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Prosodic and segmental effects on EPG contact patterns of word-initial German clusters

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ABSTRACT

This study investigates the effects of segmental composition and prosodic variation, namely boundary strength and lexical stress, on the production of word-initial clusters in German. The internal structure of the clusters /kl, kn, ks, sk/ has been analyzed by means of EPG recordings from seven speakers of German. Derived temporal and spatial parameters indicate that /kn/ is consistently produced with a lag between the consonants and /kl/ with considerable overlap. This categorical difference is also stable across stress and boundary conditions and is attributed to manner-based and perceptual recoverability constraints. No clear pattern emerges for /sk/ and /ks/. Therefore, stability of temporal organization across prosodic conditions is only tested for /kl/ and /kn/. Temporally, boundary level affects the duration of the adjacent consonant and the overlap within the clusters /kn/ and /kl/, whereas spatially /k/ is affected only in /kn/ but not in /kl/. Stress effects are not restricted to the nucleus but also affect the internal organization of the clusters. The interplay between segmental and prosodic timing effects indicates that the internal structure of clusters shows linguistically crucial and highly constrained timing patterns which can only vary within certain limits.

1. Introduction

Speech is produced by a highly intricate interplay between articulatory actions whose underlying principles are far from being fully understood. For example, the gestural coordination of a sequence of two consonants C_1 and C_2 has been found to vary between the two extremes of total synchronicity and a very long delay. Depending on the gestures involved, the first extremum (i.e. total synchronicity/overlap) may have the following results: Assimilation and the perceptual loss of one of the consonants, diachronic metathesis of the consonants (Blevins & Garrett, 2004), or a complex doubly articulated segment (Maddieson, 1993). The opposite extremum of unconstrained delay might lead to the perception of intrusive vowels (Hall, 2003; Davidson, 2005; Davidson & Roon, 2008) for voiced consonant sequences.

This paper discusses two factors affecting the internal coordination of clusters: cluster type and prosodic variation. Our study aims at investigating production and perception related aspects contributing to the internal structure of clusters by means of the temporal analysis of physiological tongue-palate contact measurements during the word-initial clusters /kl/, /kn/, /sk/ and /ks/ of seven speakers of German. The stability of the observed patterns is furthermore tested by using prosodic variation as a probe. Boundary strength and lexical stress (confounded with accent) are varied orthogonally in order to achieve this. For several reasons, consonant coordination patterns are discussed here with regard to word-initial clusters only: Clusters in other positions have been reported to show different coordination patterns (see e.g. Browman & Goldstein, 2000; Marin & Pouplier, in press). In this current study, however, we focus on segmental composition and prosodic variation. Furthermore it has been found that final and heterosyllabic clusters are more variable in general. Since we expect only subtle prosodic effects we preferred to analyze the more stable word-initial position. The third rationale for using initial clusters is that German does not show place assimilation in this position whereas place and manner assimilations are frequently found at morpheme boundaries (Bergmann, 2008) and in word final position (Kühnert & Hoole, 2004). Clusters in word medial and word final position therefore do not play a role in this study.

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1.1. Cluster type

Three principles that seem to underlie and govern the temporal organization of speech gestures will be discussed in this paper[2]: manner-based ranking of overlap, recoverability of segmental content, and biomechanical/anatomical constraints. These three approaches give different reasons for observed differences in timing. They do not necessarily differ with respect to their predictions. The first principle is based on Mattingly's (1981) assumption that coarticulation, or more specifically overlap between gestures, assists the transmission of information in that information about multiple gestures is available simultaneously. This parallel transmission is supposed to increase the speed of transmission because by overlapping gestures more sounds can be uttered within an allotted time frame. Furthermore, it facilitates the recognition and recovery of gestures because it results in a robust encoding of information in the signal (Wright, 2004). For CV sequences, parallel transmission can be maximal, i.e. gestures for both the C and V elements were found to be initiated simultaneously. In his seminal work, Öhman (1967) showed for VCV sequences that the gesture for the second vowel is even initiated before the consonant's gesture.

For consonant sequences, however, overlap must not prevent the emergence of acoustic correlates of any of the involved constrictions. Mattingly (1981) suggested that this restriction corresponds to the degree to which one segment allows encoding of information on the overlapping segment. In his view this lower bound of overlap follows quite neatly from the constriction degree. Accordingly, the segments with the closest constriction, the obstruents, allow the least amount of overlap. Nasals, liquids, glides and vowels permit increasingly more overlap in this order. This manner-based ranking of consonant classes also resembles sonority hierarchies as proposed by e.g. Sievers (1901) and Selkirk (1984).[3]

Further evidence for a constriction based ordering of overlap was found very recently by Kühnert, Hoole, and Mooshammer (2006): French stop+nasal clusters were produced with less overlap than stop+lateral clusters, which would also be predicted by Mattingly (1981). Violations of the sonority hierarchy within a syllable result in a more constrained phasing with a longer delay, as was for example found for word-initial stop–stop sequences in Georgian by Chitoran, Goldstein, and Byrd (2002).

There are, however, certain regularities found across languages, which cannot be explained by a manner-based hierarchy such as the very consistent place order effect. This term describes the finding that less overlap is permitted in clusters if the first segment is articulated at a place posterior to the following consonant (e.g. /kt/ or /kp/ clusters, henceforth called back-to-front) as compared to the opposite order (e.g. /tk/ or /pk/), everything else being equal. This regularity and its consequences for a universal preference of front-to-back clusters has been explained by perceptual recoverability. Since in a back-to-front sequence (e.g. /kt/) the first segment /k/ is produced posterior to the second segment (i.e. /t/), overlap can easily cause the complete deletion of the audible release of the first segment (i.e. /k/) by the following segment /t/. Hence, the recoverability of the first segment is obscured by the ongoing production of the following more anterior consonant. This situation is much less likely to occur in front-to-back clusters. The place order effect is extremely consistent across different languages and word positions (word-initial, word-medial, across word boundaries), e.g. English stop-stop sequences across word boundaries (Byrd & Tan, 1996; Hardcastle & Roach, 1979, /d#g/, /s#g/ vs. /g#d/, /g#s/); Georgian in word-initial and word-medial positions (Chitoran et al., 2002, /dg/ vs. /gd/, /bg/ vs. /gb/, /p^{h}t^h/ vs. /t^{h}b/), Russian and Korean across word and higher boundaries (Kochetov, Pouplier, & Son, 2007; Zsiga, 2000, /pt/ vs. /kp/, /kt/). However, there seems to be a ceiling effect, meaning that only speakers who produce clusters with an overlap exceeding a lower threshold show a place order effect (see EMA results for Moroccan Arabic by Gafos, Hoole, Roon, & Zeroual, 2010). Since there are no stop–stop sequences in German in word initial position, the place-order effect cannot be tested with our data. However, this effect exemplifies that strictly manner-based approaches cannot account for all patterns. Evidence for more extensive overlap in word-medial stop–stop clusters as compared to fricative-stop and stop-fricative clusters was presented by Byrd and Tan (1996). The reason for the longer delay, if a fricative is a member of the cluster, could be that fricatives require a longer minimal stationary phase with friction noise in order to be correctly identified. According to Jongman (1989) an /s/ must have at least a duration of 50 ms in order to be identifiable. Similar findings have been presented by Meynadier, Pitermann, and Marchal (1998). This argument therefore again points in the direction of perceptual recoverability rather than a sonority-based account. Finally, Kühnert et al. (2006, see above) do not attribute their findings to a manner-based ranking of overlap. The authors' account for the effect is that the place of the stop articulation might not be recoverable in stop+nasal clusters if the naso-pharyngeal port is opened before the stop is audibly released. In this case the only potential place cue in utterance-initial position would be distorted by nasal release because only insufficient air pressure can be built up for the production of a salient burst. This is not the case for a following lateral.

A third factor possibly governing the inter-gestural organization within clusters could be biomechanical linkages between articulators and their anatomical properties. For instance, for the difference in /tk/ vs. /kt/, Hardcastle and Roach (1979) suggest that for the tongue movement from /t/ to /k/ in /tk/ only the contraction of the *longitudinalis inferior* may be necessary, while higher complexity and extrinsic muscles are involved in what they call tongue repositioning for /kt/. If this is the case (there is hardly any data on the *longitudinalis inferior*) this could account for less co-production in the latter cluster. While the tongue repositioning account is also applicable to other oral clusters (e.g. /sʃ/ vs. /ʃs/) it does not cover observations of the place-order effect on clusters involving labials. This assumption of biomechanical linkages between articulators and their anatomical properties has been formalized within the DAC (degree of articulatory constraint) Model by Daniel Recasens with substantial evidence from EPG data mainly on Catalan (e.g. Recasens, Pallarès, & Fontdevila, 1997). The DAC model predicts that sounds produced with a high degree of articulatory involvement in the achievement of a constriction resist coarticulation from neighboring segments and at the same time exert coarticulation on these segments. This means that the coarticulatory resistance and exertion are inversely related to each other. For example, at the one end, sounds produced with active predorsal involvement, such as /s, ʃ/ and trilled /r/ or postdorsal retraction, as in dark /l/, have high DAC values because they affect the neighboring segments to high degree but are only minimally influenced by them. At the other end, sounds like bilabials are specified with a low DAC value because during a labial the tongue is free to anticipate the position of the adjacent segments. According to Recasens and Pallarès (1999), dentals and alveolars, such as /t, d, n/

[2] We are aware of the fact that other factors also affect the timing of gestures, such as language-specific constraints, grammar (see e.g. Gafos, 2002), word frequency and phonotactic probability (Vitevitch, Armbruster, & Chu, 2004).

[3] Mattingly does not distinguish between stops and fricatives and combines them to the more general class of obstruents as does Sievers (1901). Selkirk (1984), on the other hand, attributes more sonority to fricatives than to stops.

and clear /l/, exhibit an intermediate DAC level with the lateral showing a somewhat higher value than the others (Recasens, 2007) due to laterality requirements. With regard to the clusters analyzed in the current study, the DAC index would predict that /ks/ is produced with more overlap than /kn/ because /n/ has a lower DAC value than /s/ which exerts more coarticulation on /k/ (see Recasens & Pallarès, 2001). Clear /l/ should exert slightly more coarticulation on /k/ than /n/ due to laterality requirements as mentioned above. There have, however, been indications that German /l/ might be more resistant to coarticulation than clear /l/ in French or Spanish (Recasens, Fontdevila, & Pallarès, 1995). Accordingly, /l/'s DAC value may have to be adjusted upwards. Another view presented by Kühnert et al. (2006) as an alternative to the perceptual recoverability account relates to the fact that, as opposed to the lateral /l/, the nasal /n/ is composed of two gestures, oral closure and velar opening. In terms of inter-articulator coupling, this added articulatory complexity might account for the observed timing differences. Unlike English /l/ (e.g. Sproat & Fujimura, 1993), German /l/ does not have a dorsal gesture.

It is a central concern of the DAC model to account for coarticulatory directionality. In the case of /sk/ and /ks/—based on findings for the relative salience of the anticipatory and carryover effects from /s/ on /a/ in Recasens et al. (1997)—it can be expected that /s/ will exert stronger coarticulation on /k/ than *vice versa* in both cases. With regard to co-production, the DAC model makes use of another factor (Recasens, 1999, 2004; Recasens & Pallarès, 2001): Tongue repositioning, as outlined above, is needed in /ks/ as opposed to the production of /sk/. Therefore /sk/ is expected to show more overlap than /ks/. In summary, the predictions based on the DAC account yield a decrease of overlap in the following order: $/\mathrm{sk}/ > /\mathrm{ks}/ > /\mathrm{kl}/ > /\mathrm{kn}/$.

1.2. Prosody

The second topic to be considered here is prosodic variation. It has been found in many studies (e.g. Bombien, Mooshammer, Hoole, Kühnert, & Schneeberg, 2006; Cho, McQueen, & Cox, 2007; Fougeron & Keating, 1997; Kuzla, Cho, & Ernestus, 2007; Pierrehumbert & Talkin, 1992) and for a number of languages that prosody affects the phonetic realization of segments depending on the type of prosodic variation and the segments involved. For example, prosodic phrasing generally induces a change in the temporal and spatial characteristics of the segments adjacent to the boundary, but not all segments are affected in the same way and to the same degree. For example, Fougeron and Keating (1997) and Keating, Cho, Fougeron, and Hsu (2003) found in an EPG study that lingual stops, laterals and nasals are lengthened and produced with more contact following higher boundaries. However, the fricative /s/ in French seemed to resist strengthening because of fewer articulatory and acoustic degrees of freedom. Similar interactions have been found for accent and stress: whereas tense vowels lengthen considerably in German when stressed and accented, for lax vowels only the quality but not the quantity is affected (Hoole & Mooshammer, 2002; Mooshammer & Fuchs, 2002). Applying these examples of segmental resistance to prosodic changes in the current study of consonant clusters, the question arises whether clusters are affected as a whole, i.e. the onset of the syllable as a phonological constituent, or as two independent components, i.e. sequence of consonants.

In this study, we investigate the influence of prosodic variation on initial clusters. Regarding the prosodic factors here, prosodic boundary strength and stress, two different theoretical approaches will be tested. Based on an acoustic study on realizations of /ʔ/ and /h/ in American English, Pierrehumbert and Talkin (1992) proposed that CV syllables become more consonant-like at phrasal junctures, i.e. the syllable onset lengthens and exhibits more consonant-like characteristics such as more frequent and longer glottalization. This view can also account for findings such as lower nasal air-stream for /n/ adjacent to higher boundary levels in French (Fougeron, 2001) making the nasal more obstruent-like. Accent in the Pierrehumbert and Talkin (1992) study shifts the syllable in a vocalic direction with longer durations and larger gestures. Further evidence for the differential mechanisms for signaling accent and boundary strength have been presented by e.g. Beckman, Edwards, and Fletcher (1992) and Cho and McQueen (2005). The latter, however, also provided counter-evidence to the observed strengthening effects from stop aspiration in Dutch with shorter VOTs at higher levels of prominence and prosodic boundaries. Within Pierrhumbert and Talkin's model prosodic effects vary according to the constituents of the syllable they enhance, i.e. the syllable onset is affected by prosodic boundaries and the nucleus by accent. However, no particular prediction concerning initial consonant clusters can be derived from this account.

Concerning boundaries a different view has been taken by Byrd and colleagues (e.g. Byrd, Kaun, Narayanan, & Saltzman, 2000; Byrd & Saltzman, 2003). They proposed that most of the phenomena related to phrase marking can be modeled by trans-gestural perturbations of clock rate due to a so-called π-gesture. This is an abstract non-tract prosodic boundary gesture that in earlier versions affected the stiffness of the trans-boundary gestures approximately proportionally to the boundary strength. Byrd and Saltzman (2003) replaced the stiffness approach with local clock slowing, generating temporal lengthening by lengthening the activation intervals of tract-variable gestures and the spatial strengthening by a lesser degree of overlap or truncation (see Harrington, Fletcher, & Roberts, 1995). However, it is not clear how shortening of VOT in Dutch (Cho & McQueen, 2005) and lesser velum lowering in French (Fougeron, 2001) at higher boundaries could be explained by π-gestures. An important feature of the π-gesture is that the activation strength varies smoothly, i.e. it waxes continuously towards the π-gesture's peak activation and then it wanes in a similar manner (Byrd, Krivokapić, & Lee, 2006; Byrd & Saltzman, 2003). Therefore, the prosodic effect on the constriction gestures—such as lengthening and strengthening—is strongest at the activation peak and diminishes with the distance from the peak. Generally, it has been found that temporal lengthening effects are more consistent than articulatory strengthening effects, especially when measured with EMA rather than EPG (see Keating, 2006 for an overview).[4] With respect to the current investigation the π-gesture approach would predict that the initial consonant of the cluster which is directly preceded by the boundary is affected to a greater extent than the second consonant, which is further removed from the boundary. Gestural overlap is expected to be affected in that the constriction gestures move farther apart from each other at high prosodic boundaries. Indeed, Byrd and Choi (2010) found in an EMA study of three speakers of American English that all speakers consistently lengthened the first consonant of /sp, sk, kl/ clusters for higher boundary levels. The effect on duration of the second element of these clusters was smaller and also less consistent but significant for two speakers. In an EPG study of French /kl/ clusters in two speakers, Fougeron (1998) found that effects were limited to the first consonant while the second consonant was only inconsistently influenced. Regarding the overlap between the

[4] In yet a newer version by Saltzman, Nam, Krivokapić, & Goldstein (2008), the π-gesture is replaced by the more general μ (modulation) gestures which modulate two aspects of the vocal-tract gestures: μ_T-gestures modulate the temporal course of vocal-tract gestures such as the above described slowing down of the clock, and μ_S-gestures serve to model articulatory strengthening effects.

consonants, in both studies initial clusters were relatively insensitive to prosodic changes. This gives room to the interpretation that consonants in initial clusters are more cohesive since stronger and more consistent timing effects attributed to prosodic variation were found in heterosyllabic and in coda clusters.

To our knowledge the π-gesture model has only been used for modeling the effects of prosodic boundaries. However, Saltzman, Goldstein, Holt, Kluzik, and Nam (2007) have already presented a proof of concept for the application of the π-gesture on the syllable level. Furthermore, given evidence from the literature that stress and accent are generally found to affect vowels to a greater degree than consonants (see e.g. Cho & Keating, 2007; Pierrehumbert & Talkin, 1992), the peak activation of the π-gesture for stress can be assumed to be positioned around the middle of the vowel with decreasing strength towards the onset and the coda of the stressed syllable. For accent the peak activation is probably again situated in the middle of the stressed syllable but—as was found by Turk and White (1999)—the effect spreads to the preceding and the following syllables in the same phonological word with more consistent lengthening effects on the following than on the preceding syllables. In our data, stress and accent are confounded, i.e. the initial and stressed syllable in *Claudia* also carries a pitch accent and the initial unstressed syllable in *Klausur* /klaʊ.'zuɐ/ precedes the accented syllable. If the π-gesture model can be applied to stress confounded with accent in the current data then the second consonant is affected by stress to a greater degree than the first one because it is closer to the peak activation of the π-gesture. We want to point out here that it is not the aim of the current study to test the π-gesture model in all its details or to implement the prosodic level stress in this model. Rather, the aim here is to provide and discuss a theoretical background for the extent and domain of prosodic effects on word-initial consonant clusters as a probe for the stability of internal structure of clusters.

1.3. Predictions

This section gives an overview of our predictions. Items (a)–(c) summarize the outcome of the three principles concerning segmental make-up as discussed in the introduction. Items (d) and (e) deal with prosodic variation.

(a) Manner-based ordering would predict more overlap for /kl/ vs. /kn/ clusters. The same amount of overlap for /sk/ as for /ks/ can be expected (under the assumption that /s/ and /k/ have the same degree of sonority) but, as both violate the sonority sequencing constraint, less overlap can be expected than for /kl/ and /kn/ clusters.[5]

(b) Similar predictions follow from perceptual recoverability, but for different reasons. Here a longer delay would be expected for /kn/ than for /kl/ in order to avoid reduction of the perceptual salience of /k/ by nasal leakage. Predictions following perceptual recoverability are restricted to the clusters /kl/ and /kn/ because /kl/ and /kn/ both consist of a velar stop and a coronal sonorant. Differences in /ks/ vs. /sk/ could be as likely due to different C1 articulators as they could be due to different C1 place of articulation.

(c) Based on the assumptions of the Degree of Articulatory Constraint (DAC) model, more overlap would be predicted in /ks/ than in /kn/ and /kl/ as /n/ and /l/ have lower DAC values and thus exert less coarticulation on /k/. /kl/ and /kn/ should display a tendency of more overlap in /kl/ than in /kn/. /ks/ is expected to be less overlapped than /sk/ due to tongue repositioning in the former.

(d) Regarding the internal coordination within clusters, the theoretical framework of the π-gesture predicts a decrease in overlap between the two consonants for higher levels of prosodic boundaries and for clusters in stressed syllables. However, the extent to which this effect takes place depends on the position of the cluster in the syllable. The timing of clusters in word-initial position is very stable (Byrd & Tan, 1996) and the interval during which the two consonants might show overlap is at some distance from the center of the prosodic effect (i.e. the prosodic boundary). Therefore we assume that changes in overlap might be very subtle. No changes in overlap duration could indicate that the overlap is specified by cluster type and therefore its variation due to prosody is highly constrained.

(e) The durations of the consonants are supposed to be more susceptible to prosodic variation as compared to the overlap. If boundary strength affects the adjacent segments as predicted by the π-gesture model, then the first consonant in the cluster should lengthen to a greater degree than the consonant further away from the boundary. Palatal contact for the first consonant should also increase for higher levels of prosodic boundaries, whereas the second consonant might be less or not at all affected. The vowel duration will remain the same. For stress confounded with accent the vowel is hypothesized to be the center of the π-gesture. Since the second consonant is closer to this center it should be lengthened and possibly strengthened spatially for higher levels of stress. The initial consonant should not be influenced by stress or only very slightly. This is largely in line with the account of Pierrehumbert and Talkin (1992) with the exception that this account only predicts boundary conditioned strengthening of the entire onset without being specific with regard to complex onsets.

2. Experiment

2.1. Speakers and speech material

Seven speakers (five female, two male) between the ages of 25 and 42 were recorded by means of EPG (Reading EPG3; 62 contacts in eight rows: six contacts in the front row, eight in the remaining). All of the subjects had experience participating in EPG experiments and were equipped with custom-made pseudo-palates; none of them reported any speech or hearing disorders. All speakers originate from the North or the East of Germany with long-term residence either around Kiel or Berlin without any particular dialect coloring. The target words consisted of three pairs, where each pair shared the initial consonant cluster but differed in lexical stress in that it was either on the first (henceforth stressed) or the second (henceforth unstressed) syllable: *Claudia* (name) /'klaʊ.dia/–*Klausur* 'written exam' /klaʊ.'zuɐ/; *Kneipe* 'pub' /'knaɪ.pə/–*Kneipier* 'pub owner' /knaɪ.'pjeː/; *Scarlett* (name) /'skaː.lət/–*Skandal* 'scandal' /skan.'daːl/. Additionally, the word *Xaver* (name) /'ksaː.vɐ/ was included, even though no real-word could be found beginning with /ks/ stressed on the second syllable except for scientific terms rarely used by none-specialists, e.g. *Xanthan, Xylose* (orthographic *x* is canonically realized as /ks/ in German). In German, initial /ks/ is quite rare. However, the speakers are accustomed to these clusters from e.g. the name *Xaver* or *Xylophon* in the musical education of most

[5] This is in accordance with the sonority hierarchy as proposed by Selkirk (1984). If, following e.g. Sievers (1901), stops are considered less sonorous than fricatives, /ks/ does not violate the hierarchy and less overlap should be expected here than for /sk/. This study's focus is not on corroborating either scale.

Table 1
Cross-category table for mapping from syntactical to prosodic categories (for abbreviations see text).

Syntactic categories	Prosodic groups per speaker																							
	f01			f02			f03			f04			f05			m01			m02			all		
	BG	SM	WD	BG	SM	WD	BG	SM	WD	BG	SM	WD	BG	SM	WD	BG	SM	WD	BG	SM	WD	BG	SM	WD
U	39	21	0	7	40	0	45	0	0	30	5	1	53	2	0	56	0	0	33	11	0	263	79	1
P	4	51	0	0	32	15	14	30	0	4	36	2	30	29	1	37	20	0	6	38	0	95	236	18
L	2	9	49	1	4	41	1	5	39	0	3	38	0	1	59	26	25	11	0	1	42	30	48	279
W	0	0	66	0	1	54	0	0	45	0	0	44	0	0	59	0	0	59	0	0	53	0	1	380

schools. As a later addition it was only recorded for five of the seven speakers, one of whom realized the initial cluster as [ts] instead of [ks]. Hence, results for /ks/ can only be presented for four out of seven speakers. The word preceding the test item always ended in /ɐ/ or unstressed /a/.

In order to elicit different prosodic boundaries preceding the target words, they were embedded in four syntactically similar contexts each: In the utterance-initial condition (U), the target word came at the beginning of the second of two sentences; in the phrase-initial condition (P), it was the first word of a sub-clause; in the list condition (L), it appeared as the third item of a list; the word-initial condition (W) had only a Prosodic Word boundary preceding the target word. All utterances were carefully designed to avoid nuclear accent on the target words. Tables 6–9 show the complete speech material. The speakers were presented all utterances in randomized order in 10 repetitions yielding a total of 300 trials per speaker.

2.2. Measurements

For acoustical labeling, the Munich Automatic Segmentation System (MAUS, Schiel, 1999) was applied. The output was converted and imported into the EMU Speech Database System (Bombien, Cassidy, Harrington, John, & Palethorpe, 2006) in order to facilitate hierarchical annotations. Following Cho and McQueen (2005), all utterances were assigned to one of three prosodic groups, each group defined by the prosodic boundary preceding the target word. The mapping from syntactical to prosodic boundaries is displayed in Table 1 for all speakers and across all speakers. Obviously, the realizations of the syntactical categories may scatter across different prosodic categories and are speaker dependent. Prosodic groups were defined as follows:

1. Big Boundary (BG): a boundary tone and a pause.
2. Small Boundary (SM): a boundary tone and no pause.
3. Prosodic Word (WD): no boundary tone and no pause.

Prosodic labeling was done by two skilled transcribers, one of them deciding the unclear cases. A pause was constituted not only by the presence of acoustical silence but also by the perception of a pause, which in turn might be evoked by final lengthening, another major cue for boundaries. Determining pauses before stops is obviously problematic. Details on this problem are given below in the list of temporal parameters. Boundary tones were identified by inspecting f0 contours displayed in Emu and generated by the accompanying f0 tracking tool (tkassp/f0ana).

Articulatory landmarks in the EPG data were labeled using two indices: The anteriority index indicates the relative amount of (un-weighted) linguo-palatal contact in the anterior region (rows 1–5) of the pseudo-palate (number of active contacts in rows 1–5 divided by total number of contacts in rows 1–5, e.g. Fontdevila, Pallarès, & Recasens, 1994[6]). Here it was applied for C_2 in /kl/, /kn/ and /ks/ and for C_1 in /sk/ for which linguo-palatal contact only occurs in the anterior region. The dorsality index does the same for the posterior region (rows 6–8) of the pseudo-palate. In order to take speaker-specific differences in dorsal stop articulation into account we applied the method by Byrd, Flemming, Mueller, and Tan (1995) and established a set of contacts unique for velar articulations for each speaker and limited the calculation of the index to this set. This profiling was not necessary for the anterior region as tongue tip articulations were always easily separable from contextual segments which were controlled for (either open vowel or velar stop). The dorsal region for speaker f03 had to be restricted to only two contacts in the last row. This restriction arose as the result of the order in which the data were analyzed: In a first step, only /kl/ clusters were examined (Bombien, Mooshammer, Hoole, Rathcke, & Kühnert, 2007), then /kn/ and then /ks/. While for the clusters /kl/ and /kn/ some contacts in the next to last row of the pseudo-palate were involved in /k/ closure formation, in /ks/ these contacts only produced noise, which had to be filtered out by further restricting the dorsal region for /ks/. The use of this procedure was necessary for one speaker only but underlines the difficulties in the analysis of velars with EPG as pointed out by Fougeron, Meynadier, and Demolin (2000).

The following articulatory landmarks were labeled (see also Fig. 1[7]).

1. Onset and offset of constriction plateau (70% threshold) (*pon*, *poff*).
2. Maximum constriction at the center of the plateau.

All thresholds are relative to the local maximum constriction and the local minimum constriction before/after the movement as measured in the time-course of the anteriority index for consonants with tongue front contact or the dorsality index for consonants with tongue dorsum contact. The 70% threshold criterion was defined operationally by looking at the contact patterns of all speakers. This value yielded time-points which were most closely related with the acoustic landmarks like the offset of the preceding vowel and the burst. For analysis, the following temporal parameters were derived:

- Acoustical duration of the syllable nucleus following the cluster.

[6] Fontdevila et al. (1994) provide formulas also for weighted indices. A weighted anteriority index provides a measure of how far back or front an articulation in the anterior region is. We used the unweighted versions here as we were only interested in the *amount* of contact in a specific area, not the exact position of the contact.

[7] In Fig. 1, the additional landmarks onset and offset of articulatory movement (20% threshold) (*on*, *off*) are also displayed. They are of no relevance here.

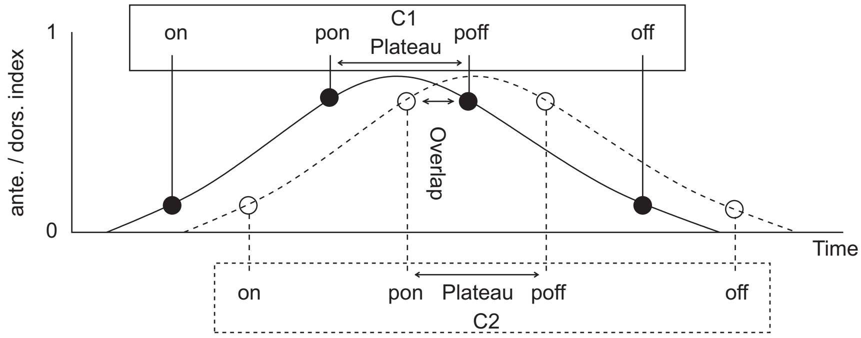

Fig. 1. Articulatory landmarks and definition of temporal parameters.

- Articulatory plateau duration of both consonants as the difference between the respective plateau offset and onset.
- Plateau overlap as the time difference between plateau onset of C_2 and plateau offset of C_1, i.e. positive values indicate overlap, negative values indicate lag.
- Where applicable (see below) these parameters were also examined normalized by the interval from plateau onset of C_1 to plateau offset of C_2, to compensate for possible effects of speech rate. The standard deviation of speech rate varied from 15 ms for speaker f02 to 65 ms for speaker f05. To normalize a given value for C_1/C_2 plateau duration or plateau overlap it was divided by the interval from plateau onset of C_1 to plateau offset of C_2.

$$x_{norm} = \frac{x}{C2_{poff} - C1_{pon}},$$
$$x \in \{C1\ Plateau,\ C2Plateau,\ PlateauOverlap\}$$

- The parameter pause (P) aims to serve as a means of validating the results for C_1 plateau duration. It was observed that when pauses preceded the cluster, velar contact was established at the beginning of the pause and maintained until the release of C_1 even through the longest pauses. Thus the validity of C_1 plateau duration can be questionable in co-occurrence with pauses. Pause (P) is the sum of the duration of the acoustical pause (p) preceding the target word (if present) and the difference of the acoustical duration of C_1 (C_1) and its per-speaker mean ($\overline{C}_{1s}$) (if positive):

$$P = \begin{cases} p + (C_1 - \overline{C}_{1s}) & \text{if } C_1 > \overline{C}_{1s} \\ p & \text{else} \end{cases}$$

This procedure yields a positive value for each C_1 longer than $\overline{C}_{1s}$ even where the acoustical pause p equals 0 s. Thus there are occurrences of non-zero pause values even in tokens of the conditions SM and WD where a true pause cannot be present by definition. These occurrences are not to be confused with acoustical pauses and are negligible in magnitude, see Section 3.2.1. It has to be noted that the acoustical onset of C_1 = /k/ was often indeterminable when preceded by a pause. In these cases it had to be set arbitrarily just to mark the existence of a pause. C_1 durations of these cases were excluded from per-speaker mean $\overline{C}_{1s}$ calculation.

2.3. Statistics

Analyses of variance (ANOVA) were calculated for individual speakers and pooled over all speakers using R (R Development Core Team, 2006). For the individual speakers all valid data were included. Main effects and interactions were computed. Independent variables were prosodic group "PG" and stress level "S". In order to evaluate speaker-independent strategies, additionally ANOVAs pooled over all speakers were calculated based on the data averaged over up to 10 repetitions so that each speaker contributed only one experimental score per condition (see e.g. Max & Onghena, 1999). This data reduction is necessary in order to avoid artificially inflating the error terms and degrees of freedom. Whether prosodic group and stress level affected temporal data was evaluated by calculating repeated-measures ANOVAs with the within-subject factors PG and S. Degrees of freedom were corrected by calculating the Greenhouse–Geisser epsilon in order to avoid violation of the sphericity assumption. Therefore, fractional degrees of freedom are often given in the tables. Pairwise t-tests with Bonferroni adjustments for multiple comparisons were carried out for individual statistics and for the repeated-measure ANOVAs in order to assess significant differences between the three-level-factor PG. Significance codes as given in the tables follow R's standard notation: "0 *** 0.001 ** 0.01 * 0.05" meaning that a probability between 0.05 and 0.01 ($p < 0.05$) is marked by one star, a probability between 0.01 and 0.001 ($p < 0.01$) by two stars and a probability between 0.001 and 0 ($p < 0.001$) by three stars.

3. Results

The results section is organized into two parts: The first part addresses the question of how sequence type affects the temporal organization of clusters. Therefore, the potential influence of prosody was ruled out by restricting the analysis to stressed /kl/, /kn/, /ks/ and /sk/ in the word-initial condition (W) as defined in Section 2.1, i.e. not preceded by a phrase boundary. /ks/, as mentioned in Section 2.1, is not available for all speakers. In the second part of the results section the prosodic conditions boundary and word stress will be investigated in greater detail in order to find out which characteristics of a particular cluster are stable across different prosodic conditions.

Figs. 2, 3 and 5 show overlap patterns of the clusters under analysis in this study as bar plots. They all follow the same scheme: In the cases where C_1 and C_2 do not overlap, white space is drawn between the respective bars. Where C_1 and C_2 do overlap, this is indicated by a different gray shade. This area is to be considered part of both consonants. Standard errors are indicated at the inner edge of the respective consonant's bar which includes the overlap area, if present.

3.1. Cluster type

Table 2 shows statistical results of the comparison of the clusters. To compensate for effects of speech rate, for plateau overlap both absolute and time-normalized values were analyzed. Fig. 2 illustrates the normalized timing patterns of

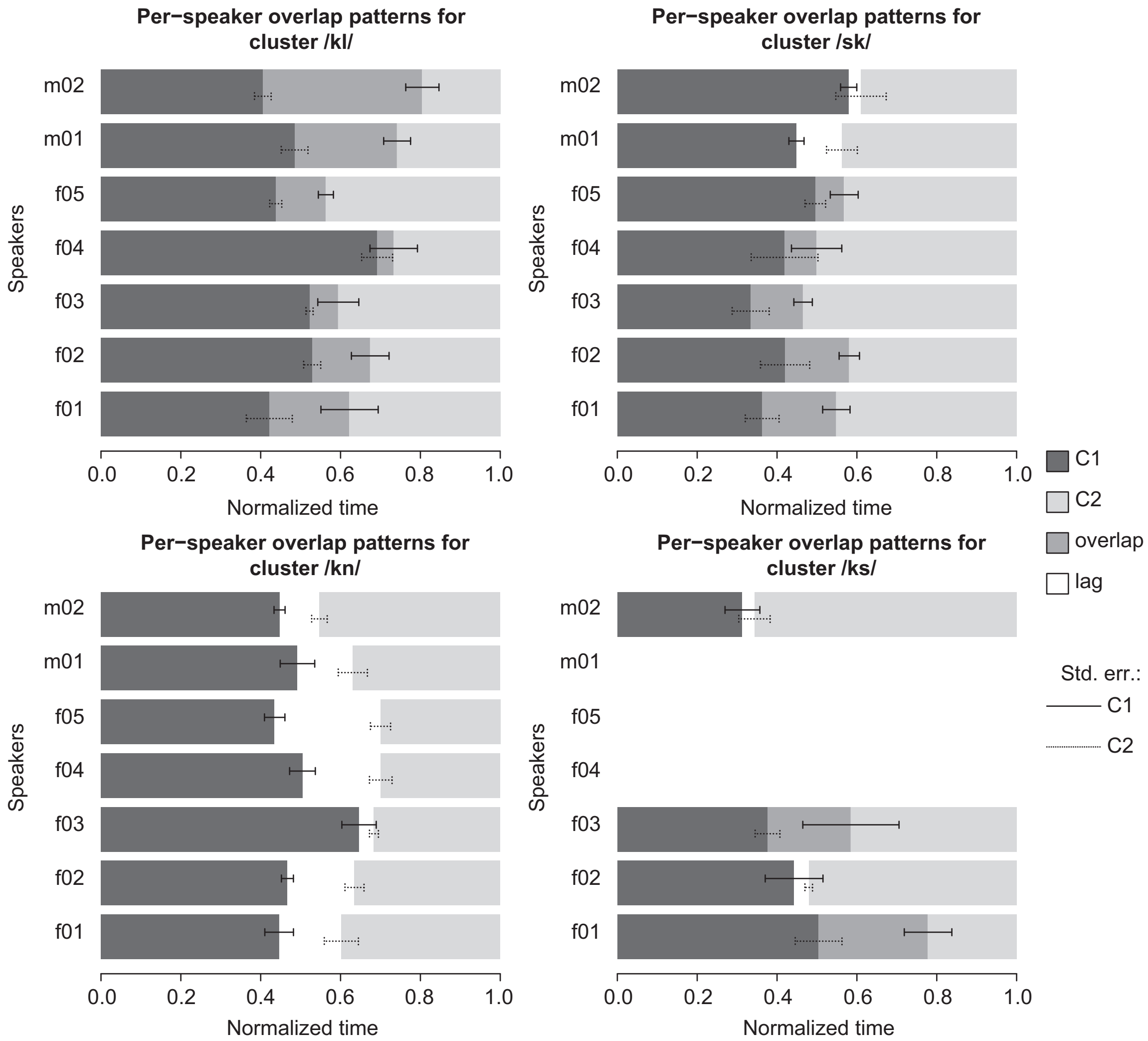

Fig. 2. Time-normalized overlap patterns of the mean C_1 and C_2 contact plateau durations for the clusters /kl/, /kn/, /ks/ and /sk/ for all speakers. Standard errors are drawn at the inner border of the respective bar, which includes the overlap if any. Standard error bars for C1 (solid lines) are drawn slightly above those for C2 (dotted lines).

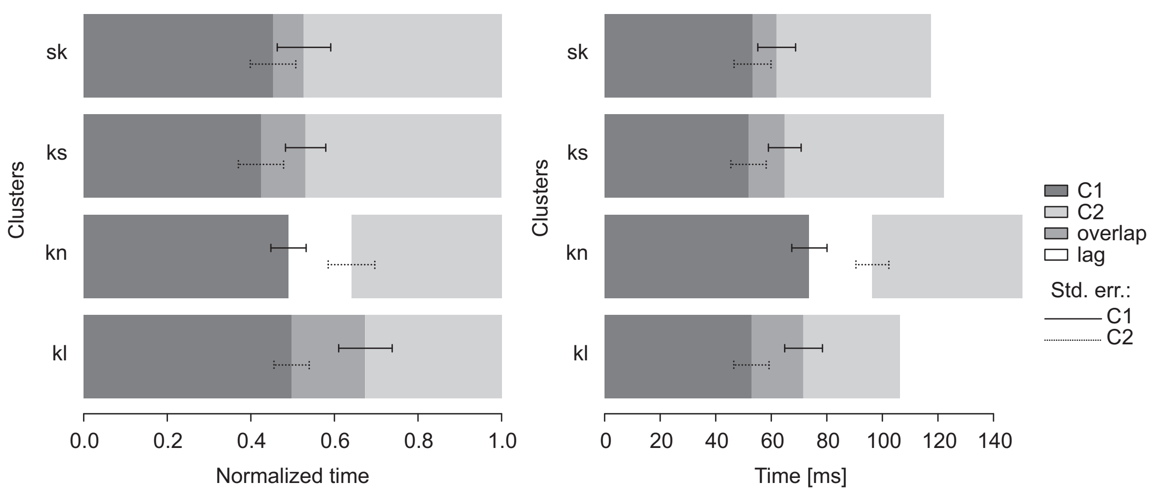

Fig. 3. Normalized (left) and absolute (right) overlap pattern's for clusters /kl/, /kn/, /ks/ and /sk/ across all speakers. Standard errors are drawn at the inner border of the respective bar, which includes the overlap if any. Standard error bars for C1 (solid lines) are drawn slightly above those for C2 (dotted lines).

all four clusters for each speaker in order to visualize inter-individual differences in overlap patterns. Fig. 3 shows normalized (left) and non-normalized (right) timing patterns across all speakers.

The duration of the C_1 plateau is not significantly affected by the manner of the first consonant, i.e. fricative vs. stop. This is reflected by the very inconsistent results for the individual speakers. A similar picture emerges for the C_2 plateau duration.

Table 2
Consonant plateau durations and overlap in /kl/, /kn/, /ks/ and /sk/ for each speaker (rows 1–7) and across all speakers (row 8; cluster /ks/ excluded, missing for f04, f05, m01). Word boundary (WD) condition only.

Spk	Measure								
	C1 plateau duration			C2 plateau duration		plateau overlap		norm. overlap	
	df	F	p	F	p	F	p	F	p
f01	3 32	/ks/ > /kn/, /kl/, /sk/ 10.6	 ***	 2.72	 n.s.	/kn/ < /kl/, /sk/, /ks/ 15.0	 ***	/kn/ < /kl/,/sk/, /ks/ 14.1	 ***
f02	3 27	 2.5	 n.s.	/sk/ > /kl/ 3.79	 *	/kn/ < /ks/ < /kl/, /sk/ 23.0	 ***	/sk/ > /ks/ 19.9	 ***
f03	3 24	/kn/ > /ks/, /sk/ 5.9	 **	/sk/ > /kn/, /kl/, /ks/; /ks/ > /kn/ 16.95	 ***	/kn/ < /ks/ 3.4	 *	/kn/ < /ks/ 3.8	 *
f04	2 19	 0.8	 n.s.	/sk/ > /kn/, /kl/ 11.1	 ***	/kn/ < /kl/, /sk/ 12.2	 ***	/kn/ < /kl/, /sk/ 12.1	 ***
f05	2 26	 0.2	 n.s.	/kl/, /sk/ > /kn/ 8.6	 **	/kn/ < /kl/, /sk/ 67.9	 ***	/kn/ < /kl/, /sk/ 55.5	 ***
m01	2 28	/kn/ > /sk/ 4.5	 *	 1.2	 n.s.	/kn/, /sk/ < /kl/ 52.2	 ***	//kn/, /sk/ < /kl/ 67.0	 ***
m02	3 27	/kl/, /kn/ > /sk/ > /ks/ 32.7	 ***	/ks/, /kn/, /kl/ > /sk/ 17.9	 ***	/kn/, /ks/, /sk/ < /kl/ 37.7	 ***	/kn/, /ks/, /sk/ < /kl/ 45.1	 ***
All	2 12	 2.5	 n.s.	2 12 1.0	 n.s.	1.7 /kn/ < /sk/, /kl/ 10.5 16.2	 **	1.4 /kn/ < /sk/, /kl/ 8.6 16.3	 **

Significance codes: 0 "*** " 0.001 "**" 0.01 "*" 0.05. Example: for speaker f01, C_1 plateau duration is larger in /ks/ than in /kn/, /kl/ and /sk/ (highly significant).

However, we see that plateau overlap varies clearly across the four clusters. While there is always overlap in /kl/, never overlap—rather lag—in /kn/, it may be one or the other for /ks/ and /sk/. This is apparent in Figs. 2 and 3 where there is always a void in-between the bars representing C_1 and C_2 for /kn/ while these bars always overlap for /kl/. Also, the standard errors for /kl/ and /kn/ do not overlap while those for /ks/ and /sk/ do, indicating that the latter clusters allow for more variability in their temporal organization.

The repeated measures ANOVA shows less overlap for /kn/ than for /sk/ and /kl/. For the single speakers, /kn/ also exhibits the least overlap, while overlap in /sk/ and /ks/ may be shorter or equal to /kl/. While in Fig. 2 it seems that in clusters with /s/ overlap can be greater than in /kl/, this is not statistically significant. Only speaker f03 does not distinguish significantly between overlap in /kl/ and /kn/. All of this holds for both absolute and normalized data.

Overall, the most stable findings appear to be that /kn/ and /kl/ show a reversed pattern of temporal coordination: /kl/ is produced with considerable overlap between the two plateaus whereas for /kn/ a lag between the two plateaus seems to be obligatory. Fig. 4 illustrates this behavior. The data for these palatograms were taken from speaker f05. Both are tokens from the syntactical word-initial class with stress on the first syllable.

In the next section, the stability of the observed patterns will be tested across varying prosodic conditions. This analysis will be restricted to the clusters exhibiting the most stable patterns. Accordingly, /sk/ and /ks/ will be excluded. Further reasons for the exclusion are the asymmetrical material for /ks/ (stress variation missing, only *Xaver*) and the problematic cross-cluster comparability: dealing with the intrinsic differences between stop-sonorant and stop-fricative clusters would be beyond the scope of this section. Furthermore, the vowels in target syllables lacked comparability to those of clusters /kl/ and /kn/ under prosodic variation. This does not affect the results of the cluster type analysis.

3.2. Prosody

Effects of prosodic variation are described in two parts. First, the temporal parameters C_1 plateau duration, C_2 plateau duration, plateau overlap and pause duration are considered. Then we will discuss effects in the spatial domain.

3.2.1. Temporal effects

Normalization of durational and overlap measures as carried out in Section 3.1 is not applicable here since prosodic variations can be expected to influence all durational measures in a non-uniform way. As C_1 and C_2 durations are hypothesized to lengthen at strong boundaries or under lexical stress, respectively, using any of these two measures for normalization could conceivably either enhance or conceal possible effects. A separate analysis of boundary strength and stress is not feasible here since the two are varied orthogonally in our material. Tables 3 and 4 show the results of ANOVAs for all individual speakers as well as repeated measures ANOVAs across all speakers with the factors "Prosodic Group" (levels: Big Boundary (BG), Small Boundary (SM) and Word (WD)) as defined above and "Stress" (levels:

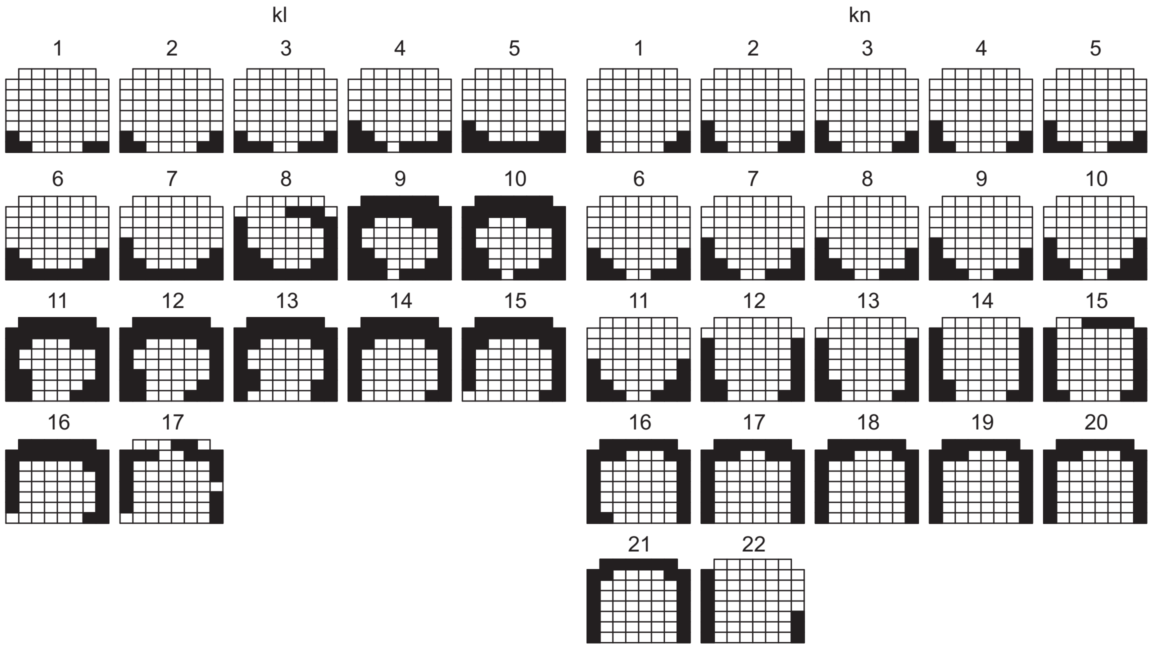

Fig. 4. On the left: Palatograms for the cluster /kl/. Apical closure for /l/ (upper rows) is initiated distinctly before /k/ closure release (lower rows). C_1 plateau ranges from frames 4 to 10, C_2 from 9 to 16. On the right: Palatograms for the cluster /kn/. Apical closure for /n/ (upper rows) is initiated distinctly after /k/ closure release (lower rows). C_1 plateau ranges from frames 7 to 11, C_2 from 16 to 21. Frames were sampled at a rate of 100 Hz. Begin and end of the data displayed corresponds to the onset of C_1 and the offset of C_2. See Fig. 1 for the definition of these landmarks.

stressed (S) and unstressed (U)). In Fig. 5 the durations of the articulatorily defined consonants (dark gray and light gray) and the overlap (mid gray) or lag (white) are shown. Additionally the acoustically measured vowel duration (black) is given. This is to give evidence concerning our prediction (e) above where we assume that stress has the strongest effect on the nucleus. Intervals of syllables starting with /kl/ are presented on the left side and with /kn/ on the right side.

First, results on pause durations are presented because the boundary categories were distinguished by the presence or absence of a pause. Therefore, quite unsurprisingly, pause duration significantly distinguishes BG boundaries from SM and WD. For SM and WD the durations differ only in very few cases (kl: f01, f02 and m02). This parameter mainly serves the purpose of validating the results for C_1 plateau duration. As mentioned above, full dorsal contact for /k/ was often established within and maintained throughout the pauses. In these cases it was not clear whether the constriction was intended for speech articulation or an artifact introduced by the EPG pseudo-palate, e.g. swallowing and so forth.

The duration of C_1 is clearly affected by boundary strength for both /kl/ and /kn/. Generally, we find longer plateau durations in the BG condition as compared to the weaker boundaries. Only in three cases (/kl/: m02, /kn/: f03 and m01) do plateau durations for C_1 differ significantly between the SM and WD boundary levels as well. The main difference was between BG boundary on the one hand and SM and WD on the other hand.

Effects on overlap are less consistent than those on C_1 duration. In some speakers—not necessarily the same ones—both /kl/ and /kn/ exhibit less overlap at strong boundaries than at weak boundaries. This is significant in three speakers (f03, f04, f05) for /kl/ and in four speakers (f01, f03, f05, m01) and across speakers for /kn/. Mainly, the BG boundary is distinguished from the two other levels.

Boundary strength does not, however, appear to play a role in the duration of C_2. Significant differences are very rare and directionally inconsistent (/kl/: m02 SM $<$ WD, f02 SM $>$ WD; /kn/: f04 BG $<$ SM, m02 BG $<$ WD; see Tables 3 and 4). The overall insensitivity of C_2 duration to boundary strength is furthermore demonstrated across speakers in the repeated measures ANOVA. As was expected the nucleus duration was not affected by boundary strength (/kl/: $F=2.4$, /kn/: $F=1.7$).

No effects of stress could be observed on C_1 and C_2 plateau durations or on the duration of a pause (only speaker m01 appears to lengthen pauses before stressed /kn/). However, speakers f02, f03 and f04 produce both /kl/ and /kn/ with less overlap in stressed syllables as do speakers m01 for /kl/ and m02 for /kn/. Across speakers, no significant effect of lexical stress could be found for any of the parameters except for less overlap in stressed syllables in /kn/. The data follow our prediction with respect to the syllable nucleus being the center of the effect of stress. Nucleus durations are longer in stressed than in unstressed syllables (/kl/: $F=4.5$ (only marginally significant), /kn/ $F=57.0$, $p<0.001$), as can be seen in Fig. 5.

3.2.2. *Spatial effects*

Articulatory strengthening is often equated with an increase of palatal contact. Table 5 and Fig. 6 show the effects of prosodic variation on /kl/ and /kn/ in the spatial domain, i.e. maximum contact percentage for the first and the second consonants. Boundary strength affects the contact patterns of /k/ only in /kn/ not in /kl/. For /kn/ this effect—with stronger boundaries inducing more palatal contact—is very consistent for six speakers and over all speakers in the repeated measures ANOVA. The strength of the boundary effect diminishes with distance from the boundary but is still significant in C_2 for three speakers and across speakers only for /kn/. Stress strengthens both consonants in some cases for the cluster /kl/ but not for /kn/: Three speakers increase the amount of palatal contact in /k/ and two in /l/. As can be seen in Fig. 6, the spatial stress effect on /l/ in /kl/ tends to increase at lower levels of boundary strength.

Table 3
Statistical results for temporal parameters in cluster /kl/ under prosodic variation for each speaker (rows 1–7) and across all speakers (row 8; prosodic groups (PG): BG, SM, WD: stress levels: S, U).

Spk	Effect	Measure								
		C1			C2		Overlap		Pause	
		df	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
f01	PG	70		n.s.		n.s.		n.s.	BG > SM > WD 151.8	***
	Stress			n.s.		n.s.		n.s.		n.s.
f02	PG	58	BG > SM, WD 10.2	***	SM > WD 4.7	*	3.5	*	BG > SM, WD 81.9	***
	Stress			n.s.		n.s.	S < U 4.3	*		n.s.
	Inter.			n.s.		n.s.		n.s.	U: SM > WD 17.3	***
f03	PG	54	BG > SM, WD 20.2	***		n.s.	9.5	***	BG > SM,WD 169.7	***
	Stress			n.s.		n.s.	*S < U* 30.7	***		n.s.
	Inter.			n.s.		n.s.	S: BG, WD > SM U: BG, SM < WD 8.7	***		n.s.
f04	PG	42	BG > SM, WD 21.8	***		n.s.	SM < WD 8.2	***	BG > SM, WD 331.0	***
	Stress			n.s.		n.s.	S < U 14.3	***		n.s.
			U: SM < WD 10.1	***		n.s.		n.s.		n.s.
f05	PG	68	BG > SM, WD 18.9	***		n.s.	BG < WD 4.1	*	BG > SM, WD 86.8	***
	Stress			n.s.	S > U 4.0	*		n.s.		n.s.
	Inter.			n.s.	SM, WD: S > U 3.2	*		n.s.		n.s.
m01	PG	65	BG > SM, WD 12.5	***		n.s.		n.s.	BG > SM, WD 23.6	***
	Stress			n.s.		n.s.	S < U 6.5	*		n.s.
	Inter.			n.s.		n.s.	3.7	*		n.s.
m02	PG	52	BG > SM > WD 12.4	***	WD > SM 3.7	*		n.s.	BG > SM > WD 70.2	***
	Stress			n.s.		n.s.		n.s.		n.s.
All	PG	6.8 1.1 6	BG > SM, WD; 14.0	*		n.s.		n.s.	6.4 BG > SM, WD 1.1 43.2	***
	Stress			n.s.		n.s.		n.s.		n.s.

Interactions (Inter.) are included if present. The degrees of freedom for the factors are fixed (PG: 2, Stress: 1). Significance codes: 0 "*** " 0.001 "**" 0.01 "*" 0.05. Example: for speaker f05 in SM and WD condition, C_2 plateau duration is longer in stressed than in unstressed tokens.

4. Summary and discussion

In this section we will summarize and discuss the results of this study according to the predictions stated in Section 1.3. Concerning cluster type, the most obvious finding in this study is that overlap for /kl/ appears to be mandatory while the timing in /ks/ and /sk/ is less rigidly specified. /kn/ does not appear to allow for overlap, as measured here, at all. The difference between /kl/ and /kn/ was predicted correctly by manner-based ordering (a). /ks/ and /sk/, however, were assumed to overlap less than the stop+sonorant clusters, which is not confirmed. (b) The difference between /kl/ and /kn/ is accounted for by perceptual recoverability, albeit for different reasons than manner-based ordering: A lag between /k/ and /n/ would presumably prevent the stop burst being obscured by early velar opening. (c) According to the predictions of the DAC model, ordering the four clusters by the amount of overlap should yield a sequence of /sk/ > /ks/ > /kl/ > /kn/. As for /sk/ and /ks/, the predicted higher overlap in the former was not found. Rather, the two clusters behave quite similarly with large variability in the emergence of overlap. The prediction of the DAC model for /kl/ to show more overlap than /kn/ is confirmed, although this effect

Table 4
Statistical results for temporal parameters in cluster /kn/ under prosodic variation for each speaker (rows 1–7) and across all speakers (row 8; prosodic groups (PG): BG, SM, WD: stress levels: S, U).

Spk	Effect	Measure								
		C1			C2		Overlap		Pause	
		df	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
f01	PG	74	BG > SM, WD				BG < WD		BG > SM, WD	
			16.7	***		n.s.	4.9	**	99.4	***
	Stress									
				n.s.		n.s.		n.s.		n.s.
f02	PG	56	BG > SM, WD						BG > SM, WD	
			21.9	***		n.s.		n.s.	81.9	***
	Stress						S < U			
				n.s.		n.s.	8.1	**		n.s.
f03	PG	48	BG > SM > WD						BG > SM, WD	
			34.8	***		n.s.		n.s.	95.3	***
	Stress		S > U				S < U			
			7.2	**		n.s.	8.6	**		n.s.
	Inter.						U: BG < SM, WD			
				n.s.		n.s.	8.7	*		n.s.
f04	PG	56	BG > SM, WD		BG < SM				BG > SM, WD	
			58.6	***	3.5	*		n.s.	33.1	***
	Stress						S < U			
				n.s.		n.s.	11.9	**		n.s.
f05	PG	74	BG > SM, WD				BG < SM, WD		BG > SM, WD	
			20.9	***		n.s.	6.9	**	226.3	***
	Stress									
				n.s.		n.s.		n.s.		n.s.
m01	PG	77	BG > SM > WD				BG < SM, WD		BG > SM, WD	
			42.1	***		n.s.	19.9	***	107.8	***
	Stress								S > U	
				n.s.		n.s.		n.s.	4.4	*
m02	PG	57	BG > SM, WD		BG < WD				BG > SM, WD	
			22.3	***	4.0	*		n.s.	241.5	***
	Stress						S < U			
				n.s.		n.s.	8.7	**		n.s.
All	PG	8.4	BG > SM, WD				11.3 BG < SM, WD		6.1 BG > SM, WD	
		1.4	53.1	***		n.s.	1.9 10.3	**	1.0 50.7	***
	Stress	6					S < U			
		1		n.s.		n.s.	6.7	*		n.s.

Interactions (Inter.) are included if present. The degrees of freedom for the factors are fixed (PG: 2, Stress: 1). Significance codes: 0 "*** " 0.001 "**" 0.01 "*" 0.05. Example: for speaker f03 in unstressed tokens, overlap is smaller in BG than in SM and WD.

might actually be stronger than it should be expected, since the DAC value of /l/ is assumed to be only slightly higher than that of /n/. Contrary to the predictions, overlap in /kl/ is even larger than in /ks/ and /sk/. As mentioned in Section 1.1 this might be accounted for by assigning /l/ a higher DAC value following the findings of Recasens et al. (1995) that German /l/ appears to be less clear than clear /l/ in other languages. Indeed, if /l/ was assigned a dorsal target, as e.g. dark /l/ in Catalan, the tongue predorsum would be lowered for both /k/ and /l/ and the /kl/ transition could therefore proceed without tongue repositioning as opposed to /kn/ and /ks/. Following this line of thought, Catalan and German should show a tendency for more overlap in /kl/ clusters than other languages. Data collected by Gibbon, Hardcastle, and Nicolaidis (1993), however, indicate that /kl/ clusters in Catalan show significantly more overlap than in German and other languages. Moreover, EMA data (Geumann, Kroos, & Hoole, 1999) indicate that spatial variability of the tongue dorsum in German /l/ is very high and at least certainly not less than for /n/.

Several alternative reasons might explain the consistently longer lag in /kn/ clusters: In the first place, aero-dynamic reasons, as already mentioned in Section 1.1, might constrain the timing between the two consonants in order to avoid a velo-pharyngeal leakage before oral release of C_1 occurs.[8]

[8] Should this be the case, the same pattern might be predicted in initial fricative+nasal clusters, since fricatives also require a tight velo-pharyngeal closure, in order to maintain a sufficient air flow for turbulence. However, data collected by Kühnert et al. (2006) do not support this prediction, Fricatives, with their continuous acoustic information, are presumably in less danger of becoming difficult to recover. Acoustic information on the plosives on the other hand is concentrated at the burst.

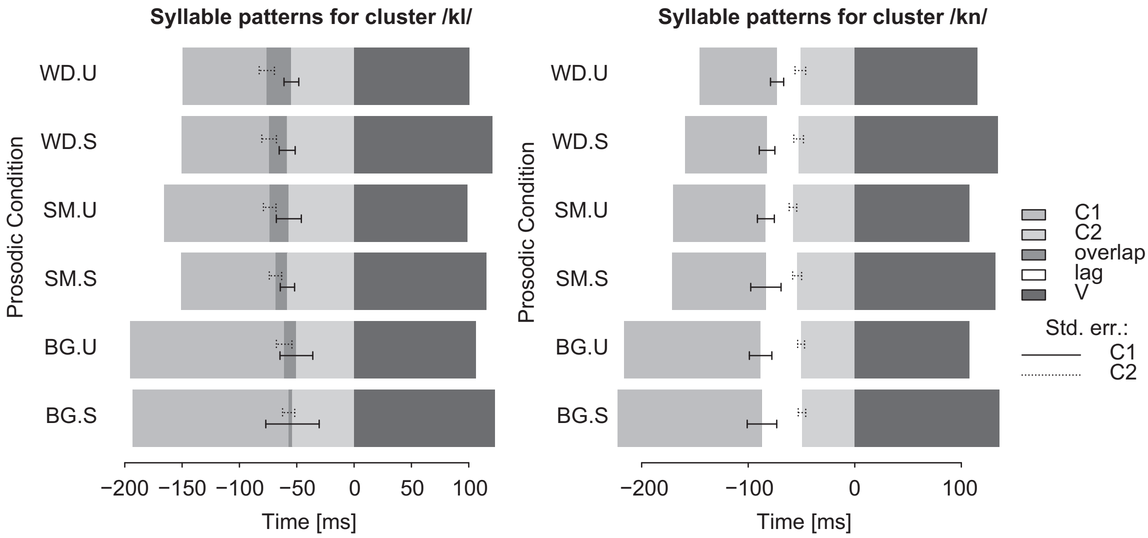

Fig. 5. Syllable patterns of the mean C1 and C2 contact plateau durations for the clusters /kl/ and /kn/ as well as the acoustical nucleus duration across all speakers for each prosodic condition (see text). Standard errors are drawn at the inner border of the respective bar. Standard error bars for C1 (solid lines) are drawn slightly below those for C2 (dotted lines). Zero-point is aligned with the beginning of the nucleus. The patterns are drawn in a pairwise fashion (stressed S and unstressed U), one pair for each prosodic group (BG, SM, WD).

Secondly, bio-mechanical linkage could prevent early velar lowering because the tongue dorsum presses against the soft palate during velar stops. However, Kühnert et al. (2006) show that in /pn/ and /pl/ clusters, where bio-mechanical linkage can be neglected, the timing of lips and tongue tip differs in the same way as for tongue dorsum and tip in /kn/ or /kl/ clusters.

Thirdly, it could be argued that, in terms of inter-articulator coordination, /n/ is more complex in German than /l/ since apart from the tongue tip gesture the nasal requires an additional velar opening gesture. Therefore, a larger gap, i.e. less overlap, might be induced between the consonants in /kn/ than in /kl/. As several studies showed (Byrd, Tobin, Bresch, & Narayanan, 2009; Kollia, Gracco, & Harris, 1995; Krakow, 1993), in syllable initial position the velum and the primary articulator in nasals reach their targets simultaneously. To our knowledge, however, these studies do not address how onsets of velum and oral gestures are temporally coordinated. It could be speculated that in simple nasal onsets the velar opening gesture starts earlier than the oral constriction gesture. In complex /Cn/ onsets, then, velar opening onset, and not the oral constriction gesture of the nasal, might be timed with the constriction of the preceding consonant and therefore does not start until after the release of the preceding stop's closure. Thus, given that the velar opening onset is likely to occur after the release of the preceding oral consonant, and given that the targets of the velar opening gesture and its associated oral constriction gesture are likely to be attained simultaneously, there is likely to be a substantial gap between the oral constriction gesture associated with the nasal consonant and the preceding oral constriction gesture.

Prosodic boundary strength and lexical stress were varied in the current study as a probe in order to test which of the observed patterns for clusters remain stable. For reasons of comparability (see predictions in Section 1.3) only /kl/ and /kn/ were considered in this part. While overlap to some extent showed sensitivity to prosodic variation (less overlap at high boundaries and in stressed syllables), the range of variation was limited so that the categorical difference found between /kl/ and /kn/ remained unaffected. Therefore the assumption that the temporal coordination in /kl/ and /kn/ is highly specified and constrained by the segmental make-up of the cluster receives considerable support.

There is more evidence for changes due to prosodic variations in temporal coordination in /kn/ than in /kl/. The extent to which variation is allowed in overlap depends therefore on the segmental make-up. As was explained in Section 1.1, the upper limit of overlap is probably constrained by perceptual recoverability demands. The violation of the lower limit of overlap—or rather the upper limit of lag—might yield the production of a transitional vowel. Evidence for transitional vowels has been found by Davidson (2005) for illegal clusters in American English and by Gafos (2002) in Moroccan Arabic. It would be interesting to see if a lag in /kl/ would induce the perception of such a transitional vowel. If so, it would explain why speakers avoid the drifting apart of the consonant gestures in /kl/. Accordingly, for /kn/ the upper limit of lag before perception of a transitional vowel would be higher.

Apart from the internal structure, the consonants themselves are affected by prosodic variation in both the temporal and the spatial domain. The strength of the boundary affects mainly the duration of C_1's plateau in both /kl/ and /kn/, i.e. /k/ was lengthened at higher boundaries. Articulatory strengthening was restricted to C_1 in /kn/ and at higher boundaries only. The second consonant is not sensitive to boundary strength, i.e. we could not replicate the findings of Byrd and Choi (2010) who found lengthening of C_2 in onset clusters in two out of three speakers. Additionally, the pause duration was the most consistently affected measure in this study. As was pointed out in Section 2.2, during the pause at big boundaries speakers varied in their timing of C_1 constriction: frequently constriction was achieved at the beginning of the pause, resulting in overlong plateau durations. In these cases, the lengthening of C_1 is reducible to the occurrence of a pause. Indeed, C_1 plateau duration mainly distinguished big boundaries from lower boundary levels. However, the occurrence of a pause cannot be made responsible for the effects observed on overlap. In summary we found stronger effects of boundary strength on duration and palatal contact of C_1. The overlap was affected less consistently and the second consonant only spatially in /kn/. Stress, on the other hand, only influenced the duration of the nucleus (longer in stressed syllables) and the overlap (less in stressed syllables).

In the introductory section, we proposed two models explaining how segments are affected by prosodic variation. We will

Table 5
Statistical results for spatial parameters in clusters /kl/ and /kn/ under prosodic variation for each speaker (rows 1–7) and across all speakers (row 8; prosodic groups (PG): BG, SM, WD; stress levels: S, U).

Spk	Effect	/kl/					/kn/				
		C1 Max			C2 Max		C1 Max			C2 Max	
		df	*F*	*p*	*F*	*p*	df	*F*	*p*	*F*	*p*
f01	PG	70		n.s.		n.s.	74	BG, SM > WD 4.5	*	BG, SM > WD 7.2	**
	Stress			n.s.		n.s.			n.s.		n.s.
f02	PG	58		n.s.		n.s.	56		n.s.		n.s.
	Stress		S > U 15.8	***	S > U 36.1	***			n.s.		n.s.
	Inter.			n.s.		n.s		U: BG > WD SM: S < U 3.6	*		n.s.
f03	PG	54		n.s.		n.s.	48	BG > WD 6.6	**		n.s.
	Stress			n.s.		n.s.			n.s.		n.s.
f04	PG	42		n.s.		n.s.	56		n.s.	SM > WD 5.9	**
	Stress		S > U 4.6	*		n.s.			n.s.		n.s.
f05	PG	68		n.s.		n.s.	74	BG > SM, WD 35.3	***		n.s.
	Stress			n.s.		n.s.			n.s.		n.s.
	Inter.		S: SM < BG, WD 8.5	***		n.s.			n.s.		n.s.
m01	PG	65		n.s.		n.s.	77	BG > SM > WD 49.6	***		n.s.
	Stress				S > U 28.6	***			n.s.		n.s.
m02	PG	52		n.s.	5.0	*	57	BG, SM > WD 8.3	*	BG > WD 11.2	***
	Stress		S > U 6.5	*		n.s.			n.s.	U > S 13.3	***
All	PG	12		n.s.		n.s.	8.2 1.4	BG > WD 11.3	*	11.9 2.0 11.5	**
	Stress	6		n.s		n.s.	6		n.s.		n.s.

Interactions (Inter.) are included if present. The degrees of freedom for the factors are fixed (PG: 2, Stress: 1). Significance codes: 0 "*** " 0.001 "**" 0.01 "*" 0.05. Example: for speaker m01 in cluster /kn/ maximal C_1 contact is larger in BG than in SM than in WD.

discuss effects of boundary strength first. Pierrehumbert and Talkin suggest (for CV and VC syllables) that initial strengthening shifts the articulatory magnitude in a more consonantal direction. No specific predictions concerning consonant clusters can be derived from this account, but it is confirmed to the extent that articulatory strengthening takes place. The π-gesture approach more specifically predicts a decrease of the effect with distance from the boundary. In fact, our data corroborate this prediction with regard to the diminishing effects going from C_1 to overlap and C_2.

However, there is no simple way of modeling the differential behavior of /kl/ and /kn/ induced by prosodic variation within the framework of π-gestures. /kn/ is more susceptible to effects of this kind than /kl/ in the temporal and the spatial domain. We assume that this is strongly related to the internal structure of /kl/ vs. /kn/: The former shows overlapping consonant plateaus during which the tongue is highly constrained by multiple affordances. Apart from the central alveolar contact, lateral aperture is required to produce an /l/. In /kl/ clusters the tongue is further constrained by a simultaneous dorsal closure. In /kn/ on the other hand, contact patterns are less constrained because the dorsal constriction for /k/ and the apical constriction for /n/ are produced sequentially, i.e. there is a lag between the consonant plateaus. In so being less constrained, the components of the cluster have more degrees of freedom for adjustments to prosodic variation. /kl/ behaves in this respect similarly to what Fougeron and Keating (1997) found for /s/, namely that this consonant is less susceptible to articulatory strengthening at higher prosodic boundaries.

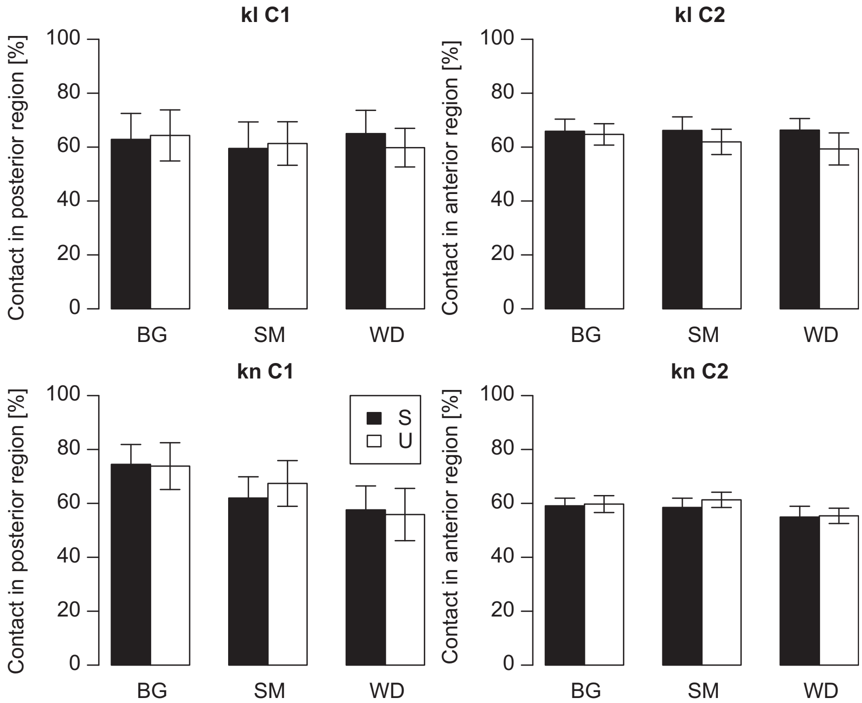

Fig. 6. Contact percentage in the respective region of the pseudo-palate for C_1 and C_2 ind /kl/ and /kn/, calculated across all speakers, separately for each boundary and stress level.

For stress, the π-gesture approach would predict the largest impact on the syllable's nucleus and a continuous decrease from the nucleus to the onset. In our data, we find a *dis*-continuity: While C_2 as the closest segment to the nucleus remains largely unaffected, there is a significant decrease in overlap in stressed syllables. Evidence for the discontinuity of prosodic effects was also found by Turk and Shattuck-Hufnagel (2007) on the syllable level: In their data, final lengthening affected the main-stress-syllable and the rime of domain final words but skipped the phonological material in between these two syllables. Final lengthening is thus unevenly or discontinuously distributed.

5. Conclusions

The major finding of this study is that the gestural coordination for /kl/ is categorically different as compared to /kn/ with an obligatory lag between the consonant plateaus for /kn/ and overlap for /kl/. This is accounted for by all three principles introduced in Section 1.1: perceptual recoverability, manner-based ordering and the DAC model. However, while the recoverability based account does not make a prediction for the clusters involving /s/, neither the manner-based ordering nor the DAC model can account for the internal structure of these clusters. Prosodic variation can influence the differential coordination between the clusters' consonants only within certain limits determined by the segmental make-up of the clusters. Our results give evidence that effects due to prosodic variation are rather subordinate to segmental setup and specifically that stop+nasal sequences play a special role. This might be of particular interest to research in sound change as well, e.g. loss of /k/ in English *knee* due to unmet parallel transmission requirements in terms of insufficient overlap.

Table 6
Utterances for cluster /kl/.

Stress on first syllable	
Utterance initial	*Thomas studiert in Fulda.* ***Claudia*** *geht noch zur Schule.*
	'Thomas goes to college in Fulda. Claudia ist still in school.'
Phrase initial	*Olga sagt immer,* ***Claudia*** *sei noch zu jung.*
	'Olga always says that Claudia is still too young.'
List	*Thomas, Peter,* ***Claudia*** *und Elke fahren in den Süden.*
	'Thomas, Peter, Claudia and Elke are driving south.'
Word initial	*Gestern war* ***Claudia*** *noch gesund.*
	'Yesterday, Claudia was still OK.'
Stress on second syllable	
Utterance initial	*Die Arbeit war super.* ***Klausur*** *und mündliche Prüfung waren nicht so toll.*
	'The thesis was great. Written and oral exams were not as good.'
Phrase initial	*Tine sagt immer,* ***Klausur*** *schreiben macht Spaß.*
	'Tine always says it's fun to write exams.'
List	*Hausarbeit, Wetter,* ***Klausur*** *und Erkältung machen schlechte Laune.*
	'Housework, weather, written exams and a cold cause sulkiness.'
Word initial	*Morgen muss sie wieder* ***Klausur*** *schreiben.*
	'Tomorrow she has to write a test again.'

Prosodic variation was successfully applied as a probe to investigate the stability of the internal organization within clusters in finding the limits in timing variation that prosodic conditioning induced. Furthermore, we found that not only do different segments display different susceptibility to prosodic variation but also groups of segments, such as clusters. In agreement with Articulatory Phonology (Browman & Goldstein, 1992) and especially the notion of C-Center coordination

Table 7
Utterances for cluster /kn/.

Stress on first syllable	
Utterance initial	*Peter ist Fussballtrainer.* ***Kneipe*** *und Stadion sind sein Leben.*
	'Peter is a football coach. Pub and stadium are his life.'
Phrase initial	*Thomas sagt immer,* ***Kneipe*** *oder Café machen zu viel Arbeit.*
	'Thomas always says a pub or a coffee shop are too much work.'
List	*Restaurant, Bar,* ***Kneipe*** *und Disco wollen sie heute noch besuchen.*
	'The plan to visit a restaurant, a bar, a pub and a disco today.'
Word initial	*Sie arbeitet in einer* ***Kneipe*** *als Kellnerin.*
	'She works in a pub as a waitress.'
Stress on second syllable	
Utterance initial	*Walter trinkt gerne Vodka.* ***Kneipier*** *ist sein Traumberuf.*
	'Walter likes Vodka. He dreams of being a pub owner.'
Phrase initial	*Peter sagt immer,* ***Kneipier*** *ist ein schöner Beruf.*
	'Peter always says that pub owner is a nice job.'
List	*Koch, Kellner,* ***Kneipier*** *oder Barkeeper würde er gern werden.*
	'He would like to be cook , waiter, pub owner or barkeeper.'
Word initial	*Er wollte immer* ***Kneipier*** *werden.*
	'He always wanted to be a pub owner.'

Table 8
Utterances for cluster /sk/.

Stress on first syllable	
Utterance initial	*Olga studiert in Jena.* ***Scarlett*** *geht noch zur Schule.*
	'Olga goes to college in Jena. Scarlett is still in school.'
Phrase initial	*Walter sagt immer,* ***Scarlett*** *sei zu jung.*
	'Walter always says that Scarlett is still too young.'
List	*Peter, Walter,* ***Scarlett*** *und Olga fahren in den Süden.*
	'Peter, Walter, Scarlett and Olga are driving south.'
Word initial	*Gestern war* ***Scarlett*** *noch gesund..*
	'Yasterday Scarlett still was well.'
Stress on second syllable	
Utterance initial	*Walter hört immer Schlager. "****Skandal*** *um Rosi" mag er besonders gern.*
	'Walter likes Schlager music. "Skandal um Rosi" is his favourite.'
Phrase initial	*Peter sagt immer, "****Skandal*** *um Rosi" geht ihm auf die Nerven..*
	'Peter always says, "*Skandal* um Rosi" gets on his nerves.'
List	*Affäre, Schickeria,* ***Skandal*** *und Betrug gehören in Thomas Kolumne..*
	'Affairs, jet set, scandals and deceit are part of Thomes' column.'
Word initial	*Das war der größte* ***Skandal*** *im letzten Jahr.*
	'It was last year's greatest scandal.'

Table 9
Utterances for cluster /ks/.

Stress on first syllable	
Utterance initial	*Volker studiert in Jena.* ***Xaver*** *geht noch zur Schule.*
	'Volker goes to college in Jena. Xaver is still in school'
Phrase initial	*Walter sagt immer,* ***Xaver*** *sei zu jung..*
	'Walter always says that Xaver is still too young.'
List	*Inge, Walter,* ***Xaver*** *und Elke fahren in den Süden.*
	'Inge, Walter, Xaver and Elke are driving south.'
Word initial	*Am Montag war* ***Xaver*** *noch gesund.*
	'On monday Xaver was still well.'

(Browman & Goldstein, 1988, 2000; Byrd, 1995), we therefore assume that the temporal coordination (here in terms of overlap) is part of the phonological specification. Prosodic variation in clusters on the other hand appears to have limits determined by segmental setup. This is in accordance with limits of prosodic variation on singleton consonants such as the highly constrained /s/ (e.g. Shadle & Scully, 1995).

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Appendix A. Complete speech material

Utterances for clusters /kl/, /kn/, /sk/ and /ks/ are shown in Tables 6–9.

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