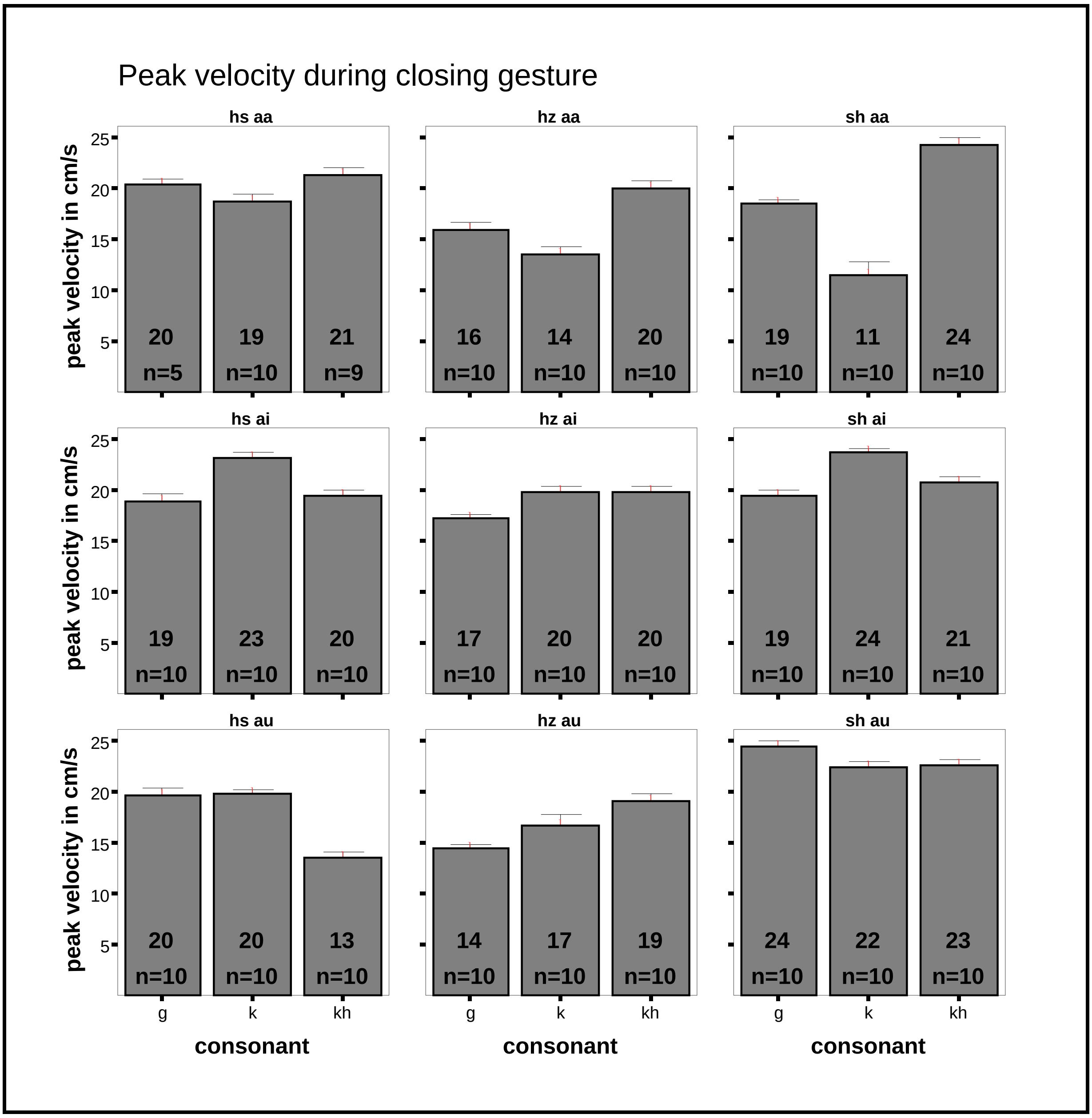


Figure A11: Peak velocity in cm/s for speakers HS (first column), HZ (second column) and SH (third column)

Table A7: Analysis of variance for peak velocity

Speaker	*Context*	*Consonant*	*Consonant*	*Standard error*	*Significance*
HS	a_a	g	k’	1.174	.401
			k^h	1.196	.738
		k’	k^h	.985	.053
	a_i	g	k’	.841	.000
			k^h	.841	.777
		k’	k^h	.841	.001
	a_u	g	k’	.769	.986
			k^h	.769	.000
		k’	k^h	.769	.000

HZ	a_a	g	k’	1.033	.108
			k^h	1.033	.002
		k’	k^h	1.033	.000
	a_i	g	k’	.721	.004
			k^h	.721	.004
		k’	k^h	.721	1.000
	a_u	g	k’	1.184	.188
			k^h	1.184	.002
		k’	k^h	1.184	.120
SH	a_a	g	k’	1.274	.000
			k^h	1.274	.001
		k’	k^h	1.274	.000
	a_i	g	k’	.695	.000
			k^h	.695	.215
		k’	k^h	.695	.001
	a_u	g	k’	.847	.069
			k^h	.847	.121
		k’	k^h	.847	.957

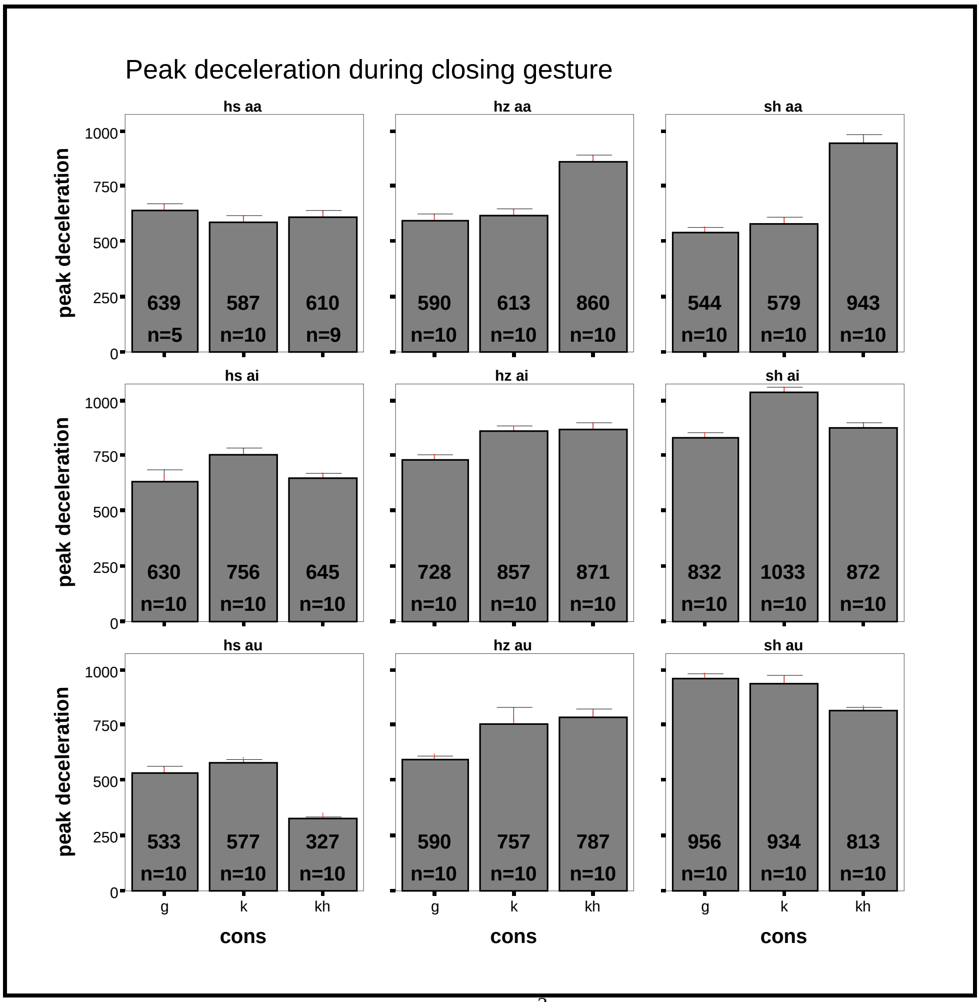


Figure A12: Peak deceleration in mm/s² for speakers HS (first column), HZ (second column) and SH (third column)

Table A8: Analysis of variance for peak deceleration

Speaker	*Context*	*Consonant*	*Consonant*	*Standard error*	*Significance*
HS	a_a	g	k’	46.733	.549
			k^h	47.591	.827
		k’	k^h	39.203	.849
	a_i	g	k’	55.420	.092
			k^h	55.420	.964
		k’	k^h	55.420	.151
	a_u	g	k’	30.927	.375
			k^h	30.927	.000
		k’	k^h	30.927	.000
HZ	a_a	g	k’	49.694	.900
			k^h	49.694	.000
		k’	k^h	49.694	.000
	a_i	g	k’	35.144	.004
			k^h	35.144	.002
		k’	k^h	35.144	.928
	a_u	g	k’	67.037	.063
			k^h	67.037	.024
		k’	k^h	67.037	.900
SH	a_a	g	k’	41.052	.686
			k^h	41.052	.000
		k’	k^h	41.052	.000
	a_i	g	k’	34.464	.000
			k^h	34.464	.523
		k’	k^h	34.464	.000
	a_u	g	k’	42.508	.874
			k^h	42.508	.008
		k’	k^h	42.508	.028

Table A9: Analysis of variance for peak acceleration

Speaker	*Context*	*Consonant*	*Consonant*	*Standard error*	*Significance*
HS	a_a	g	k’	40.097	.016
			k^h	40.833	.590
		k’	k^h	33.636	.060
	a_i	g	k’	37.564	.021
			k^h	37.564	.140
		k’	k^h	37.564	.645
	a_u	g	k’	36.062	.935
			k^h	36.062	.002
		k’	k^h	36.062	.001
HZ	a_a	g	k’	60.873	.000
			k^h	60.873	.005
		k’	k^h	60.873	.003
	a_i	g	k’	43.615	.000
			k^h	43.615	.161
		k’	k^h	43.615	.006
	a_u	g	k’	67.690	.443
			k^h	67.690	.992
		k’	k^h	67.690	.378

SH	a_a	g	k’	38.504	.000
			k^h	38.504	.005
		k’	k^h	38.504	.013
	a_i	g	k’	51.332	.002
			k^h	51.332	.952
		k’	k^h	51.332	.005
	a_u	g	k’	48.101	.491
			k^h	48.101	.056
		k’	k^h	48.101	.426

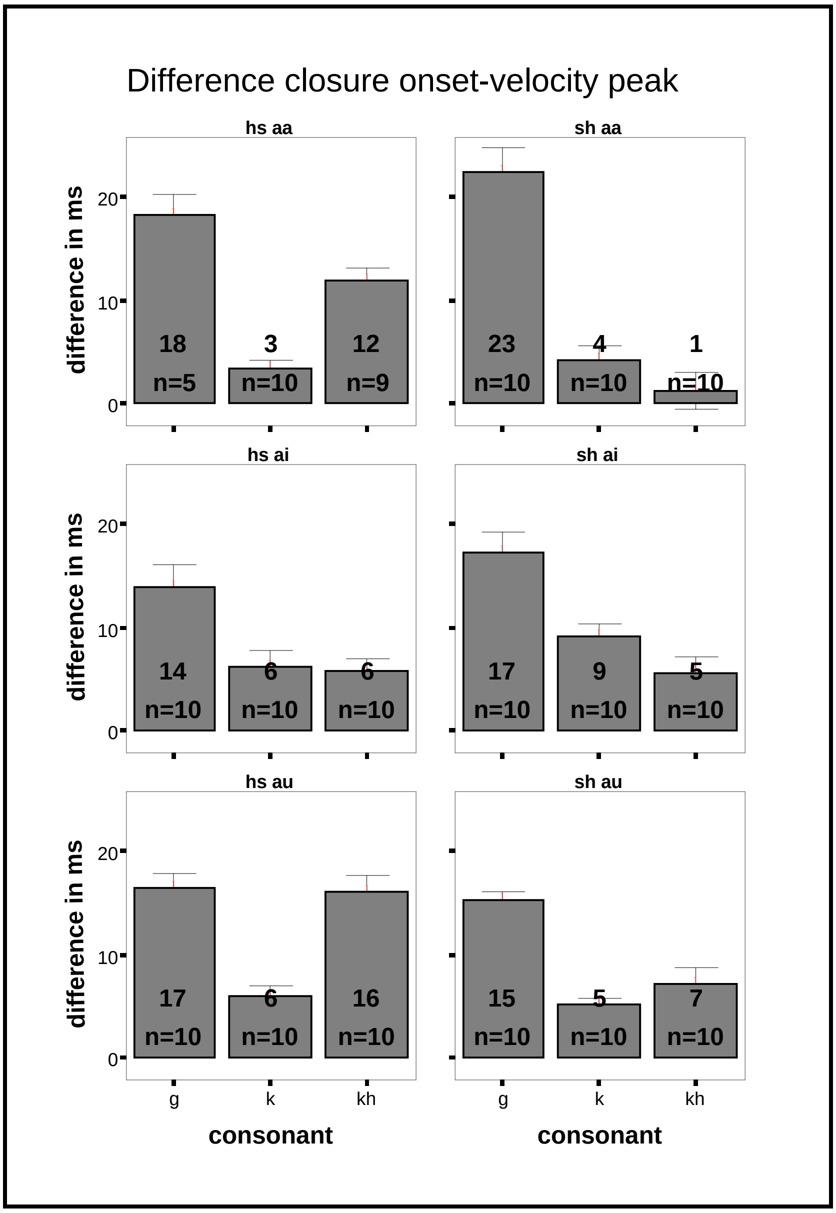


Figure A13: Difference closure onset-velocity peak in ms for speaker HS (first column) and speaker SH (second column) for different vowel contexts

Table A10: Analysis of variance for the difference velocity peak-closure onset

Speaker	*Context*	*Consonant*	*Consonant*	*Standard error*	*Significance*
HS	a_a	g	k’	.002	.000
			k^h	.002	.021
		k’	k^h	.002	.000
	a_i	g	k’	.002	.010
			k^h	.002	.007
		k’	k^h	.002	.983
	a_u	g	k’	.002	.000
			k^h	.002	.965
		k’	k^h	.002	.000
SH	a_a	g	k’	.003	.000
			k^h	.003	.000
		k’	k^h	.003	.551
	a_i	g	k’	.002	.009
			k^h	.002	.000
		k’	k^h	.002	.356
	a_u	g	k’	.002	.000
			k^h	.002	.000
		k’	k^h	.002	.405

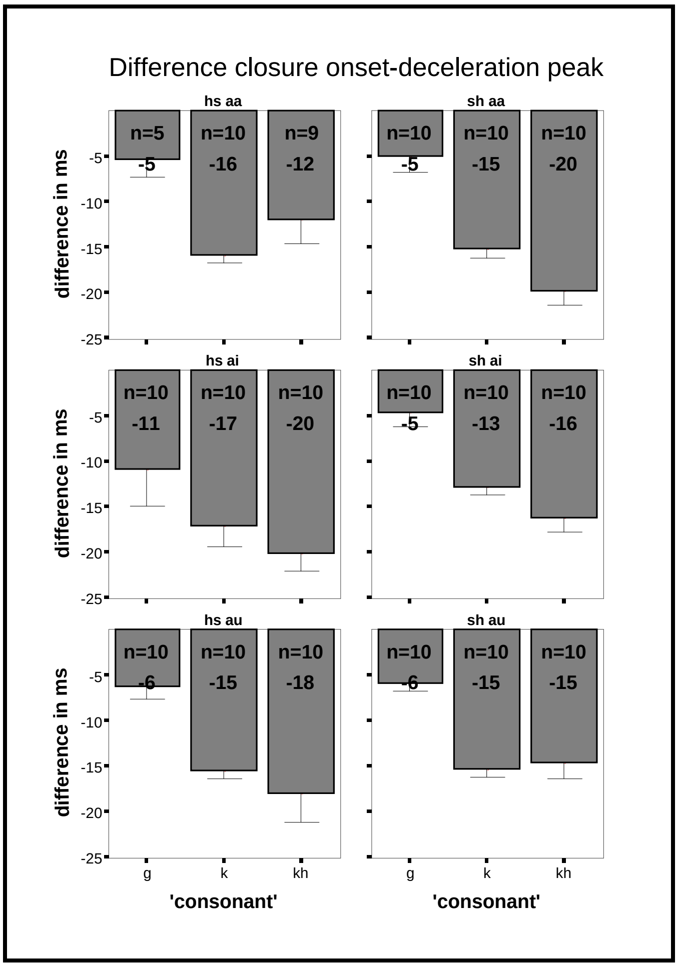


Figure A14: Difference closure onset-deceleration peak in ms for speaker HS (first column) and speaker SH (second column) for different vowel contexts

Table A11: Analysis of variance for difference closure onset-deceleration peak in ms

Speaker	*Context*	*Consonant*	*Consonant*	*Standard error*	*Significance*
HS	a_a	g	k’	3.087	.009
			k^h	3.144	.133
		k’	k^h	2.590	.333
	a_i	g	k’	4.221	.349
			k^h	4.221	.108
		k’	k^h	4.221	.773
	a_u	g	k’	3.005	.018
			k^h	3.005	.002
		k’	k^h	3.005	.699
SH	a_a	g	k’	2.128	.000
			k^h	2.128	.000
		k’	k^h	2.128	.103
	a_i	g	k’	1.975	.001
			k^h	1.975	.000
		k’	k^h	1.975	.249
	a_u	g	k’	1.713	.000
			k^h	1.713	.000
		k’	k^h	1.713	.907

Table A12: Analysis of variance for closure duration. Results for three groups

Speaker	*Context*	*Consonant*	*Consonant*	*Standard error*	*Significance*
HS	a_a	g	k’	4.2414	.000
			k^h	4.3193	.000
		k’	k^h	3.5580	.000
	a_i	g	k’	4.0635	.000
			k^h	4.0635	.000
		k’	k^h	4.0635	.000
	a_u	g	k’	3.5265	.000
			k^h	3.5265	.000
		k’	k^h	3.5265	.007
	i_a	g	k’	4.2597	.000
			k^h	4.2597	.000
		k’	k^h	4.0161	.218
	u_a	g	k’	5.4567	.000
			k^h	5.4567	.000
		k’	k^h	4.4554	.086
	u_i	g	k’	6.8186	.000
			k^h	6.8186	.000
		k’	k^h	3.9367	.243
SH	i_i	g	k’	6.3984	.007
			k^h	6.3984	1.000
		k’	k^h	4.3469	.000
	u_i	g	k’	7.4377	.000
			k^h	7.4377	.051
		k’	k^h	5.0529	.000
	u_u	g	k’	14.4249	1.000
			k^h	13.0024	.752
		k’	k^h	10.8187	.688

Table A13: Analysis of variance for closure duration. Results for two groups (for HS /ugu/ and /uk'u/, in all other cases /k'/ and /k^h/)

Speaker	*Context*	*Significance*
HS	i_i	.964
	i_u	.867
	u_u	.000
HZ	a_a	.000
	a_i	.001
	a_u	.000
	i_a	.813
	i_i	.004
	i_u	.004
	u_a	.000
	u_i	.014
	u_u	.000
SH	a_a	.000
	a_i	.000
	a_u	.000
	i_a	.446
	i_u	.006
	u_a	.000

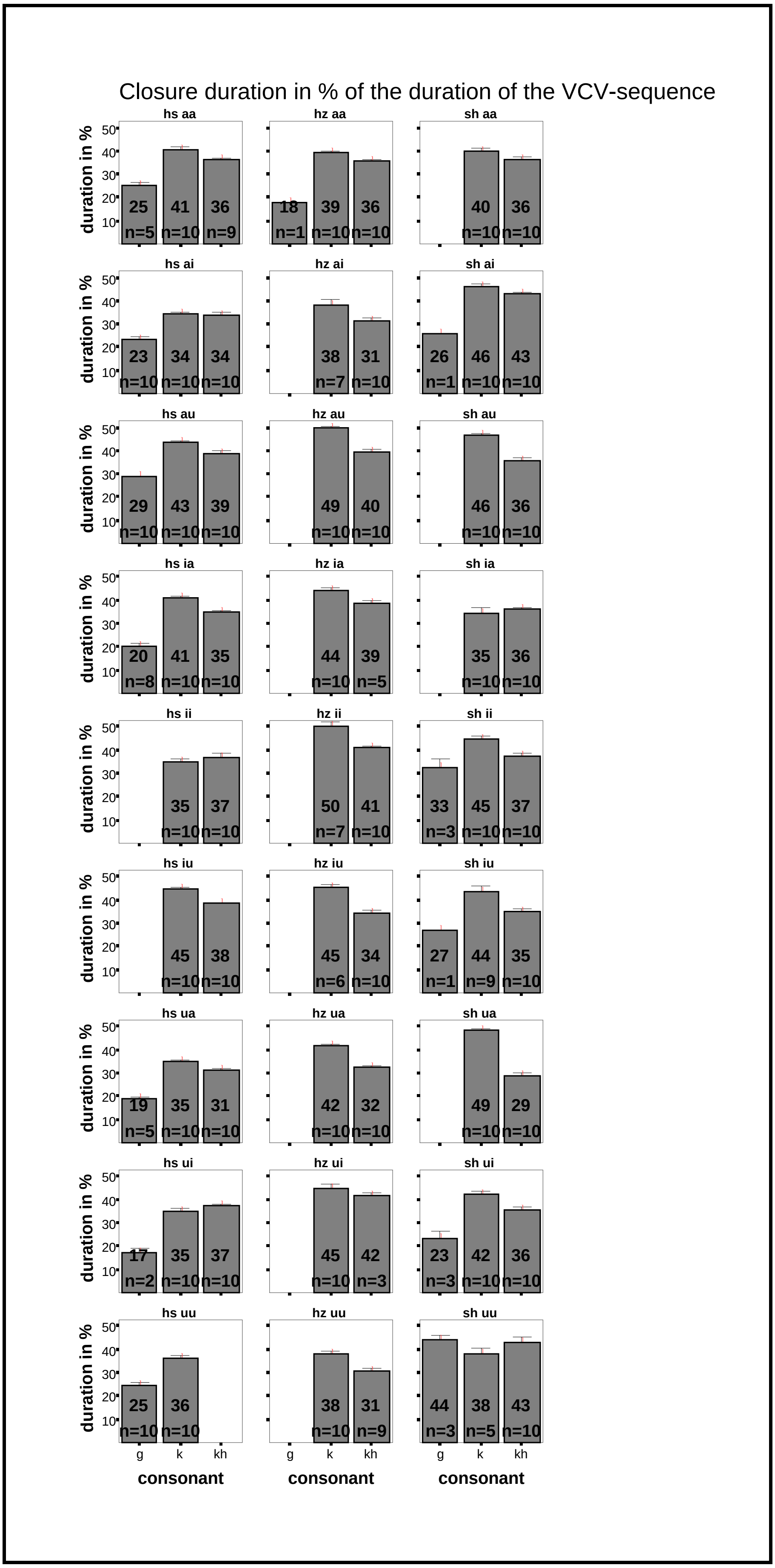


Figure A15: Closure duration in % of the duration of the VCV-sequence

Table A14: Analysis of variance for closure duration as percentage of the VCV-sequence. Results for three groups

Speaker	*Context*	*Consonant*	*Consonant*	*Standard error*	*Significance*
HS	a_a	g	k’	1.205	.000
			k^h	1.227	.000
		k’	k^h	1.011	.001
	a_i	g	k’	1.481	.000
			k^h	1.481	.000
		k’	k^h	1.481	.997
	a_u	g	k’	.733	.000
			k^h	.733	.000
		k’	k^h	.733	.000
	i_a	g	k’	1.218	.000
			k^h	1.218	.000
		k’	k^h	1.148	.000
	u_a	g	k’	.980	.000
			k^h	.980	.000
		k’	k^h	.800	.001
	u_i	g	k’	2.382	.000
			k^h	2.382	.000
		k’	k^h	1.375	.403
SH	i_I	g	k’	2.585	.001
			k^h	2.585	.237
		k’	k^h	1.756	.001
	u_i	g	k’	2.894	.000
			k^h	2.894	.001
		k’	k^h	1.966	.014
	u_u	g	k’	5.322	.544
			k^h	4.797	.958
		k’	k^h	3.991	.531

Table A15: Analysis of variance for closure duration as percentage of the VCV-sequence. Results for two groups

Speaker	*Context*	*Significance*
HS	i_i	.469
	i_u	.000
	u_u	.000
HZ	a_a	.000
	a_i	.031
	a_u	.000
	i_a	.016
	i_i	.000
	i_u	.000
	u_a	.000
	u_i	.406
	u_u	.000
SH	a_a	.010
	a_i	.000
	a_u	.000
	i_a	.581
	i_u	.002
	u_a	.000

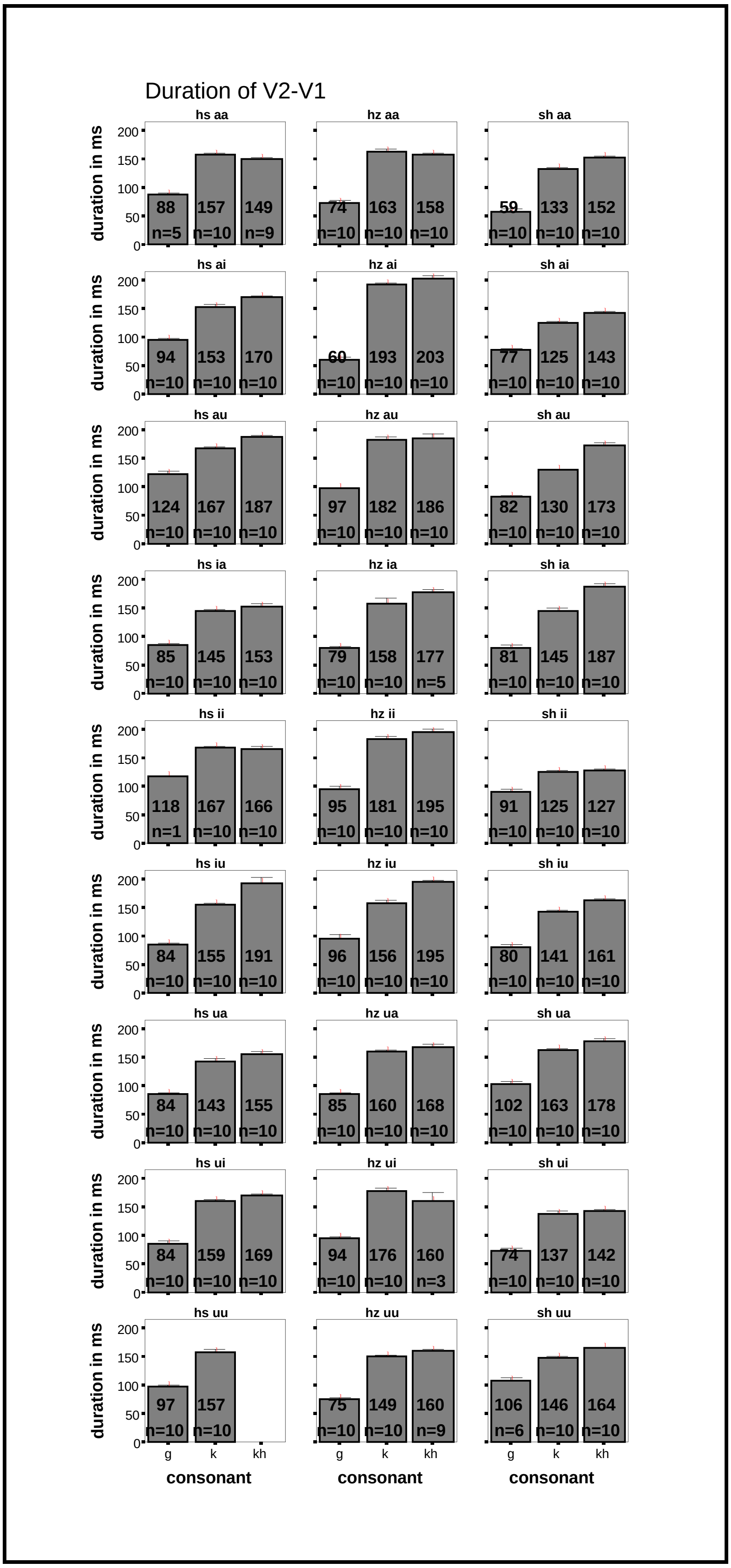


Figure A16: Durations of V2-V1 for HS (first column), HZ (second column) and SH (third column) in different vowel contexts.

Table A16: Analysis of variance for V2-V1 for the distinction /g/ vs. /k'/

Speaker	*Contexts*	*Cons.*	*Cons.*	*Standard error*	*Significance*
HS	a_a	g	k’	4.6218	.000
	a_i	g	k’	4.7962	.000
	a_u	g	k’	5.0294	.000
	i_a	g	k’	4.7951	.000
	i_u	g	k’	9.2961	.000
	u_a	g	k’	4.9737	.000
	u_i	g	k’	5.2275	.000
HZ	a_a	g	k’	6.1028	.000
	a_i	g	k’	5.7080	.000
	a_u	g	k’	6.6763	.000
	i_a	g	k’	9.3219	.000
	i_i	g	k’	7.7960	.000
	i_u	g	k’	7.9128	.000
	u_a	g	k’	4.9424	.000
	u_i	g	k’	7.3271	.000
	u_u	g	k’	4.6427	.000
SH	a_a	g	k’	3.6983	.000
	a_i	g	k’	2.7429	.000
	a_u	g	k’	4.1281	.000
	i_a	g	k’	5.8999	.000
	i_i	g	k’	4.3484	.000
	i_u	g	k’	5.0316	.000
	u_a	g	k’	4.2384	.000
	u_i	g	k’	5.7788	.000
	u_u	g	k’	4.9108	.000

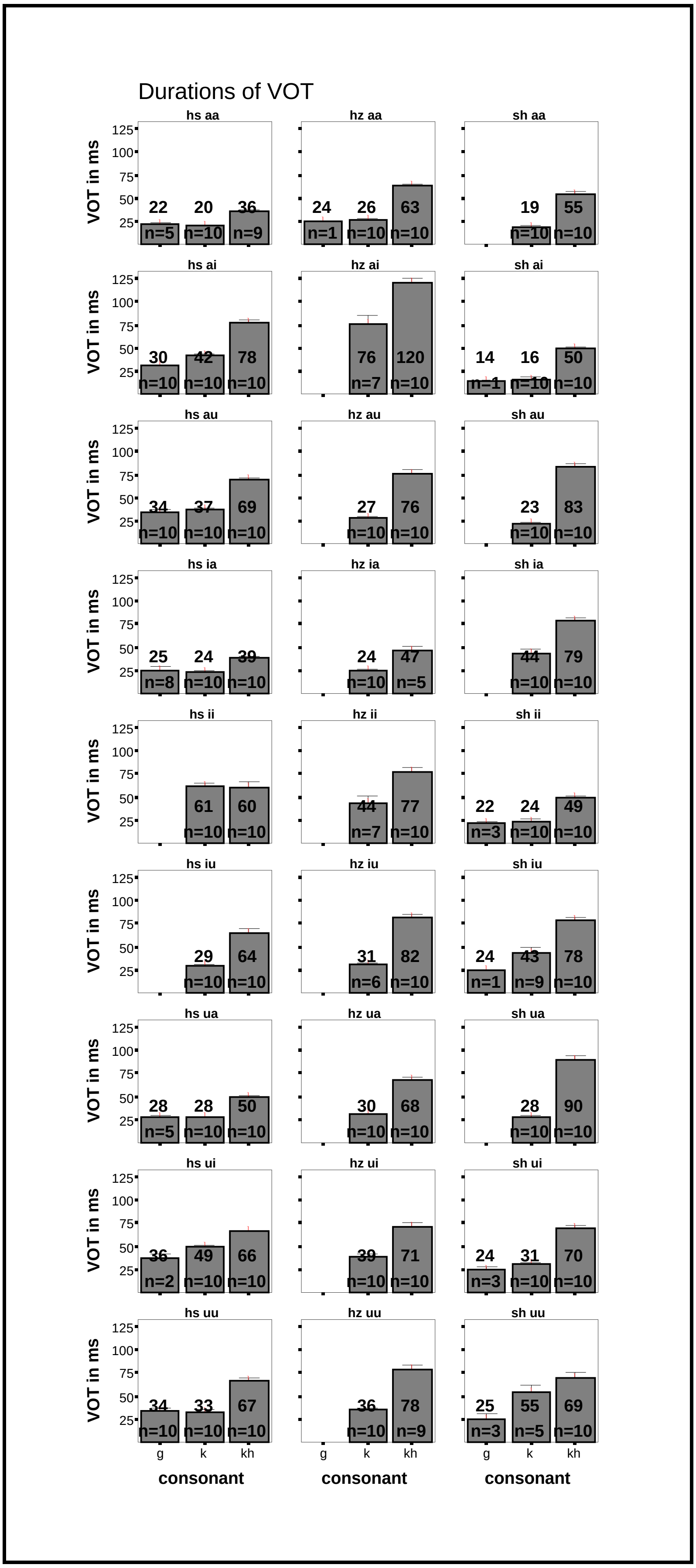


Figure A17: Durations of VOT for HS (first column), HZ (second column) and SH (third column) in different vowel contexts.

Table A17: Analysis of variance for VOT. Results for two groups, /Vk’V/ vs. /Vk^{h}V/

Speaker	*Context*	*Significance*
HS	i_i	.881
	i_u	.000
HZ	a_a	.000
	a_i	.001
	a_u	.000
	i_a	.000
	i_i	.000
	i_u	.000
	u_a	.000
	u_i	.000
	u_u	.000
SH	a_a	.000
	a_i	.000
	a_u	.000
	i_a	.000
	i_u	.000
	u_a	.000

Table A18: Analysis of variance for VOT. Results for three groups

Speaker	*Context*	*Consonant*	*Consonant*	*Standard error*	*Significance*
HS	a_a	k^h	g	1.816	.000
			k’	1.496	.000
	a_i	k^h	g	2.363	.000
			k’	2.363	.000
	a_u	k^h	g	3.118	.000
			k’	3.118	.000
	i_a	k^h	g	3.566	.002
			k’	3.362	.001
	u_a	k^h	g	2.579	.000
			k’	2.106	.000
	u_i	k^h	g	5.146	.000
			k’	2.971	.000
	u_u	k^h	g	3.590	.000
			k’	3.590	.000
SH	i_i	k^h	g	4.589	.000
			k’	3.118	.000
	u_i	k^h	g	5.443	.000
			k’	3.698	.000
	u_u	k^h	g	11.543	.006
			k’	9.605	.348

Table A19: Analysis of variance for percentage of voicing during closure. Results for three groups

Speaker	*Context*	*Consonant*	*Consonant*	*Standard error*	*Significance*
HS	a_a	g	k’	2.587	.000
			k^h	2.635	.000
	a_i	g	k’	3.258	.000
			k^h	3.258	.000
	a_u	g	k’	4.009	.000
			k^h	4.009	.000
	i_a	g	k’	2.486	.000
			k^h	2.486	.000
	i_i	g	k’	3.713	.000
			k^h	3.713	.000
	i_u	g	k’	3.006	.000
			k^h	3.006	.000
	u_a	g	k’	3.327	.000
			k^h	3.327	.000
	u_i	g	k’	5.881	.000
			k^h	5.881	.000
HZ	a_a	g	k’	1.782	.000
			k^h	1.782	.000
	a_i	g	k’	4.136	.000
			k^h	3.753	.000
	a_u	g	k’	1.036	.000
			k^h	1.036	.000
	i_a	g	k’	3.772	.000
			k^h	4.619	.000
	i_i	g	k’	1.901	.000
			k^h	1.725	.000
	i_u	g	k’	3.371	.000
			k^h	2.919	.000
	u_a	g	k’	1.169	.000
			k^h	1.169	.000
	u_u	g	k’	4.053	.000
			k^h	4.164	.000
SH	a_a	g	k’	1.753	.000
			k^h	1.753	.000
	a_i	g	k’	1.423	.000
			k^h	1.423	.000
	a_u	g	k’	1.414	.000
			k^h	1.414	.000
	i_a	g	k’	4.450	.000
			k^h	4.450	.000
	i_i	g	k’	3.124	.000
			k^h	3.124	.000
	i_u	g	k’	7.430	.000
			k^h	7.430	.000
	u_a	g	k’	2.745	.000
			k^h	2.745	.000
	u_i	g	k’	2.604	.000
			k^h	2.604	.000

	u_u	g	k’	10.733	.021
			k^h	10.733	.000

Table A20: Analysis of variance for percentage of voicing during closure. Results for two groups

Speaker	*Context*	*Significance*
HS	u_u	.713
HZ	u_i	.000

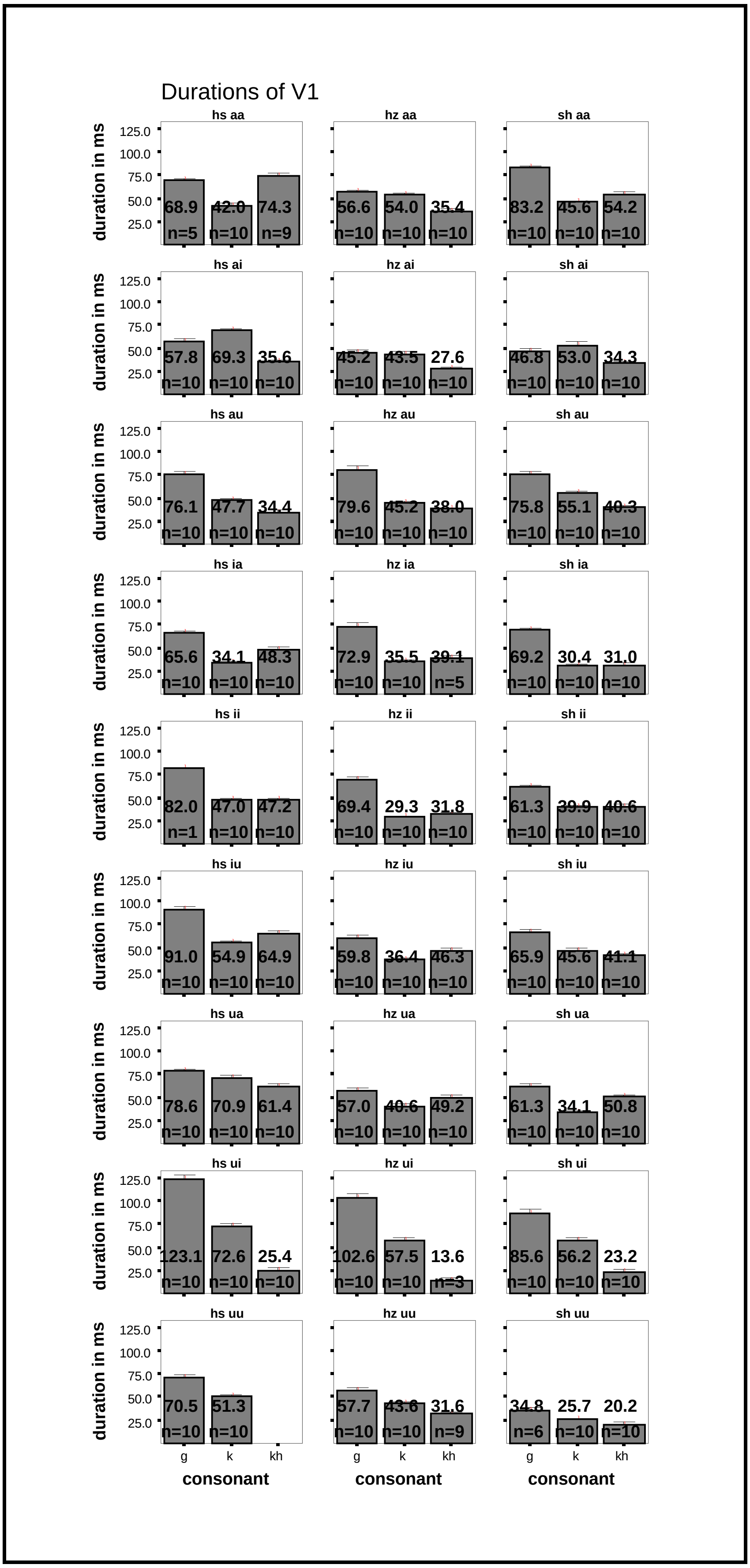


Figure A18: Duration of V1 for HS (first column), HZ (second column) and SH (third column) in different vowel contexts

Table A21: Analysis of variance for duration of V1. Results for three groups

Speaker	*Context*	*Consonant*	*Consonant*	*Standard error*	*Significance*
HS	a_a	g	k’	4.1990	.000
			k^h	4.2760	.459
	a_i	g	k’	3.4513	.009
			k^h	3.4513	.000
	a_u	g	k’	3.1354	.000
			k^h	3.1354	.000
	i_a	g	k’	3.0968	.000
			k^h	3.0968	.000
	i_u	g	k’	3.7740	.000
			k^h	3.7740	.000
	u_a	g	k’	4.3548	.224
			k^h	4.3548	.002
	u_i	g	k’	4.8506	.000
			k^h	4.8506	.000
HZ	a_a	g	k’	2.8757	.677
			k^h	2.8757	.000
	a_i	g	k’	3.4496	.892
			k^h	3.4496	.000
	a_u	g	k’	4.0917	.000
			k^h	4.0917	.000
	i_a	g	k’	3.8368	.000
			k^h	4.6990	.000
	i_i	g	k’	2.3131	.000
			k^h	2.3131	.000
	i_u	g	k’	4.1810	.000
			k^h	4.1810	.012
	u_a	g	k’	3.7816	.001
			k^h	3.7816	.143
	u_i	g	k’	5.9349	.000
			k^h	8.7360	.000
	u_u	g	k’	2.5249	.000
			k^h	2.5941	.000
SH	a_a	g	k’	2.8884	.000
			k^h	2.8884	.000
	a_i	g	k’	3.5933	.244
			k^h	3.5933	.007
	a_u	g	k’	2.6904	.000
			k^h	2.6904	.000
	i_a	g	k’	3.0636	.000
			k^h	3.0636	.000
	i_i	g	k’	3.3303	.000
			k^h	3.3303	.000
	i_u	g	k’	4.1159	.000
			k^h	4.1159	.000
	u_a	g	k’	3.0859	.000
			k^h	3.0859	.008
	u_i	g	k’	5.5927	.000
			k^h	5.5927	.000

	u_u	g	k’	3.6645	.067
			k^h	3.6645	.002

Table A22: Analysis of variance for duration of V1. Results for two groups

Speaker	*Context*	*Significance*
HS	i_i	.001
	u_u	.000

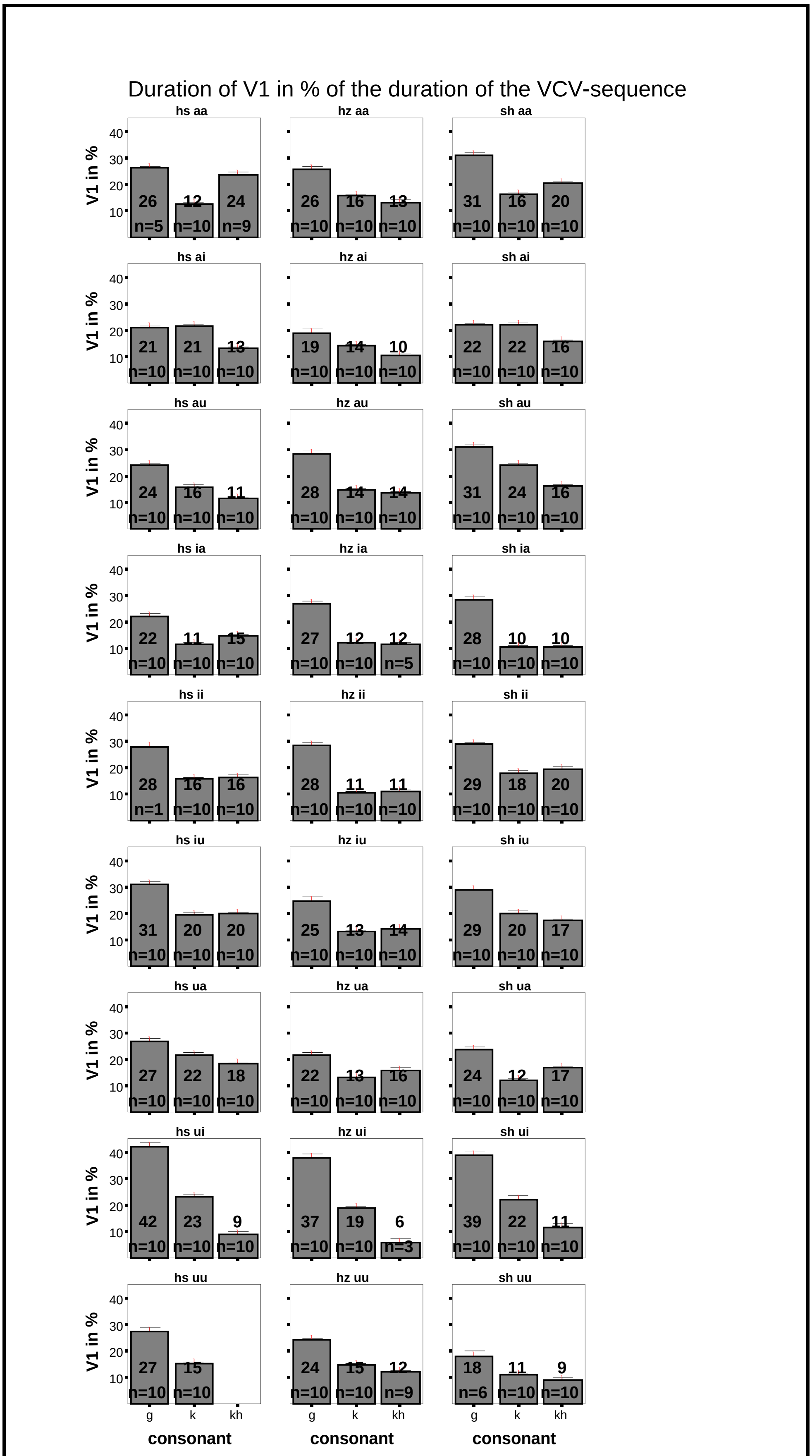


Figure A19: Duration of V1 in % of the duration of the VCV-sequence

Table A23: Analysis of variance for duration of V1 in % of duration of the /VCV-sequence. Results for three groups

Speaker	*Context*	*Consonant*	*Consonant*	*Standard error*	*Significance*
HS	a_a	g	k’	1.168	.000
			k^h	1.189	.140
	a_i	g	k’	.910	.870
			k^h	.910	.000
	a_u	g	k’	.822	.000
			k^h	.822	.000
	i_a	g	k’	.853	.000
			k^h	.853	.000
	i_u	g	k’	1.093	.000
			k^h	1.093	.000
	u_a	g	k’	1.056	.000
			k^h	1.056	.000
	u_i	g	k’	1.380	.000
			k^h	1.380	.000
HZ	a_a	g	k’	1.108	.000
			k^h	1.108	.000
	a_i	g	k’	1.215	.001
			k^h	1.215	.000
	a_u	g	k’	1.019	.000
			k^h	1.019	.000
	i_a	g	k’	1.529	.000
			k^h	1.872	.000
	i_i	g	k’	.899	.000
			k^h	.899	.000
	i_u	g	k’	1.635	.000
			k^h	1.635	.000
	u_a	g	k’	1.171	.000
			k^h	1.171	.000
	u_i	g	k’	1.647	.000
			k^h	2.424	.000
	u_u	g	k’	.745	.000
			k^h	.766	.000
SH	a_a	g	k’	1.110	.000
			k^h	1.110	.000
	a_i	g	k’	1.200	.978
			k^h	1.200	.000
	a_u	g	k’	1.188	.000
			k^h	1.188	.000
	i_a	g	k’	1.182	.000
			k^h	1.182	.000
	i_i	g	k’	1.350	.000
			k^h	1.350	.000
	i_u	g	k’	1.311	.000
			k^h	1.311	.000
	u_a	g	k’	1.025	.000
			k^h	1.025	.000
	u_i	g	k’	2.184	.000
			k^h	2.184	.000

	u_u	g	k’	1.503	.001
			k^h	1.503	.000

Table A24: Analysis of variance for duration of V1 in percentages of duration of the /VCV-sequence. Results for two groups

Speaker	*Context*	*Significance*
HS	ii	.001
	uu	.000

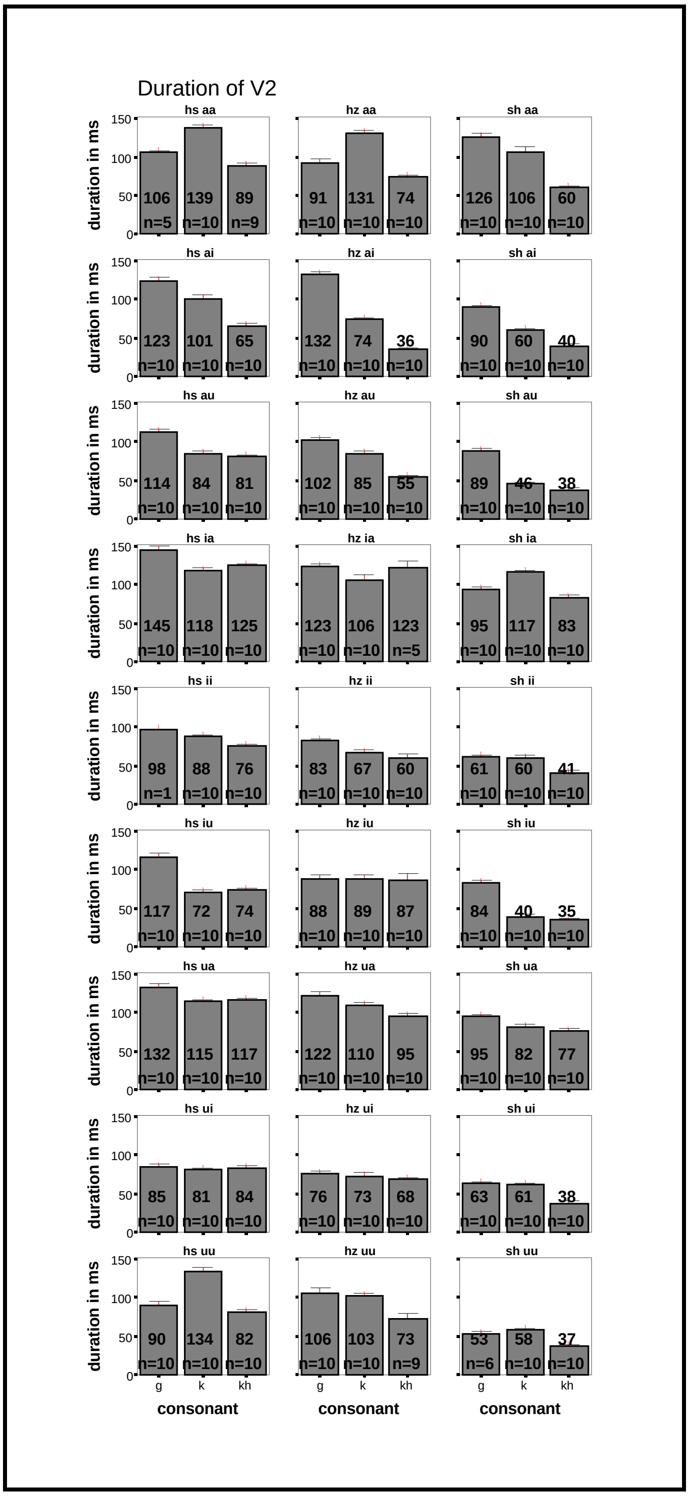


Figure A20: Duration of V2

Table A25: Analysis of variance for duration of V2. Results for three groups

Speaker	*Context*	*Consonant*	*Consonant*	*Standard error*	*Significance*
HS	a_a	g	k’	4.783	.000
			k^h	4.870	.011
		k’	k^h	4.012	.000
	a_i	g	k’	7.032	.017
			k^h	7.032	.000

		k'	k^h	7.032	.000
	a_u	g	k'	4.524	.000
			k^h	4.524	.000
		k'	k^h	4.524	.738
	i_a	g	k'	5.481	.000
			k^h	5.481	.006
		k'	k^h	5.481	.414
	i_u	g	k'	5.462	.000
			k^h	5.462	.000
		k'	k^h	5.462	.903
	u_a	g	k'	4.740	.003
			k^h	4.740	.014
		k'	k^h	4.740	.831
	u_i	g	k'	3.779	.638
			k^h	3.779	.955
		k'	k^h	3.779	.810
	u_u	g	k'	6.482	.000
			k^h	6.482	.482
		k'	k^h	6.482	.000
HZ	a_a	g	k'	6.311	.000
			k^h	6.311	.038
		k'	k^h	6.311	.000
	a_i	g	k'	4.442	.000
			k^h	4.442	.000
		k'	k^h	4.442	.000
	a_u	g	k'	4.175	.002
			k^h	4.175	.000
		k'	k^h	4.175	.000
	i_a	g	k'	8.148	.141
			k^h	9.979	.999
		k'	k^h	9.979	.280
	i_i	g	k'	5.017	.016
			k^h	5.017	.000
		k'	k^h	5.017	.353
	i_u	g	k'	8.995	.998
			k^h	8.995	.999
		k'	k^h	8.995	.993
	u_a	g	k'	5.874	.131
			k^h	5.874	.000
		k'	k^h	5.874	.052
	u_i	g	k'	4.511	.789
			k^h	4.511	.217
		k'	k^h	4.511	.550
	u_u	g	k'	8.056	.941
			k^h	8.277	.002
		k'	k^h	8.277	.004
SH	a_a	g	k'	6.847	.029
			k^h	6.847	.000
		k'	k^h	6.847	.000
	a_i	g	k'	2.851	.000
			k^h	2.851	.000

		k’	k^h	2.851	.000
	a_u	g	k’	4.641	.000
			k^h	4.641	.000
		k’	k^h	4.641	.202
	i_a	g	k’	4.077	.000
			k^h	4.077	.030
		k’	k^h	4.077	.000
	i_i	g	k’	4.339	.959
			k^h	4.339	.000
		k’	k^h	4.339	.001
	i_u	g	k’	3.846	.000
			k^h	3.846	.000
		k^h	g	3.846	.000
	u_a	g	k’	2.822	.000
			k^h	2.822	.000
		k’	k^h	2.822	.168
	u_i	g	k’	3.281	.836
			k^h	3.281	.000
		k’	k^h	3.281	.000
	u_u	g	k’	3.545	.452
			k^h	3.545	.000
		k’	k^h	3.070	.000

Table A26: Analysis of variance for duration of V2. Results for two groups

Speaker	*Context*	*Significance*
HS	i_i	.000

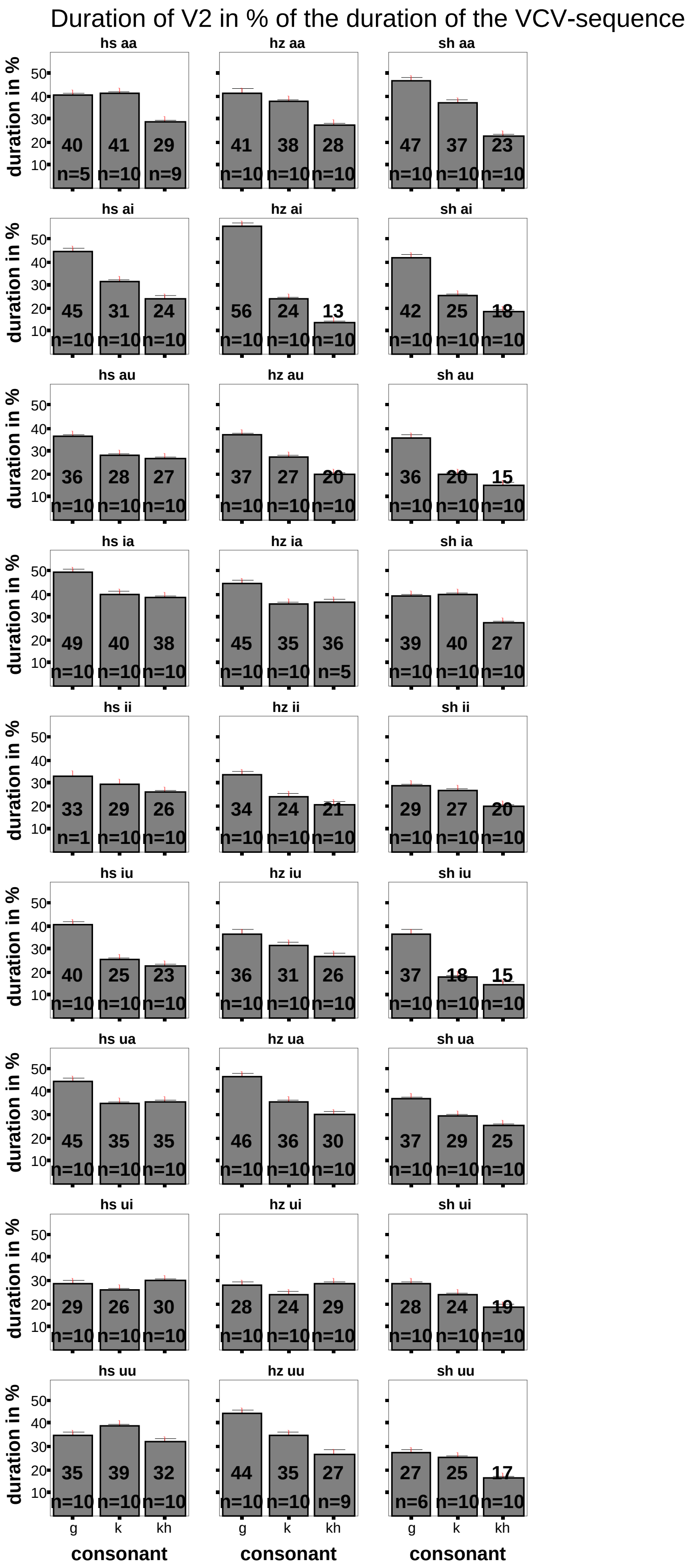


Figure A21: Duration of V2 in percent of the duration of the VCV-sequence

Table A27: Analysis of variance for duration of V2 in % of the duration of the VCV-sequence. Results for three groups

Speaker	*Context*	*Consonant*	*Consonant*	*Standard error*	*Significance*
HS	a_a	g	k’	1.081	.748
			k^h	1.101	.000
		k’	g	1.081	.748
			k^h	.907	.000
	a_i	g	k’	1.718	.000
			k^h	1.718	.000
		k’	g	1.718	.000
			k^h	1.718	.001
	a_u	g	k’	1.059	.000
			k^h	1.059	.000
		k’	g	1.059	.000
			k^h	1.059	.404
	i_a	g	k’	1.574	.000
			k^h	1.574	.000
		k’	g	1.574	.000
			k^h	1.574	.720
	i_u	g	k’	1.784	.000
			k^h	1.784	.000
		k’	g	1.784	.000
			k^h	1.784	.288
	u_a	g	k’	1.059	.000
			k^h	1.059	.000
		k’	g	1.059	.000
			k^h	1.059	.910
	u_i	g	k’	1.326	.092
			k^h	1.326	.756
		k’	g	1.326	.092
			k^h	1.326	.019
	u_u	g	k’	1.702	.053
			k^h	1.702	.387
		k’	g	1.702	.053
			k^h	1.702	.002
HZ	a_a	g	k’	1.810	.214
			k^h	1.810	.000
		k’	g	1.810	.214
			k^h	1.810	.000
	a_i	g	k’	1.232	.000
			k^h	1.232	.000
		k’	g	1.232	.000
			k^h	1.232	.000
	a_u	g	k’	1.220	.000
			k^h	1.220	.000
		k’	g	1.220	.000
			k^h	1.220	.000
	i_a	g	k’	1.288	.000
			k^h	1.578	.000
		k’	g	1.288	.000

			k^h	1.578	.877
	i_i	g	k’	1.578	.000
			k^h	1.578	.000
		k’	g	1.578	.000
			k^h	1.578	.119
	i_u	g	k’	2.440	.180
			k^h	2.440	.002
		k’	g	2.440	.180
			k^h	2.440	.150
	u_a	g	k’	1.549	.000
			k^h	1.549	.000
		k’	g	1.549	.000
			k^h	1.549	.008
	u_i	g	k’	1.728	.074
			k^h	1.728	.941
		k’	g	1.728	.074
			k^h	1.728	.036
	u_u	g	k’	2.301	.002
			k^h	2.364	.000
		k’	g	2.301	.002
			k^h	2.364	.009
SH	a_a	g	k’	1.624	.000
			k^h	1.624	.000
		k’	g	1.624	.000
			k^h	1.624	.000
	a_i	g	k’	1.167	.000
			k^h	1.167	.000
		k’	g	1.167	.000
			k^h	1.167	.000
	a_u	g	k’	1.601	.000
			k^h	1.601	.000
		k’	g	1.601	.000
			k^h	1.601	.014
	i_a	g	k’	1.166	.527
			k^h	1.166	.000
		k’	g	1.166	.527
			k^h	1.166	.000
	i_i	g	k’	1.456	.399
			k^h	1.456	.000
		k’	g	1.456	.399
			k^h	1.456	.000
	i_u	g	k’	1.743	.000
			k^h	1.743	.000
		k’	g	1.743	.000
			k^h	1.743	.268
	u_a	g	k’	.927	.000
			k^h	.927	.000
		k’	g	.927	.000
			k^h	.927	.000
	u_i	g	k’	1.406	.014
			k^h	1.406	.000

		k’	g	1.406	.014
			k^h	1.406	.003
	u_u	g	k’	1.301	.262
			k^h	1.301	.000
		k’	g	1.301	.262
			k^h	1.127	.000

Table A28: Analysis of variance for duration of V2 as percentage of the duration of the VCV-sequence. Results for two groups

Speaker	*Context*	*Significance*
HS	i_i	.000

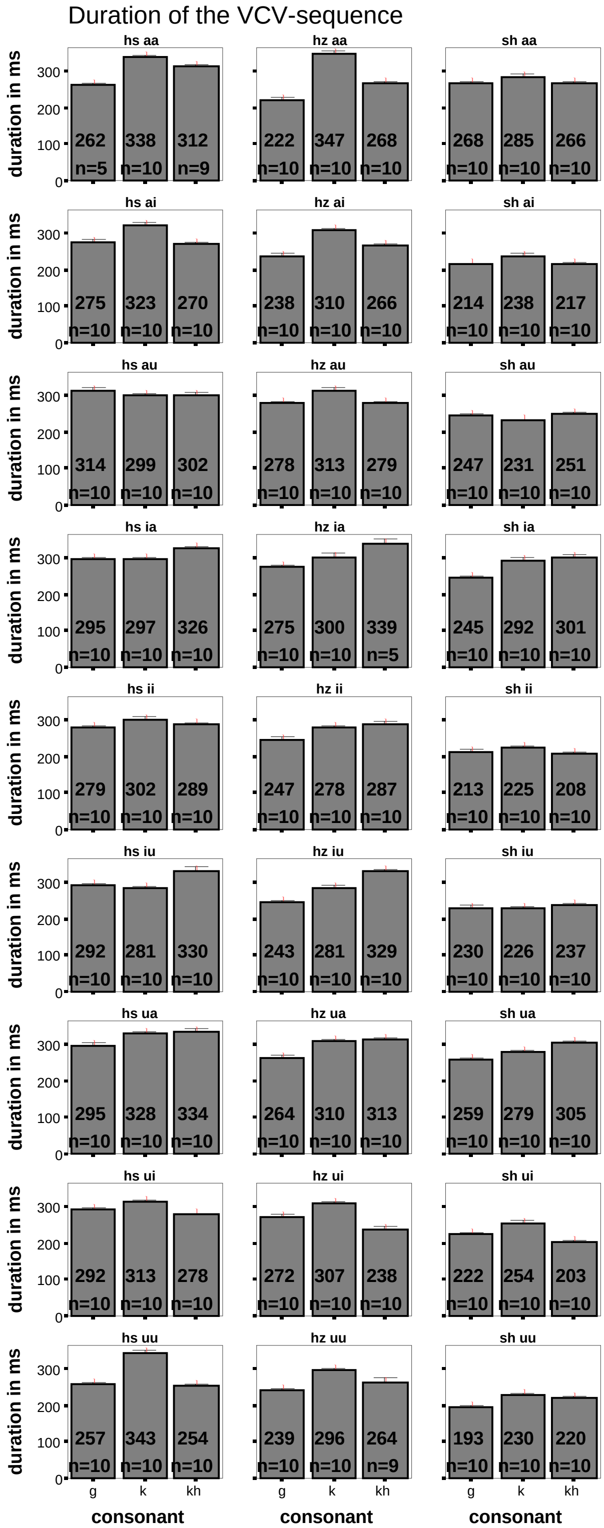


Figure A22: Duration of the VCV-sequence

Table A29: Analysis of variance for the duration of the VCV-sequence

Speaker	*Context*	*Cons.*	*Cons.*	*Standard error*	*Significance*
HS	a_a	g	k’	8.1715	.000
			k^h	8.3214	.000
		k’	k^h	6.8548	.004
	a_i	g	k’	9.2098	.000
			k^h	9.2098	.893
		k’	k^h	9.2098	.000
	a_u	g	k’	9.3460	.300
			k^h	9.3460	.481
		k’	k^h	9.3460	.937
	i_a	g	k’	7.4071	.974
			k^h	7.4071	.001
		k’	k^h	7.4071	.002
	i_i	g	k’	6.6380	.007
			k^h	6.6380	.313
		k’	k^h	6.6380	.182
	i_u	g	k’	11.6615	.654
			k^h	11.6615	.011
		k’	k^h	11.6615	.001
	u_a	g	k’	10.4580	.015
			k^h	10.4580	.005
		k’	k^h	10.4580	.890
	u_i	g	k’	4.9090	.001
			k^h	4.9090	.026
		k’	k^h	4.9090	.000
	u_u	g	k’	9.1933	.000
			k^h	9.1933	.935
		k’	k^h	9.1933	.000
HZ	a_a	g	k’	10.4710	.000
			k^h	10.4710	.001
		k’	k^h	10.4710	.000
	a_i	g	k’	8.6938	.000
			k^h	8.6938	.010
		k’	k^h	8.6938	.000
	a_u	g	k’	9.2492	.004
			k^h	9.2492	.996
		k’	k^h	9.2492	.005
	i_a	g	k’	15.3195	.297
			k^h	18.7625	.009
		k’	k^h	18.7625	.133
	i_i	g	k’	10.0726	.017
			k^h	10.0726	.002
		k’	k^h	10.0726	.692
	i_u	g	k’	11.6861	.011
			k^h	11.6861	.000
		k’	k^h	11.6861	.002
	u_a	g	k’	7.1154	.000
			k^h	7.1154	.000
		k’	k^h	7.1154	.951
	u_i	g	k’	7.0527	.000

			k^h	7.0527	.000
		k’	k^h	7.0527	.000
	u_u	g	k’	9.6019	.000
			k^h	9.8650	.058
		k’	k^h	9.8650	.013
SH	a_a	g	k’	7.5433	.088
			k^h	7.5433	.980
		k’	k^h	7.5433	.059
	a_i	g	k’	6.0135	.002
			k^h	6.0135	.900
		k’	k^h	6.0135	.006
	a_u	g	k’	5.5716	.033
			k^h	5.5716	.763
		k’	k^h	5.5716	.006
	i_a	g	k’	8.2395	.000
			k^h	8.2395	.000
		k’	k^h	8.2395	.582
	i_i	g	k’	7.4467	.339
			k^h	7.4467	.769
		k’	k^h	7.4467	.102
	i_u	g	k’	7.4304	.890
			k^h	7.4304	.622
		k’	k^h	7.4304	.354
	u_a	g	k’	5.3786	.004
			k^h	5.3786	.000
		k’	k^h	5.3786	.000
	u_i	g	k’	7.3381	.001
			k^h	7.3381	.048
		k’	k^h	7.3381	.000
	u_u	g	k’	6.3462	.000
			k^h	6.3462	.001
		k’	k^h	6.3462	.357

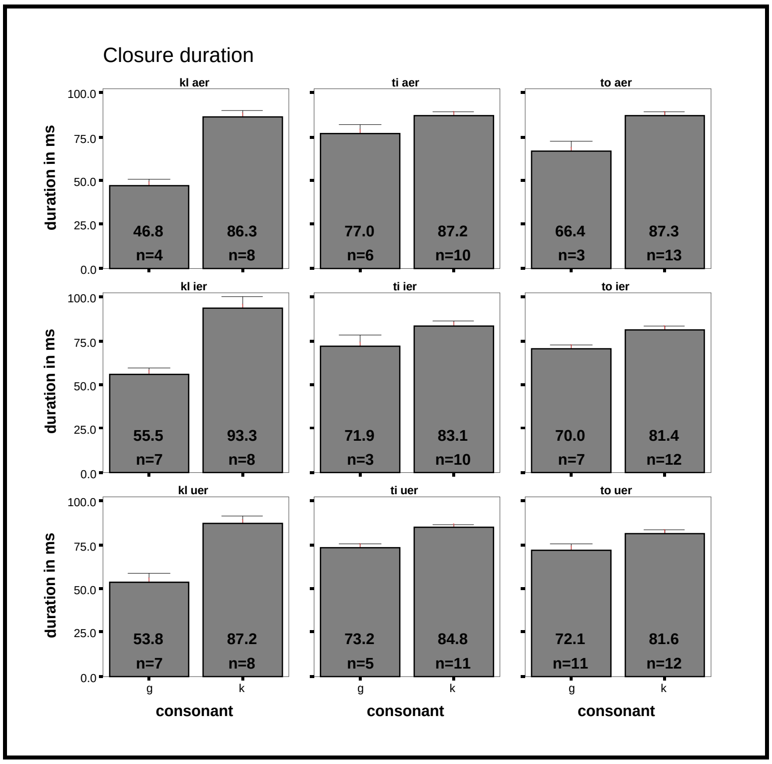


Figure A23: Closure duration for the German speakers KL (first column), TI (second column) and TO (third column) in sequences with different V1 and constant V2.

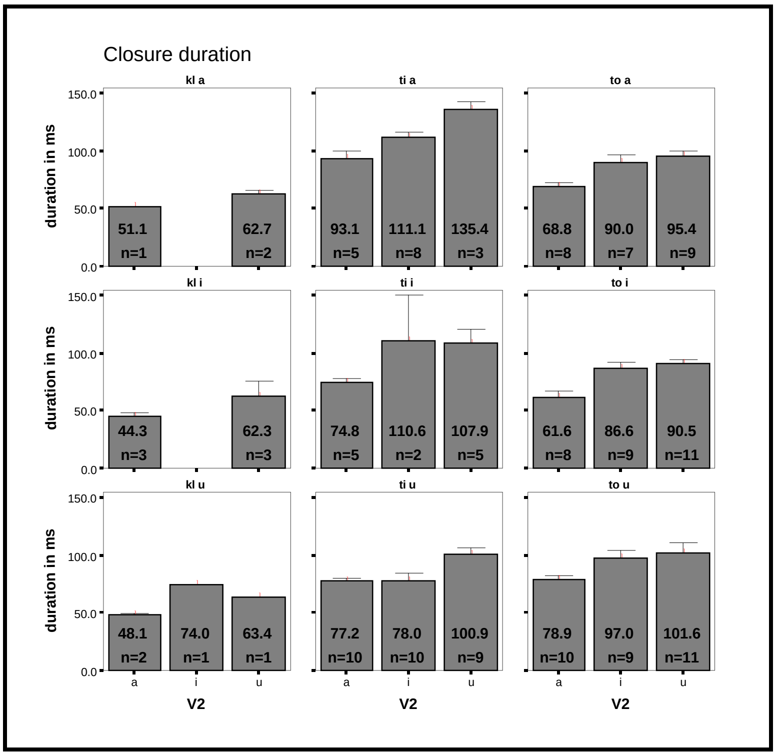


Figure A24: Closure duration of /g/ in different vowel contexts for the German speakers KL (first column), TI (second column) and TO (third column) in sequences with V1=/a/ (first row), /i/ (second row) and /u/ (third row) and V2=/a/ (first bar), /i/ (second bar) and /u/ (third bar)

Table A30: Analysis of variance for closure duration for the German speakers

Speaker	*Context*	*Significance*
KL	a_❶	.000
	i_❶	.001
	u_❶	.000
TI	a_❶	.047
	i_❶	.148
	u_❶	.000
TO	a_❶	.000
	i_❶	.007
	u_❶	.017

Table A31: Analysis of variance for closure duration of /g/ for the German speakers

Speaker	*V1*	*V2*	*V2*	*Standard error*	*Significance*
TI	a	a	i	7.8838	.111
			u	10.0993	.004
		i	u	9.3623	.067
	i	a	i	22.3625	.323
			u	16.9045	.202
		i	u	22.3625	.993
	u	a	i	7.0627	.993
			u	7.2562	.011
		i	u	7.2562	.015
TO	a	a	i	6.9875	.021
			u	6.5604	.002
		i	u	6.8040	.736
	i	a	i	6.8121	.005
			u	6.5141	.001
		i	u	6.3011	.829
	u	a	i	9.9189	.210
			u	9.4324	.073
		i	u	9.7030	.893

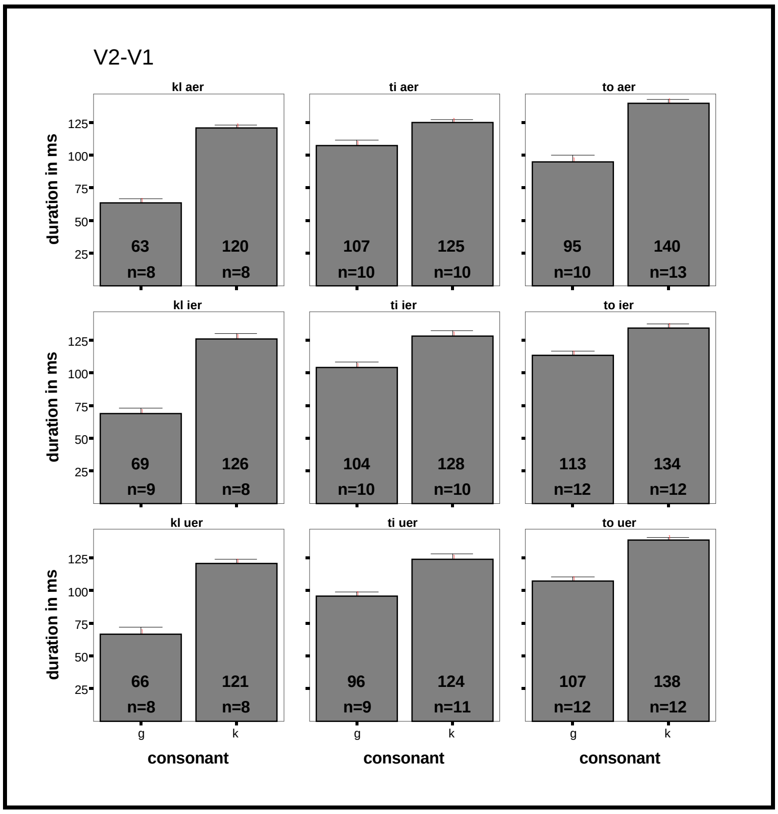


Figure A25: Duration of V2-V1 for the German speakers KL (first column), TI (second column) and TO (third column) in sequences with different V1 and constant V2

Table A32: Analysis of variance for duration of V2-V1 for the German speakers

Speaker	*Context*	*Significance*
KL	a_❶	.000
	i_❶	.000
	u_❶	.000
TI	a_❶	.002
	i_❶	.000
	u_❶	.000
TO	a_❶	.000
	i_❶	.000
	u_❶	.000

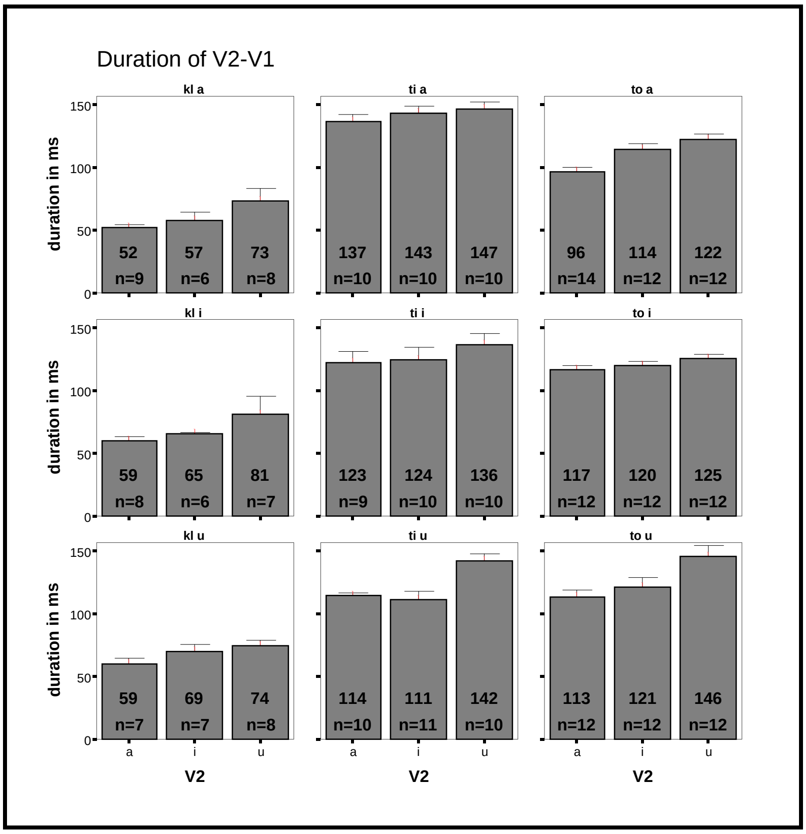


Figure A26: Duration of V2-V1 for /g/ in different vowel contexts for the German speakers KL (first column), TI (second column) and TO (third column) in sequences with V1=/a/ (first row), /i/ (second row) and /u/ (third row) and V2=/a/ (first bar), /i/ (second bar) and /u/ (third bar).

Table A33: Analysis of variance for the duration of V2-V1 for the German speakers

Speaker	*V1*	*V2*	*V2*	*Standard error*	*Significance*
KL	a	a	i	10.27615	.877
			u	9.47414	.114
		i	u	10.52992	.355
	i	a	i	12.57676	.898
			u	12.05249	.235
		i	u	12.95604	.502
	u	a	i	7.11177	.396
			u	6.88594	.121
		i	u	6.88594	.766
TI	a	a	i	7.50103	.705
			u	7.50103	.417
		i	u	7.50103	.882
	i	a	i	13.76712	.992
			u	13.76712	.613
		i	u	13.39993	.675
	u	a	i	7.59576	.942
			u	7.77451	.004
		i	u	7.59576	.001
TO	a	a	i	6.23114	.026
			u	6.23114	.001

		i	u	6.46636	.467
	i	a	i	4.91044	.857
			u	4.91044	.250
		i	u	4.91044	.526
	u	a	i	10.01803	.733
			u	10.01803	.010
		i	u	10.01803	.060

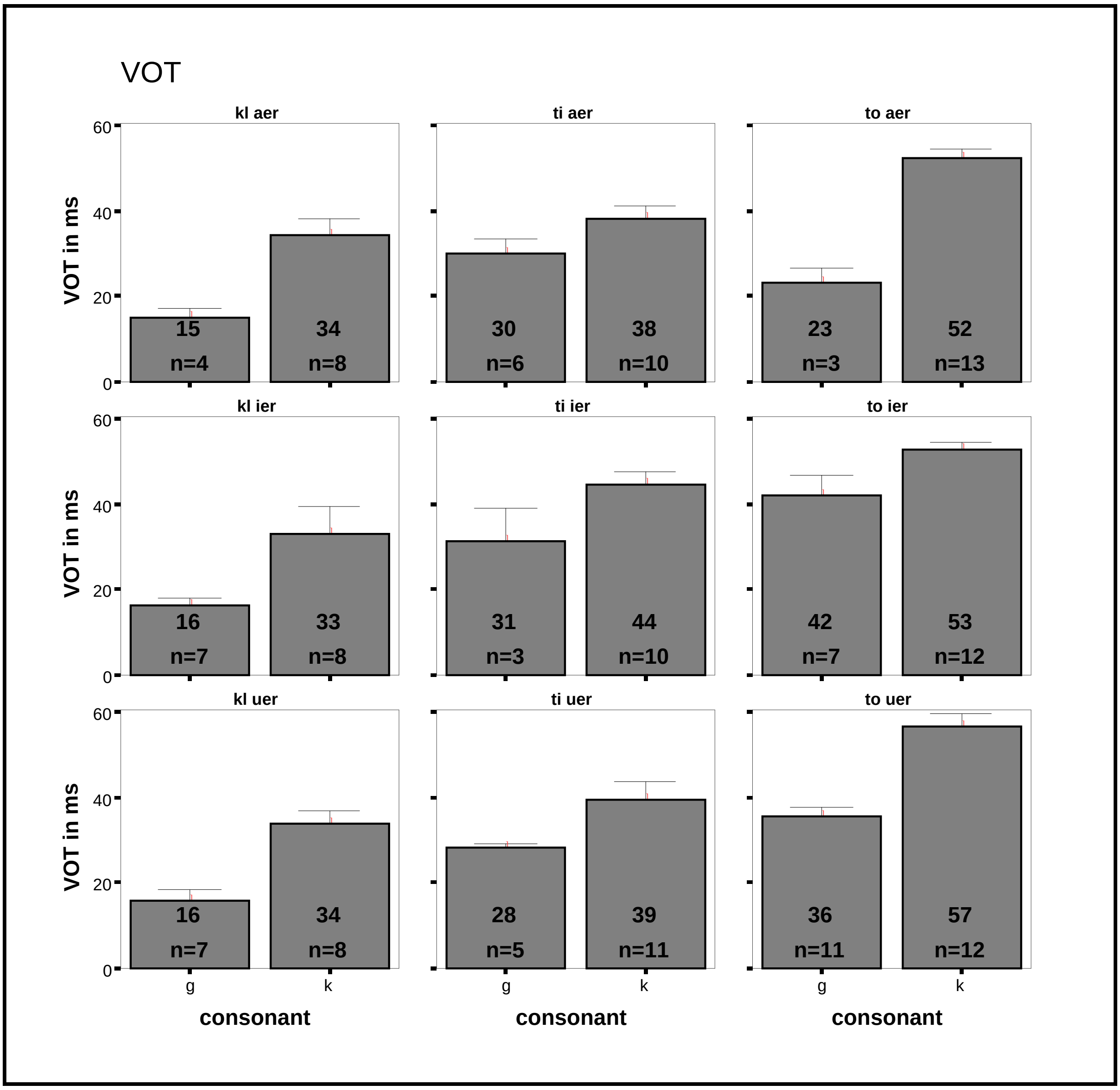


Figure A27: VOT for the German speakers KL (first column), TI (second column) and TO (third column) in sequences with different V1 and constant V2

Table A34: Analysis of variance for VOT for the German speakers

Speaker	*Context*	*Significance*
KL	a_ɐ	.007
	i_ɐ	.036
	u_ɐ	.001
TI	a_ɐ	.123

TO	i_ɐ	.086
	u_ɐ	.120
	a_ɐ	.000
	i_ɐ	.025
	u_ɐ	.000

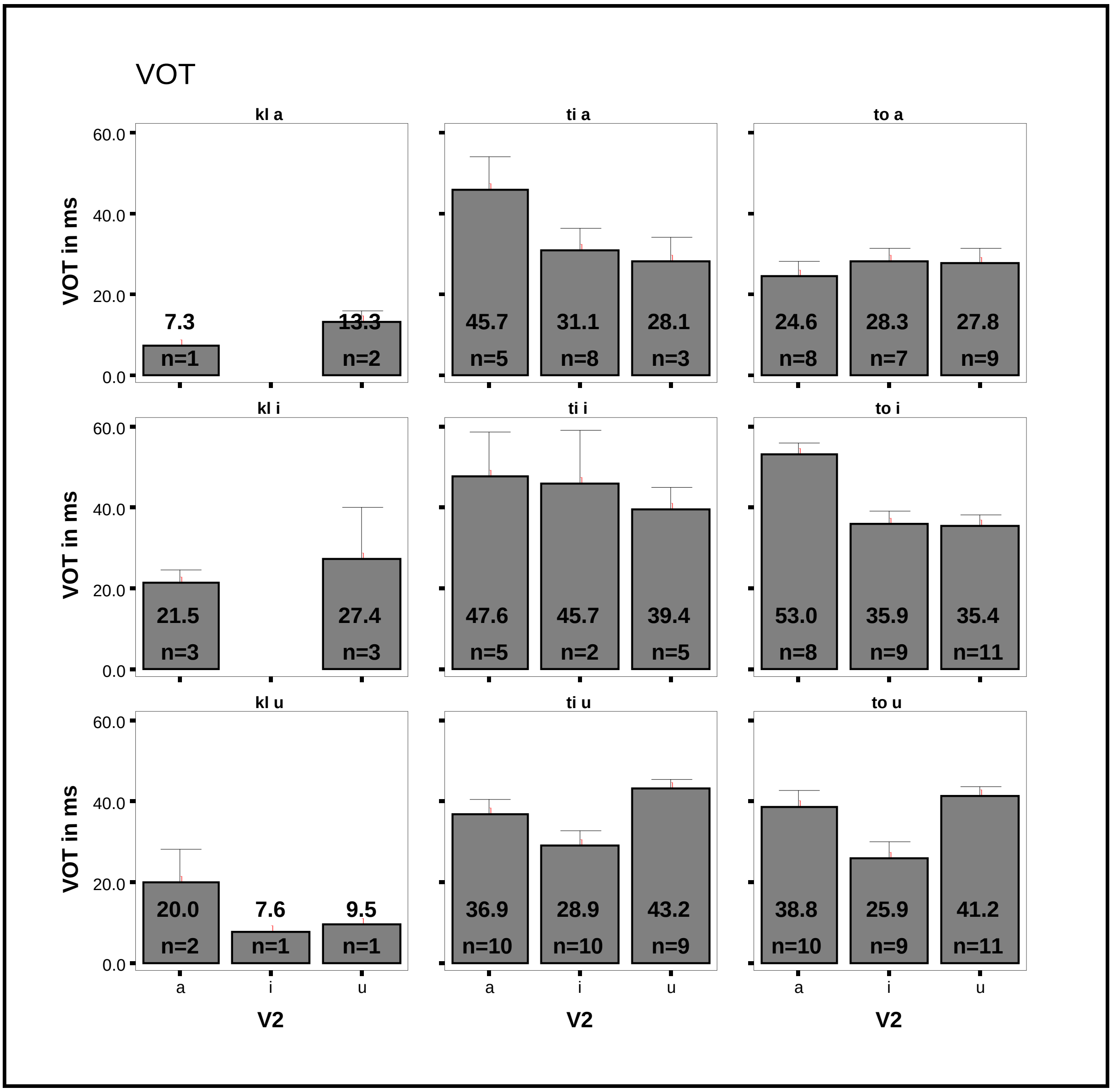


Figure A28: VOT for /g/ in different vowel contexts for the German speakers KL (first column), TI (second column) and TO (third column) in sequences with V1=/a/ (first row), /i/ (second row) and /u/ (third row) and V2=/a/ (first bar), /i/ (second bar) and /u/ (third bar)

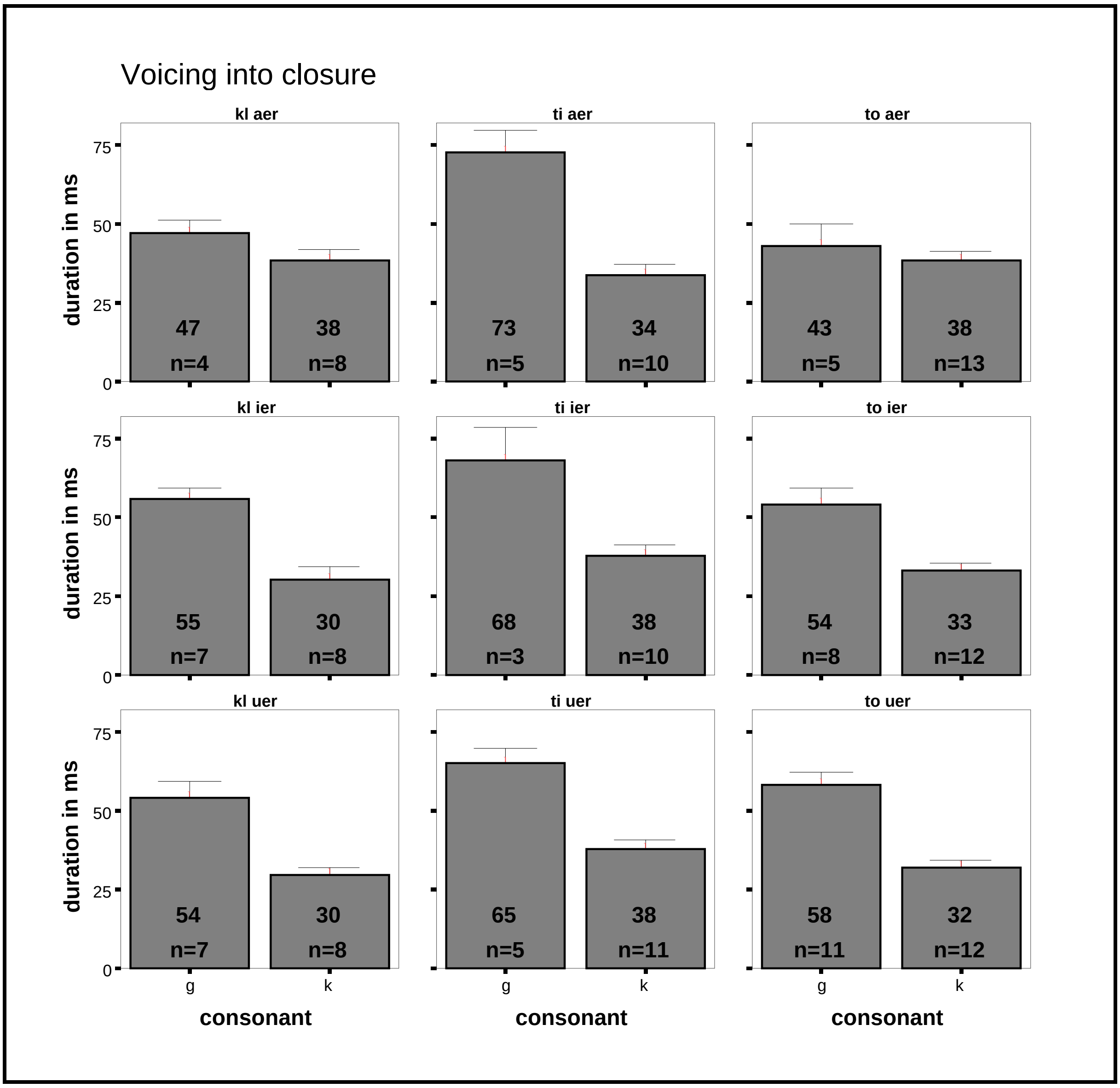


Figure A29: Duration of voicing into closure for the German speakers KL (first column), TI (second column) and TO (third column) in sequences with different V1 and constant V2

Table A35: Analysis of variance for voicing into closure for the German speakers

Speaker	*Context*	*Significance*
KL	a_❶	.152
	i_❶	.000
	u_❶	.001
TI	a_❶	.000
	i_❶	.004
	u_❶	.000
TO	a_❶	.417
	i_❶	.001
	u_❶	.000

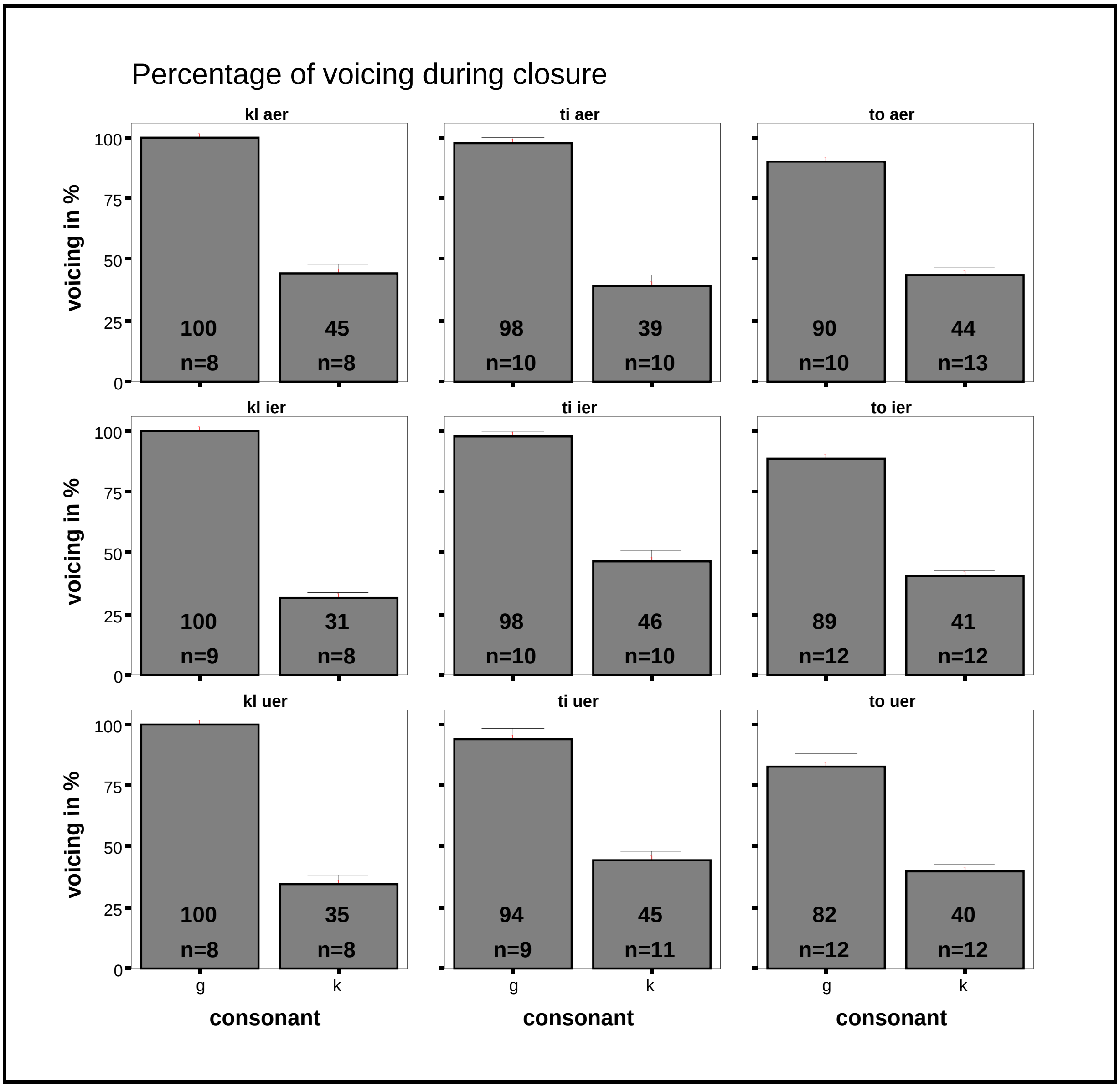


Figure A30: Percentage of voicing during closure for the German speakers KL (first column), TI (second column) and TO (third column) in sequences with different V1 and constant V2

Table A36: Analysis of variance for voicing into closure in % of closure duration for the German speakers

Speaker	*Context*	*Significance*
KL	a_❶	.000
	i_❶	.000
	u_❶	.000
TI	a_❶	.000
	i_❶	.000
	u_❶	.000
TO	a_❶	.000
	i_❶	.000
	u_❶	.000

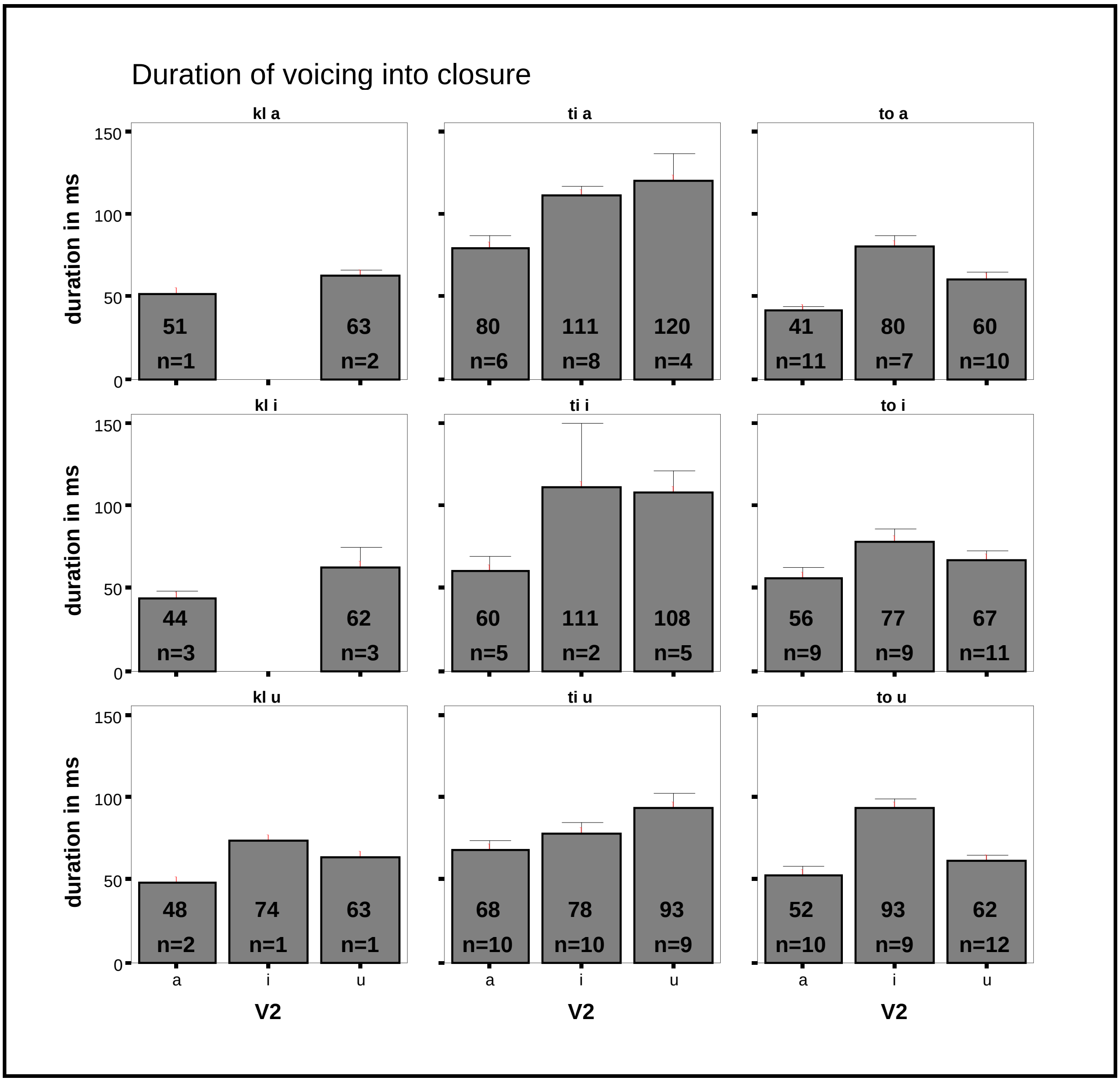


Figure A31: Voicing into closure for /g/ in different vowel contexts for the German speakers KL (first column), TI (second column) and TO (third column) in sequences with V1=/a/ (first row), /i/ (second row) and /u/ (third row) and V2=/a/ (first bar), /i/ (second bar) and /u/ (third bar)

Table A37: Analysis of variance for voicing into closure of /g/ for the German speakers

Speaker	*V1*	*V2*	*V2*	*Standard error*	*Significance*
TI	a	a	i	11.009	.037
			u	13.159	.027
		i	u	12.483	.800
	i	a	i	24.442	.174
			u	18.476	.082
		i	u	24.442	.994
	u	a	i	9.808	.577
			u	10.077	.058
		i	u	10.077	.345
TO	a	a	i	6.888	.000

			u	6.224	.023
		i	u	7.020	.029
	i	a	i	9.353	.099
			u	8.918	.515
		i	u	8.918	.501
	u	a	i	7.287	.000
			u	6.791	.404
		i	u	6.994	.001

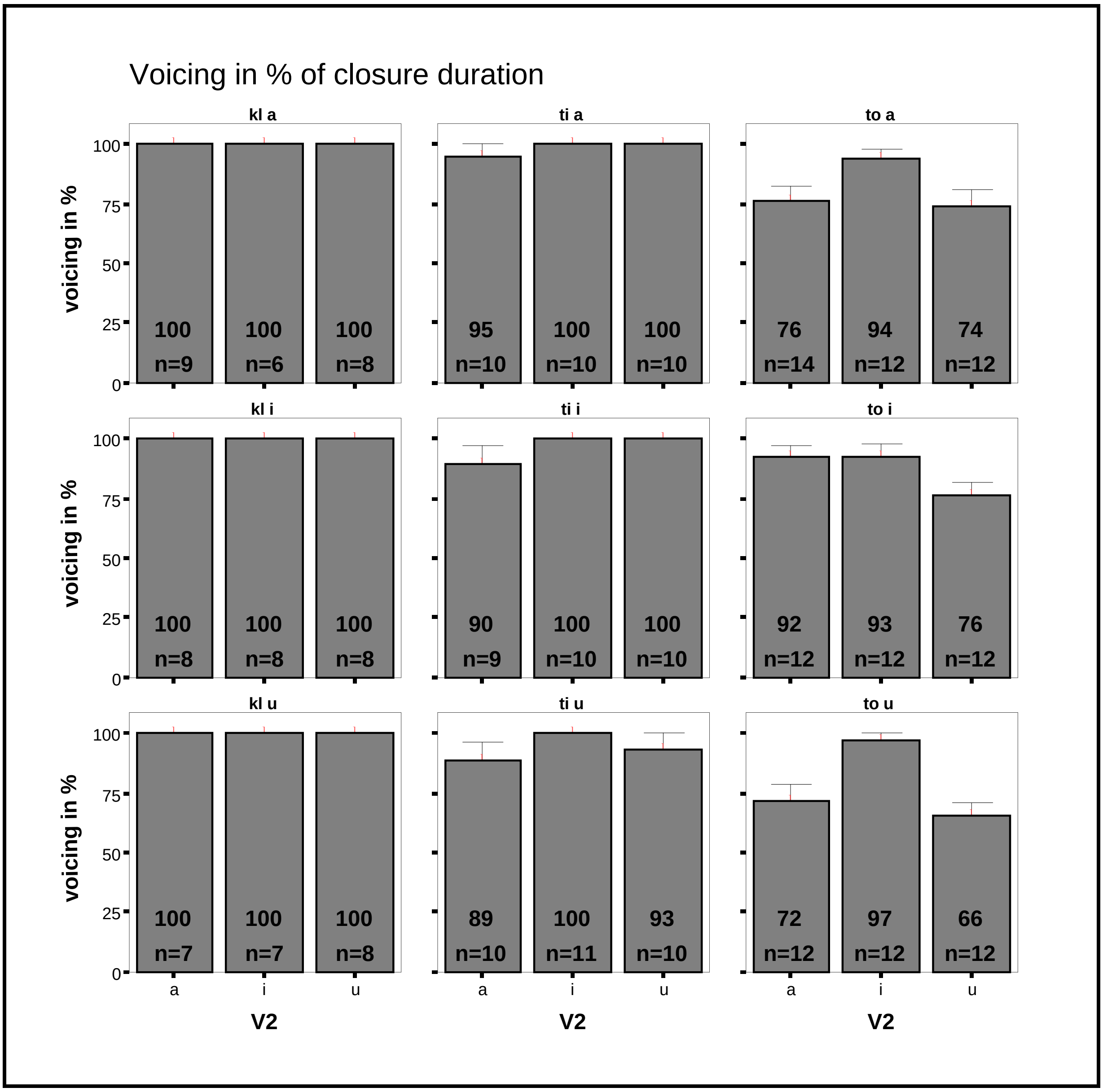


Figure A32: Voicing in % of closure duration for /g/ in different vowel contexts for the German speakers KL (first column), TI (second column) and TO (third column) in sequences with V1=/a/ (first row), /i/ (second row) and /u/ (third row) and V2=/a/ (first bar), /i/ (second bar) and /u/ (third bar)

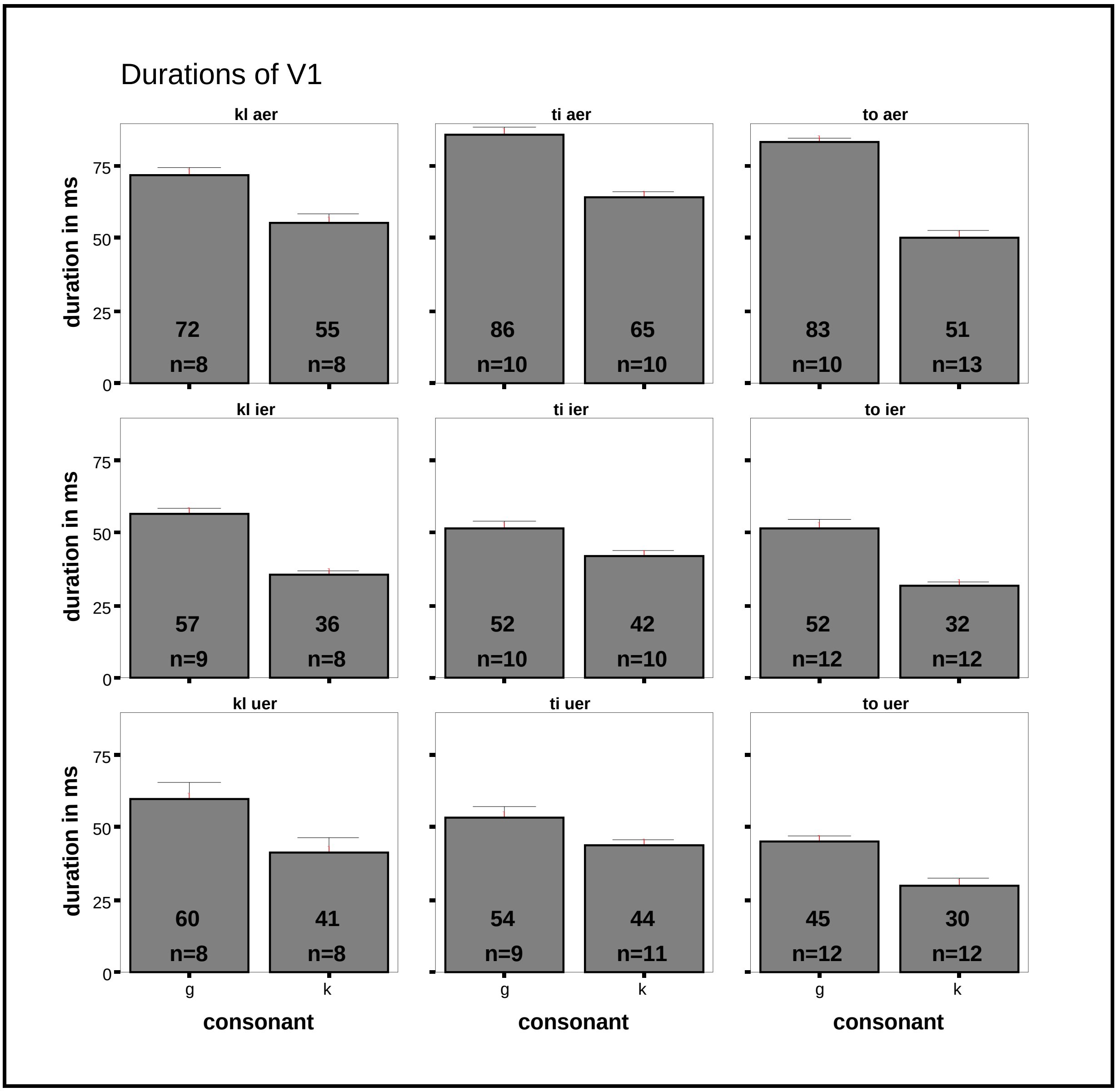


Figure A33: Duration of V1 for the German speakers KL (first column), TI (second column) and TO (third column) in sequences with different V1 and constant V2

Table A38: Analysis of variance for duration of V1 for the German speakers

Speaker	*Context*	*Significance*
KL	a_❶	.001
	i_❶	.000
	u_❶	.023
TI	a_❶	.000
	i_❶	.002
	u_❶	.022
TO	a_❶	.000
	i_❶	.000
	u_❶	.000

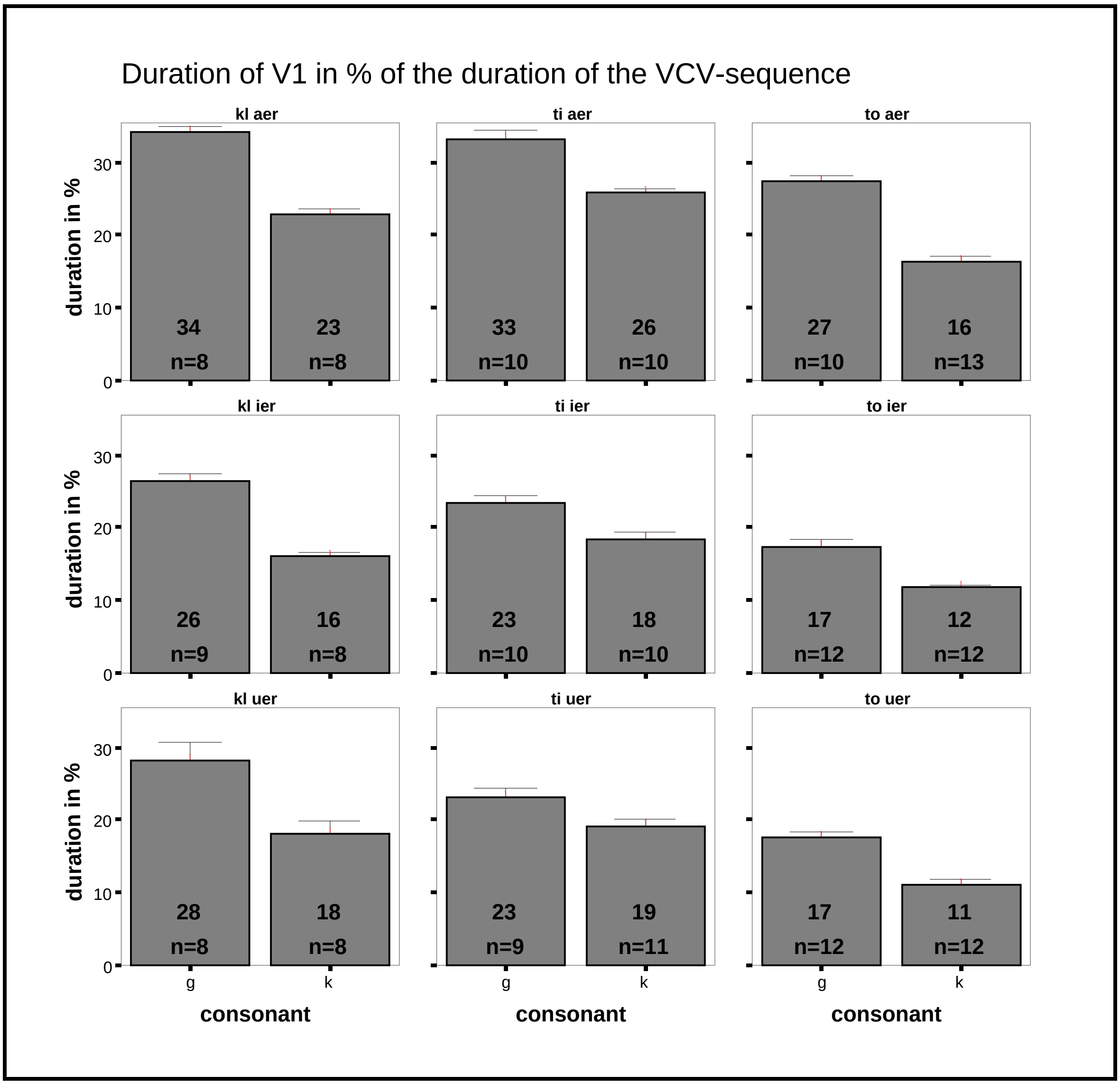


Figure A34: Duration of V1 in % of the duration of the VCV-sequence for the German speakers KL (first column), TI (second column) and TO (third column) in sequences with different V1 and constant V2

Table A39: Analysis of variance for the duration of V1 in % of the duration of the VCV-sequence for the German speakers

Speaker	*Context*	*Significance*
KL	a_❶	.000
	i_❶	.000
	u_❶	.005
TI	a_❶	.000
	i_❶	.001
	u_❶	.012
TO	a_❶	.000
	i_❶	.000
	u_❶	.000

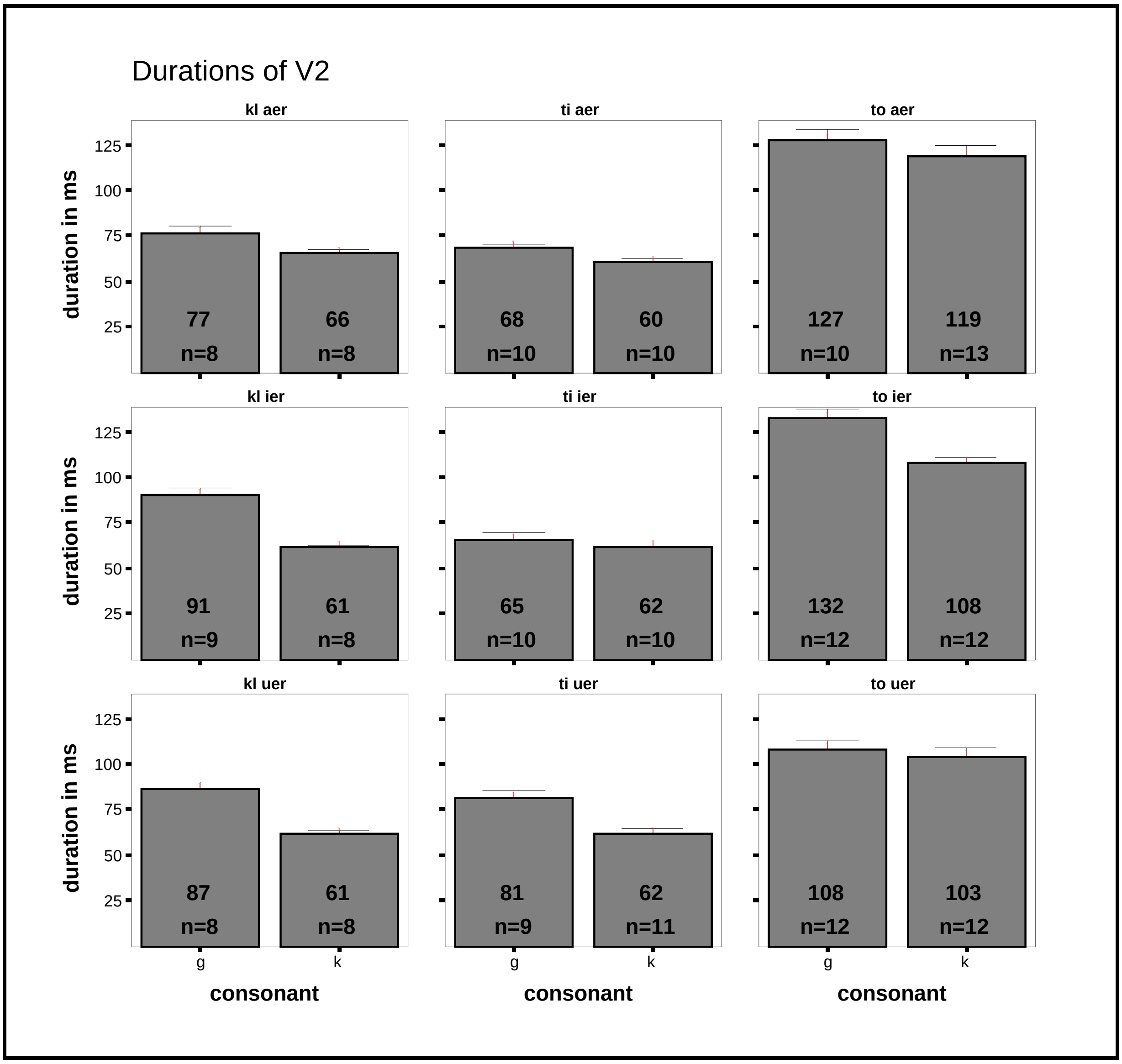


Figure A35: Duration of V2 for the German speakers KL (first column), TI (second column) and TO (third column) in sequences with different V1 and constant V2

Table A40: Analysis of variance for the duration of V2 for the German speakers

Speaker	*Context*	*Significance*
KL	a_➊	.017
	i_➊	.000
	u_➊	.000
TI	a_➊	.046
	i_➊	.568
	u_➊	.001
TO	a_➊	.299
	i_➊	.000
	u_➊	.541

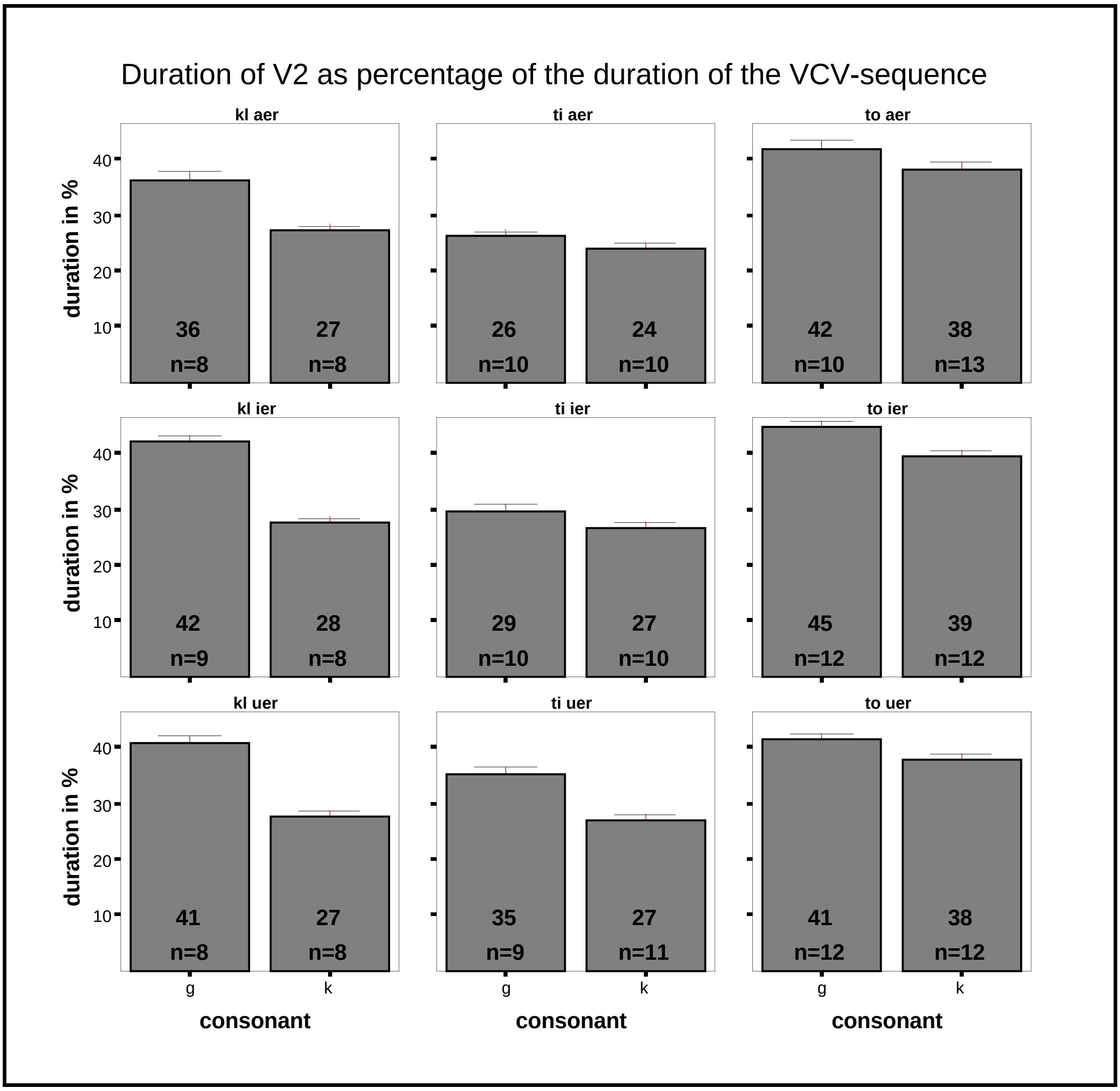


Figure A36: Duration of V2 in % of the duration of the VCV-sequence for the German speakers KL (first column), TI (second column) and TO (third column) in sequences with different V1 and constant V2

Table A41: Analysis of variance for the duration of V2 in % of the duration of the VCV-sequence for the German speakers

Speaker	*Context*	*Significance*
KL	a_❶	.000
	i_❶	.000
	u_❶	.000
TI	a_❶	.060
	i_❶	.137
	u_❶	.000
TO	a_❶	.101
	i_❶	.003
	u_❶	.021

Table A42: Analysis of variance for the duration of V2 in % of the duration of the VCV-sequence for the German speakers

Speaker	*V1*	*Significance*
KL	a	.260
	i	.254
	u	.039

Figure A37:Ensemble averages of the trajectories of VgV-sequences in German. From Mooshammer & Hoole (1993: 256-257)

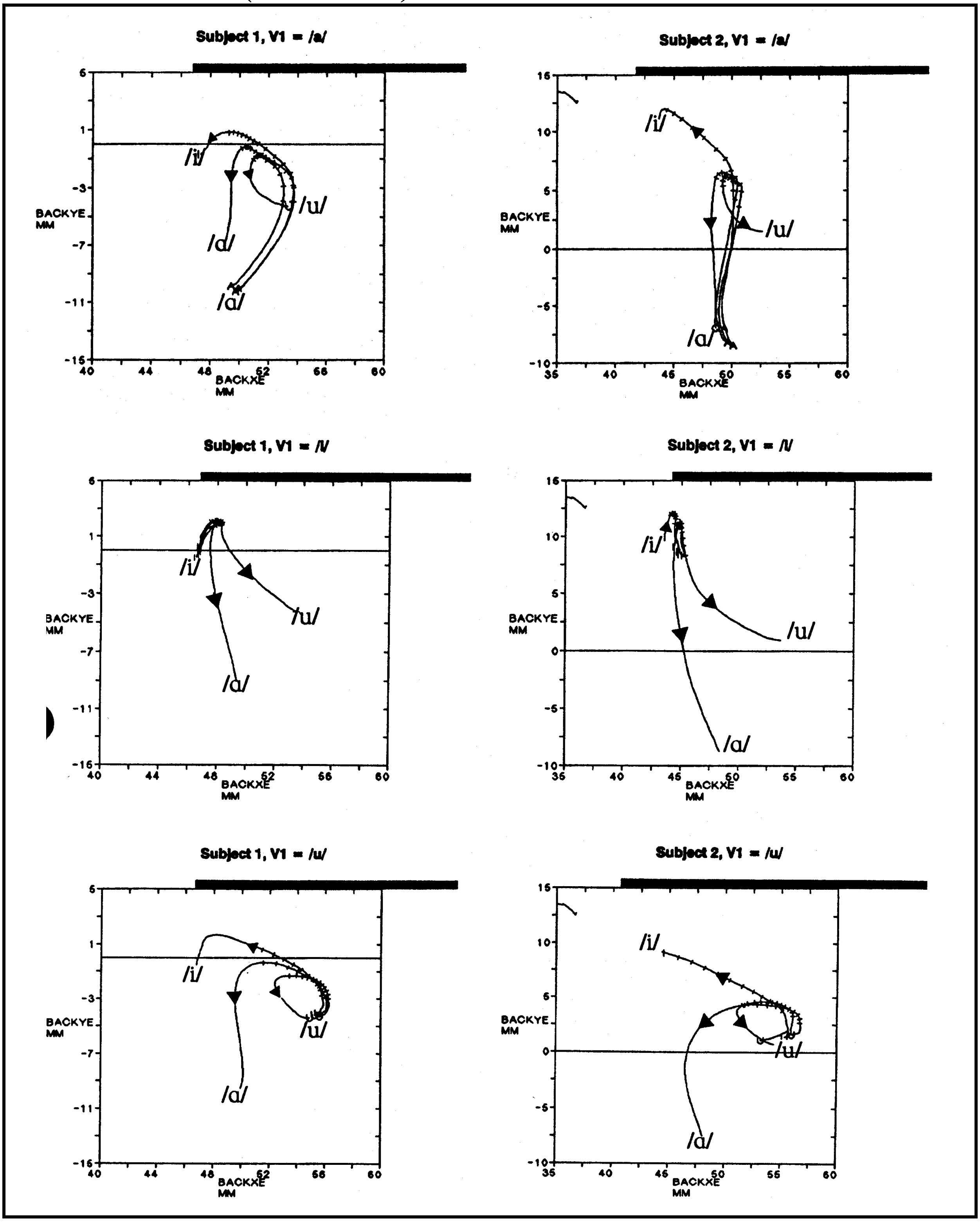
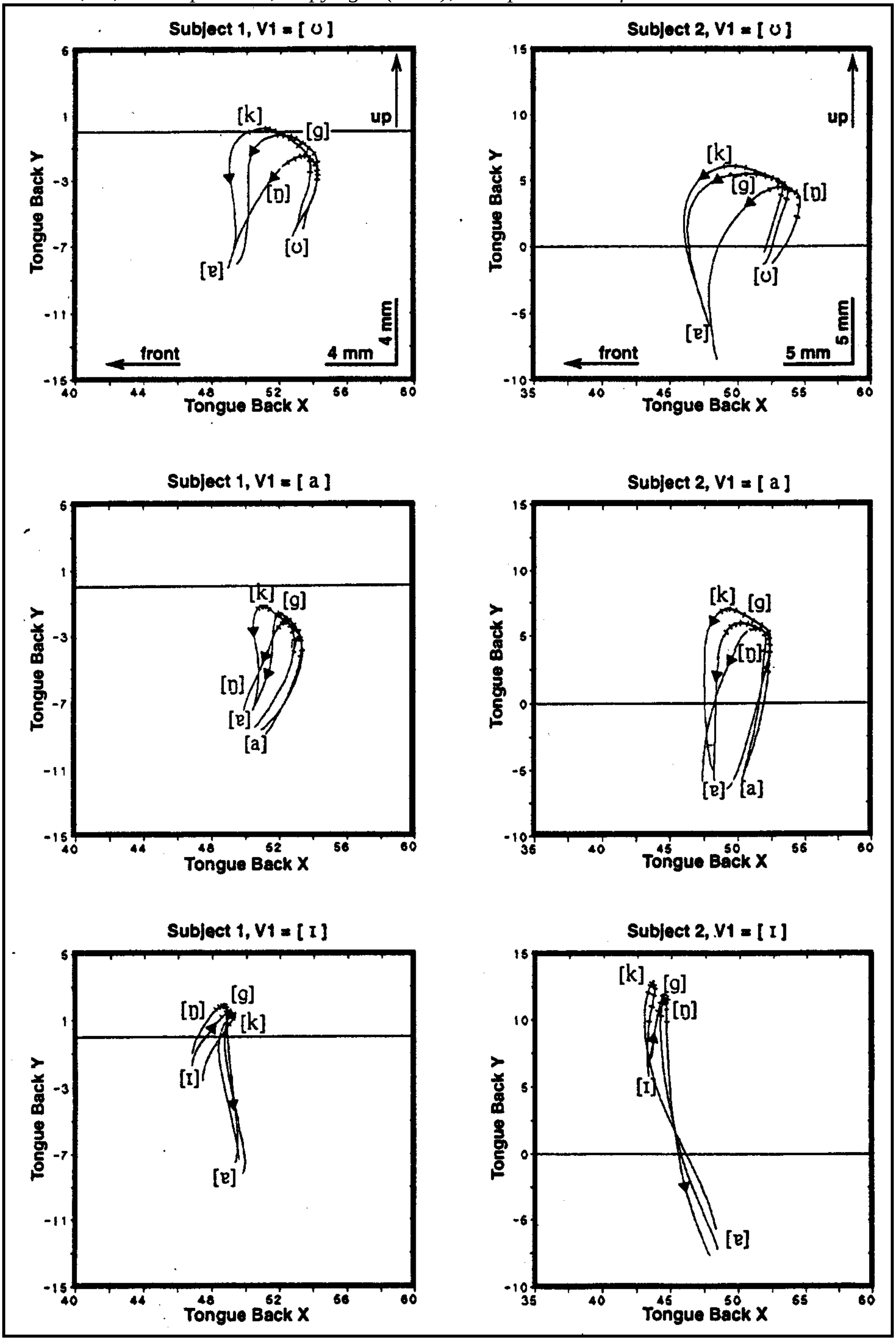


Figure A38: Ensemble averages of trajectories for /VCɒ/ sequences in German. C is either /g/ or /k/ or a velar nasal. Reprinted from Journal of Phonetics, 23, Mooshammer, C, Hoole, P & Kühnert, B., On loops: 3-21, Copyright (1995), with permission from Elsevier



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