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Christine Mooshammer, Philip Hoole and Anja Geumann

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Christine Mooshammer[1]
Philip Hoole[2]
Anja Geumann[3]

[1] *Christian-Albrechts Universität Kiel*
[2] *Ludwig-Maximilians Universität München*
[3] *University College Dublin*

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Abstract

It is well-accepted that the jaw plays an active role in influencing vowel height. The general aim of the current study is to further investigate the extent to which the jaw is active in producing consonantal distinctions, with specific focus on coronal consonants. Therefore, tongue tip and jaw positions are compared for the German coronal consonants /s, ʃ, t, d, n, l/, that is, consonants having the same active articulators (apical/laminal) but differing in manner of articulation. In order to test the stability of articulatory positions for each of these coronal consonants, a natural perturbation paradigm was introduced by recording two levels of vocal effort: comfortable, and loud without shouting. Tongue and jaw movements of five speakers of German were recorded by means of EMMA during /aCa/ sequences. By analyzing the tongue tip and jaw positions and their spatial variability we found that (1) the jaw's contribution to these consonants varies with manner of articulation, and (2) for all coronal consonants the positions are stable across loudness conditions except for those of the nasal. Results are discussed with respect to the tasks of the jaw, and the possible articulatory adjustments that may accompany louder speech.

1 Introduction

It is generally acknowledged that the jaw actively contributes to the production of a variety of speech sounds and prosodic conditions. For vowel production, Wood

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Address for correspondence. Christine Mooshammer, Institut für Phonetik und digitale Sprachverarbeitung, Christian-Albrechts Universität Kiel, 24098 Kiel, Germany; e-mail: < timo@ipds.uni-kiel.de >. Philip Hoole, Institut für Phonetik und sprachliche Kommunikation, Ludwig-Maximilians Universität München, Schellingstr. 3, 80799 München, Germany. Anja Geumann, School of Computer Science and Informatics, University College Dublin, Belfield, Dublin 4, Ireland.

(1979), among others, has suggested that different vowel heights or vocalic constriction degrees are produced by adjusting the jaw height whereas place of articulation or constriction location for vowels is achieved by appropriately positioning the tongue body. On the other hand, researchers such as Saltzman and Munhall (1989) and Browman and Goldstein (1990) propose that the role of the jaw is mainly restricted to a helping function, that is, to move active articulators such as the lower lip and tongue tip towards the place of articulation. This proposal suggests that the jaw position should be similar for consonants having the same constriction degree and location, such as the coronal consonants /t, d, n/. For consonants with a smaller constriction degree, such as fricatives as compared to stops, a somewhat lower jaw position could be expected because of the lower positions of the active articulator. However, as has been pointed out in a number of studies, the sibilants constitute a well-known exception: Here the lower incisors serve as a second noise source and therefore the jaw position is controlled actively to provide a small distance between the upper and lower incisors for the generation of salient high frequency frication (see Amerman, Daniloff, & Moll, 1970; Lee, Beckman, & Jackson, 1994; Shadle, 1985).[1] Furthermore, some studies also found a higher and less variable jaw position for /t/ as compared to stops produced at other places of articulation (e.g., Keating, Lindblom, Lubker, & Kreiman, 1994), and as compared to the coronal consonants /d, n, l/ (Kühnert, Ledl, Hoole, & Tillmann, 1991). These latter results give stronger evidence for segment-specific jaw targets than for a helping function that is uniform for consonants of the same place of articulation. On the one hand, segment-specific jaw targets and the extent of contextual variability for sounds have been proposed to be the crucial factor for determining sonority hierarchies by Lindblom (1983). On the other hand, Keating (1990) suggested that jaw height co-varies with the range of contextual variability. However, most previous studies have focused on comparing the jaw targets of segments whose active articulators differ (see, e.g., Keating et al., 1994; Lee, 1996; Lindblom, 1983). Consequently, the measured jaw height is affected by the fact that the jaw's effect on the position of the active articulator decreases with the distance of the main consonantal articulator from the condyle, assuming predominantly rotational movement of the jaw. The general aim of this study is to systematically investigate the spatial contribution of mandibular and lingual articulation for apical or laminal coronal sounds contrasting in manner of articulation. The relevance of the jaw's contribution to a specific sound will be evaluated by its spatial stability across contextual variation, that is, the less the jaw position during a consonant varies the more important it is for the production of this sound. The contextual variation is introduced by two speaking conditions: comfortable vocal effort and speaking up without shouting.

1.1
Background

Previous studies have discussed the role of the jaw for the achievement of segment-specific vocal-tract configurations with regard to three issues: (1) jaw targets, (2) contextual variation, and (3) compensation.

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[1] Saltzman and Munhall (1989) included a lower teeth height tract variable exactly for modeling tongue blade fricatives which was unfortunately not followed up in later versions of the model.

1.2
Jaw targets

This first aspect is generally concerned with the question of whether the jaw has to assume a target of its own in consonant production. A certain amount of mandibular involvement is assumed for the production of all oral consonants for lifting the articulator up towards the place of articulation (see, e.g., Browman & Goldstein, 1990). The ordering of oral consonants according to their jaw target has been investigated in a number of studies. For instance, Lindblom (1983) analyzed the jaw height of several Swedish consonants of one speaker in initial and final position before and after the vowels /a, ɑː/. According to the measured jaw height, Lindblom (1983) grouped the consonants into classes with approximately the same height within the groups: the sibilants /s, ɧ/ had the highest jaw position, the consonants /p, t, k, b, d, g, f/ showed a somewhat reduced jaw height, followed by the nasals /m, n, ŋ/ and the consonants /j, v/. The liquids /r, l/ were produced with the lowest jaw position. Since this consonant-specific jaw height closely resembles the ranking of sounds established in the sonority hierarchy for Swedish, Lindblom (1983) proposed that sonority hierarchy groupings are correlated with jaw positions for reasons of movement economy: Consonants with a high jaw position are more remote from the vowel because they are articulatorily more incompatible with the following or preceding vowel whereas consonants with a lower jaw height such as /r, l/ tend to assume a closer position to the vowel in consonant clusters. Note that Lindblom's sonority hierarchy groupings differ from traditional views especially with respect to the fricatives; in his view they range from the lowest sonority for the sibilants to an intermediate degree for /v/. As was already pointed out above the exceptional status of the sibilants has been explained by the fact that the upper and lower incisors serve as a second high-frequency noise source (see, e.g., Shadle, 1985). Therefore the vertical position of the lower incisors is more tightly controlled than for the other fricatives. Additionally, there is very recent evidence that the horizontal position of the lower jaw might also play a crucial role for the generation of a high frequency noise: As Howe and McGowan (2005) point out the acoustically relevant effect is the "diffraction" at the edges of the upper and lower teeth caused by a small horizontal distance in-between.

Apart from the sibilants, many studies gave evidence that the details of Lindblom's measurements of jaw heights could not be replicated for other languages, speakers, and measurement methods. For example, in contrast to Lindblom's sonority group /p, t, k, b, d, g, f/, defined by their similar jaw height, most studies found a higher jaw position for the voiceless alveolar stop compared to the other oral voiceless stops (Elgendy, 1999; Keating et al, 1994; Lee, 1996; Perkell, 1969; Tuller, Harris, & Gross, 1981), and jaw positions for /k/ which were even lower than for some of the sonorants (Keating et al., 1994). Furthermore, the lateral /l/ was often produced with active jaw lowering in high vowel context (see, e.g., Geumann, 2001a). The lower jaw position for velar stops as opposed to the high jaw position for alveolar stops can be explained by anatomical factors: Due to biomechanical coupling, that is, the tongue riding on the jaw, the passive influence of the jaw on the active articulator increases with the distance from the condyle because of the predominantly rotational movement component of the jaw during speech (see, e.g., Edwards, 1985), that is, a higher jaw position, as measured at the front teeth, affects the tongue tip to a greater degree than the tongue dorsum, because the tongue dorsum is closer to the origin of the rotational movement. Therefore the jaw position also depends on place of articulation with an increasing influence of the jaw on the tongue going from the back to the front. This dependence on place of articulation indicates that the jaw height cannot be the only determining factor for the sonority hierarchy ordering, as suggested by Lindblom (1983), because sonority hierarchies are usually based on manner specifications without reference to segmental features such as place of articulation or articulator.

On the basis of jaw involvement Goldstein (1994) proposed a phonological feature for distinguishing oral from guttural consonants, the latter being defined by him as uvular, pharyngeal, and laryngeal sounds such as /ħ, ʕ, h/. Accordingly, all oral consonants are produced with at least some degree of mandibular activity whereas for nonoral, guttural consonants, the jaw does not contribute to their production. In two follow-up studies by Lee (1996) and Elgendy (1999) it was shown that gutturals are produced with a lower jaw position compared to jaw positions of surrounding low vowels, which gives evidence for an active jaw lowering gesture and therefore contradicts Goldstein's proposal. Again, biomechanical reasons are involved: a low jaw position causes the tongue root to be retracted towards the pharyngeal wall. Therefore jaw height cannot simply be equated with the importance of jaw involvement in consonant production.

1.3

Contextual variation

The spatial definition of targets is no straightforward matter for a number of reasons such as coarticulation, compensation, speaker-dependent strategies and anatomical differences, language specific constraints, prosodic influences, and so forth. Even though obviously not all of these sources of variation can be avoided (individual differences, for example), coarticulatory effects due to vowel height and prosodic variation have provided a useful paradigm for the definition of "targetness" for specific consonants: By controlling the source of variation, that is, by varying vowel height in VCV sequences, the resulting range of articulatory positions during the consonant has been taken as being reciprocally related to the importance of an articulator to the production of a specific sound. The major disagreement between Lindblom (1983) and Keating (1983) is concerned with the question of whether the jaw position of consonants accommodates to the vowels' jaw position, which implies that the vowels vary less than the consonants (Lindblom's proposal), or the other way around (Keating's proposal). In Lindblom's view sonority is related to the propensity of the consonant to coarticulate with the following or preceding vowel. Additionally, segments within the syllable are ordered according to it; this means that some consonants adopt their jaw height from the vowel context, while other consonants have an intrinsic jaw height. This proposal was seriously questioned by Keating (1983) on theoretical, methodological, and empirical grounds. Specifically, she criticized the limited set of data with no consonant clusters and only the low vowels /a, ɑː/ as vowel context which eliminates the possibility of detecting which segment accommodates to which, the vowel or the consonant. From her own data she concluded that the positions of vowels are more variable than those of consonants, and that vowels also accommodate to the jaw positions of a few consonants such as /s/. Therefore, the jaw is not the determining factor for syllable composition but rather the course of the jaw movement is determined by those few segments with a fixed target. However, in their collaboration which is documented in Keating et al. (1994), more evidence was found for Lindblom's proposal that in consonants the jaw positions accommodate to the neighboring vowels.

The amount of contextual variability was used for defining windows of coarticulation in Keating (1990). The underlying hypothesis here is that the functional importance of the jaw's contribution to consonant production is, on an operational level, inversely related to the measured contextual influence on consonantal jaw height, that is, the smaller the measured contextual influence on consonantal jaw height, the more important the jaw's contribution to the consonant production. For jaw variability a similar gradation was found as for jaw height in most studies: Mandibular positions of consonants and vowels with a low jaw height tended to be affected by context to a higher degree and also showed more variability than sounds produced with a closed jaw (e.g., Edwards, 1985; Elgendy, 1999; Geumann, Kroos, & Tillmann, 1999; Hoole & Kühnert, 1996). Again this relationship depended on place of articulation: the more retracted the constriction location, the lower the jaw and the higher the variability (see Keating et al., 1994; Lee, 1996). As mentioned in the previous section, this result can be explained by the predominantly rotational movement of the jaw: the same amount of variability of the jaw — measured at the lower incisors — affects the precision of a posterior constriction to a lesser degree and therefore the jaw accommodates to the segmental context to a greater degree for dorsal consonants. Because of this dependency of jaw variability on place of articulation, the importance of the jaw for different sounds can only be analyzed within a single place of articulation. Within the group of coronal consonants it was found by Geumann et al. (1999)[2] that the sibilants and /t/ required the highest amount of precision and the highest jaw position whereas the sonorants /n, l/ varied most with vowel context and were also produced with a lower jaw position (see also Stone & Vatikiotis-Bateson, 1995, for /s/ vs. /l/). These findings are also consistent with Lindblom's (1983) results on the relationship between sonority and jaw height.

Contextual variation is not only induced by varying the identity of the neighboring segments but also by loudness, sentence accent and speech rate. All these factors are known to influence the jaw position during the vowel, but the effect on consonants has been less extensively studied. As was found by Schulman (1989), Munhall, Ostry, & Flanagan (1991), McClean & Tasko (2003) and Geumann (2001a), global vocal effort increases are accompanied by a lower jaw position during the vowel independently of vowel height. Low vowels bearing sentence accent or emphasis are also produced with lower jaw positions (see, e.g., Erickson, 1998, Harrington, Fletcher, & Roberts, 1995; Summers, 1987), whereas results for high vowels are more controversial, that is, some studies show very limited effects on the jaw (see de Jong, 1995) while others show a clear jaw lowering effect for nuclear accented high vowels

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[2] We used a subset of the data from Geumann et al. (1999) and Geumann (2001a,b). They analyzed the data in three symmetrical vowel contexts /i, e, a/ whereas in the current study we considered only data during the consonants with surrounding /a/'s.

(e.g., Harrington, Fletcher, & Beckman, 2000; Palethorpe, Beckman, Fletcher, & Harrington, 1999).

Whereas the relationship between prosodic prominence and mandibular height has been extensively investigated for vowels, the same cannot be said for consonants, despite the fact that a great number of papers have been dedicated to effects of prominence and prosodic boundaries on consonantal strength as measured by palatal contact (see, e.g., Fougeron & Keating, 1997; Keating, Cho, Fougeron, & Hsu, 2003).[3] De Jong (1995) found that the jaw was higher during /t/ in word-initial position for nuclear accented than for unaccented words for all three of his subjects and in word-final position only for one subject. The accent effects on jaw position during /p/ differed in a highly speaker-dependent way: For nuclear accent versus pre- and postnuclear accent one speaker showed a higher jaw, one no difference and one a lower jaw (see also Beckman & Edwards, 1994). Tabain (2003) found no significant effects of phrasal boundaries on the jaw position during the consonants /b, d, g, f, s, ʃ/ in French, whereas increased loudness lowered the jaw during /b/ for three of four speakers in Schulman's study (1989). Effects of vowel height and loudness on articulator positions for the coronal consonants /s, ʃ, t, d, n, l/ were analyzed by Geumann et al. (1999) and Geumann (2001a,b). Increased vocal effort did not yield a consistent pattern of jaw position changes for their six German subjects when data were pooled across vowels. From these results it can be concluded that contextual variation due to prosodic accent and loudness affect jaw positions of vowels in a more consistent manner than consonants. The reasons for this could be twofold: first a lower jaw position might increase the acoustic prominence only for vowels and not for consonants. Speakers may therefore aim to lower the jaw during vowels only and not during consonants. The second reason could be that the task of the jaw for the production of vowels is more uniform than for consonants, that is, for the latter sound group the jaw is involved to a large extent for the sibilants but may not play a major role for a subset of consonants such as the nasals or lateral. Evidence for this hypothesis has been found by the above-mentioned studies on vowel-induced variation, for example, less variable jaw positions in sibilants and /t/ as compared to the sonorants.

1.4
Compensation and Precision

To reduce the degrees of freedom for individual articulator movements, it has been suggested that the tongue and the jaw act as components of a coordinative structure (see Fowler Rubin, Remez, & Turvey, 1980; Saltzman & Munhall, 1989) and compensate for each other, for example, in a fixed jaw condition the tongue body assumes the task of the jaw (see, e.g., Lindblom, Lubker, & Gay, 1979). Besides artificial static and dynamic perturbation by artificially obstructing the natural path of an articulator, contextual effects — for the first time proposed by Edwards (1985) — can

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[3] Kinematic studies on stress, accent, emphasis, prosodic phrasing and final lengthening usually analyze *jaw distance* for opening and closing movements (e.g., Beckman, Edwards, & Fletcher, 1992), which renders it impossible to conclude whether an increase in distance is due to a lower *jaw position* for the vowel or/and a higher jaw position for the consonant.

also be interpreted as some kind of naturally occurring perturbation: As suggested by Edwards (1985) and further investigated by Kühnert, Ledl, Hoole, & Tillmann (1991), the positions of the composite articulators for a particular sound are highly affected by the neighboring sounds. Hence, coarticulatory influences on the position of one articulator might be compensated for by the adjustments of the composite articulator. This strategy is applied in order to keep the contextual variability for this particular sound within acceptable limits or — to put it differently — to meet the required precision for this sound. Interarticulatory adjustments between the composite articulators can be shown by a negative covariation, that is, assuming that in a low vowel context the jaw contributes less to an apical consonantal target, the tongue tip has to move more extensively and vice-versa for high vowel context. Support for this view came from Edwards (1985) in her single-speaker study for the intervocalic consonant /t/ and from Kühnert et al. (1991) for one out of three speakers for the alveolar consonants /s, ʃ, t, d, l, n/. This particular speaker displayed tongue-jaw trade-offs exactly for those sounds which were produced with the least coarticulatory variability, that is, for /s/ and /t/ (as measured by the areas of two-sigma dispersion ellipses in the x/y plane). Therefore compensatory articulation seems to be applied by the speaker in a flexible but sound-specific manner. However, for the other two subjects significantly negative correlations were not related to a high precision in tongue positioning for a particular sound. Thus, the authors conclude that for limiting spatial variability speakers use alternative strategies besides motor equivalence, such as simply positioning the tongue in a very precise manner. The former result, that is, achieving high precision of the resulting positions by covariation of the composite articulators, could not be replicated by Geumann et al. (1999), who analyzed tongue-jaw interaction of the same coronal consonants for six speakers in two loudness conditions: none of the speakers displayed reciprocal covariation between the two articulators in order to minimize the variability of the resulting positions for sounds produced in a very precise manner. In contrast, evidence for motor equivalence only occurred for /n/ and /l/ which also showed the highest variability at the constriction, whereas /s/ and /t/, the sounds most precisely articulated, usually exhibited the lowest negative correlation or even positive ones. As the authors conclude, the notion of compensation is based on the assumption that the articulators involved are of equal importance for the achievement of the target, that is, a negative correlation can only occur if both articulators vary in the opposite direction to a similar extent. If only one of the articulators varies, which is the case for, for example, /s/ and /t/, the individual articulators are controlled very precisely and therefore there is no need for adjustments.

A completely different approach for assessing the relevance of an articulator for the production of a given speech sound has been taken by Koenig, Lucero, & Löfqvist (2003). They analyzed the *SD*s of lower lip, jaw, and several tongue sensors for the stops /p, t, k/ not calculated for a specific so-called "magic moment" but for all samples over a stretch of time, in their case from the velocity peak of the closing movement to the velocity peak of the opening movement. They found that spatial variability, measured as the *SD* of the samples over time during the three stops /p, t, k/, decreased for those articulatory structures which were required for the production of a consonant as compared to articulators not directly involved for this sound, for example, for the velar stop the tongue dorsum varies less over time as compared to the tongue tip.

1.5
Aims of the present study

The present study aims to investigate further the relative contribution of the jaw to the production of several consonants that are all specified as coronal but vary in manner of articulation. We ask to what extent the jaw is actively involved in the production of the consonants /s, ʃ, t, d, n, l/. Predictions differ according to the theoretical backgrounds considered in the present study:

(1) *Helping function:* Assuming that the jaw's task consists of lifting up the tongue tip towards the constriction location, this predicts similar jaw involvement for the consonants /t, d, n, l/ and less involvement for the fricatives because the tongue tip will be somewhat lower for a critical constriction as compared to a full medial closure. The same amount of spatio-temporal variability of individual articulators is expected for the consonants considered here.

(2) *Sonority defined by Lindblom (1983):* The contribution of the jaw should be most relevant to the sibilants, less relevant to /t, d/ and least to /n/ and /l/. Contextual variation should approximately follow this order. If sonority is defined in a more conventional way, that is, phonologically based on unmarked consonant sequences, and if it is related with the segment-specific jaw position, then the ordering within the group of obstruents differs from Lindblom's predictions: All obstruents should either have the same jaw height (see e.g., Clements, 1990) or stops should be produced with somewhat higher jaw positions as compared to the fricatives (see, e.g., Vennemann, 1988).

(3) *Coarticulation:* The consonants differ in their propensity to coarticulate which is, however, not necessarily related to sonority. From the literature very little contextual variation would be expected for the sibilants because of the special role the jaw plays for their production. The other consonants might or might not differ in their degree of jaw involvement, as measured as jaw height. More explicit predictions are given within Keating's (1990) window model with increasing variability for lower jaw positions.

These hypotheses will be assessed as follows:

(1) By analyzing target configurations of the composite tongue tip, the jaw and the intrinsic tongue tip; the latter corresponds to the active tongue tip independent of the jaw movement. As was pointed out above, the helping function would predict a positive correlation between the tongue tip and the jaw height. The other two approaches, sonority and coarticulation, would not assume a special relationship between the tongue tip and the jaw target positions. In order to investigate the relationship between the jaw and the tongue contribution, the active tongue movement has to be extracted from the measured tongue movement, because the recorded tongue movement's signal consists of two components, the active or intrinsic tongue movement and the passive consequences of the jaw move-

ments. Therefore, we extracted the intrinsic, active tongue movement, from the measured tongue position and analyzed the positions of the intrinsic tongue tip, the jaw and the composite tongue tip.

(2) By comparing the consonantal jaw targets for normal and loud speech. The stability of spatial contributions is tested by varying vocal effort. As was also pointed out above, the excursion of the jaw movement towards the vowel is larger in loud speech. Therefore speaking up can be interpreted as magnifying the vowel-directed movement. If the jaw's contribution to the production of a consonant is crucial, then its position during the consonants should not be affected by the lower jaw positions of the surrounding vowels. If ease of articulation is more important than segmental constraints as measured in movement extent, then the jaw should be lower during the consonants for loud speech because of the lower position during the surrounding vowels. Consequently, if the jaw had a uniform helping function, then all consonants should be affected by vocal effort increase in a similar way. If the jaw's function is related to the sonority values of the consonants, then the sonorants should be more strongly affected by vocal effort increase than the obstruents. Following the third hypothesis, i.e., that consonants vary in their degree of coarticulation, the jaw position during the sibilants should be relatively unaffected by vocal effort increase.

(3) By analyzing the precision of the composite articulators during the time-course of the consonant. The current study investigates whether high precision of posture, measured at a single time point, also implies postural stability during the course of the consonant as proposed by Koenig et al. (2003). A uniform helping function would predict no difference in variation over time between the consonants under consideration in the current study because in this case the role of the jaw should be the same for all consonants. For the sonority hypothesis less jaw movement during the course of the consonant would be expected for the less sonorous consonants, the obstruents. An exceptional special role of the jaw for the sibilants, however, would predict that the lower incisors do not move during these fricatives because of their relevance for the generation of high-frequency noise.

2 Method

2.1

Speakers

The current study uses the same set of data as Geumann et al. (1999) and Geumann (2001a,b). Six native speakers of German, one female (AW) and five male (HP, KH, RS, SR, UR), were recorded by means of electromagnetic midsagittal articulography (EMMA). Because speaker HP was recorded with a slightly different corpus and one sensor came off during the recording session, his data were not considered for the present study. The speakers were students, graduate students or faculty staff of the Institute of Phonetics and Speech Communication at the University of Munich and not familiar with the aim of this study. The age range was between 23 and 31. None of them had a known history of speech or hearing problems.

2.2
Speech material

The six coronal consonants /s, ʃ, t, d, n, l/ were recorded in VCV sequences. The symmetrical vowel context consisted of /i/, /e/, and /a/ but only items with /a/ preceding and following the medial consonant will be considered here because jaw movements for high and mid vowels were often too small and noisy for the kinematics to be analyzed. The first vowel was always stressed and long and the second one unstressed but unreduced. All VCV sequences were embedded in the carrier phrase "Hab das Verb ___ mit dem Verb ___ verwechselt" (I mixed up the verb ___ with the verb ___). Therefore both target sequences received contrastive sentence accent. The sentences were repeated six times in randomized order which gives 12 repetitions per item and loudness condition. Stimuli were presented on a computer screen.

The increase in vocal effort was elicited by instructing the subjects to speak as loud as possible without shouting. They were told to imagine that, with the microphone turned off, they had to be heard in the control room adjacent to the recording room. In the normal condition, the speakers were instructed to speak at a comfortable volume level. Since both conditions were randomly varied, the loud condition was additionally marked on the prompt screen below the test sequence.

By measuring the RMS amplitude during the vowels, it was found that all speakers increased the intensity significantly for loud speech as compared to normal. Speaker UR showed in general the highest intensity for loud speech, and largest difference between the two volume levels (mean sentence intensity for the normal condition was 61dB and for loud condition 72dB). This is in accordance with the auditive impression of the investigator, that this speaker's loud volume came close to shouting. The smallest change was observed for speakers AW and KH with a change from normal volume to loud of about 5dB.

2.3
Procedure

Articulatory data were collected by using the electromagnetic midsagittal articulograph AG100 manufactured by Carstens Medizinelektronik (for details on the measurement principle see Hoole & Nguyen, 1999). Four sensors were glued on the tongue surface by using a dental cement (Ketac) (*T1* to *T4* in Fig. 1). For the current study only the tongue tip sensor, placed approximately 1 cm behind the apex, was analyzed (see *T1* in Fig. 1). For monitoring jaw movements, three sensors were used, the first and the second placed in the midsagittal plane on the outer and inner surface of the lower gums (*J1* and *J2* in Fig. 1), just below the lower edge of the teeth, and the third on the angle of the chin (*J3* in Fig. 1). This study is based on the signals from the tongue tip (*T1*) and the first jaw sensor attached to the outer surface of the lower gums (*J1*).[4] One sensor each on the bridge of the nose (*R2* in Fig. 1) and the upper

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[4] By monitoring the jaw movement with three sensors we hoped that the origin of the rotational movement, the condyle, could be recovered which would have improved the algorithm for the decomposition of the tongue signals. However, since this was not the case, additional MRI recordings were used for this purpose as explained below.

incisors (*R1*) were recorded for the correction of head movements. For the jaw and the reference sensors Cyanoveneer adhesive was applied to the sensors.

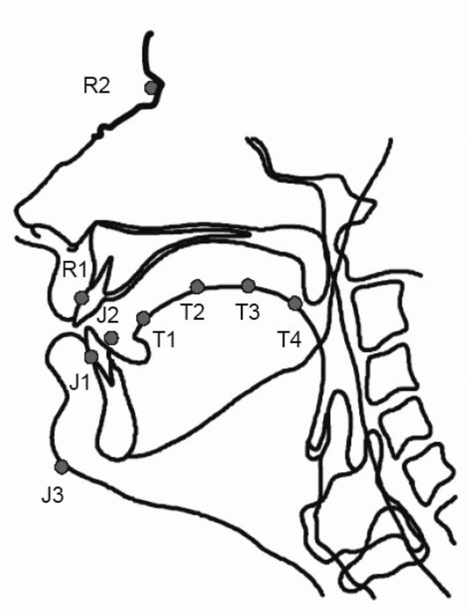


Figure 1

Approximate positions of sensors J1 to J3 for monitoring jaw movements, T1 to T4 for tongue movements, R1 and R2 serve as reference sensors

After the recording session, data were rotated to the occlusal plane and the origin of the new coordinate system was located at the lower edge of the upper incisors. The procedure to orient the data with the horizontal axis parallel to the occlusal plane was as follows: The investigator made a trace of the subject's hard-palate during the experiment using a spare sensor. Then this trace was aligned with a hard-palate trace taken from a dental impression placed in the EMMA apparatus. A plastic t-bar bearing two sensors was placed on the dental impression (resting on the upper incisors at the front and the second molars at the back) to provide a definition of occlusal plane orientation.

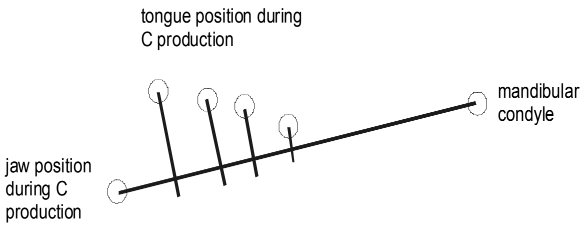
The articulatory data were sampled at a frequency of 500 Hz. For further processing all signals were downsampled to 250 Hz and low-pass filtered with a FIR filter (Kaiser window design, −6dB at 50 Hz). Horizontal, vertical, and tangential velocities were calculated and smoothed with a further Kaiser-window filter (−6dB at 20 Hz).

The measured tongue tip signal is composed of the active tongue tip and the jaw. Thus the tongue tip signal has to be decomposed into the active tongue tip movement and the passive consequence of the jaw movements (for an extensive overview see Westbury, Lindstrom, & McClean, 2002) which is complicated by the fact that the measured jaw movement consists of a rotational and a translational component. From MRI data (for details of data acquisition see Hoole, Wismüller, Leinsinger, Kroos, Geumann, & Inoue, 2000) for each speaker, the center of the mandibular condyle was estimated by tracing and averaging the position in those slices where the condyle could be identified. The estimated condyle positions were then mapped onto the

EMMA coordinates (see Fig. 2). Euclidean distances between condyle and outer-jaw and condyle and tongue sensors on the midsagittal plane were calculated during the temporal midpoint of consonant production for each speaker. The tongue to condyle distance in percent of the outer-jaw to condyle distance was taken as a weighting factor for the jaw, that is, the further away the tongue sensor from the condyle, the closer is the weight to 1. Before subtracting the jaw from the tongue sensors, the instantaneous vertical jaw position is multiplied with this weighting factor between 0 and 1. This procedure which follows that of Edwards (1985) was applied, because simple subtraction disregards the fact that jaw rotation affects the tongue tip to a greater degree than the tongue dorsum. The resulting signals are termed intrinsic tongue tip for the remainder of this article.

Figure 2

Estimation of weighting factors for determination of intrinsic tongue signals (see text for details)



2.4
Analysis

Articulatory positions were analyzed at acoustically defined landmarks of the consonant. The onset of the consonant was set at the offset of high energy in F2 for the obstruents or a general energy drop for the nasal or lateral. The offset of the consonant was specified depending on the consonant's manner: the burst for both stops, the onset of regular voicing for the sibilants, and a rise in energy for the nasal and the lateral. An alternative to using acoustically defined time-points is to extract the articulatory data at the maximal jaw excursion during the consonant: This yielded similar results but had the disadvantage that it depended on the timing of the jaw peak during the consonant which sometimes occurred as late as at the second vowel. Therefore most analyses discussed here are based on data from the acoustically defined temporal onset, midpoint, and offset of the consonant.

For measuring the precision of articulatory posture, the displacement during the consonant was calculated as the integral of the tangential velocity between the acoustically defined consonantal onset and offset. This procedure has the advantage that movements in the horizontal and the vertical direction are taken into account and that distances of loopy movements deviating from a straight line are measured more accurately. The average velocity was also computed as the mean of all tangential velocity samples during the consonant. A low value means that the tongue blade or the jaw is moving slowly and also very little during the acoustically defined consonant.

The lack of movement, either corresponding to very small displacements or to velocities close to zero, during the acoustically defined consonant can be interpreted as a requirement of a high precision during the consonant because any movement would modify the acoustical output. Since results did not differ for distance and mean velocity, only the results on the former will be discussed here.

2.5
Statistics

Speaker-independent statistics were calculated based on the *z*-scores of the positional data. For computing *z*-scores, the speaker-specific means and *SD*s of the jaw and tongue blade movement signals were calculated for the stretches when the subjects actually spoke. The means for all trials in both volume conditions were subtracted from measurement points and the results divided by the *SD*.

Analyses of variance were calculated for individual speakers and pooled over all speakers using the script language R (R Development Core Team, 2005). For the individual speakers all valid data were included. Main effects and interactions were computed. Independent variables were Manner of Articulation (MN) and vocal effort level (VE).

Additionally ANOVAs pooled over all speakers were calculated based on the data averaged over up to 12 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. To evaluate whether manner of articulation and vocal effort affected positional and temporal data we calculated repeated measures ANOVAs with within-subject factors Manner and Volume (abbreviated to ‘Vol’ in the tables). 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. These corrected degrees of freedom were then used in generating *F* ratios and *p* values. Pairwise *t*-tests with Bonferroni adjustments for multiple comparisons were carried out for individual statistics and for the repeated measures ANOVAs in order to assess significant differences between the six-level factor Manner.

3 Results

3.1
Spatial differences due to manner of articulation

The aim of this section is to evaluate the assumption that the task of the jaw consists in uniformly lifting the tongue tip towards the constriction location. In this case jaw height should be ordered according to the height of the tongue blade, that is, the higher the consonant-specific tongue height, the higher the jaw height.

The positional differences between the coronal consonants /s, ʃ, t, d, n, l/ are shown in Figure 3 for the composite tongue tip signal, that is, the tongue tip signal before subtraction of the jaw. Because the height of the tongue tip depends on the palatal outline, then the more retracted the tongue, the higher it has to move to approach the target. The vertical and the horizontal dimensions are displayed in Figure 3. The tongue tip position better replicates the vocal tract configuration at the relevant constriction location than the intrinsic tongue tip position. The involvement of the jaw is shown in Figures 4 and 5 and will be discussed in the second part of this section.

Figure 3

Positions of the tongue tip sensor during the acoustic midpoint of the consonant for individual speakers in mm and for all speakers in *z* scores. Dispersion ellipses are set to one *SD*. Only results from normal volume condition are shown. The black lines indicate the front part of the palate contour. The space between ticks is one mm (1/10 of an *SD* for *z* scores)

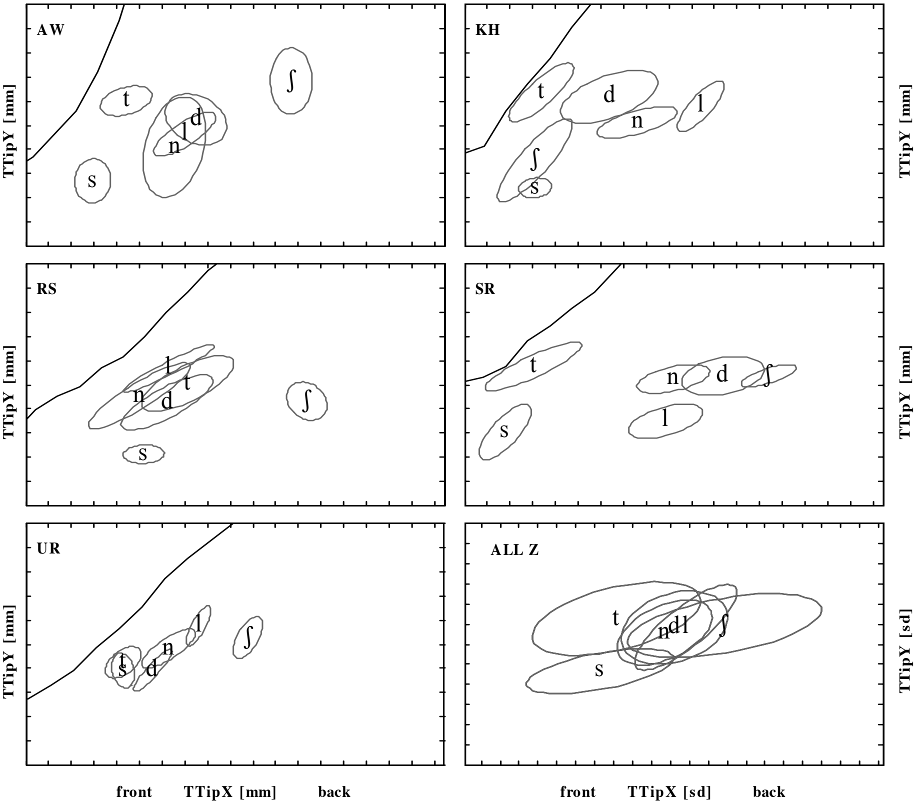


Figure 3 shows the tongue tip positions at the acoustic temporal midpoint of the consonant for individual speakers. The lower right panel gives the *z*-scores for all speakers. For reasons of clarity only data for the "normal" volume condition are shown in this figure. Table 1 gives for all tongue and jaw parameters the results of a two-way Analysis of Variance for individual speakers indicating main effects and interactions in the upper part and results of post hoc pairwise *t*-tests at the bottom. Table 2 lists the results of a repeated measures Analysis of Variance calculated across speakers.

The vertical tongue tip height varied for the coronal consonants with /s/ generally showing the lowest tongue tip position. This result is quite consistent for all

Table 1

Results of a two-way Analysis of Variance for individual speakers with the dependent variables horizontal and vertical position of the intrinsic tongue tip (ITX, ITY), the jaw (JAWX, JAWY) and the vertical position of the composite tongue tip (TTY) during the temporal midpoint of the consonant and the independent factors speaker, manner of articulation and volume (Since TTX gives the same results as ITX it has not been included.). The upper part shows degrees of freedom (*df*), *F*-values, and significance levels for the main effects and the interactions with * $p < .05$, ** $p < .01$, and *** $p < .001$. The last two rows indicate the results of pairwise *t*-tests with Bonferroni adjustments for multiple comparisons for normal (N) and loud (L) speech. The lesser than sign indicates a more fronted position for horizontal dimensions and a lower position for vertical dimensions

Speaker	*Main effects*	*df*	*ITX*	*ITY*	*JAWX*	*JAWY*	*TTY*
AW	Manner	5 128	104.5 ***	149.1 ***	121.2 ***	196.7 ***	30.6 ***
	Vol	1 128	0.8	2.4	1.6	4.8 *	0.1
	Manner*Vol	5 128	1.4	0.4	0.6	0.4	0.7
	Post hoc tests	*N*	st<nld<ʃ	s<t<dʃn<l	ʃ<s<tdnl, t<l	l<n<d<ʃts	s<ldtʃ,n<tʃ
		L	s<nld<ʃ, t<l	s<tdʃn<l, t<n	ʃ<s<tdnl		snl<tʃ, d<ʃ
KH	Manner	5 131	88.6 ***	115.6 ***	20.1 ***	71.34 ***	51.9 ***
	Vol	1 131	0.4	2.5	7.2 **	12.2 ***	0.3
	Manner*Vol	5 131	0.4	0.7	0.5	0.8	0.1
	Post hoc tests	*N*	ʃst<dn<l	sʃ<ntd<l	ʃ<nl, tsd<l	l<n<dʃst	sʃ<nldt
		L			ʃ<nl, ts<l		
RS	Manner	5 127	63.8 ***	269.9 ***	48.2 ***	371.3 ***	40.6 ***
	Vol	1 127	1.4	10.3 **	5.3 *	9.5 **	2.1
	Manner*Vol	5 127	0.8	5.3 ***	1.6	10.5 ***	2.2 *
	Post hoc tests	*N*	nsdlt<ʃ	sʃ<tdn<l, t<n	ʃ<lndts, ln<s	l<nd<t<s<ʃ	s<dʃntl,dʃ<l
		L	snl<t<ʃ	s<ʃ<tdnl, td<l	ʃ<lnstd, l<td	ln<d<t<ʃs	s<ʃndlt,ʃn<t
SR	Manner	5 123	168.7 ***	248.2 ***	95.5 ***	428.7 ***	44.7 ***
	Vol	1 123	0.1	6.2 *	5.6 *	10.7 **	0.1
	Manner*Vol	5 123	0.9	0.6	0.3	0.6	0.5
	Post hoc tests	*N*	st<lndʃ, ln<ʃ	s<ʃ<t<dnl	ʃ<s<tdnl,t<l	l<dn<t<ʃ<s	sl<ndʃt
		L	st<lnd<ʃ, l<d				
UR	Manner	5 130	129.6 ***	62.8 ***	24.53 ***	134.6 ***	14.2 ***
	Vol	1 130	26.9 **	24.4 **	9.25 **	119.4 ***	0.8
	Manner*Vol	5 130	6.9 ***	5.1 ***	1.7	32.4 ***	3.1 *
	Post hoc tests	*N*	st<dn<l<ʃ	stdʃn<l, s<n	s<nl, ʃt<l	l<nd<tsʃ	sd<ʃl, t<l
		L	tds<n<ʃ, t<l	sʃdt<n<l, s<t	sʃ<nl, td<l	l<n<dtsʃ,d<sʃ	s<tʃ, d<ʃ

speakers, although not significant in all cases (see Table 1, last column TTY). For four out of five speakers, the two sibilants were distinguished by a more retracted and therefore higher position for /ʃ/. Speaker KH produced the postalveolar fricative almost at the same place as the alveolar /s/. Generally /s/ and /t/ exhibited similar horizontal tongue tip positions but a lower vertical tongue tip position for /s/ except for speaker UR.[5]

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[5] /s/ and /t/ dispersion ellipses for UR showed a considerable overlap but differed in the direction

Table 2

Results of a repeated measures Analysis of Variance with the dependent variables horizontal and vertical position of the intrinsic tongue tip (ITX, ITY), the jaw (JAWX, JAWY) and the vertical position of the composite tongue tip (TTY) during the temporal midpoint of the consonant and the independent factors speaker, manner of articulation, and volume (since TTX gives the same results as ITX it has not been included). The upper part shows degrees of freedom (*df*), corrected for violations of the sphericity assumption, *F*-values, and significance levels for the main effects and the interactions with **.** $p<.1$, * $p<.05$, ** $p<.01$, and *** $p<.001$. The last two rows indicate the results of pairwise *t*-tests with Bonferroni adjustments for multiple comparisons for normal (N) and loud (L) speech. The lesser than sign indicates a more fronted position for horizontal dimensions and a lower position for vertical dimensions

Main effects	*df*	*ITX*	*df*	*ITY*	*df*	*JAWX*	*df*	*JAWY*	*df*	*TTY*
Manner	1.8 7.1	4.4 .	2.0 8.0	16.5**	1.9 7.5	8.7*	1.8 7.2	27.0***	1.8 7.1	4.2 .
Vol	1 4	1.7	1 4	79.9***	1 4	0.01	1 4	7.5 .	1 4	0.1
Interaction										
Manner*Vol	2.9 11.6	2.7 .	1.9 7.7	3.2 .	2.3 9.2	0.7	1.2 4.9	3.1	2.3 9.1	3.0 .
Post hoc tests										
N	st<ʃ		s < dnl ʃ<l		ʃ< tdnl		l<dtsʃ n<sʃ			
L	s<ʃ		s < tdnl ʃ<l		ʃ< tdnl s<l		l<ndtsʃ n<tsʃ d<sʃ			

The voiceless stop was usually more fronted than the voiced (not significant for speaker UR, loud condition, speaker RS, normal condition and /t/ more retracted for RS loud condition). The voiced consonants /d, n, l/ differed only in a speaker-dependent manner with no general pattern.

Spatial characteristics of jaw involvement for the different consonants are also given in Table 1 and 2 (columns JAWX and JAWY) and are shown in Figure 4, which displays the horizontal and vertical mandibular positions at the acoustic midpoint of the consonant spoken at normal volume for individuals and for all speakers computed as *z*-scores. No significant difference between the two sibilants in the vertical position at the temporal midpoint of the consonant could be found but a significantly more fronted jaw position for /ʃ/ which might come about because /ʃ/ is rounded. Turning now to individual mandibular positions for the sibilants, the following patterns emerged: Two speakers (KH and UR) produced both sibilants with the same horizontal and vertical jaw position, which is especially interesting for speaker KH whose lingual articulations (in the vicinity of the tongue-tip sensor) were also very similar for these two sounds (see Fig. 3). The other three speakers protruded the jaw significantly for /ʃ/ compared to /s/ but differed with respect to jaw height. /s/ had a significantly lower jaw position than /ʃ/ for speaker RS (both conditions), a higher position for speaker SR (normal condition) and the same height for speakers AW (both

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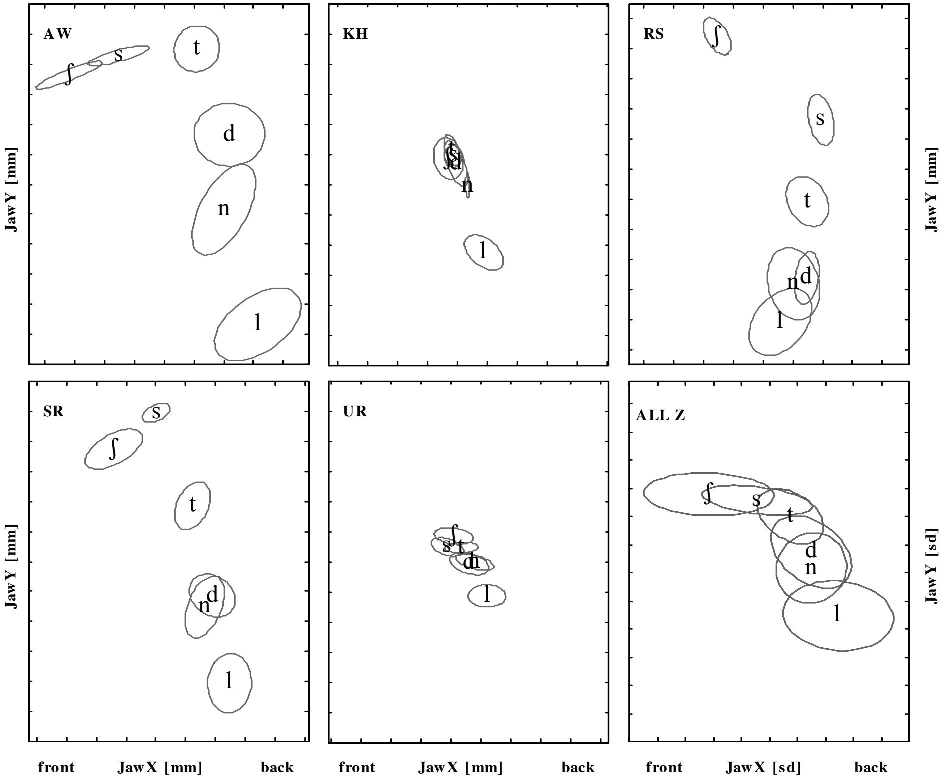
of variation. For this speaker, the orientation of the major axis of the ellipsis for /t/ is directed approximately along the palate which has often been assumed to be equivalent to constriction location whereas /s/ varies perpendicular to the palate, that is, constriction degree.

Figure 4

Positions of the jaw sensor during the acoustical midconsonant for individual speakers in mm and for all speakers in *z* scores. Dispersion ellipses are set to one *SD*. Only normal volume is shown. The space between ticks is one mm and half a *SD* for *z* scores



conditions) and SR (loud condition). Jaw protrusion for sibilants was also found by Lee (1996) in Korean, French, and Arabic and gives evidence for a tight control of the horizontal gap between the edges of the lower and upper teeth as proposed by Howe and McGowan (2005).

The voiceless stop was produced with a significantly lower jaw position than the sibilants in both conditions for overall speaker comparisons. Again this result was not consistent for all speakers: only speakers RS and SR made this distinction but for the other speakers, no significant difference for jaw height was found between the sibilants and the voiceless stop. The results so far indicate that especially the tongue tip and jaw positions for the consonants /s/ and /t/ (both produced at a similar place of articulation) contradict the notion of a simple helping function because /s/ was generally produced with a lower tongue tip position compared to /t/ but with a higher or equal jaw height.

Speaker-independent results showed a significantly lower jaw position for the voiced stop compared to the voiceless, which was partly confirmed by speaker-dependent results: three (AW, RS, SR) of the five speakers made this distinction for both conditions (UR only for normal intensity). The nasal was generally produced with a lower jaw position than the voiced stop (significant for speakers AW, KL loud, RS loud, and UR loud) and more closed compared to the lateral (significant for speakers AW, KH, SR, and UR). Therefore /l/ was produced with the lowest jaw position for most speakers. For the stops and the sonorants, the jaw was generally more retracted the lower the jaw because for rotational movements the jaw sensors move along a circle. Only speaker RS showed a different pattern: he protruded the jaw for lower jaw positions in /l/ and /n/.

Figure 5

Jaw positions during the consonant in cm: first symbol (circles and triangles) in a group: onset of the consonant, second: midpoint, third: consonantal offset. Filled circles: normal volume, empty triangles: loud volume. Last panel: *z* scores of all speakers

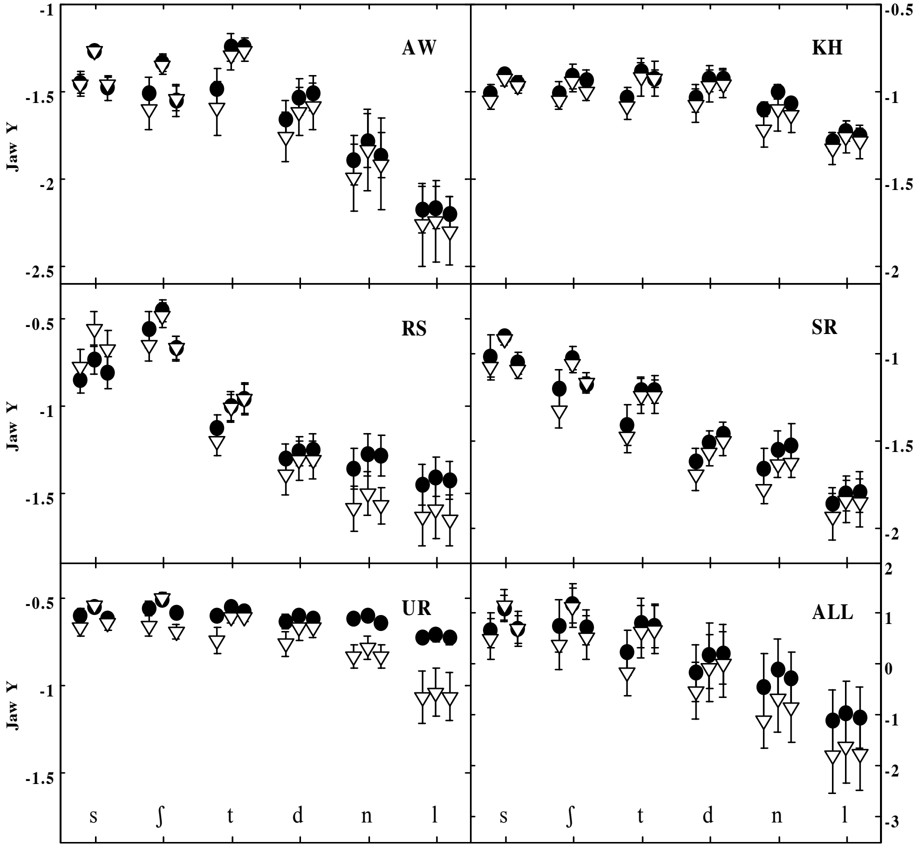


Figure 5 schematically indicates the course of the jaw movements during the consonants for individuals and for all speakers computed as *z*-scores. The first symbol of each group displays the mean and *SD* of jaw positions at the acoustic consonant onset. The offset of the consonant is given by the last symbol of each group. For the sibilants and partly the sonorants, all speakers first elevated the jaw from the onset to the temporal midpoint of the consonant and then moved the jaw downwards. This pattern differed for the stops: here the jaw either moved further upwards or maintained the same position until the burst. (Speakers KH and UR, whose mandibular involvement was generally reduced compared to that of the other speakers, did not follow this pattern as clearly.) For all speakers, the voiced stop showed the same pattern of jaw movement during the closure as /t/ but at a lower position. An asymmetrical pattern was also found for the sonorants of speaker SR. For this speaker the jaw maximum was often obtained as late as in the middle of the second unstressed low vowel, that is, no turning point occurred during /n/ and /l/ whereas for the stop a late jaw target occurred approximately simultaneously with the burst (see also Mooshammer, Geumann, Hoole, Alfonso, van Lieshout, & Fuchs, 2003 and Mooshammer, Hoole, & Geumann, 2006) with a subsequent lowering movement towards the following vowel.

In summary the results on positional data from the literature can be confirmed: Jaw involvement is higher for the coronal fricatives and for the voiceless stop compared to the other coronal consonants despite the fact that the tongue tip was lower for the fricatives and for some speakers highest for the lateral. Therefore a more active role of the jaw for /s, ʃ, t/ has to be assumed and a uniform helping function for the analyzed coronal consonants refuted. Furthermore the movement pattern for the stops was different from that of the other consonants: For the stops the highest jaw position was reached towards the burst or later whereas for the other coronal consonants the jaw moved in a symmetrical pattern with an initial upwards and a final downwards movement.

3.2
Contextual variation due to an increase in vocal effort

Our second hypothesis was that if the jaw is crucial for the production of a given consonant then it will vary very little due to vocal effort increase. To investigate whether jaw positions are stable across varying vocal effort conditions, results of *t*-tests for displacements and durations of the analyzed consonants are shown in Table 3. Only significant effects are shown by arrows in the direction of positional changes (upper part) and smaller/greater signs for distances and durations (lower part). *t*-tests were also calculated for the cell means over all speakers. Since none of the comparisons reached significance, results are not presented here. Effects of volume increase on lingual position during the consonant were rather inconsistent and speaker-dependent. The postalveolar fricative, for example, was fronted for speaker AW and more retracted for speakers SR and UR. /t/ showed a higher tongue tip position for two speakers and /d/ for one speaker. The distance traveled by the intrinsic tongue tip during the consonant was larger for increased intensity and reached significance only for the obstruents. As can be seen in Table 3 below, there was again considerable variation between speakers: Whereas speakers AW and KH showed no significant effects, speaker RS increased intrinsic tongue tip movement during all obstruents in loud speech, speaker SR only for /ʃ/ and speaker UR for /ʃ, t, d/. One reason why only obstruents were affected might be because the increased air-pressure for loud speech passively moved the tongue forward for consonants with a tighter constriction.

Table 3

Significant effects ($p < .05$) due to increase in vocal effort on tongue tip position (TT), intrinsic tongue tip position (IT), jaw positions (JAW) measured at the temporal midpoint, the acoustic duration of the consonant (DurC), the distance traveled by the intrinsic tongue tip (DistIt) and jaw (DistJaw). For positions, arrows give the direction of the significant changes from normal to loud volume. For the other variables '<' means shorter duration or smaller distance for the higher intensity and '>' means longer duration or larger distances for the higher intensity

Variable	Sp.	s	ʃ	t	d	n	l	Sp.	s	ʃ	t	d	n	l	Sp.	s	ʃ	t	d	n	l
TT	AW		←					KH							RS			↑	↑		
IT			←										↑			↓			↑	↑	
JAW													↙			↖				↓	↓
TT	SR		→					UR	←	→	↑	←		↙							
IT			↗						←	→	↑	←	↑	↖							
JAW						↓					↓	↓	↘	↘							
Variable	Sp.	s	ʃ	t	d	n	l	Sp.	s	ʃ	t	d	n	l	Sp.	s	ʃ	t	d	n	l
DurC	AW	<	<				<	KH	<				<	<	RS						
DistIt																>	>	>	>		
DistJaw									>							>		>		>	
DurC	SR							UR		>	<										
DistIt			>							>	>	>									
DistJaw			>	>					>	>	>	>	>	>							

For coronal consonants, speakers in the current study varied in their jaw contribution to loudness production: Whereas one speaker (AW) showed no effects, another speaker (UR) lowered the jaw for the four consonants /t, d, n, l/. As was mentioned in the Methods section, this speaker almost shouted. For the sibilants, one speaker (RS) produced /s/ with a higher jaw position in loud speech at the temporal midpoint. As can be seen in Figure 5, this speaker's jaw positions were higher in the loud condition during the whole consonant whereas for some other speakers (e.g., UR, and SR) a lower jaw position at the onset and/or offset of the consonant was frequently found but they maintained the sibilant-specific closed jaw position during the temporal midpoint. Since the jaw positions during the preceding and following /a/'s were much lower, the lower jaw positions at the onset and offset of the sibilant can be seen as adjustments, which are, however, restricted to the borders of the sibilant and do not affect the temporal midpoint.

The only more consistent result was that four out of five speakers lowered the jaw significantly for the nasal in the loud condition. The jaw positions of the lateral were affected significantly for two of the five speakers.

The amount of jaw movement during the consonant was significantly higher for all consonants for speaker UR in loud speech and showed no significant effect of volume increase on any consonant for speaker AW. For the other speakers, no general pattern could be observed except that the amount of jaw movement never decreased for loud speech.

As was also found by Schulman (1989), acoustic consonant duration tended to be shorter for loud speech but there were significant duration differences due to loudness only in some cases: /s/ was significantly shorter for two speakers, AW: $F(1, 23) = 24.8$, $p < .00$; KH: $F(1, 23) = 7.3$, $p < .05$, /ʃ/ shorter for speaker AW, $F(1, 23) = 9.4$, $p < .01$, but an even longer duration for speaker UR, $F(1, 23) = 9.6$, $p < .01$, /t/ shorter for speaker UR, $F(1, 23) = 4.4$, $p < .05$), /n/ for speaker KH, $F(1, 23) = 4.3$, $p < .05$, and /l/ for two speakers, AW: $F(1, 23) = 6.5$, $p < .05$; KH: $F(1, 23) = 4.6$, $p < .05$.

The results obtained so far suggest an active contribution of the jaw to the obstruents /s, ʃ, t, d/ because jaw position is not affected by vocal effort increase. For sonorant consonants by contrast, the jaw position is less constrained and showed significant lowering for two speakers during /l/ and for four speakers during /n/. Whether the more open jaw positions for /n/ and /l/ are actively controlled by the speaker in order to enhance the acoustical prominence of these sounds or whether the lower jaw positions are merely coarticulatory adjustments for the jaw lowering during the neighboring vowels in the loud condition, will be addressed further in the Discussion section.

3.3
Precision

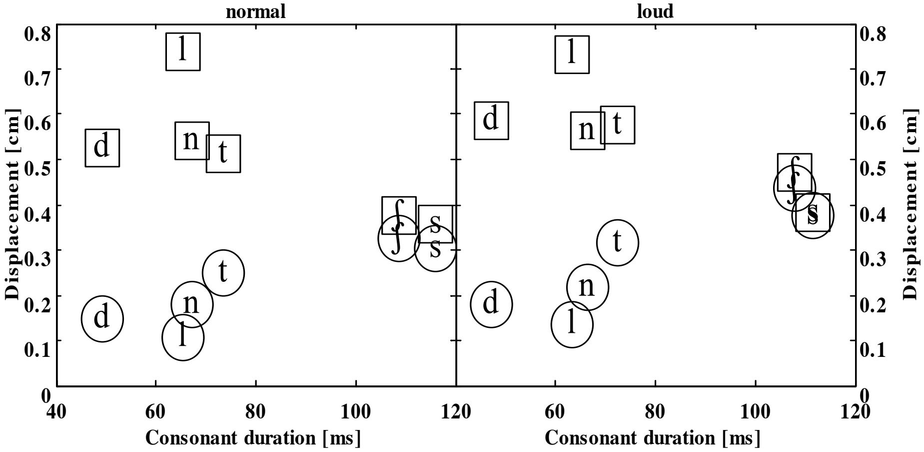
The third hypothesis is that the importance of an articulator for the production of a sound can be measured by its precision, that is, the more an articulator varies during a sound the less crucial its placement is for the achievement of constriction. Or putting it the other way around, the smaller the distance traveled the more important it is for the acoustical outcome that the respective articulator is immobile. This is what we would expect for the sibilants because of the special role of the lower incisors for generating a high-frequency noise. The assumption of a uniform helping function would predict that the analyzed coronal consonants do not differ with respect to jaw movement during the consonant. Since the distance traveled also depends on duration and since the acoustically determined consonant duration varied from about 48 ms for the voiced stop to 110 ms for the sibilants in the current study, the displacements of the jaw and the intrinsic tongue tip were analyzed and related to the duration of the consonant as shown in Figure 6.

Across all speakers, the amount of jaw movement (marked by circles in Fig. 6) was largest for the sibilants, followed by the voiceless stop. The least extensive movement was found for /l/ whose jaw movement was significantly smaller than /d/ and /n/ in the loud condition. This pattern was generally in evidence for most speakers except for speaker KH: he scarcely moved the jaw during all consonants (see also Figs. 4 and 5) and the only significant difference was a smaller amount for /l/ compared to /t/. The amount of intrinsic tongue tip movement showed a reverse pattern to that of the jaw movement: here the tongue tip moved very little for the sibilants and most for the lateral. This order was quite consistent for all speakers with minor differences between the extremes. The acoustic duration of the consonants was usually of the order /d/ shorter than /l, n, t/ and the sibilants being longest.

As can be seen in Figure 6 the amount of jaw movement increased with the acoustic duration of the consonant and the amount of intrinsic tongue tip movement

Figure 6

Relationship between consonant duration and amount of intrinsic tongue tip movement (squares) and jaw movement (circles), averaged across all speakers, left: normal volume, right: loud volume



decreased, that is, the shorter the consonant the more the tongue tip moved during the consonant. As will be shown below this can be attributed to the exceptional behavior of the sibilants. To test whether both relationships were significant, Pearson Product correlation coefficients were calculated and shown in the upper part of Table 4. The relationship between jaw displacement and consonant duration was significantly positive for all speakers whereas the negative correlation between intrinsic tongue tip displacement and consonant duration was weaker and more inconsistent for individuals.

Since the acoustic durations of the sibilants were categorically different from all other consonants, one could assume that the correlation between jaw movement and consonant duration was simply an effect of the higher amount of jaw involvement for the two longest consonants in the data. Additionally, the significantly negative correlation between intrinsic tongue tip movement and consonant duration could be attributed to a greater need of lingual precision for the sibilants. Therefore the sibilants were excluded and the resulting correlation coefficients are shown in the lower part of Table 4.

For the jaw, a highly significant positive correlation was found for all speakers even after exclusion of the sibilants (lower part of Table 4); the correlation coefficient slightly decreased compared to correlations including the sibilants (upper part of Table 4). Hence, the large amount of jaw movement during the sibilants does not solely reflect mandibular imprecision but can be attributed at least to a general relationship between the consonantal durations and jaw movements: the longer the sound, the more the jaw is able to move. For intrinsic tongue tip movement, no significant negative correlation occurred if the sibilants were excluded: this suggests that the tongue needs to be positioned more precisely in sibilants than in other consonants.

Table 4

Correlation coefficients between the distances traveled during consonants and consonant durations for the intrinsic tongue tip (It-Dur) and the jaw (Jaw-Dur). In the upper part all consonants are considered, in the lower part the sibilants are excluded

	Normal volume			Loud volume		
All consonants	n	It-Dur	Jaw-Dur	n	It-Dur L	Jaw-Dur L
AW	70	-0.447 **	0.815 **	70	-0.481 **	0.794 **
KH	72	-0.221	0.435 **	71	-0.270 *	0.560 **
RS	68	-0.469 **	0.717 **	71	-0.658 **	0.784 **
SR	68	-0.287 *	0.720 **	67	-0.161	0.800 **
UR	70	0.118	0.817 **	72	0.167	0.825 **
ALL	348	-0.326 **	0.640 **	351	-0.296 **	0.734 **
/t,d,n,l/						
AW	47	0.260	0.512 **	48	0.218	0.598 **
KH	48	0.286 *	0.604 **	48	0.192	0.659 **
RS	45	0.464 **	0.402 **	47	-0.082	0.366 *
SR	48	-0.064	0.481 **	45	0.155	0.456 *
UR	46	0.369 *	0.535 **	48	0.465 **	0.538 **
ALL	234	0.107	0.506 **	236	0.018	0.514 **

In sum, it was found that consonants which are produced with the greatest jaw height also show the most extensive jaw movement during the consonant. This is contrary to the hypothesis stated above, that if the jaw plays a crucial role for the production of a consonant, it should vary very little over time during the course of the consonant. Our contradictory results can be partly explained by the longer durations of the sibilants. Moreover, a sustained steady-state of the jaw might not be necessary to ensure perceptual stability during the entire sibilant, and therefore the jaw continues to move upwards after the onset of the lingual constriction, if a high jaw target is required.

4 Summary and Discussion

This study was concerned with the production characteristics of German coronal consonants. The major focus was on the role of the jaw for achieving the essential vocal-tract constriction for the consonants /s, ʃ, t, d, n, l/ in /aːCa/ sequences. From the literature three hypotheses concerning the role of the jaw for the production of coronal consonants could be derived: (1) the jaw's task is a simple helping function, (2) the jaw's propensity to coarticulate with neighboring segments is consonant-specific and is related to sonority, and (3) the role of the jaw is mainly special for the sibilants but not for the other consonants under consideration. These hypotheses were tested (1) by measuring the tongue tip and jaw configurations during the consonants, (2) by using a natural perturbation paradigm, namely increasing vocal effort and thereby inducing a lower jaw position in the adjacent vowels, and (3) by assessing the amount of movement during the time-course of the consonant. We obtained the following results:

(1) For the voiceless obstruents /s, ʃ, t/ a closed jaw target was found consistently for all speakers; this was not affected by increasing vocal effort.

(2) Spatial variation during the consonant is related to the segment duration for jaw movements and therefore only indirectly to its role in the production of a sound, that is, the more extensive the jaw movement is during a sound, the longer the sound.

(3) With respect to the jaw movement path, two different patterns emerged: a symmetrical one with the highest jaw position being reached approximately in the medial part of the consonant and an asymmetrical pattern with a continuous upward movement during the lingual constriction and a late jaw target achievement at the acoustic offset of the consonant (see Fig. 5). The coronals /s, ʃ, n, l/ were produced predominantly with a symmetrical pattern and the stops with an asymmetrical one.

(4) Increasing vocal effort had very few consistent effects on the analyzed parameters during the consonants. Jaw lowering as an accommodation to the lower jaw positions during the surrounding vowels was only found for the nasal.

These results will be discussed in terms of the role of jaw for different manners of articulation, for the duration of sounds and for the production of loud speech.

4.1
Jaw contribution to different manners of articulation

This study confirms that the contribution of the jaw to tongue tip raising in the production of a coronal constriction varies with manner of articulation. If the jaw contributed uniformly to the different consonants, as predicted by the helping function hypothesis, the jaw would have to be even lower for the fricatives because the position of the tongue blade is also lower for a critical constriction degree compared to full closure. Rather, the jaw seems to move quite independently of the intended tongue tip height, with a very closed jaw for the two sibilants and the voiceless stop and lower jaw positions for the voiced coronals. Whereas the reason for the high jaw position for the sibilants is very well-known, it is less immediately obvious why a closed jaw position reached late during the consonant is an essential property for the voiceless coronal stop. There are several possible explanations: Firstly, the high jaw position, achieved late during the closure, might be necessary for producing a salient burst. Since the lower teeth are quite close to the constriction location for the alveolar stop, the noise of the explosion might be enhanced by this obstacle. The proximity of the constriction location to the lower teeth might explain why for other stops (e.g., velar and bilabial) jaw positions were found to be lower and more variable (see, e.g., Elgendy, 1999; Hoole & Kühnert, 1996; Keating et al., 1994; Perkell, 1969), that is, only for the alveolar stop is the burst enhanced by a closed jaw position. Further evidence can be found by exploring the voicing distinction: The phonologically voiced stops are often — but not primarily — distinguished by their weaker and less audible burst as compared to their voiceless counterparts (see Ladefoged & Maddieson, 1996). As was found in the current study for three out of five speakers, the jaw was significantly lower during the voiced stop than during the voiceless (for a comprehensive overview on the supralaryngeal characteristics of the voicing distinction in stops see Fuchs, 2005). Since in the current study the /d/ was fully voiced in all cases, this positional difference could be attributed to a strategy for cavity enlargement to maintain voicing. This assumption is supported by the fact that all voiced coronals were produced with a lower jaw position. Thus a low jaw position could be a general strategy for facilitating the maintenance of voicing (even though there might still be a sufficient pressure drop for the lateral and the nasal). However, Geumann (2001a) observed a much higher variability due to vowel context in /d/ compared to /t/. As was already mentioned in the introductory section the current study is based on a subset of the data presented in Geumann et al. (1999) and Geumann (2001a,b). By analyzing the maximal jaw position during the consonant in symmetrical vowel context with the vowels /i, e, a/ they found that contextual variability was very restricted for the sibilants and /t/, intermediate for /d/ and much higher for the sonorants. Therefore, the lower jaw position during voiced stops is probably less tightly controlled and the jaw might accommodate to a greater degree to the vowel context for the voiced stop compared to the voiceless since only a weak burst is required. Additionally, the lower jaw position for the voiced stop seems to be a cost minimization strategy, because the jaw closing and opening amplitudes are reduced for a lower jaw position during /d/ compared to /t/, and it is assumed that smaller amplitudes are produced with less energy than larger amplitudes everything else being equal (Nelson, 1983). Because not all speakers distinguish the voiced and voiceless alveolar stops by jaw height, this strategy for saving energy seems to be optional.

The second explanation for the high jaw position during the voiceless alveolar stop was suggested by Geumann (2001a) who argues that a tight air seal during the closure might be more easily maintained by a closed jaw position. The aim would again be a prominent burst which is probably not as relevant for the voiced stop. Thirdly, she proposed that the lower jaw positions for /d/ might be attributable to a strategy for shortening the voiced stop, namely by clipping or truncating the jaw closing movement during the consonant. The truncation of the jaw closing movement by the opening movement causes a shorter duration and a lower jaw position for /d/ because the jaw does not reach its target. She found that speakers with low jaw positions also shortened the /d/ almost to a tap-like sound. As can be seen in Figure 6, /d/ was the consonant with the shortest durations with about 48 ms in the current study. A possible motivation for a short voiced stop is to avoid devoicing but the shortening might also have the consequence of a lower jaw position due to target undershoot.

In contrast to the sibilants and the voiceless stop, the voiced coronals in the current study were generally produced with a lower jaw position which was much more affected by the vocalic context (see Geumann et al., 1999). For these sounds, the role of the jaw might be a subordinate one of just supporting the tongue tip in moving upwards. For reasons of economy the tongue tip might move more by itself in low vowel context compared to high vowel context, that is, energy might be saved by less jaw movement because of its greater mass compared to the tongue tip. Evidence for this view is found by the fact that four speakers showed a more extensive jaw-lowering in /n/ due to the coarticulatory effect of the vowel in loud speech. However, it is not clear why this form of articulatory strategy is not used for /d/ and /l/ in the loud condition. Perhaps in /d/ and /l/, the lower jaw position is actively controlled because of a more apical articulation with the tongue tip curling upwards, as opposed to a laminal articulation with a flat tongue blade surface. In an analysis of French x-ray data, Dart (1991) found that laminal stops were articulated with a high jaw position and apical stops with low positions, thus providing space for curling up the tongue tip. For /l/ an even lower jaw position — compared to apical /d/ — might also be essential for avoiding lateral contact between the tongue sides and the posterior parts of the alveolar ridge (see also Geumann, 2001a; Lindblad & Lundqvist, 1999; Lindblad & Lundqvist, 2003). In a high vowel context, the jaw movement was in the opposite direction when the medial consonant was an /l/: instead of the expected upward movement towards the lateral, jaw lowering was frequently found (see Geumann, 2001a). An apical articulation can also be assumed for /d/ which was often very short and produced in a flap-like manner.

We therefore conclude that the jaw had a passive role in moving the tongue tip to the alveolar ridge only for /n/. The jaw positions during the nasal are not only significantly affected by vowel height variation but also — and this was exceptional — consistently by vocal effort changes with lower jaw positions in loud speech. This latter point can be interpreted as an accommodation to the surrounding lower jaw positions requiring an increased movement effort for the intrinsic tongue tip. An alternative view, which will be discussed in the last section, is that a lower jaw position affects the spectral properties audibly only for /n/.

4.2

Jaw involvement, precision, and segment duration

It was hypothesized that the more relevant the jaw is for the production of a sound the less it will vary during its course because movement will crucially change the acoustics of this sound. The opposite was found in our data: For consonants with high and stable jaw positions, a greater extent of jaw movement was generally found during the acoustic extent of the consonant. This result can partly be explained by the jaw movement patterns observed in Figure 5: For consonants where a closed jaw position is essential such as /s, ʃ, t/, the jaw moves upwards to a greater extent from the acoustical onset to the midpoint of the consonant, that is, even though the jaw is in a higher position at the beginning of the consonantal constriction for the voiceless obstruents, it still has to move to a greater degree towards its target compared to /d, n, l/. An alternative to measuring the movement extent is to obtain and analyze an interval which is defined by a low jaw velocity and therefore a relatively stable articulatory jaw target phase during the consonant. This measure proved to be more in agreement with our other results in previous studies (Mooshammer et al., 2003 and Mooshammer et al. 2006).

Moreover, it was found that the extent of jaw movement during the consonant is positively related to the segment duration, that is, the larger the movement involved in the production of a sound the longer its duration. For the short consonants /d, l, n, t/, which varied between 45 and 80 ms, less movement during the consonant was found than for the much longer sibilants with durations of about 110 ms. This might suggest that intrinsic consonant durations can be attributed to the amount of mandibular involvement for this consonant, that is, since the jaw is relatively heavy and therefore more sluggish than the tongue tip its peak velocity might have a lower upper limit than other articulators. A similar explanation for intrinsic vowel duration has been given by Lehiste (1970), that is, the longer durations of open vowels are a result of the greater distance the jaw has to travel. Since in the present study we have only analyzed coronal consonants in a low vowel context, data on more places of articulation are needed before the hypothesis that the jaw is the major determinant of segment durations can be substantiated.

For the intrinsic tongue tip measure, that is, the active tongue tip movement independent of the jaw, segmental duration was negatively correlated with movement extent during the sound. This negative correlation could come about because sibilants require a highly precise positioning of the tongue tip and blade despite the considerably longer duration. The high jaw position might additionally assist stabilization of the tongue when forming a medial groove at a critical distance to the alveolar ridge. These findings indicate that for the sibilants, the jaw and the tongue blade are of equal importance, which is in accordance with Ladefoged's (1990, p. 399) suggestion that the phonological specification of the jaw height partially determines the position of the tongue body for this sound class.

4.3
Vocal effort increase

The current study showed that vocal effort increase does not affect the jaw positions during the consonants /s, ʃ, t, d, l/ whereas—as found in earlier studies—vowels spoken with increased vocal effort are consistently produced with lower jaw positions. In this study vocal effort changes serve to assess the spatial stability, but the underlying mechanisms of speaking up were originally not the center of our interest. However, the results obtained here for the consonants give very interesting and far-reaching implications for the strategies used by the speakers in order to enhance their audibility.

There is general agreement that loud speech is mainly produced by increasing the expiratory force, and therefore the subglottal pressure, with the consequence of more energy in the higher frequency ranges and an increased fundamental frequency which is perceived as louder. But what is the speaker's motivation for lowering the jaw in loud vowel production? Schulman (1989) suggested two alternative explanations: firstly, because of the increased volume velocity the tight constriction of high vowels, such as /i/ and /u/, might cause a turbulent air-stream. To avoid frication the jaw is lowered. In order to explain the lower positions of the lower vowels Schulman proposes a chain reaction in order to maintain vowel height differences. Secondly, the lower jaw positions might compensate for the increased fundamental frequency, assuming that the vowel openness is judged by the listener by the difference between the fundamental frequency and the first formant frequency, as was found by Traunmüller (1981). Since a lowering of the jaw causes an increased F1, this strategy guarantees a constant distance between the frequencies of F0 and F1 and therefore the maintenance of phonological vowel height at different vocal effort levels.[6] Therefore, both of

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[6] This explanation is also not completely convincing if one accepts that listeners can perceptually parse intrinsic vowel contributions and volume-related contributions to F1 (cf. Fowler & Brown, 1997, for pitch perception). After all, the listener can normally clearly identify loud speech even independent of the replay level, for example, from changes in the glottal source. Thus active compensation by the speaker may be superfluous.

Schulman's explanations suggest an active compensation for changes due to subglottal pressure rise in order to avoid segmental confusions or distortions. Since F0 and F1 are presumably not crucial for the identification of the consonants analyzed in the current study, no compensatory strategies for increased pressure can be expected. A third explanation can be derived from Lindblom et al.'s (1979) study: by lowering the jaw, F1 increases which in turn levels the spectral slope. A fourth more speculative hypothesis is that lowering of the jaw aims at increasing the mouth opening which changes the radiation impedance. According to Stevens (1998), a rise of the impedance also increases the bandwidth of the higher formants, which has also been found to be perceived as louder (see, e.g., Zwicker, Flottor, & Stevens, 1957, for complex sounds). These last two suggestions have in common that jaw lowering further enhances the acoustical consequences of increasing the respiratory force by reshaping spectral properties. Obviously, the audibility of obstruents would not benefit from a greater mouth opening, which is in accordance with the results of our study, namely that the jaw target did not change for /s, ʃ, t, d/. For the lateral, however, jaw lowering was found for two speakers which might imply an active strategy of these speakers in order to affect their spectral properties in the expected direction. For the nasal, which was consistently produced with a lower jaw position in loud speech, the acoustic effects of jaw lowering are not apparent to us, because most of the energy is escaping through the nostrils and lingual constriction location is probably only slightly affected by the jaw position. Therefore, we assume that the lower jaw positions in loud speech during the nasal can be attributed to an accommodation of the jaw to the lower jaw positions in loud speech of the surrounding vowels.

A more kinematic attempt at explanation is that the lower jaw positions during vowels are a consequence of the speakers' primary intention to lengthen the vowel since these best convey the spectral enhancements. Lengthening the jaw movement cycle causes a target overshoot if lengthening is produced by simple modifications such as less overlap between opening and closing movement or proportional rescaling (see, e.g., Harrington et al., 1995). These strategies might be more economical than reorganizing the motor plan for a specific vowel because the latter, that is, modification of a phonetic target, might involve the activation of different muscles whereas the former is simply accomplished by a temporal shift of a gesture or a rescaling of the activation of the same muscles. Moreover, acoustic results of changes of the jaw position for the vowel can probably be parsed by the listener as a property of speaking up. The consonants would figure as anchor points with relatively fixed jaw positions and therefore change minimally or not at all. In this view the jaw has a time-keeping role by determining the durations of vowel categories and consonants and, moreover, by adjusting these durations to the communicative requirements such as enhancing the more sonorous stretches of speech, namely the vowels.

5 Conclusions

The current study replicates the results of other studies by showing that, since the jaw's contribution to consonant production varies with manner of articulation, the jaw cannot simply have a passive supporting function in achieving the lingual constriction. A helping function would imply that coronal consonants produced with a low tongue tip position also show a low jaw position. However, the opposite was the case for /s/ as compared to the other analyzed consonants, that is, for most speakers the tongue tip height for this consonant was lower than for /l/ but the jaw position was still much more closed for /s/.

Because of the high and invariant position of the jaw during sibilants, Lee et al. (1994) suggested the introduction of a jaw gesture with its own fixed task, that is, provision of a second noise source. In our view, there could only be evidence that the jaw makes an independent contribution if there were a language in which two sounds were distinguished by jaw activity alone. As proposed by Ladefoged and Maddieson (1996), this might be the case for the alveolar fricatives in Icelandic: /s/ produced with a closed jaw and /θ̠/ with teeth apart. Since this is only based on results of one speaker, more data on Icelandic are needed.

Apart from the exceptional status of the sibilants, the jaw seems to play a special role for the alveolar stop which is also produced with a high and invariant jaw position. Since from the literature we know that a closed jaw position has only been observed for the voiceless alveolar stop but not for /p, k/, this result is contrary to the sonority groups established by Lindblom (1983). Therefore, jaw height and the propensity of the jaw to coarticulate with the neighboring segments are only partly applicable to the description of phonotactical constraints on the ordering of segment sequences. Concerning the role of the jaw in producing an alveolar stop, our hypothesis was that bringing the lower teeth to a closed position enhances the salience of the burst. Movement patterns of the jaw with a late jaw target for the stops provide evidence for this hypothesis but further temporal analysis is needed for substantiating it.

The contribution of the jaw to speaking up is restricted to a greater jaw opening during the vowel. Coronal consonants are generally not affected by global vocal effort changes except for the nasal. Because the jaw was lower for /l/ compared to /n/, Keating's window model would predict more variability for the lateral than for the nasal, which was not the case for vocal effort increase. The most probable reason for this adjustment is that the nasal is produced without a specific jaw target and hence the jaw can accommodate to the lower positions of the surrounding vowels; by contrast the jaw has a more active role in /l/ and /d/ in order to increase the size of the oral cavity and to avoid lateral contact (for /l/). Therefore, we conclude that low and variable jaw positions cannot simply be interpreted as a low degree or even absence of jaw involvement (as proposed for the oral/guttural distinction by Goldstein, 1994), but rather the two dimensions, jaw height and jaw variability, vary independently.

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