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Variability in jaw height for segments in English and Swedish VCVs

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This study compares the extent of coarticulatory influences of vowels on consonants and consonants on vowels in VCV utterances from English and Swedish speakers. Three vowels and ten consonants form the VCV utterances, with V1 = V2 and the nuclear stress on the second vowel. The measure of coarticulation is the vertical height of the jaw, which was determined using the Stockholm University Movetrack magnetometer system. Results of the experiment indicate that the two languages behave similarly overall, and that vowels are overall more open and overall more variable than are consonants. However, little of the variation in vowel height is attributable to consonant context, whereas much of the variation in consonant height is attributable to vowel context, and the effect of vowel context on consonant height is statistically reliable whereas the effect of consonant context on vowel height is not. These results support the proposal by Lindbolm (1983) that consonant segments may accommodate their jaw heights to those of neighboring vowels. The results also weakly support his proposal that consonants differ in their propensity to coarticulate, with ȃlveolar consonants showing less effect of vowel context and /h/ the most.

1. Introduction

Lindblom (1983) proposed that consonant segments differ in their propensity to coarticulate jaw heights with neighboring segments: some consonants adopt the jaw

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height of their vowel nucleus, while other consonants do not. The latter consonants, he proposed, are those that tend to occupy syllabic positions that are further from vowels, with other consonants intervening between the incompatible consonants and vowels. Lindblom presented experimental data on the height of the jaw for different consonants before /ɑ/. These data were taken to indicate the consonants' degree of coarticulation with the vowel. Keating (1983) took issue with this interpretation. She noted that different observed heights directly reflect degree of coarticulation only if all consonants have some identical inherent height very different from vowels' heights. She also pointed out that the jaw heights for the vowel were not reported, and could possibly be varying even more than the consonant heights. Keating cited data of Condax (1980) on Fijian, in which vowels appear to vary more than consonants, with overall variability of a segment seemingly correlated with its overall openness. She also presented new data on English consonant clusters suggesting that vowels and some consonants adopt jaw heights to accommodate other consonants such as /s/. Keating (1988) introduced the term *anchor* to refer to a segment which determines aspects of articulation over a segment span, to which neighboring segments accommodate themselves. Anchors should be less variable, and non-anchors more variable.

On any model of speech production which incorporates Ohman's (1966) idea of a vowel-to-vowel cycle with consonants superimposed on it, such as Fowler (1980) and more recently Saltzmann and Munhall (1989), a consonant's jaw height will vary along with that of the vowel(s) on which it is riding. The vowel(s) may in turn be somewhat affected by the consonant's jaw height, but presumably to a much lesser extent. Thus Lindblom's hypothesis, though driven by other considerations, is more consistent with this class of models than is Keating's.

Lindblom viewed vowels as anchoring jaw height in a syllable, with consonants accommodating the vowels, and therefore consonants more variable than vowels. On the other hand, Keating viewed some consonants as anchoring jaw height, with vowels and other consonants accommodating, and therefore vowels more variable than consonants. The issue then can be framed as one of relative influence—does vowel context have a larger effect on consonant jaw height, or the reverse?—or of relative variability—do consonants vary contextually more than vowels, or the reverse? The present experiment addresses the issue in these terms. Data on jaw height were collected for combinations of consonants and vowels, and segments compared across contexts. The experiment also addressed another possibility: Lindblom and Keating studied different languages, which perhaps behave differently in the relevant respects. Therefore Swedish and English are examined together here.

2. Method

2.1. *Speakers*

The speakers were all visiting or working at Stockholm University. They included two of the authors and some others familiar with the purposes of the experiment. The Swedes were three men and two women, while the Americans were two men and three women. All speakers served as subjects only for their native language, but all of the Swedes knew English as well, and four of the Americans knew Swedish.

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2.2. *Speech materials*

Most of the items used in the experiment were VCVs, uttered in isolation. The first vowel received weak stress and the second received stronger stress and the nuclear accent; the resulting pattern was like the usual pronunciation of English *Aha!*. Broadly speaking, the vowels were /i/, /e/ (English) or /ɛ/ (Swedish), and /ɑ/, and the consonants were /f, b, t, d, s, n, l, r, k, h/ in both languages.

However, speakers in each language used their own appropriate, natural, qualities of these phonemes for each context, resulting in phonetic differences across the languages, the phonetic contexts, and the individual speakers. The most obvious differences in the consonants involved /r/ and /l/ across the languages. The American /r/ is an approximant [ɹ], while the Swedish /r/ is most often an apical trill. The American /l/ is most often strongly velarized, while the Swedish /l/ is not.

The vowels also differed somewhat across the two languages. With front vowels it is difficult to match the phonetic qualities across the two languages without phonotactic violations. The Swedish unrounded high vowel used was [ɪ] in the weakly stressed initial syllable but [iː] in the final stressed syllable. The English mid vowel phoneme used was /e/, typically diphthongized to [eɪ] in both syllables. The Swedish unrounded mid vowel phoneme used was /ɛː/ in the final stressed syllable, which occurs only as short [ɛ] (occasionally [e]-like) in the weakly stressed initial syllable. Throughout this report the mid front vowels of both languages will be represented simply as /e/.

Since Swedish long vowels occur only in stressed syllables, there is noticeable variation in length, as well as quality, between the two vowel allophones in the Swedish VCVs. Particularly noticeable to American listeners is the difference between initial [a] and final [ɔː], [ɒː], or [ɑː] for /ɑ(ː)/. Throughout this report the low vowel of both languages will be represented simply as /ɑ/. The American vowels did not differ as much auditorily in initial compared to final position; the initial vowels, with weak stress, were not audibly reduced or centralized. However, one of the five Americans tended to use [ɔ] for /ɑ/ in final position; this speaker was asked to use [ɑ] instead, like the other Americans.

2.3. *Equipment*

Data was collected using an early version of the Movetrack magnetometer system designed and built at the Phonetics Laboratory of Stockholm University, described in detail in Branderud (1985). In brief, the system set up a magnetic field around the subject's head and then tracked the position in two dimensions of a small magnetic coil within that field. The subject wore a helmet that held in position two large parallel coils, one in front of the head and one behind, that set up the field. Movement of the small coil was detected with reference to a fixed point outside the body, similar for all speakers. Prior tests of the system indicated that the position of the helmet and the reference coil was extremely stable. Although this and other such systems can be unreliable in tracking coils on the tongue, coils attached to the jaw are not subject to the same difficulties. The spatial resolution of the transducer is on the order of 0.01 mm.

In this experiment the small coil was attached with soft wax at the midline on the gum ridge at the lower teeth. It was tracked only in the vertical dimension.

Simultaneous audio and movement signals were recorded on FM tape, though for one session the recording failed. For all subjects, however, these signals were also available as printed by an oscillomink.

2.4. *Procedure*

Each subject served during one experimental session. At the beginning of a session, the procedure was described, the speech materials gone over, and a reference position for the jaw found and practiced. This was described to subjects as "starting to swallow, letting your teeth touch, and holding the teeth in that position without completing the swallow", and all subjects seemed able to use this kind of description to find a repeatable reference position. (This instruction had been developed from past experience that the clenched position of the molars in a swallow is highly replicable, and more understandable to subjects than an instruction to assume a "rest" position.)

Next, still outside the experimental room, the small magnetic coil was attached in the mouth and the helmet put on. The subject then entered the room with the experimenters, sat in the chair and was hooked up to the apparatus. After the connections, etc., had been tested, the experimental recording began. One experimenter remained in the room with the subject (either Lindblom or Keating, depending on the native language) and first triggered an automatic calibration device, whose output was recorded. Then the experimenter asked the subject to assume the clench reference position. Next, the experimenter read the speech items one at a time, and the subject repeated each one.

The original motivation for this modeling technique was that the helmet worn by the subjects made reading from a list awkward; however, it became apparent in preliminary sessions that the modeling offered the additional advantages of standardizing the prosody used by the speakers, and eliminating confusions about the phonetic transcription of the nonsense items. These advantages seem to outweigh the potential danger of artificial homogeneity in the data. The two models themselves also served as subjects, reading the by-then-familiar test materials. After every block of items, the experimenter asked the subject to repeat the clench position.

For 7 of the 10 speakers, three signals were printed. One was the rectified and integrated audio signal; the second was the vertical jaw movement signal taken from the output of the tape recorder; the third was this same vertical jaw movement signal after low-pass filtering at 100 Hz. These latter two signals are virtually identical except for a slight difference in gain. For the other three speakers, not all of these signals were available due to mechanical problems during recording.

2.5. *Analysis*

Figure 1 reproduces a sample token of a VCV item taken from the paper oscillomink print-outs made during each experimental session. From such tokens, vertical jaw displacement for each V and C was measured. Where two jaw movement signals were available (as in Fig. 1), the filtered (lower) one was used. Measurements were made to the nearest half millimeter of paper, which after calibration usually corresponded to about a quarter millimeter of spatial position.

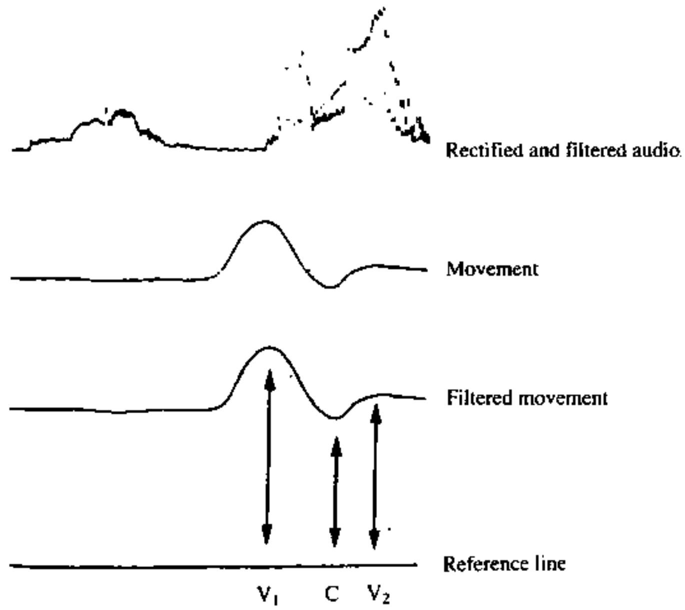

Figure 1. Sample oscillomink printout showing how data were analyzed for the three segments in a VCV utterance. Raw jaw height measurements are distances from a reference line to extrema in the filtered movement signal.

For each of the two vowels in each token, the most open displacement was measured. For the consonant in each token, the most closed displacement was measured. That is, the measurement for vowels is a maximum opening, while the measurement for consonants is a minimum opening, each often corresponding to turning points in the jaw movement trace. In some cases no upward movement was associated with a consonant, especially in /i/ contexts and with /h/; the measurement then was the highest value during the consonant interval (sometimes the same as the Vowel 1 measurement, sometimes intermediate between the two vowel measurements). In general, the movement extrema for the consonant and the second (stressed) vowel occurred during their corresponding acoustic segments, but the maximum opening for the first vowel often occurred before the segment's (and hence utterance's) acoustic onset.

The actual measurements made from the printout were distances from the jaw tracing to a reference line printed by the oscillomink (see Fig. 1). The clench positions were also measured with respect to this line, in between every block of repetitions. Because of variations in the reference line (and possibly the clench position), this measure varied by about 1 mm (though sometimes up to 3–4 mm) across a subject session. Therefore the average value of the clenches before and after each block was subtracted from the jaw measurements in that block, giving jaw heights with reference to this averaged clench. Finally, all measurements for a given subject were multiplied by the calibration factor for that subject, to convert millimeters paper to millimeters vertical jaw displacement. Thus all the jaw "height" measurements reported here are in fact jaw *opening* measurements, distances from a clench position such that larger numbers represent lower jaw positions. We note that some other studies have not measured jaw height relative to an arbitrary reference position, as we have, but instead have measured the displacement from each segment to the next, so that each segment in effect serves as the reference for the next. Such a method makes it very difficult to say how adjacent segments influence each other's heights. We also note that all data and analyses presented here use raw measures in mm, not normalized as in Keating *et al.* (1990).

3. Results

3.1. *Jaw heights of consonants and vowels*

Table I gives the height measurement for each segment in each VCV combination, averaged across the five speakers in each language. In general, the vowels are more open than the consonants, by about 3 mm on average. In this section of the paper (Section 3.1.), group data will be presented and analyzed for vowels and consonants separately, while in Section 3.2, individual subject results for the entire dataset will be the focus.

3.1.1. *Vowel height measurements*

Analysis of Variance on jaw opening measurements for both vowels in the VCVs was used to evaluate the effects of Vowel Identiy (i, e, ɑ), Language (English vs.

TABLE I. Jaw heights (openings) in mm, each value the average for 5 subjects, 6 repetitions per subject

English	i	C	i	e	C	e	a	C	a
s	4.8	2.6	4.7	8.3	2.4	7.5	8.9	2.5	8.0
t	4.8	2.8	4.5	8.3	2.8	7.4	9.0	2.5	7.8
d	4.8	3.2	4.6	8.6	3.5	7.6	9.5	2.9	7.9
f	5.7	3.9	5.3	9.5	4.0	8.1	10.4	3.1	7.9
r	5.4	3.3	5.3	9.2	3.9	8.6	9.8	3.5	9.3
n	6.4	4.4	5.8	8.8	4.9	7.6	9.9	4.6	8.1
b	5.5	4.1	5.6	9.8	5.0	9.0	10.9	4.8	9.5
l	5.7	4.2	5.2	9.6	4.5	8.2	10.5	4.9	8.9
k	5.1	4.7	6.0	8.9	5.7	8.9	9.9	6.0	9.0
h	5.4	5.4	6.0	9.5	7.8	9.4	10.0	9.7	9.8
Swedish	**i**	**C**	**i**	**e**	**C**	**e**	**a**	**C**	**a**
s	4.5	3.4	5.2	6.3	3.4	8.7	7.9	3.0	7.7
t	4.8	3.7	4.9	6.4	3.8	8.6	8.4	3.3	7.5
d	4.9	3.6	4.7	6.8	4.1	8.1	8.9	3.4	7.9
f	5.5	4.4	5.4	7.5	4.7	9.0	9.2	3.8	8.8
r	5.0	4.4	5.1	7.3	5.2	9.3	9.5	4.3	8.7
n	5.4	4.5	6.1	6.7	4.8	8.4	9.6	4.4	8.4
b	4.9	4.3	5.3	7.3	5.6	9.4	10.1	5.4	9.2
l	5.5	5.6	6.1	7.5	6.9	10.0	9.8	6.9	10.0
k	5.3	5.2	6.2	7.2	6.2	9.2	10.0	6.0	9.2
h	5.1	5.2	5.2	8.2	8.5	9.1	10.6	9.4	9.5

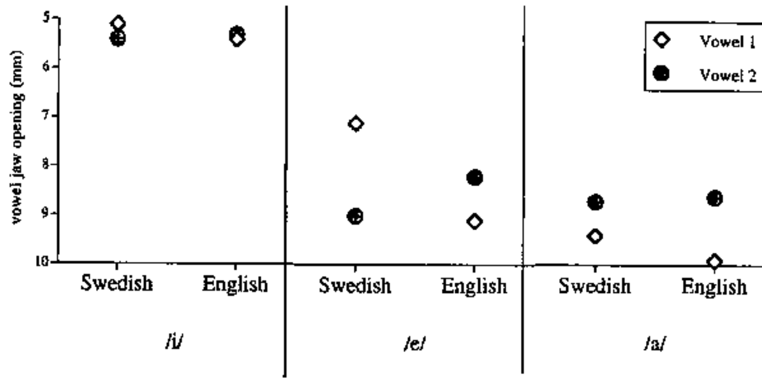

Figure 2. Mean jaw heights (openings) for the vowels of English and of Swedish, by position in the VCV. "Vowel 1" (diamonds) is the first, less-stressed vowel, and "Vowel 2" (filled circles) is the second, nuclear-stressed vowel.

Swedish), Consonant Context (the 10 consonants), and Position/Stress (the second vowel bears nuclear stress); Repetition (6 per subject) was the repeated-measure variable.

As expected, Vowel Identity was a highly significant influence ($p = 0.0001$) on overall jaw opening: /i/ is the least open vowel (mean = 5.3 mm) while /e/ is overall slightly less open than /ɑ/ (means = 8.3 *vs.* 9.1 mm). However, neither Language nor Position/Stress significantly affected vowels' overall jaw opening. Figure 2 shows the average data in terms of these three factors. (In this and in subsequent similar figures, the vertical axis has been reversed so that the figure is more iconic: a higher position on the graph (a smaller value of jaw opening) indicates a higher position for the jaw.)

Although neither Language nor Position/Stress had an overall effect on vowel opening, their interaction was significant ($p = 0.01$), as was the interaction of Vowel Identity and Position/Stress ($p < 0.026$). Averaging across the three vowels, V2 (filled circles) is more open than V1 (open diamonds) in Swedish, whereas in English V1 is more open than V2; the difference between the languages is much greater with V1 than with V2. Averaging across the two languages, the three vowels are more different in initial position (open diamonds) than in final position (filled circles); /e/ and /ɑ/ have virtually identical average values in final position. While /i/ has about the same opening in initial and final position, /e/ is less open initially than finally but /ɑ/ is more open initially than finally. Although there was no significant interaction of Vowel Identity with Language ($p > 0.6$) and only a trend towards an interaction of all three factors ($p > 0.08$), the trend can be seen in Fig. 2 for the strongest effects of Language and of Position/Stress to occur with the vowel /e/. Only for this vowel do the two languages show an appreciable opposite effect of Position/Stress. Swedish /e/ is more open in final position, whereas English /e/ is more open in initial position. This difference for /e/ may be linked to that vowel's allophones in Swedish: the large quality difference between initial (higher) [e] and final (lower) [ɛː] is clearly audible. The two languages differ from each other much less for /i/ and /ɑ/. In both languages, /i/ and /ɑ/ differ in that /i/ shows a small effect of position while /ɑ/ is much more open in the less-stressed initial position.

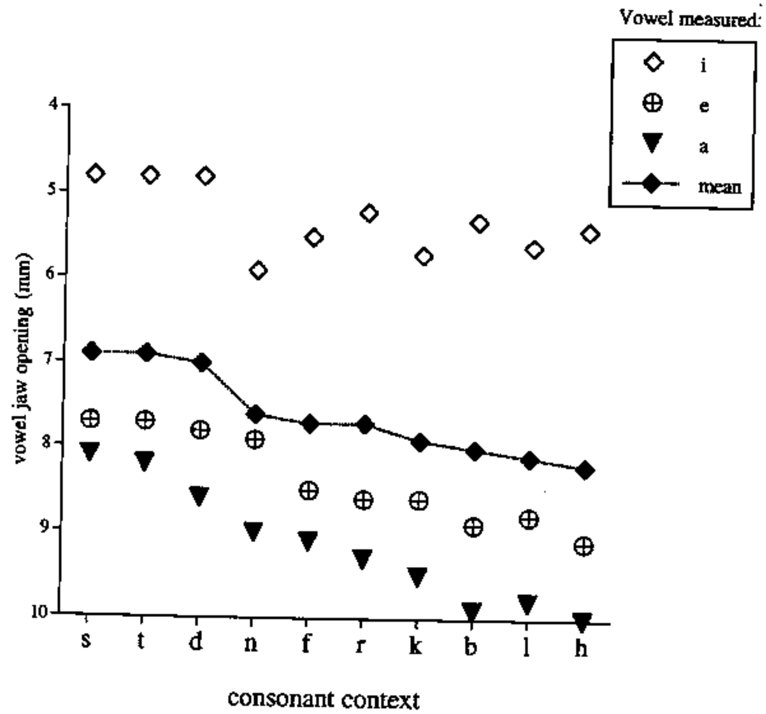

Figure 3. Mean jaw heights (openings) for the three vowels, and for the average of the three vowels, according to consonant context; data from the two languages combined.

Vowel opening was only marginally affected by Consonant Context ($p = 0.0666$), and no interactions with this factor were at all significant (all F-ratios < 1). Figure 3 displays averaged jaw heights for each vowel in each consonant context, and an average value for the 3 vowels combined in each consonant context. The consonant axis is ordered from highest to lowest average vowel values. In every consonant context, /i/ is the least open and /ɑ/ is the most open vowel. The 3-vowels-averaged points show that overall the jaw is highest for vowels in VCVs containing /s/, /t/, and /d/, and lowest for vowels in VCVs containing /k/, /b/, /l/, and /h/. These differences are small, however: the average values in the /s/ *vs.* the /h/ context differ by less than a millimeter, and as noted the statistical effect is only a trend. The individual vowels each show much the same pattern in terms of their relative height in the different consonant contexts, as indicated by the lack of any Vowel Identity × Consonant Context effect.

3.1.2. *Consonant height measures*

ANOVA on jaw opening measurements for the consonants in the VCVs was used to evaluate the effects of Consonant Identity (10 consonants), Vowel Context (i, e, ɑ contexts), and Language (English *vs.* Swedish); Repetition (6 per subject) was the repeated-measure variable. Note that the Position/Stress factor used in the analysis of the vowel height measurements is not relevant to the analysis of the consonant height data.

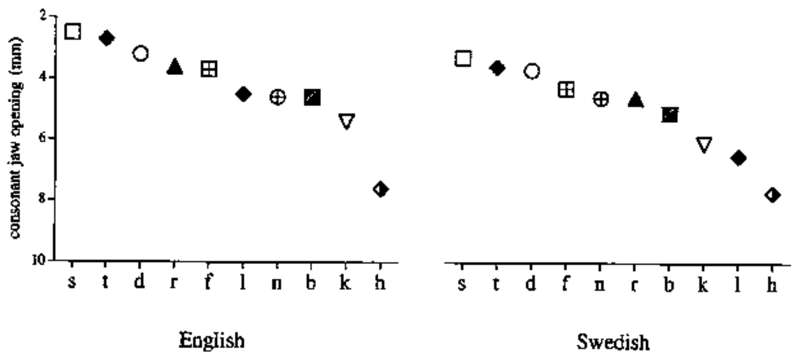

Figure 4. Mean jaw heights (openings) for the consonants of English and of Swedish, across all vowel contexts.

As expected, Consonant Identity has a highly significant effect on overall jaw opening for consonants ($p < 0.0001$). The two languages are also significantly different overall ($p = 0.0014$). Averaged across the ten consonants, the Swedish consonants are more open by about 0.7 mm than the English consonants. Figure 4 shows the averaged heights of the consonants in each language, ordered from highest to lowest in that language. In the figure, the same coding symbol is used for a given consonant in the two languages, so that the absolute and relative jaw heights of any consonant can be compared. In both languages the alveolar obstruents and /f/ are in the higher half of consonants while /b/, /l/, /k/, and /h/ are in the lower half, but details of the rankings differ. Since no interactions involving the Language factor were significant (all F-ratios < 1), these differences of detail are not statistically reliable; the consonants in the two languages differ reliably only in their overall openness.

Vowel Context also had a significant effect on consonant height ($p = 0.01$). Figure 5 shows the effect of Vowel Context on each of the 10 consonants for the two languages combined. Since, as seen above, the vowel /i/ has the highest jaw height while the vowel /ɑ/ is the most open vowel, it might be expected that consonants would be highest in the /i/ context and most open in the /ɑ/ context. On average, consonants are indeed highest in the /i/ context (mean = 4.1 mm), but, contrary to expectation, consonants are overall no higher in the /e/ context than the /ɑ/ (mean = 4.9 mm for /e/ *vs.* 4.8 mm for /ɑ/).

The interaction of Consonant Identity and Vowel Context approached significance ($p = 0.0649$), indicating that not all consonant–vowel combinations show precisely the same pattern of consonant height. Figure 5 suggests a number of VCV-particular patterns. Most prominent in the figure is the range of values seen for /h/ across vowel contexts, a range much greater than that for any other consonant. Also striking is that the consonants which are highest on average are highest in the /ɑ/ context (/s, t, d, f/), but the consonants which are lowest on average are highest in the /i/ context and lowest in the /ɑ/ context (/l, k, h/).

The data from Figure 5 allows us to make a rough comparison of the variation of individual consonants across vowel contexts. It can be seen that /s/, /t/, and /n/ are the least affected by vowel context, while /h/ and, to a lesser extent, the other three lowest consonants /b, l, k/ and /f/ are the most affected by vowel context. Vowel

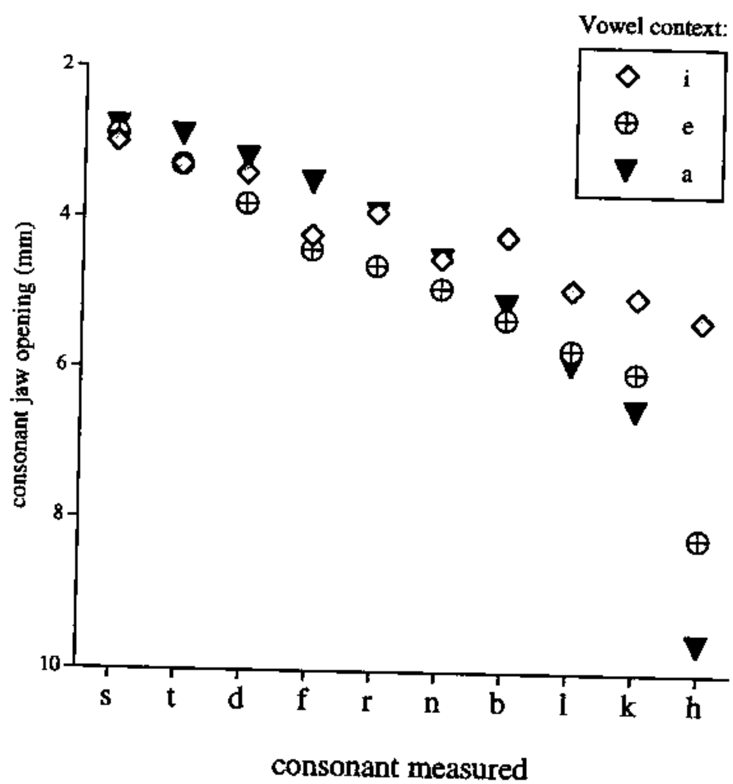

Figure 5. Mean jaw heights (openings) for consonants according to vowel context; data from the two languages combined.

influence is intermediate for /d/ and /r/. In general, the consonants that are highest in the /ɑ/ context vary relatively little across vowel contexts. The four consonants /h, k, l, b/ are much lower in the /ɑ/ context than are the other six consonants, and they are four of the five most variable consonants, /f/ being the other. It can also be seen that, overall, the ten consonants differ one from another least in /i/ contexts (diamonds) and most in /ɑ/ contexts (triangles).

3.2. *Consonant versus vowel variability*

Having presented the data on jaw heights for consonants and vowels, we turn now to the question of which contributes more overall to variability in jaw height: vowel contexts or consonant contexts? The fact that in the analyses above, the effect of Vowel Context on consonant height was strongly significant, while the effect of Consonant Context on vowel height showed only a trend to significance, suggests already that consonants vary more as a function of their context than vowels do as a function of theirs. A more direct statistical test on the question considers the variances of the consonant and vowel measurements. Unlike in other studies of variability (e.g. Smith 1992), we do not want to consider the raw variances or standard deviations, because we are not interested simply in how much variation is in the data from all sources. Instead, we want to know about the non-random variation in the data condition by the variables of interest. We also want to consider each subject separately, to be sure that the overall effects hold for each individual subject.

The data were therefore reanalyzed separately for each subject using a variance-components model Analysis of Variance. This model separates the variance due to the different factors and their interactions, and produces estimates of the variance components associated with each of these factors. These estimates are "absolute", and may be compared directly (see e.g. Winer, 1971; Hayes, 1973). This absolute variance (square of the standard deviation, in mm^2) was computed for the measures for each segment position (V1, C, V2). For each subject, the total variance for a given segment position was partitioned into the variance due to changes in vowel identity, consonant identity, and neither (error). When the datapoints are for the V1 and V2, the effect of consonant is the context effect, and the effect of vowel is first removed before calculating the effect of consonant or error. When the datapoints are for the C, the effect of vowel is the context effect, and the effect of consonant is first removed before calculating the effect of vowel or error.

These variances are shown in Table II, where for each of Vowel 1, Consonant, and Vowel 2, the total variance equals the vowel variance plus the consonant variance plus the error variance. It can be seen that the total variance is different for the different subjects, and that the total variance for the Consonant position is on average about half of that for either of the Vowel positions. That is, the consonants are overall less variable than the vowels. However, this might be so for any number of reasons. The key comparisons for our purposes are in the highlighted columns. The first highlighted column shows how much of the variation in Vowel 1 is due to consonant context (mean = 0.48 mm^2). The second highlighted column shows how much of the variation in Consonant is due to vowel context (mean = 2.34 mm^2). The third highlighted column shows how much of the variation in Vowel 2 is due to consonant context (mean = 0.74 mm^2). It can be seen that the middle highlighted column has larger values than either of the other highlighted columns for every

TABLE II. Variances from variance-components model ANOVA analyses of data for each subject, for Vowel 1, Consonant, and Vowel 2 in VCVs. Vowel, consonant, and error variances sum to the total variance for each segment position. Highlighted columns indicate the variance due to segmental context for each segment position

Jaw Height Variance Components (mm^2)													
		Vowel 1				Consonant				Vowel 2			
Lang	Sub	vowel	cons	error	total	vowel	cons	error	total	vowel	cons	error	total
Swed	1	1.16	0.83	0.90	2.89	3.19	1.00	0.42	4.60	2.38	0.83	0.66	3.87
Swed	2	6.56	0.35	1.13	8.05	2.27	0.97	0.40	3.64	7.91	0.55	1.63	10.09
Swed	3	8.40	0.34	0.73	9.47	1.52	0.76	0.50	2.77	2.37	0.55	0.40	3.31
Swed	4	0.31	0.18	1.06	1.54	1.08	0.12	0.84	2.04	1.13	0.42	0.88	2.43
Swed	5	14.42	0.78	1.46	16.66	2.53	4.78	0.65	7.96	22.68	0.94	3.13	26.74
Eng	1	10.52	0.25	1.32	12.09	2.14	0.81	0.31	3.27	7.62	0.91	1.03	9.55
Eng	2	3.42	0.32	1.35	5.09	0.96	0.41	0.26	1.64	1.19	0.44	0.39	2.02
Eng	3	3.25	0.19	1.98	5.42	3.08	0.72	0.68	4.48	2.97	1.04	0.95	4.96
Eng	4	0.99	0.71	0.68	2.39	3.17	0.15	0.46	3.78	0.31	0.66	0.44	1.41
Eng	5	18.82	0.86	1.88	21.56	3.47	3.2	0.30	6.97	8.80	1.07	0.78	10.64
mean		6.79	0.48	1.25	8.52	2.34	1.29	0.48	4.11	5.73	0.74	1.03	7.50

TABLE III. Percentage of variance in all experimental data for each factor contributing more than 5% of the total variance

Factor	Estimated variance component	Proportion accounted for
Segment type (consonant *vs.* vowel)	0.0141	22.2%
Vowel identity	0.009	14.2%
Consonant identity	0.0032	5.1%
Subject (speaker)	0.0039	6.2%
Initial *vs.* final vowel	0.005	7.9%
Subject × vowel × language	0.0033	5.2%

subject. This means that for every subject the absolute variation in jaw height in the Consonant position as a function of vowel context, controlling for C-induced variation, is larger than the variation in either of the Vowel positions as a function of consonant context, controlling for V-induced variation. On average, the vowel-related variance in consonants is over twice as large as the consonant-related variance in vowels. Most strikingly in the table, for vowels the vowel-related variation dwarfs the consonant-related variation, as would be expected, but for consonants the vowel-related variation is also larger than the consonant-related variation. Most of the variation in the vowel measurements is due to the vowels themselves or to "error", whereas most of the variation in the consonant measurements is due to the vowel context. This is seen perhaps more clearly when ratios are formed of vowel-related variance to noise variance, and consonant-related variance to noise variance (*F*-like statistics). For the vowels, initial and final, the consonant-related variance is never significantly above the noise variance, while for the consonants the vowel-related variance is significantly above the noise variance for most subjects.

This same result is presented across all subjects in Table III. In an analysis including a full set of experimental factors, the percentage of variance accounted for by each factor and interaction was computed. Factors which account for more than 5% of the variance in the data are listed in the table. These numbers reflect the amount of variance in jaw height (across segments) accounted for by a factor alone, after all other experimental factors have been accounted for. As this table shows, vowel identity accounts for nearly three times more variance in overall jaw height than does consonant identity. Neither factor alone accounts for a large amount of the variance in this model; however, both amounts are significantly greater than zero. These low values reflect the large number of factors that affect jaw height in speech; enough factors are involved that no one factor accounts for a preponderance of the variance.

2.3. *Summary of results*

This study compared jaw heights in two languages, English and Swedish. The first set of analyses collapsed across subjects but analyzed vowel and consonant measurements separately. For vowels, the two languages were quite similar;

ıctor contributing more

Proportion accounted for
22.2%
14.2%
5.1%
6.2%
7.9%
5.2%

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however, some small differences were seen in connection with the allophonic positional variation in Swedish /e/. For consonants, Swedish consonants are overall slightly more open, but the rank ordering of consonants by height is quite similar in the two languages, with the alveolar obstruents and /f/ higher than other consonants. Overall, then, these language effects are relatively minor—the two languages are generally quite similar with regard to jaw height.

The effect of Consonant Context on vowel height showed only a trend to significance, with vowels tending to be highest when next to alveolar obstruents. In contrast, the effect of Vowel Context on consonant height was robust, with consonants higher when between /i/ vowels than between either of the other two vowels. There was a trend towards differences in consonant height between VCVs, associated with special behavior of /h/ and with the fact that higher consonants are higher in the context of /ɑ/ rather than /i/. In sum, consonants varied reliably in height as a function of vowel context, whereas vowels showed only a statistical tendency to vary in height as a function of consonant context.

The second set of analyses was carried out separately for each subject on vowel and consonant measurements together to assess the contributions of different factors to variance components of the data. For all subjects, consonants are less variable than vowels, but most of the variation in consonants is due to vowel context while little of the variation in vowels is due to consonant context. In absolute terms, the vowel-induced variation in consonants is greater than the consonant-induced variation in vowels.

4. Discussion

4.1. *Relative heights of different consonants and vowels*

The present study is unusual in the number of consonant segments combined with different vowels for which jaw height measurements have been collected for so many speakers. Other researchers have reported data on the relative jaw heights for consonants and/or vowels, but generally for much smaller samples. Perkell (1969) examined several consonants before /ɛ/ for one speaker of English, and found alveolars to have higher maximum displacements than /p/ or /k/. Similarly, Kim (1972) found more displacement from /ɑ/ to /t/ than from /ɑ/ to labial stops in /ɑCɑ/ tokens (that is, presumably /t/ was higher than labials, though heights *per se* are not reported). The consistently high jaw height of /s/ was pointed out also by Amerman *et al.* (1970). Tuller *et al.* (1981) found that /t/ was higher than /f/, which was higher than /p/, which was higher than /k/. Westbury (1988) found that for English oral and nasal stops alveolar stops were highest and velars the lowest at both closure and release of stop occlusion. Perkell also examined several vowels after /t/, and found /u/ the highest (due to lip rounding), followed by other high vowels, then /ɛ/, /ɑ/, and /æ/ lowest of all. Tuller *et al.* found that /u/ was higher than /i/ which was higher than /ɑ/. These results for both consonants and vowels are all consistent with the present data, to the extent that the same segments are examined. However, the present data differ somewhat from our own earlier findings (Lindblom 1983, Keating 1983) on consonant jaw height: with five speakers of each language, and three vowel contexts, we now find /r/ in both languages to have relatively higher jaw positions than reported earlier. The most general finding common to all these studies is that alveolars, especially alveolar obstruents, tend to have high jaw positions. This is not surprising, given that the tongue must be positioned so as to form a constriction directing airflow at the teeth. In our data, and in Tuller *et al.*'s, /f/ also has a fairly high jaw height, presumably due to the requirement of touching the lower lip to the upper teeth and/or forming a narrow constriction between them.

Farnetani and Faber (1992) found that in Italian initial stressed vowels are more open than final unstressed vowels. In our English data, initial vowels are also more open, though they lack strong stress. This finding may be related to the fact that the maximum opening measured as the displacement for V1 generally occurred before the onset of acoustic vowel. In our Swedish data, the effect of position/stress is not consistent across vowels.

4.2. *Context effects on jaw height*

Data has also been previously reported on the effects of context on jaw height for some vowel and consonant segments. With respect to consonants, inspection of Perkell's (1969) figures indicates that /t/ maintained a fairly consistent height across following-vowel contexts. Tuller *et al.* (1981) found that /p/ and /k/ vary with vowel context, but /f/ and /t/ do not. Similarly, Kiritani *et al.* (1983) compared heights for /p, t, k, s/ in different vowel contexts, and found that only /p/ and /k/ varied with context. Jun *et al.* (1991) compared stops before and after different accented and unaccented vowels. They found that initial alveolars varied little, but other consonants, especially velars, were more affected by vowel context. (They noted as well that velars were sometimes lower in height than adjacent vowels. In our data this held for /h, b, l/ as well as /k/.) Thus, across studies, it seems that alveolar obstruents and /f/ vary less according to vowel context than do other consonants. Our results are similar, with /s, t, n/ the least affected by vowel context, but in our data /f/ is more variable than these.

With respect to vowels, Perkell's figures indicate that jaw height for /ε/ varied greatly across the different preceding-consonant environments. Abbs, Netsell & Hixon (1972) found that in CVC, /æ/ was lower when surrounded by /p/ or /k/ than by /t/. Imagawa, Kiritani, Masaki & Shirai (1985) found that high vowels /i/ and /u/ vary much less across contexts than do non-high vowels /e/ and /ɑ/. They also found that vowels were higher adjacent to /s/ or /t/ than to /p/ or /k/. Westbury (1988) found that his lowest token of /ɑ/ occurred between labials and his highest between /t/ and /g/. On the other hand, Farnetani and Faber (1992) found no effect of different intervocalic consonants on vowel height in Italian. Tuller *et al.* (1981) found that consonants affected only the second vowel in VCVs, though not consistently; vowels were higher after /f/ than after /t, p, k/. Imagawa *et al.* (1985) also found that vowels have higher jaw positions in CVCs than they do in isolation, much as Farnetani and Faber (1992) found in comparing VCV with CVCV. Thus, across studies, it seems that lower vowels vary more than higher ones, and vowels are higher adjacent to alveolars and /f/ than to other consonants. Although similar trends can be seen in our results, none reached statistical significance.

Sussman, MacNeilage & Hanson (1973) combined three vowels and three bilabial stops in VCV utterances, and measured changes in jaw height from segment to segment (i.e. not absolute height), so their results are difficult to compare with ours.

Finally, Imagawa *et al.* (1985) found that vowels /a/ and /e/ were more variable in frames which also contained /a/ vowels than in frames which also contained /i/ vowels. This finding was due to a result also found in our study—the consonants which are highest on average (/s, t, d, f/) are actually higher in /a/ contexts than in /i/ contexts. In Imagawa *et al.*'s test items, the higher /s/ or /t/ carried over into higher /a/ or /e/, resulting in greater overall variability of /a/ and /e/ in /a/ contexts. The fact that consonants with high jaw position are higher in low-jaw contexts than in high-jaw contexts seems paradoxial, but Imagawa *et al.* relate it to the high velocity used to travel from a low to a high position. In effect, the high velocity caused the jaw to overshoot the usual high height for /t/ or /s/. The same may be true of our data, though we did not measure velocity to test this possibility.

Our results on overall variability can be related to a finding of Crystal and House (1988): longer segments are overall more variable, and vowels are overall both longer and more variable than consonants. This generalization is likely true of jaw height in our data: the vowels, which are presumably longer, are more open (by about 3 mm average) and more variable overall. But little of this variation can be attributed to consonant context. This is so even though there are more consonants to influence the vowels than there are vowels to influence the consonants, and the average consonant displacements cover an overall larger range of values. Just from these sheer numbers, we might have expected the consonants to make the vowels highly variable, but this is not the case.

4.3. *Lindblom and Keating*

The disagreement between Lindblom (1983) and Keating (1983) centers around the issue of whether consonants or vowels are more variable as a function of their segmental context. If consonants are more variable as a function of context, it makes sense to view consonants as accommodating to contextual vowels, whereas if vowels are more variable, then the accommodation is in the reverse direction. In our present joint study, the clear pattern emerges that the effect of vowels on consonants is much greater than the effect of consonants on vowels. This pattern holds for all speakers in both languages. Overall, though not for every speaker, the effect of vowel on consonant is highly significant while the effect of consonant on vowel is not. These results support Lindblom's proposal that consonants may accommodate their jaw heights to those of neighboring vowels. The results also weakly support his proposal that consonants differ in their propensity to coarticulate, with alveolar consonants showing less effect of vowel context and /h/ the most.

As noted above, the distinction between overall variability and variability attributable to context is crucial in understanding the difference between consonant and vowel effects on jaw height. The points about variability made by Keating can now be seen to refer to the greater overall variability of vowels as compared to consonants. Lindblom's proposal is supported by the results on variability attributable to segmental context.

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