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特集論文

Quantifying the Effects of Vowel Quality and Preceding Consonants on Jaw Displacement: Japanese Data

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母音と子音の下顎運動への影響の数量化―日本語を通して

要旨：本研究では，日本語の下顎の開き具合がどのような音声要因によって決定されるかを検証した。EMA を用いた調音実験を用い，日本語話者の様々な CV モーラの発音時の顎の動きを測定した。結果として，母音では /a/ > /e/ > /o/ > /i/ > /u/ という順番で顎の開きが大きいことが判明した。この結果から母音の高さ，前後性ともに顎の動きに影響するという結論を得た。顎の動きの大きさを，過去の日本語の音響研究と照合すると，F1 と多少の相関があるが，母音長と最も強く相関することがわかった。また子音による顎の動きの阻害（inhibition）も観察された。子音による阻害は舌先音（coronal）でもっとも強く見られ，これは他の同時調音（coarticulation）に関する実験とも整合性がある。

Key words: vowel height, vowel backness, jaw displacement, consonants, Japanese, EMA

1. Introduction

Every student in an introductory phonetics class will learn that vowel height affects the opening of mouth, that vowels like /a/ and /æ/ are open, and vowels like /i/ and /u/ are closed. Low vowels are sometimes referred to as “open vowels”, whereas high vowels are referred to as “closed vowels” (see e.g. Clements and Hume 1995: 282–283). Indeed these are the labels deployed by the current International Phonetic Alphabet (IPA) system.

Less obvious, however, is exactly how much—i.e. how many millimeters—vowel height affects the opening of the mouth. The primary purpose of this research note is to answer this question, by offering exact quantitative measures of the five Japanese vowels, which would be useful for further phonetic research on Japanese, and we hope, phonetic research in general.

Even less obvious than the effect of vowel height is whether or not vowel backness affects the opening of the mouth, just like vowel height. The phonological literature assumes, more or less, that vowels of the same height involve the same amount of mouth opening (either at the abstract phonological level or at the phonetic implementation level)[1]. However, this issue should be investigated with an empirical method rather than being taken for granted, and we take up this issue, again using Japanese as the target language.

The third issue that is tested in this report is whether surrounding consonants affect jaw displacement patterns in substantial ways through coarticulation. This issue was recently addressed for Catalan by Recasens (2012), where certain consonants were found to be more resistant to coarticulation than others in terms of jaw displacement. We report the Japanese data in this regard.

In summary, we use jaw opening to investigate how vowel quality—both vowel height and backness—and preceding consonants affect Japanese speakers’ articulation of their jaw. A general theme that is pursued in this research is that jaw displacement provides a good quantifiable measure of articulatory patterns. This thesis is not new: jaw displacement patterns have been studied in this light for languages like Arabic, Korean and French (Lee 1994), Catalan (Recasens 2012), and English and Swedish (Keating et al. 1994). A series of recent work by Donna Erickson and her colleagues has

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pursued the same issue in English (Erickson et al. 2012, 2014b), and the current paper can be understood as a sister-piece to that project.

Overall the general purpose of this report is rather modest; in essence, we attempt to offer quantified measures of various phonetic effects on jaw displacement in Japanese, which would be useful for future phonetic work. Before delving into the main discussion, we also admit one fundamental limitation of this study: one would probably be interested in the correlation between the jaw displacement patterns and their acoustic realizations—we certainly are. The acoustic analyses of the current results are in progress. Due to time and space limitation, however, we cannot report them in this paper. When necessary, therefore, we resort to previous acoustic work in Japanese.

2. Method

This study was conducted as a part of a larger project that investigates how various phonetic and phonological factors affect the patterns of jaw displacement in Japanese, both in their L1 and L2 speech (Erickson et al. 2014b, Kawahara et al. 2014). This research used a 3D EMA (ElectroMagnetic Articulograph, Carstens AG500), hosted in the Japan Advanced Institute of Science and Technology (JAIST), to measure the degree of jaw displacement for investigating these effects. For further details of the current methodology, see Erickson et al. (2012, 2014b) and Kawahara et al. (2014).

2.1 Stimuli

The stimuli for the current study, mixed with the stimuli for other studies (in particular that of Kawahara et al. 2014), consist of a subset of Japanese syllabaries, shown in (1). This set was intended to include all types of major place articulation (/p/ = labial, /t, n/ = coronal, /k/ = dorsal, /h/ = pharyngeal)2). /n/ was included in addition to /t/, because /t/ is affricated in front of high vowels in Japanese (Vance 2008), and may induce unexpected complications. This paradigm, upon hindsight, does not allow us to examine the effect of voicing or manner (except for /n/ vs. /t/), which must be left for future research.

(1) Stimuli of the experiment

a	i	u	e	o
あ	い	う	え	お
ka	ki	ku	ke	ko
か	き	く	け	こ
ta	tʃi	tsu	te	to
た	ち	つ	て	と
na	ni	nu	ne	no
な	に	ぬ	ね	の
ha	hi	hu	he	ho
は	ひ	ふ	へ	ほ
pa	pi	pu	pe	po
ぱ	ぴ	ぷ	ぺ	ぽ

It turned out that one of the speakers (J08; see below) found reading [ta, tʃi, tsu, te, to] in various different orders too hard, and therefore she did not read these five syllabaries3).

To control for—and study—the effect of reading order, for each CV combination, the current stimulus set contained the following five orders for each of the five CV combinations, exemplified in (2). For each line, the initial vowel at the end was repeated to avoid the effect of sentence-final stress (Kawahara et al. 2014). However, upon examination of the obtained data, no effect of the final stress (see section 3.3 below) was observed; therefore, all data are included in the analysis.

(2) Five different ordering patterns (applied for all the syllabaries)

Order 1:	a	i	u	e	o	a
Order 2:	i	u	e	o	a	i
Order 3:	u	e	o	a	i	u
Order 4:	e	o	a	i	u	e
Order 5:	o	a	i	u	e	o

Each CV combination was read six times in total by both speakers.

2.2 Speakers

One male (J07) and one female (J08) speaker participated in this study. Speaker J07 is a native speaker of Tokyo Japanese4). Speaker J08 is from Kanazawa Japan.

2.3 Procedure

In order to track jaw motion, one sensor was placed on the lower medial incisors, and four additional sensors were used as references to correct for head movement. The occlusal plane was estimated using a biteplate with three additional sensors. The articulatory and acoustic data were digitized at sampling rates of 200 Hz and 16 kHz, respectively. In post-processing, the articulatory data were rotated to the occlusal plane and corrected for head movement using the reference sensors after low-pass filtering at 20 Hz.

The stimuli, together with stimuli for other experiments, were presented in a randomized order on a Powerpoint screen in front of the speaker. The speakers were instructed to put a pause between each syllabary, especially for the vowel-only sequences, in order to make the segmentation possible in the subsequent analyses.

Custom software (mview, Haskins Laboratories) was used to analyze the data. The lowest vertical position (maximum displacement) of the jaw with respect to the biteplane was located for each target syllable of each utterance using the snapex tool in mview.

3. Results and discussion

3.1 Vowel quality effect

3.1.1 The data and statistical analyses

The first two figures, Figures 1 and 2, show the effect of vowel quality, abstracting away the effects of preceding consonants and reading order. In this paper, in illustrative figures here and throughout, error bars represent 95% confidence intervals.

The order observed of jaw displacement for both speakers is: /a/ > /e/ > /o/ > /i/ > /u/. Low vowels show the largest jaw opening; mid vowels next; and high vowels the smallest. This is the same order that is found for American English vowels (Williams et al. 2013). Within pairs of the same height, front vowels show larger jaw opening than back vowels. Again, the same is seen for American English vowels (Williams et al. 2013).

To assess these observations statistically, degrees of jaw displacements were regressed against a model with vowel height and backness as independent variables, using lm function of R (R Core Development Team 1993–2014). /a, o, u/ were coded as [+back], whereas /i, e/ were coded as [–back]; /i, u/ were coded as having level 1 height, /e, o/ having level 2 height, and /a/ having level 3 height. For both speakers, both height effects and backness effects were significant, as shown in Table 1.

We thus conclude that, as with many other languages, vowel height affects degrees of jaw opening. In addition, vowel backness affects jaw displacement in such a way that front vowels involve more opening than back vowels. Note also, however, that the coefficient estimates—estimate of how many mms each factor affects jaw opening—are larger for height than for backness, for both speakers.

Since the actual exact average values may be of some important for future research, we provide them in Table 2[5].

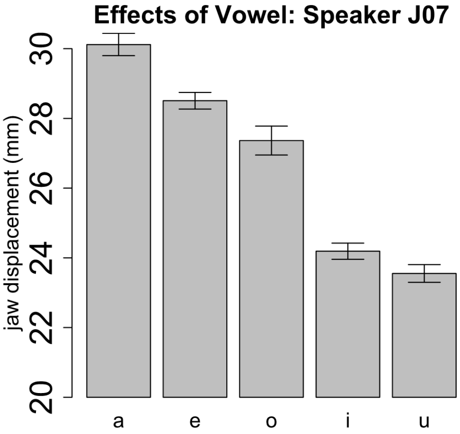

Figure 1 The effects of vowel quality on jaw displacement for Speaker J07. The error bars here and throughout represent 95% confidence intervals.

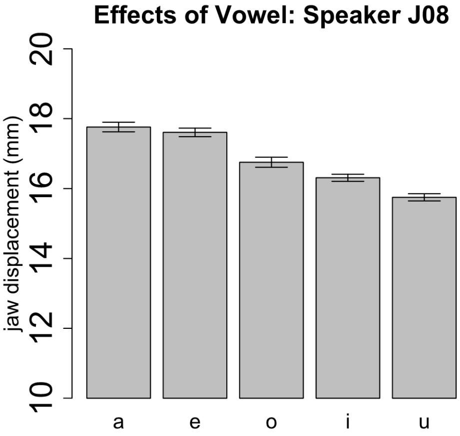

Figure 2 The effects of vowel quality on jaw displacement for Speaker J08.

Table 1 Results of linear regression.

Speaker J07

	Estimate	St. Err	t-value	p-value
(Intercept)	18.96325	0.32213	58.868	<2e-16***
Height	3.48813	0.09714	35.910	<2e-16***
Backness	1.06964	0.14937	7.161	1.39e-12***

Speaker J08

	Estimate	St. Err	t-value	p-value
(Intercept)	13.89268	0.13052	106.44	<2e-16***
Height	1.06470	0.03951	26.95	<2e-16***
Backness	0.73294	0.06056	12.10	<2e-16***

Table 2 Actual jaw displacement average values for the two speakers (mm).

	a	e	o	i	u
Speaker J07	30.12	28.51	27.36	24.19	23.55
Speaker J08	17.76	17.61	16.75	16.31	15.75

3.1.2 Correlation between jaw opening and F1

Previous studies have found a positive correlation between F1 and the amount of jaw opening (Erickson et al. 2012, 2014b), because more oral constriction results in lower F1 in general (Stevens 1998). To address the correlation between jaw opening and F1, we obtained F1 values for the five Japanese vowels from the three previous acoustic studies on Japanese: Hirahara and Kato (1992), Keating and Huffman (1984), and Nishi et al. (2008). The data are summarized in Table 3. Analysis of data from our study is forthcoming.

These studies show that vowel height indeed affects F1, confirming the expectation that more opening of the jaw results in higher F1. However, jaw opening differences within the same height are not necessarily reflected in F1 in the expected way: F1 is not substantially higher for /e/ than for /o/, or for /i/ than for /u/—for the latter pair, we observe a consistent reversal in all three acoustic studies. Articulatorily speaking, the jaw is more closed for /u/ than /i/, but F1 is higher for /u/ than /i/.

The discrepancy between the jaw displacement patterns and F1 presumably comes out for the following reason. Helmholtz resonation, which is responsible for F1 (at least for high vowels), is affected by many factors, such as area and length of the back tube, as shown in (3) (Johnson 2003: 106–107).

(3) Helmholtz resonation

$$f = \frac{c}{2\pi}\sqrt{\frac{A_c}{A_b l_b l_c}}$$

where A = area; l = length; X_b *= back tube;* X_c *= constriction tube*

The Helmholtz resonation is inversely correlated with the length of the back cavity (l_b), which is longer for /i/ than /u/, because /i/ is a front vowel.

Jaw opening is unlikely to be the only factor determining the constriction area (A_c). For example, the tongue tip can also be raised for /i/, independent of jaw lowering, which would result in lower F1; and/or the tongue body may not be raised as much for /u/, which would result in higher F1. In short, jaw displacement is one factor determining F1, but not the only factor. We in fact have recorded tongue movement in our EMA recordings in addition to acoustic data, which would allow us to quantitatively assess this hypothesis. This task however is left for future research.

Table 3 F1 values of the five Japanese vowels from previous acoustic studies (Hz).

	a	e	o	i	u
H&K	750	469	468	281	312
K&H	631	475	481	359	405
Nishi et al.	615	437	430	317	349

3.1.3 Correlation between jaw opening and duration for the five vowels

Next, we look at the correlation between jaw opening and duration for the five Japanese vowels. The results from the previous studies on the durational differences between the five Japanese vowels are shown in Table 4. The studies (almost) always show the order of /a/ > /e/ > /o/ > /i/ > /u/, a complete positive correlation with the degree of jaw opening.

In short, there is a straightforward relationship between jaw opening and duration for each vowel, in such a way that a vowel with a more open jaw is longer. Tentatively, we conclude that in Japanese at least, (acoustic)[6] duration is a better acoustic correlate than F1 for jaw movement.

In this regard, our result raises a promising line for future cross-linguistic studies. Although the effect of duration of vowel height is (most likely) universal, the effect of backness on duration varies cross-linguistically; i.e., it is not always the case, as in Japanese, that back vowels are shorter than front vowels. It would be interesting to investigate whether such longer back vowels show larger jaw displacement patterns; i.e. whether the correlation between duration and jaw displacement holds universally.

3.2 Effects of consonants

Next, we discuss the effects of preceding consonants, first for Speaker J07 and then for Speaker J08. Consider Figure 3 first.

For Speaker J07, jaw opens the most without preceding consonants (the left most bar). The rest follows the order of /h/ > /k/ > /p/ > /n/ > /t/.

No one to our knowledge, other than Recasens (2012), has explicitly examined the effect of syllable onset on the amount of jaw displacement of the vocalic nucleus. What follows here is an interpretation of our data, based primarily on previous work about conso-

Table 4 The results of the previous studies on the duration of each of the five Japanese vowels. They all show the order of /a/ > /e/ > /o/ > /i/ > /u/, except the order between /e/ and /a/ in Arai et al. (2002).

Sources	/a/	/e/	/o/	/i/	/u/	Notes
Han 1962	1.44	1.37	1.26	1.17	1.00	Ratios with respect to /u/. Lab speech based on ca. 300 tokens.
Sagisaka 1985 (see also Sagisaka and Tohkura 1984)	99	93	88	70	62	In ms. Real words with a frame phrase or a frame sentence. 310 tokens. One male speaker.
	86	79	71	61	58	In ms. Durations of V_2 in a nonce-word frame: amV_1CV_2 *mari*. 310 tokens.
Campbell 1992	83.7	80.0	77.7	69.8	58.3	In ms. Lab speech by a professional broadcaster. 10,196 sentences taken from newspapers and magazines.
Arai et al. 2001	82.3	85.7	75.4	67.5	56.8	In ms. Natural speech taken from telephone conversion. N: /u/ = 447, /i/ = 1022, /o/ = 1196, /e/ = 848, /a/ = 1855.

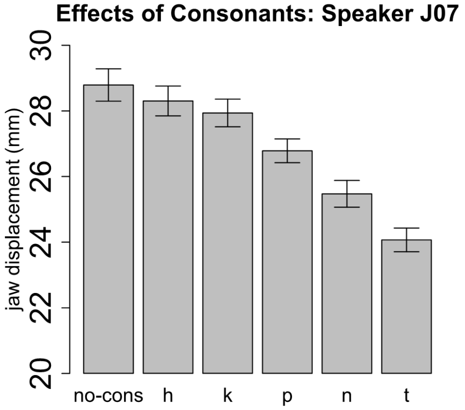

Figure 3 The effects of the preceding consonants for all vowels on jaw displacement patterns, Speaker J07. "no-cons" represents onsetless syllables (=no consonants).

nants on tongue articulation during production of vocalic nuclei, as well as previous work on differences between different consonants in coarticulation in terms of tongue movement. We note that these studies, except for Recasens, are primarily concerned with F2 and tongue rather than F1 and jaw, so the comparison needs to be taken with caution.

Since consonants in general inhibit jaw opening, we would expect that onsetless syllables should show the largest jaw opening, as was found in our data (the leftmost bar). /h/ would inhibit jaw opening the least, because /h/ does not involve any supralaryngeal constriction, arguably acquiring its place of articulation from the following vowel (Keating 1988, Pierehumbert and Talkin 1992). Tongue articulation during vocalic nuclei is not substantially affected by dorsal consonants (e.g. Iskarous et al. 2010, Sussman, McCaffrey and Matthews 1991)7) nor probably by labial consonants.

On the other hand, coronal consonants, which our data show inhibit jaw opening the most (Figure 3), are the consonants known to change the tongue articulation of vowels (Iskarous et al. 2010, Sussman et al. 1991). The fact that the two coronal consonants in our data inhibit the jaw opening the most (Figure 3) accords well with the above observations. However, as mentioned above, no work has been done about the effect of consonants on jaw displacement; our future work will examine both tongue and jaw articulation during production of the syllable nucleus as a function of initial consonants.

As regards the difference between /t/ and /n/, one possibility is that since /t/ causes affrication before high vowels in Japanese, high vowels coarticulate in terms of tongue displacement more with /t/ than with /n/. Alternatively, it may be the case that since the vowel quality of the high vowels can be inferred from the phonetic realizations of /t/ ([tʃ] before /i/ and [ts] before /u/: Vance 2008) in Japanese, speakers can be "sloppy" about high vowel articulation after /t/. These hypotheses predict differences between /t/ and /n/ only before high vowels, not before non-high vowels. Figure 4 addresses this prediction.

Although the difference between /t/ and /n/ is slightly larger before high vowels, the prediction is only partially correct, since we do observe a robust difference before non-high vowels as well.

Michinao Matsui (p.c.) pointed out an interesting alternative: Japanese vowels are shorter after voiceless consonants than after voiced ones (Port, Al-Ani and Maeda 1980, Sagisaka and Tohkura 1984). Therefore, speakers may have less time to implement jaw dis-

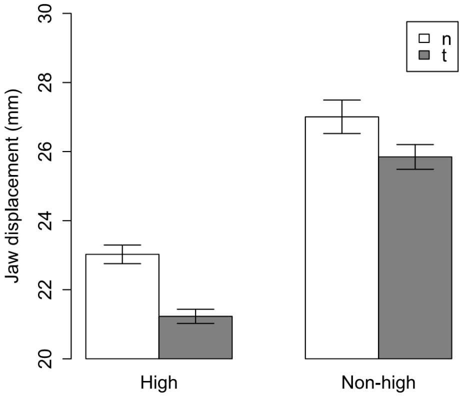

Figure 4 Comparing /t/ and /n/ before high and nonhigh vowel environments, Speaker J07.

Figure 6 The effects of position, Speaker J07.

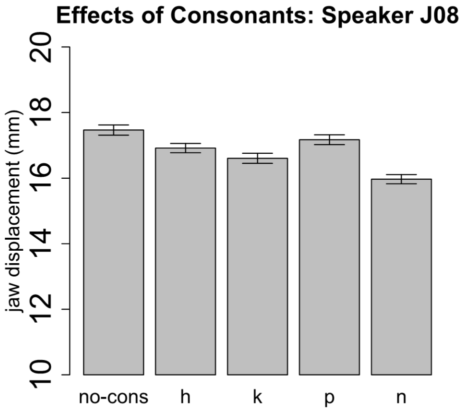

Figure 5 The effects of the preceding consonants on jaw displacement patterns, Speaker J08. "no-cons" represents onsetless syllables (=no consonants).

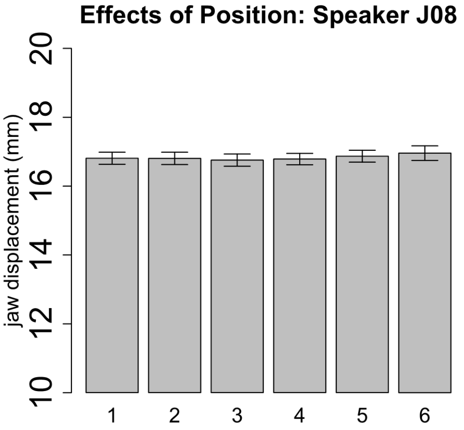

Figure 7 The effects of position, Speaker J08.

placement after voiceless consonants than after voiced ones. This hypothesis can be tested against pairs like /k/-/g/ and /p/-/b/, which were not unfortunately included in the current dataset. A final possible explanation is the difference in sonorancy: in an experiment using reiterant speech, Vatikiotis-Bateson and Kelso (1993: 240) found that their kinematic measures were larger in /ma/-speech than /ba/-speech; it is possible then that obstruents inhibit vowel production more than sonorants do. These possibilities need to be addressed in future studies.

Figure 5 shows the pattern of Speaker J08. As observed, the general patterning is very similar to that of Speaker J07. Jaw opens the most without a preceding consonant; and /h/ and /k/ follow. /n/, the coronal consonant, inhibits jaw opening the most (recall that this speaker did not produce /t/). What is different from Speaker J07 is that /p/ inhibits jaw opening less than /k/ or /h/. This speaker may have more independent articulatory control between the lips and the jaw than Speaker J07.

3.3 Position

Finally, we look at the effects of the positions of the vowel within each syllabary line. Figures 6 and 7 show the effect of reading orders, averaging over vowel qualities and consonant effects.

Unlike other previous studies of ours (Erickson et al. 2014b, Kawahara et al. 2014), we did not observe consistent effect of position, except that we see very small, non-significant large jaw opening in initial and final position for Speaker J07 (A regression analysis with only position as an independent variable did not yield a significant effect: *t* (1210) = 0.07, *n.s.*).

Other studies of ours on the jaw displacement pattern of Japanese found large jaw opening at the end of sentences, both in L1 speech (when reading Japanese sentences) and L2 speech (when they are reading English sentences) (Erickson et al. 2014b, Kawahara et al. 2014). There are two possible reasons for this lack of final prominence. First, the stimuli were essentially sequences of meaningless syllables, so they were not assigned rhymes, which would be otherwise imposed upon more meaningful speech. Second, recall that the speakers put a pause between each syllable, and therefore, each syllable may have been phrased as a separate phrase.

3.4 Summary

By way of summary, we provide the results of multiple linear regression with vowel quality, preceding consonant quality, and position in the utterance as independent variables, and jaw displacement as dependent variables (Tables 5 and 6). The baseline for the vowel quality was set to be /a/; the baseline for the consonant effects was set to be onsetless syllables.

These regression analyses show that for both speakers, [a] has the largest jaw opening. Every other vowel has a negative coefficient, indicating how much lower each vowel is compared to [a]. Likewise for consonants, the jaw opens the most when there are no consonants. The negative estimates given show how much each consonant inhibit jaw opening.

We conjecture that these coefficient estimates can be used to “wash away” the vowel quality effects when studying jaw displacement patterns of sentences with different vowel qualities. This sort of research strategy

Table 5　Results of the multi-linear regression, Speaker J07.

	Estimate	Std. Er	t-value	p-value
(Intercept)	32.26015	0.17486	184.490	<2e-16***
Vowel: baseline = /a/				
/e/	–1.60464	0.14405	–11.140	<2e-16***
/o/	–2.78799	0.14294	–19.505	<2e-16***
/i/	–6.00179	0.14167	–42.364	<2e-16***
/u/	–6.60143	0.14294	–46.184	<2e-16***
Position	–0.02107	0.02653	–0.794	0.42717
Consonant: baseline = vowel-initial				
/h/	–0.48500	0.16623	–2.918	0.00359**
/k/	–0.71658	0.15825	–4.528	6.54e-06***
/p/	–2.00500	0.16623	–12.061	<2e-16***
/n/	–3.32054	0.16362	–20.295	<2e-16***
/t/	–4.76008	0.15316	–31.079	<2e-16***

Multiple R-squared: 0.7939, Adjusted R-squared: 0.7922.

Table 6　Results of a multiple linear regression, Speaker J08.

	Estimate	Std. Er	t-value	p-value
(Intercept)	18.30847	0.08198	223.330	<2e-16***
Vowel: baseline = /a/				
/e/	–0.16007	0.07148	–2.239	0.0254*
/o/	–1.00794	0.07087	–14.222	<2e-16***
/i/	–1.44474	0.07034	–20.541	<2e-16***
/u/	–2.01237	0.07087	–28.394	<2e-16***
Position	0.02394	0.01312	1.824	0.0685
Consonant: baseline = vowel-initial				
/h/	–0.55056	0.06942	–7.930	6.31e-15***
/k/	–0.82051	0.07208	–11.383	<2e-16***
/n/	–1.49833	0.07204	–20.797	<2e-16***
/p/	–0.29667	0.07204	–4.118	4.17e-05***

Multiple R-squared: 0.644, Adjusted R-squared: 0.6405.

is proposed by Williams et al. (2013) using average values (which are provided in Table 2), an algorithm which is referred to as "vowel neutralization algorithm". The coefficient estimates are probably as useful if not more useful as average values.

4. Conclusion

The research aimed here was rather modest and exploratory; we wanted to explore how various factors affect jaw displacement patterns in Japanese. We observed substantial effect of vowel quality and preceding consonants. Our aim was not only to provide general patterns, but to offer concrete numerical values which can be deployed in future phonetic and phonological investigation of Japanese. It goes without saying that more speakers need to be recorded and analyzed in order to generalize the current findings. As stated above, the acoustic analyses of the current results are in progress, and will be compared in detail with the articulatory patterns.

Acknowledgments

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Notes

1) Work on phonological sonority, whose one alleged phonetic correlate is the "openness of the mouth" (see Parker 2002: Chapter 2, especially Tables 2.1 and 2.2), usually treats vowels of the same height as having the same sonority (see Parker 2002: 27 for references cited therein). Indeed, for example, when sonority differences matter for the computation of stress placement (de Lacy 2002: 55), backness seems irrelevant.

2) /h/ is termed "pharyngeal" in this paper, even though it becomes supraglottally articulated before high vowels.

3) Indeed, these five moras, when presented in several orders as in (2), are almost like a tongue twister. This sequence was particularly hard when speaking with sensors in the mouth.

4) This speaker is the first author of this report. If this were a better world, we would only obtain data from those speakers who are naive to the purpose of the experiment. However, since this study is exploratory without much prior expectation, and since it is not trivial to find speakers who are willing to speak for hours with EMA sensors in their mouth, we assume that this use of our own speech provides an acceptable start of this research program. We also assume that a speaker cannot consciously control details of jaw displacements.

5) For American English vowels, there is an approximately 2mm difference between high, mid and low vowels (Menezes and Erickson 2013, Williams et al. 2013). Speaker J07 shows a similar amount of differences for each vowel height, whereas Speaker J08's differences are much more modest.

6) Acoustic duration may not be identical to articulatory duration. See Erickson et al. (2014a) for details.

7) In these works, differences in slope in the locus equation were considered to reflect the resistance of coarticulation for different places of articulation (e.g. Iskarous et al. 2010, Sussman et al. 1991). We repeat, however, that locus equations are based on F2 measurements rather than F1 values. Moreover, these locus equations are calculated based on the production of English speakers, not based on Japanese data (cf. Sussman et al. 1993). We thus would like to explore more in the future how coarticulation differences manifest themselves in jaw movement and tongue body gestures, and how languages may or may not differ in this respect.

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