INTRINSIC AND PROSODIC EFFECTS ON ARTICULATORY COORDINATION IN INITIAL CONSONANT CLUSTERS

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ABSTRACT

EMA was used to study the coordination of the articulatory gestures for C1 and C2 in onset clusters, firstly as a function of the segmental make-up of the clusters, and secondly as a function of stress and prosodic boundary conditions. The segmental results, which compared German and French, indicated a much lower degree of overlap of C1 and C2 for C2=/n/ compared to C2=/l/ (with C1=/p, b, k, g/). Overlap was also less for voiceless compared to voiced C1 for German. Prosodic boundary strength affected the duration of the C1 articulatory constriction more strongly than that of C2, while, conversely, differences in lexical stress affected C2 more strongly than C1. The coordination relations between C1 and C2 were, however, not systematically affected by prosodic conditions. Nor did the different clusters studied (/kl, kn, sk/) appear to differ in their internal cohesiveness. The results are discussed with respect to how articulatory coordination is constrained to allow acoustic recovery of segmental information by the listener; the possibility of cross-language differences in these constraints is raised.

Keywords: consonant clusters, articulatory coordination, prosodic strengthening

1. INTRODUCTION

This study examines how articulatory coordination in heterorganic initial consonant clusters is modulated firstly by the segmental make-up of the cluster itself, and secondly by the prosodic conditions in which the cluster is spoken. The relevant background as well as the results to these two areas will be presented in two fairly self-contained sections (section 2: segmental make-up; section 3: prosodic conditions), and will be followed by general discussion in section 4.

2. SEGMENTAL STRUCTURE OF CLUSTERS

2.1 Background

The main impetus for this first area comes from the contention advanced in Chitoran et al. [4] that generalizations about preferred syllable structures (such as the sonority hierarchy) reflect at a more fundamental level the outcome of successful compromises between parallel transmission of segmental information, i.e a high degree of overlap among gestures (assumed to be efficient for the speaker) and clear modulation of the acoustic signal (assumed to be efficient for the hearer). One illustration of this is the place-order effect in stop-stop clusters reported for Georgian by these authors: C1(back) + C2(front) clusters show less overlap than the reverse order, presumably to ensure recoverability of C1 by the listener (see also Gafos et al. [7] for Moroccan Arabic).

Nonetheless, relative to the very large number of complex syllabic onsets found across languages there has still been little detailed exploration of these principles. We focus here on a potentially revealing comparison among onset clusters found, for example, in German and French, but not in English, namely plosive + /l/ vs. plosive + /n/. The latter appear to be less stable diachronically than the former (cf. Vennemann [14]), and occur less frequently in extant languages. Why might they then be less suitable for the formation of complex syllable onsets? One possibility is that C1 and C2 need to overlap less (than in the case of plosive + /l/) to ensure that acoustic properties of the C1 burst are not compromised by velar lowering.

As a further manipulation of the phonetic properties of the syllable onset, the study also systematically varies the voicing category of the C1 plosive. This can be assumed to have a substantial effect on the nature of the acoustic information available to the hearer particularly in the C1 to C2 transition. But whether this may in turn lead to different preferred coordination patterns for C1 with C2 is, to our knowledge, essentially unknown. German and French were considered to be particularly appropriate for study here, since they are known to differ substantially in the timing of voice onset following voiceless plosives.

2.2 Material and Recordings

The main structure aimed for in the material for both German and French was to use real monosyllabic words (CCVC) with all combinations of C1 = /p, b, k, g/, C2 = /l, n/, V=/i, a/.

Not all of these combinations are lexically attested; for example, /bn/ combinations are missing in both languages and /pn/ is lexically somewhat marginal in German.

Since preliminary analysis indicated no consistent effects of vowel category on overlap between C1 and C2, and since gaps in the lexicon occasionally required the use of vowels other than /i/ and /a/, for the purposes of the present paper we will present the results averaged over vowels. In short, results can be presented for all four combinations of C1 with /l/, and three with /n/ (/bn/ missing).

Each target word was embedded in a carrier phrase with additional material not of concern here and recorded 10 times in randomized order.

Movements of the articulators were measured by means of a 3D EMA system (AG500, Carstens Medizinelektronik; cf. Hoole et al. [10]). Of the three sensors located on the tongue the frontmost one was used to analyze the tongue-tip gesture for /l, n/, the rearmost one for the tongue-dorsum gesture for /k, g/. The sensors located on lower and upper lip were combined to a lip aperture measure for analysis of the labial gesture for /p, b/. The key dependent variable is the measure of overlap between C1 and C2. This is illustrated in Fig. 1. Different measures of overlap have been used in previous investigations (Chitoran et al. [4], Gafos et al. [7]). The one used here is based on the constriction phases of C1 and C2. Specifically, the timepoint of the onset of the constriction phase of C2 (phase 4 in the figure) is subtracted from the timepoint of the offset of the constriction phase of C1 (phase 2 in the figure). This time difference is normalized by the time interval from the onset of C1 constriction to offset of C2 constriction and expressed as a percentage. The important point to bear in mind for the interpretation of the results is that, with this definition, increasingly positive values correspond to increasing overlap of C1 and C2 (negative values in effect mean that the constriction phases do not overlap)[1].

[1] The pattern of results presented below remains essentially the same if an absolute rather than normalized measure of overlap is used, and also if C2 timing is indexed by the onset of movement towards constriction (i.e. onset of phase 3 in Fig. 1) rather than the onset of constriction itelf.

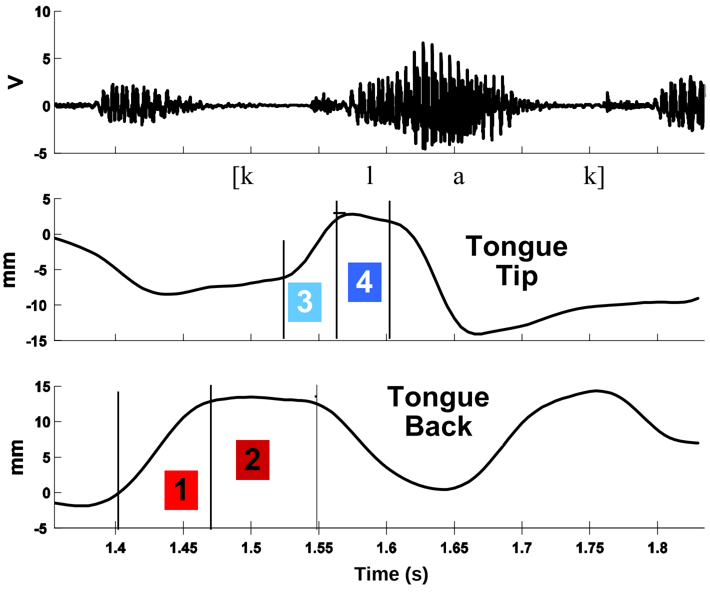

Figure 1: Illustration of determination of C1-C2 overlap for a /kl/ sequence. The constriction phases for the two consonants (labelled '2' and '4') are determined using a 20% velocity criterion in the tongue-back and and tongue-tip signals respectively. For illustrative purposes only the vertical movement component is shown.

2.3 Results

Regarding the manner of articulation of C2 (lateral vs. nasal), for German there is a clear effect in the form of the anticipated lower degree of overlap for the plosive-nasal sequences (see Fig. 2, left column). This appears to be a very robust effect because the same effect is observed (for the cluster pair /kl/, /kn/) in the different corpus used for the prosodic investigation reported in section 3 below. Moreover, with the prosody corpus used in section 3 the effect has been observed not only for the speakers analyzed there with EMA but also for an additional 7 speakers recorded by electropalatography (Bombien et al. [1]).

For French the pattern is less consistent, the speakers showing strong, weak and non-existent trends in the expected direction for AM, NN and CG, respectively (see Fig. 2, right column). For CG the overlap between plosive and /n/ often seemed large enough to lead to nasal release of the plosive.

Regarding voicing of C1 there is a very consistent effect for German showing less overlap between C1 and C2 when C1 is voiceless. For French no consistent effect of voicing is seen. On the basis of only three speakers per language it is, of course, too early to be confident about possible cross-linguistic differences. Nonetheless, it is intriguing that voicing-related differences are observed in that language, namely German, where acoustic properties of C2 are more strongly affected by the voicing status of C1. Perhaps this fits in with the first finding too: The constraint to maintain low overlap between plosive and /n/ may be stronger in languages where glottal opening is wide at the release of C1.

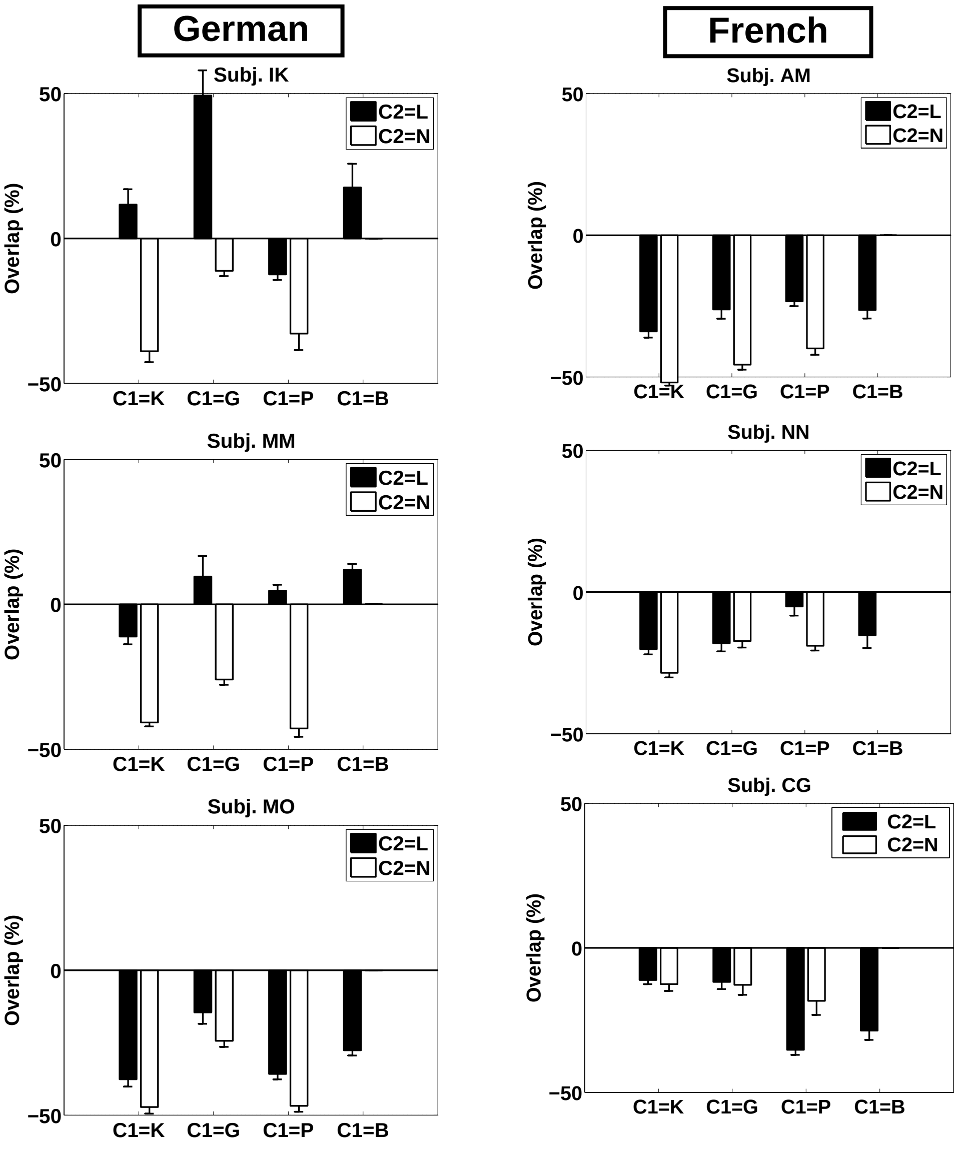

Figure 2: C1-C2 overlap for three German subjects (left column) and three French subjects (right column). See text for definition of overlap measure (expressed here as percentage). More positive values indicate more overlap. From left to right, bars in each panel are /kl, kn, gl, gn, pl, pn, bl/ (/bn/ not in corpus). Error bars give standard error of mean.

3. PROSODIC INFLUENCES ON CLUSTERS

3.1 Background and material

The second main area of the study extends to clusters the well-established experimental paradigm (e.g Fougeron & Keating [6]; Keating et al. [11]) of investigating articulatory strengthening at prosodic boundaries, as part of an overall concern to better understand what information on prosodic structure the speaker makes available to the listener. A plausible hypothesis – consistent, for example, with the pi-gesture approach of Byrd & Saltzman [2] – is that prosodic boundary effects on articulation decrease with increasing distance from the boundary. However, with a few exceptions (e.g Byrd & Choi [3]), most work within this paradigm has used rather simple syllable structures. Thus it is currently difficult to estimate whether boundary effects are indeed best modelled as a simple function of distance from the boundary, or whether structural properties of the syllable (e.g consonantal onset versus vocalic nucleus) have an independent influence.

The material investigated included the clusters /kl, kn, sk/; they formed the onset of the target words, i.e the words immediately following the prosodic boundaries. These were varied in four steps of assumed decreasing boundary strength from utterance initial to no boundary, as shown in the following examples for the /kl/ cluster at the onset of the target-word “Claudia”:

Utterance initial	Thomas studiert in Fulda. Claudia geht noch zur Schule. (*Thomas goes to college in Fulda. Claudia is still in school.*)
Phrase initial	Olga sagt immer, Claudia sei zu jung. (*Olga always says that Claudia is too young.*)
List element	Thomas, Peter, Claudia und Elke fahren in den Süden. (*Thomas, Peter, Claudia and Elke are travelling south.*)
Word boundary	Gestern war Claudia noch gesund. (*Yesterday, Claudia was still well.*)

(Notes: (1) “Word boundary” is used to refer to the condition where no prosodic boundary is expected; the punctuation of the English translation is misleading. (2) “Utterance initial” might be better referred to as “Sentence intial”. Here it simply indicates the condition where the strongest prosodic boundary is to be expected.)

With respect to the location of prosodic effects in the articulatory patterns, the basic expectation was that C1 would exhibit more boundary-induced variation than C2.

In addition to the boundary condition the experiment also contained orthogonal variation of a second prosodic variable, namely word stress: The target clusters formed the onsets of words with lexical stress on either the first or second syllable (e.g ‘Claudia, vs. Klau’sur). For this prosodic manipulation the literature gives even less to go on than for the boundary condition. A tentative hypothesis was based on the assumption that stress effects are centered on the nucleus of the stressed syllable and decline towards the syllable margins. Accordingly, stress effects were expected to be more visible in C2 than in C1.

Analyses focussed on whether C1 or C2 showed durational or spatial enhancement at higher boundary levels and in the stress condition. In addition it was hypothesized that overlap between C1 and C2 would be reduced at higher boundary levels and in the stress condition.

In addition to the interest in prosodic effects in their own right, the manipulation of prosodic conditions in the present experiment can also be regarded as a probe to elucidate the internal cohesion of clusters (cf. Byrd & Choi [3]), thus linking up with the topic of segmental organization dealt with in Section 2 above. We saw there that /kn/ had less overlap of the component oral gestures than /kl/. Could it also be the case that the components are also less cohesive in /kn/, such that the coordination relations (as captured by the overlap measure) are more strongly affected by ‘external’ conditions? (See Rialland [13] for distributional arguments in favour of analyzing /k/ in /kn/ as extrasyllabic in French.)

3.2 Recordings and analysis procedures

EMA recordings have been analyzed for the three German speakers who participated in section 2 above. For this part of the recording session, in addition to the EMA data, respiratory activity of the speakers was monitored by means of Respitrace in order to give additional information on prosodic divisions into breath groups.

As a preliminary stage in the analysis the actual prosodic realization at the target word of the four boundary categories given above was assigned to one of three prosodic categories, which will be referred to as follows (cf. Cho and McQueen [5]):

Big Boundary (**BG**):	Pause and boundary tone
Small Boundary (**SM**):	No pause but boundary tone
Prosodic Word (**WD**):	No pause, no boundary tone

In the present dataset only very few big boundaries (BG) have been found, so for the following results only the SM and WD categories will be considered. The breakdown of the syntactically defined boundary categories with respect to the the SM and WD prosodic categories came out as follows:

	SM	**WD**
Utterance initial	51	8
Phrase initial	28	62
List element	14	76
Word boundary	2	89

This makes clear that the range of syntactic conditions was successful in generating different prosodic realizations. It also makes clear that particularly for intermediate syntactic conditions such as Phrase Initial it is important to determine the actual prosodic realization on a case-by-case basis; it cannot be assumed a priori. More refined approaches to prosodic categorization are currently also being explored.

The virtual absence of big prosodic boundaries (as defined above) in the present material is the reason why the results of a previous experiment in which 7 speakers were recorded with basically the same corpus by means of EPG will not be examined here: In the EPG experiment a large number of BG realizations were found (essentially for the utterance-initial condition), which would unduly complicate the comparison with the present EMA results. The results of the EPG experiment will be considered in detail in a separate publication (Bombien et al. [1]).

3.3 Results

We will first present the results for the durations of the target phases of C1 and C2, i.e the durations of the phases labelled ‘2’ and ‘4’ in the example utterance given in Fig. 1 above.

The results for C1 are shown in the left column of Fig. 3. There is a very consistent trend in the hypothesized direction of longer durations at the more prominent prosodic boundary (i.e the ‘SM’ boundary compared to the ‘WD’ boundary): Of 18 SM-WD pairs matched for stress level (and cluster and speaker), 17 are in the predicted direction. In ANOVAs carried out separately for each combination of speaker and cluster type the main effect of boundary is significant at $p<0.01$ in 6 out of 9 possible cases. On the other hand, the effect of stress on C1 appears to be very inconsistent. Of the eighteen stress-unstress pairs matched for boundary type (i.e immediately adjacent bars in the figure), 10 are in the direction of longer duration for the stress condition, and in the ANOVAs only one of nine cases showed a main effect of stress in this direction that was significant at p<0.01 (/sk/ for speaker MO).

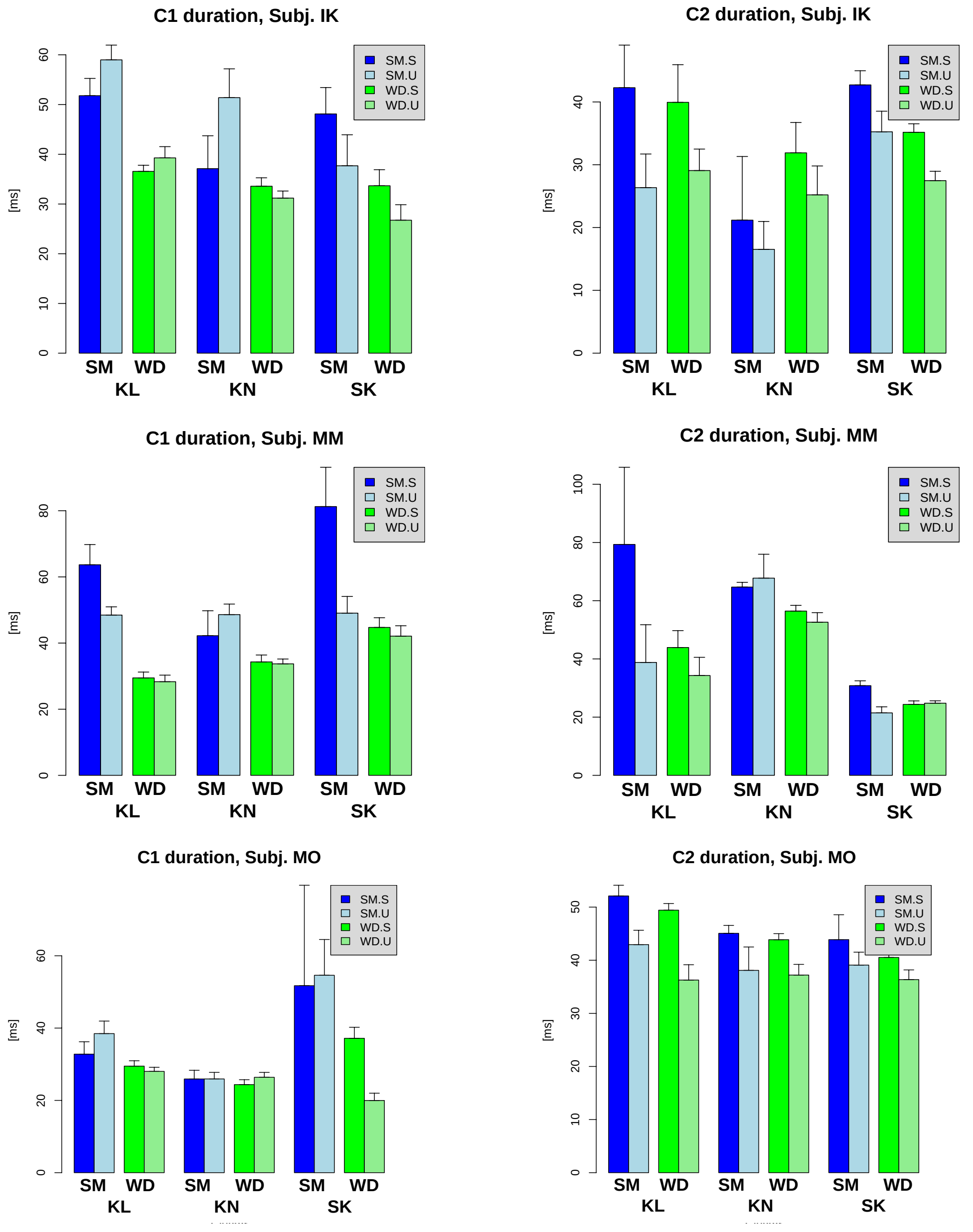

Figure 3: C1 (left column) and C2 (right column) constriction durations for three German subjects for the onset clusters /kl, kn, sk/. Each pair of bars gives the results for one prosodic boundary condition; left (darker) bar the stressed (S), right (lighter) bar the unstressed (U)condition. For each cluster, small boundary (SM) and prosodic word (WD) prosodic boundary conditions are given in adjacent pairs of bars. Error bars give standard error of mean.

The results for C2 are effectively a mirror-image of those for C1(see right column of Fig. 3 for detailed results of each subject): The effect of stress is highly consistent, with 16 of 18 matched pairs of bars in Fig. 3 showing the expected trend of longer durations for the stress condition (main effect was significant at $p<0.01$ in 3 of 9 cases). On the other hand there are very few clear effects of boundary condition: Even if the balance of the overall trend is in the direction of longer durations at higher boundary levels (14 of 18 pairs), only one of the 9 ANOVAs gave a main effect that reached $p<0.01$ (/sk/ for speaker IK).

A summary over all speakers encapsulating the mirror-image nature of the effects of boundary and stress on C1 and C2 is given in Fig. 4 by quantifying the differences between matched pairs of bars in the previous figure. The differences were calculated such that positive values for the Boundary data points in Fig. 4 indicate longer durations for the Small Boundary (SM) than the Word Boundary (WD) condtion; analogously positive values for the Stress data points indicate longer durations for the Stress than the Unstress conditions.

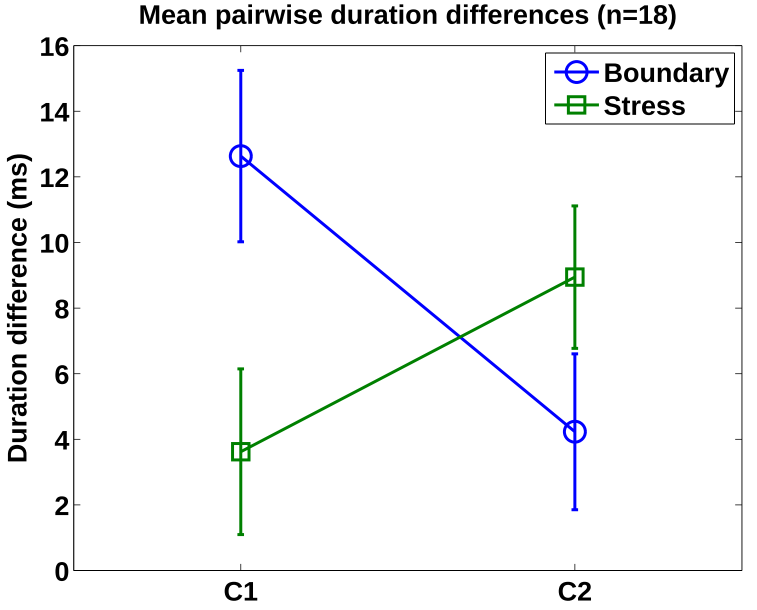

Figure 4: Comparison of boundary and stress effects on C1 and C2 durations. Positive values for the boundary effect indicate longer durations for SM than WD boundaries; positive values for the stress effect indicate longer durations for stress than unstress condition. All data points are averages (with standard error of mean) over 18 matched pairs, i.e. boundary comparisons matched for stress, cluster and speaker; stress comparisons matched for boundary, cluster and speaker.

Thus taken together, the results for C1 and C2 durations correspond quite closely to the original hypotheses that boundary effects would be more salient in C1 and stress effects more salient in C2.

Regarding the relative strength of boundary and stress effects, it seems possible that boundary may affect C1 more than stress affects C2 (particularly when it is considered that boundaries stronger than our so-called “small boundaries” could potentially occur, but did so only very rarely in these recordings); regarding the maximum temporal extent of the effects, it also seems conceivable that boundary effects may extend into C2 more often than stress effects extend to C1, but judgement on this must be reserved: Several more speakers and clusters have been recorded, but not yet analyzed.

The other main parameter relating to the temporal organization of the clusters is the overlap between C1 and C2 (defined exactly as in section 2.2 above). This is shown in Fig. 5.

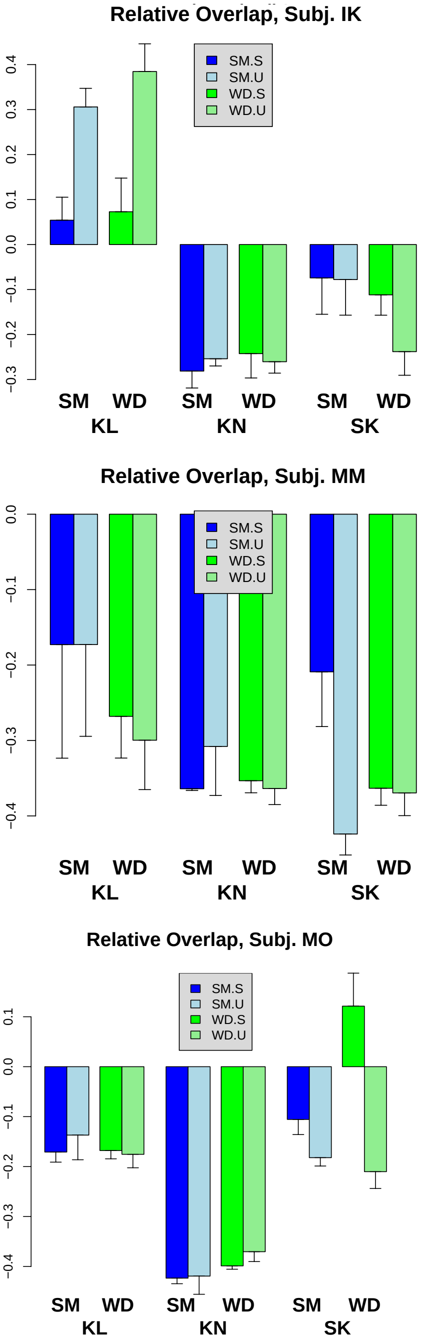

Figure 5: C1-C2 relative overlap. A value of +1.0 would indicate 100% overlap. Other details as for Fig. 3.

The main point to note is that there is a strong contrast with the durational results for C1 and C2 just shown above: No trends with respect to either boundary or stress condition can be observed. In fact, counting matched pairs for the boundary comparison and the stress comparison gives 9/18 in both cases. There is effectively only one clear case where the hypothesized greater degree of overlap in the unstressed condition is found (/kl/ for speaker IK), and even this is counterbalanced by one clear case in the opposite direction (/sk/ for speaker MO).

In short, while prosodic conditions clearly – and not surprisingly – affect the durational properties of gestures they appear to have relatively little influence on the coordination relations between gestures in onset clusters. This result is consistent with that of Byrd & Choi [3], at least in the sense that in their data it appeared much less easy to demonstrate with respect to overlap a consistent effect of boundary condition on onset clusters compared to clusters in other syllabic positions.

This absence of prosodic effects on overlap contrasts markedly with the effect of the segmental make-up of the clusters: Fig. 5 reinforces the results of the first part of the investigation with the radically different coordination patterns between the two superficially very similar clusters /kl/ and /kn/.

This leads to the final issue to consider with respect to overlap, namely whether the varying prosodic conditions can reveal differences in the internal cohesion of different clusters. Byrd & Choi [3] considered this issue for /sp, sk/ vs. /kl/, hypothesizing that the fricative-onset clusters could represent particularly cohesive gestural ‘molecules’. However, no clear differences were found. Similarly, here, there is little evidence from Fig. 5 that the three clusters /kl, kn, sk/ differ in the degree to which the prosodic manipulation affects the degree of overlap (we had speculated, in particular, that /kn/ might show less cohesion than /kl/).

The final aspect of the results to consider is whether prosodic influences manifest themselves not only temporally but also spatially. While this has not yet been exhaustively explored for the EMA data presented here, preliminary analysis indicates negligible effects of the boundary and stress conditions on positions and velocities of the articulators. This fits in with the results of our EPG investigation mentioned above (Bombien et al. [1], which also found little consistent evidence for articulatory strengthening in the form of increased tongue-palate contact at prosodically stronger locations. While this may appear to contrast with some earlier findings in the literature it should be noted that dorsal consonants and clusters have scarcely been investigated (unlike single coronal consonants). Perhaps activation in the dorsal region tends to simultaneously reduce the susceptibility to variation of an adjacent coronal articulation. Our corpus actually includes a wider range of clusters than those presented here. This issue may thus become clearer when this material has been analyzed, too.

4. CONCLUSION AND OUTLOOK

Concluding with an attempt to tie together the two different areas of this study, it was interesting to note that the prosodic effects on clusters with respect to patterns of overlap, for example, were much more subtle than the robust effects found when contrasting the different segmental structures plosive+/l/ vs. plosive+/n/. It is tempting to speculate that the robust effects emerge because intergestural timing forms an integral part of the phonological representation of words, whereas the weaker prosodic effects may reflect the greater lee-way at the disposal of speakers for implementing prosodic structure, and may also reflect greater variability (particularly, perhaps, in the context of a lab-speech experiment) in how speakers interpret the communicative demands of specific utterances. This pattern of findings may be a further facet of the often observed stability of onset clusters: this is probably the syllable-position where timing patterns specified in the phonological representation dominate overall temporal organization most strongly (see Goldstein et al. [9] for further discussion of onset stability).

Although the difference in timing patterns between plosive+/l/ and plosive+/n/ appears robust, we have not provided a direct answer as to why this pattern occurs. The obvious next step would be to use articulatory synthesis to systematically vary gestural organization: Assuming oral and velar gestures for /n/ are organized more or less in synchrony then earlier timing of /n/ relative to plosive C1 would eventually lead to a nasal release of the plosive. Even before this stage the acoustic salience of the release phase of the plosive may be reduced, leading to a situation that speakers try to avoid. This line of thought may also be relevant for the lower degree of overlap for voiceless vs. voiced C1. In languages such as German that need to distinguish a very large number of syllable onsets and in which the timing of peak glottal opening for voiceless plosives is close to the time-point of the oral release then the clarity of the acoustic information on the release of C1 may be improved by not overlapping too strongly with C2. This could simultaneously also enhance the salience of the C2 to vowel transition by increasing the chances that it is voiced rather than voiceless. The latter constraint, at least, would be of less concern in a language such as French where voice onset is timed to occur soon after the release of voiceless plosives. Currently, although more subjects have been recorded, not enough have been analyzed to be confident yet that cross-language differences in laryngeal timing may be accompanied by different preferred patterns in overlap of supraglottal gestures. But the results are suggestive enough to make this avenue appear well worth exploring further. Note that the whole thrust of the argument in this paragraph is based on the fact that the crucial acoustic information for initial plosives is concentrated at their ***release***. Thus this account predicts that the constraints on articulatory organization may be different for syllable initial fricatives, for the simple reason that fricatives make salient acoustic information available to the listener throughout their constriction phase. And indeed, data for French /fl/ vs. /fn/ initial clusters reported in Kühnert et al. [12] show that, unlike for C1 plosive, the timing of C2 /l/ vs. /n/ relative to C1 does ***not*** differ when C1 is a fricative (this is all the more remarkable because /fn/ onsets are very rare in French, and thus might have been expected to be biased towards low overlap compared to /fl/).

From the modelling point of view, recent developments in coupled-oscillator models of articulatory coordination (Goldstein et al. [9]) in which separate oscillators are implemented for closure and release phases appear to give sufficient flexibility in coupling topologies to capture the differences in overlap that we have empirically observed for the clusters with plosive C1 in the present paper.

A final area to follow up with the present data is whether the clusters show a stable pattern of timing with the following vowel, such as the C-center effect, despite the differences in within-cluster timing (see Goldstein et al. [8] for a revealing example of how cross-linguistic differences in syllable structure are reflected in different patterns of timing of consonant clusters with the following vowel; also Goldstein et al. [9] for recent modelling of cluster-vowel coordination, comparing /sp/ and /pl/ clusters in English). For two of the French speakers presented here Kühnert et al. [12] found quite stable C-center locations; this is currently being followed up for the German speakers.[2]

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[2] Work supported by German Research Council (DFG) grants HO 3271/3 and MO 1687/1 to Phil Hoole and Tine Mooshammer for the project "Articulatory cross-language study of initial consonant clusters in varying prosodic conditions" within DFG Schwerpunktprogramm 1234 "Phonological and phonetic competence: between grammar, signal processing, and neural activity".