A quantitative study of jaw opening: An EMA study of Japanese vowels*

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Abstract

One traditional parameter that is used to distinguish vowels is "openness", which is sometimes alternatively expressed as "vowel height". The openness parameter is used in the current IPA system, in which vowels are classified into four categories: "close" vs. "close-mid" vs. "open-mid" vs. "open". In order to quantitatively examine this concept of openness in detail, the current paper presents an articulatory study using EMA (ElectroMagnetic Articulograph) with Japanese as the target language. The main aim of this experiment is to provide exact measures of the amount of jaw opening of the five vowels in Japanese, and to investigate how the results would bear on the abstract concept of vowel openness. Our results show that while the traditional labeling of openness is more or less correct, we also observe that between the vowels of the same openness, front vowels are more open than back vowels (e.g. [e] is more open than [o]). Our results thus provide some information that goes beyond what the current IPA description of Japanese offers (Okada, 1999). We also examine the acoustic correlates of vowel openness, and compare them to jaw opening patterns. The result shows that, unsurprisingly, F1 is the most reliable correlate of vowel openness, but that other secondary cues, such as duration, F0, and intensity, are not very reliable, at least when measured in our task format.

Keywords: vowels, jaw opening, IPA, F1, Japanese

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1 Introduction

Narrowly construed, this paper offers new phonetic data concerning Japanese vowels: i.e., "exactly how many millimeters does the jaw open for each of the five vowels in Japanese?". When broadly construed, this paper is a case study of how the abstract notion of openness is mapped onto our actual articulatory gesture.

One standard in the phonetics theory/description is that vowels are distinguished in terms of openness of the mouth. Some researchers instead describe the same abstract distinction using the notion of vowel height, but the current IPA system deploys openness.[1] More specifically, the vowel IPA chart, reproduced in Figure 1, characterizes vowels in terms of how open the mouth is: from the top, "close" vs "close-mid" vs. "open-mid" vs. "open".

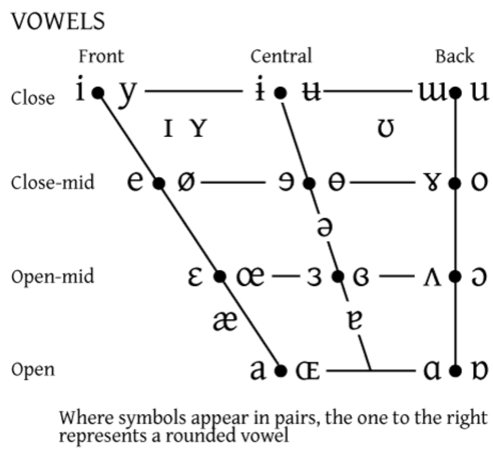

Figure 1: The current IPA chart for the vowels in human languages.

Of course this characterization of vowels in terms of openness involves some idealization,[2] but what is implied in this vowel chart is that vowels of the same openness involve the same amount of openness, regardless of backness (e.g. [e] and [o] involve the same amount of openness; the same holds true for [i] and [u]). It is this thesis of the IPA that the current paper examines, using EMA (ElectroMagnetic Articulograph) as an experimental technique and Japanese as the target language. Concretely, this paper reports an EMA experiment,

[1]Whether this distinction should be phonologically represented with [high/low] features or [close/open] features is also debated (Chomsky & Halle, 1968; Clements, 1991; Clements & Hume, 1995). Phonetically speaking, since jaw and tongue are physiologically connected, the movements of the two articulators are substantially correlated with each other. Therefore, it is difficult to decide which articulator is the point of comparison. See, for example, Lindblom & Sundberg (1971).

[2]Ladefoged (2006) is quite explicit that phonetic symbols involve some level of abstraction, and that phonetic labels represent acoustic dimensions rather than actual articulatory patterns. We thus hasten to add that we are not attempting to challenge this tradition, and we fully acknowledge that the IPA chart, including that of Okada (1999) on Japanese, may as well be acoustic-based rather than articulation-based. Nevertheless, we believe that having actual articulatory data is a valuable resource for phonetic research.

which allows us to measure the exact amount of jaw opening, for each of the five vowels found in Japanese.

Now zooming in on to Japanese, the IPA vowel chart of Japanese in the IPA handbook (Okada, 1999) actually does not assume that vowels of the same openness involve exactly the same amount of openness. As shown in Figure 2, [i] is more closed than [u], and [e] is less closed than [o]. We examine these characteristics with actual experimentation in this paper.

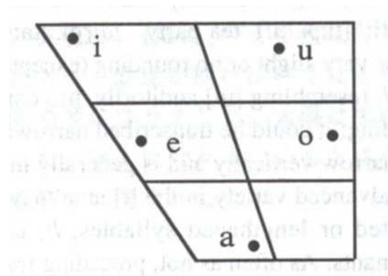

Figure 2: The IPA vowel chart of Japanese. Taken from Okada (1999: 117).

In addition, we offer some cross-linguistic data from English as well. An earlier study on English jaw opening for different vowels, though based on the data of a single speaker, shows that at least in some phrasal environments, within a pair vowels of the same openness, back vowels tend to be less open (Menezes & Erickson, 2013; Williams et al., 2013). Would we expect the same kind of pattern in Japanese?

While our main concern is the articulation of vowel openness, we also examined the acoustic correlates of vowel openness. The target acoustic measures that this study examined are listed in (1). Justification of our choice follows just below.

(1) Acoustic correlates of vowel openness

a. The more open the vowel is, the higher the F1 is.
b. The more open the vowel is, the lower the F0 is.
c. The more open the vowel is, the louder it is.
d. The more open the vowel is, the longer it is.

Regarding (1)a, the primary acoustic correlate of vowel openness is F1 (Erickson et al., 2012; Johnson, 2003; Stevens, 1998). The Helmholtz resonation, which is responsible for F1, positively correlates with the area function of the Helmholtz resonator, as given in the equation (1) (adapted from Johnson 2003). A_c, which is the numerator of the equation (1), is larger for more open vowels, resulting in higher F1. In fact, when phoneticians plot an acoustic vowel space, F1 is usually used as the correlate for vowel openness.[3]

$$f = \frac{c}{2\pi}\sqrt{\frac{A_c}{A_b l_b l_c}} \tag{1}$$

(where c is the speed of sound, A is the area function, l is the length, $_c$ is the constricted tube, $_b$ is the tube behind the constriction)

Other acoustic cues are known to correlate with vowel openness. For example, F0 is higher for higher—or more closed—vowels (Diehl & Kluender, 1989; Gandour & Weinberg, 1980; Honda & Fujimura, 1991; Maddieson, 1997). Intensity has been thought to be an acoustic correlate of sonority, where more open vowels are more sonorous (Parker, 2002, 2008). Parker (2002: 111) cites many studies which have found the correlation between sonority and intensity level, some of which include vowels of different openness. Parker (2002) himself, however, did not find this correlation between intensity and vowel openness either in English or Spanish. This inconsistency may come from the fact that on the one hand, the more open the mouth is, the less energy is trapped in the mouth (see Schulman 1989); on the other hand, lower F1—characteristics of closed vowels—results in higher intensity (Stevens, 1998).

Finally, the more open vowel is usually longer (Campbell, 1992; Lehiste, 1970; Keating, 1985; Sagisaka & Tohkura, 1984), because the more open the jaw is, the more time it takes to implement that articulatory movement. Our acoustic study is intended to test these acoustic correlates of vowel openness, summarized in (1). For previous acoustic analyses of Japanese vowels, which deal with other acoustic features including higher formant values, see Chiba & Kajiyama (1941), Hirahara & Kato (1992), Hirahara & Akahane-Yamada (2004), Keating & Huffman (1984), and Nishi et al. (2008), among others.

2 Method

2.1 EMA

This study made use of 3D EMA, which allows us to obtain exact quantitative measurements of the articulatory movements. What this paper focuses on is the jaw displacement—the distance between the bite plane and the lower incisor. We take jaw opening as the most direct correlate of vowel openness. We acknowledge that, as summarized in Kingston (1992), jaw opening is not the only relevant articulatory measure that relates to the abstract parameter

[3] Perceptually speaking, it may be the distance between F1 and F0 that determines the vowel openness (Diehl & Kluender, 1989; Kingston, 1992; Syrdal & Gopal, 1986). Since more open vowels with higher F1 show lower F0, this value—F1-F0—becomes higher.

of vocalic openness: closed vowels are produced with a more advanced tongue root, a higher soft palate, and more intruded lips (see p.100 for a summary and references cited therein). Nevertheless, we take jaw opening as the most direct measure of vowel openness. For work addressing general significance of jaw opening as a phonetic measure, see de Jong (1995), Erickson et al. (1998), Erickson (1998), Keating et al. (1994), Menezes et al. (2003), Recasens (2012), Vatikiotis-Bateson & Kelso (1993) among others.

The current experiment used Carstens AG500, hosted at Japan Advanced Institute of Science and Technology (JAIST), Ishikawa, Japan. The crucial target sensor was placed on the lower incisor of the speakers. Four additional sensors were attached to the speakers in order to correct for the head movement during recording. The distance between the bite plane and the lower incisor was calculated, as quantitative measure of mouth opening.[4]

2.2 Speakers

The participants were five native speakers of Japanese, coded as J07, J08, J09, J10, and J11 in this paper.[5] Speaker J07 is the first author of this paper (male), whose data we may have to interpret with caution. Speakers J08-11 were all female speakers, and none was aware of the purpose of this study, except for Speaker J09, who is a professional phonetician. All speakers were in their 20's or 30's at the time of recording.

2.3 Procedure

To control for the order effect, our stimulus structure took the form of a Latin-Square matrix, shown in Table 1.

Table 1: The stimulus structure

[a]	[i]	[u]	[e]	[o]	[a]
[i]	[u]	[e]	[o]	[a]	[i]
[u]	[e]	[o]	[a]	[i]	[u]
[e]	[o]	[a]	[i]	[u]	[e]
[o]	[a]	[i]	[u]	[e]	[o]

Since there are five vowels in Japanese, the stimulus structure had five rows. The order of

[4] We follow the previous studies and use the vertical displacement of the jaw as the crucial measure, without considering its rotational aspect. Whether the trajectory of rotational movement plays an important role in defining vowel openness is an interesting question, but we leave that issue for another study.

[5] This coding is due to the fact that this paper is a part of a larger general research program that addresses jaw displacement patterns in several languages. The first six Japanese speakers who participated in this general project did not produce tokens for this particular experiment.

the first row ([a]-[i]-[u]-[e]-[o]) is the standard way of reciting vowels in Japanese orthography. Within each row, all the five vowels appeared, and the initial vowel was repeated at the end of each line to avoid the effect of phrase-final large jaw opening in Japanese (Kawahara et al., 2014a, 2015). However, upon the examination of the obtained data, no effects of the phrase-final opening were observed (Kawahara et al., 2014b); therefore, all data were included in the analysis. In this structure, all the vowels appear 6 times, and the position in which each vowel occurs is controlled.

All the speakers repeated this matrix 5 times, which was presented via a Powerpoint screen, mixed with many other stimuli of other experiments. The following data analysis is thus based on 30 tokens for each vowel. There were a few mispronunciation errors, however. Syllables with onset consonants were also recorded, but this paper focuses on vowels. For a preliminary analysis of how different onset consonants affect jaw opening, see Kawahara et al. (2014b).

2.4 Acoustic analysis

The speech signals were recorded at the same time as the EMA recording, with the sampling rate of 16k Hz. Despite the instructions to the contrary, Speakers J08 and J09 did not put a pause between each vowel, and therefore acoustic measurement was impossible for them, because boundaries between each vowel were too blurry to locate precisely. Speaker J11 forgot to put a pause for about half of the tokens. For this speaker, only measurable tokens were used in the following analysis (108 tokens out of 180).

Using Praat (Boersma, 2001; Boersma & Weenink, 1999–2015), boundaries for each vowel were placed using the annotation function, as shown in Figure 3. A script was written to automatically detect the midpoint of each vowel based on these annotations, and to create a 20 ms analysis window centering that midpoint. Average values for F1, F0 and intensity within these analysis windows were then extracted. Durations were measured based on the entire intervals.

3 EMA data

3.1 Results

The result of Speaker J07, who is the first author of this paper, is shown in Figure 4. We observe that Speaker J07 shows a clear tripartite pattern: [a] is open, both [e] and [o] are semi-open, and [i] and [u] are closed. Within each pair of openness, the back vowels ([o] and [u]) are slightly—but only very slightly—more closed; we will observe the same tendencies

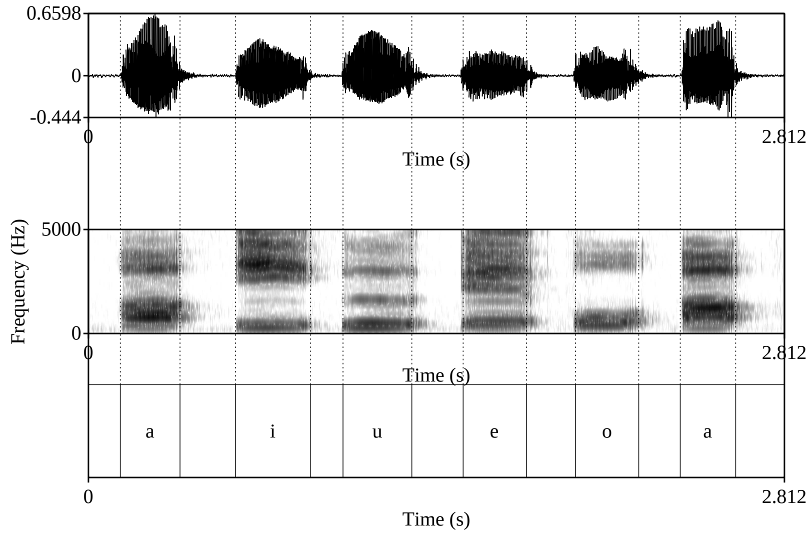

Figure 3: Illustration of the acoustic labeling using Praat.

more clearly in the other speakers.

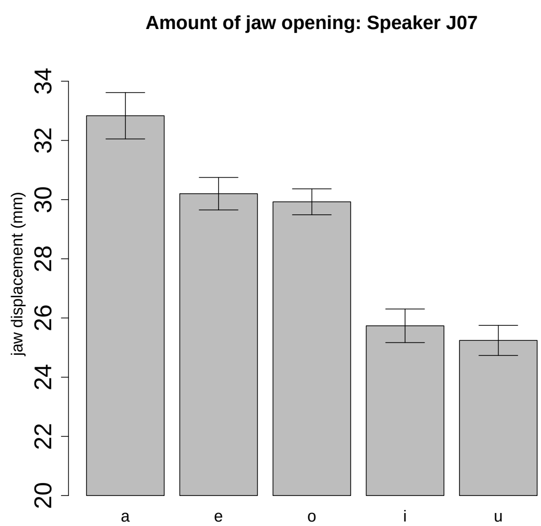

Figure 4: Amount of jaw opening for the five vowels in mm: Speaker J07. Here and throughout this paper, the error bars represent 95% Confidence Intervals (CIs). All the result figures are created using R (R Development Core Team, 1993–2015).

Nevertheless, these differences are very small, and it looks as if this speaker was an actuation of the IPA vowel chart—see Figure 1—in that he has closed, mid,[6] and open vowels. It is doubtful that this almost perfect tripartite distinction is intentional (consciously or not), but again we should interpret this data with caution.

Other speakers however show some more complicated patterns. As shown in Figure 5, Speaker J08 shows the same ordering as Speaker J07: [a] > [e] > [o] > [i] > [u]. However, the amount of mouth opening for [a] and [e] is so close to each other that it is not clear whether it is justified to consider the first vowel as open and the second one as mid. Recall also that for Speaker J07, there is a slight tendency for backer vowels to involve smaller jaw opening; this tendency is very clearly observed for this speaker: [o] and [u] are very clearly more closed than [e] and [i], respectively.

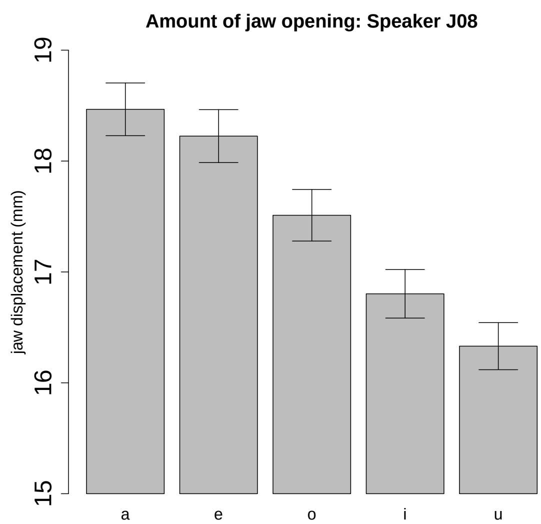

Figure 5: Amount of jaw opening for the five vowels: Speaker J08.

Speaker J09, shown in Figure 6, again shows the tripartite pattern: [a] is open, [e] and [o] are semi-open, and [i] and [u] are closed. This speaker too shows the same pattern as the previous two speakers: within vowels of the same "openness", back vowels involve less amount of jaw opening than front vowels.

[6]This level can either be classified as closed-mid or open-mid.

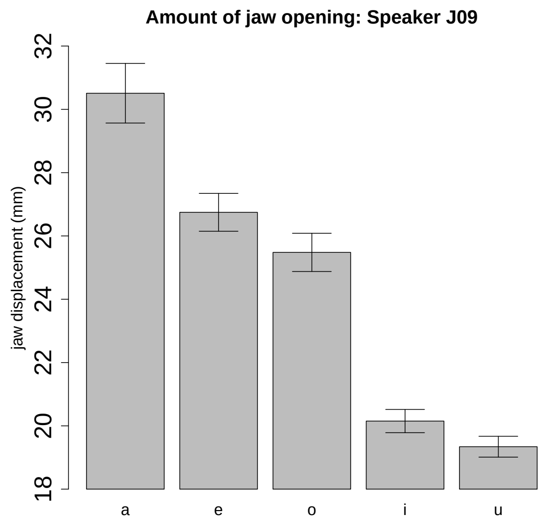

Figure 6: Amount of jaw opening for the five vowels: Speaker J09.

The results of the two additional speakers, shown in Figures 7 and 8, show the same pattern as Speaker J09. [a] is most open; [e] and [o] are semi-open; and [i] and [u] are closed. However, the assumption of the IPA vowel chart—the vowel of the same openness are in fact exactly open to the same degree—does not hold; back vowels are less open than front vowels. It seems that this is a general characteristics of Japanese (although the differences shown by Speaker J07 were very small).

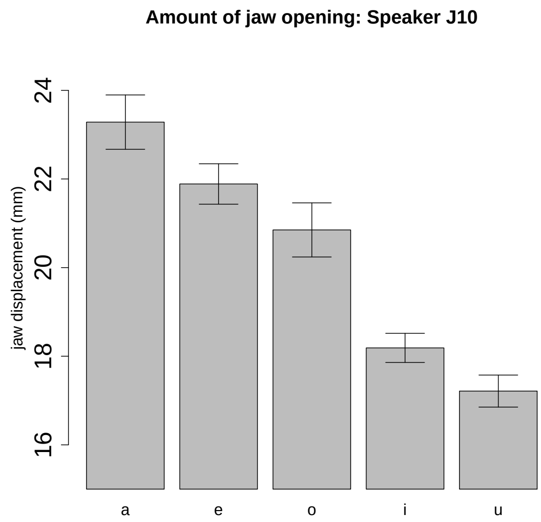

Figure 7: Amount of jaw opening for the five vowels: Speaker J10.

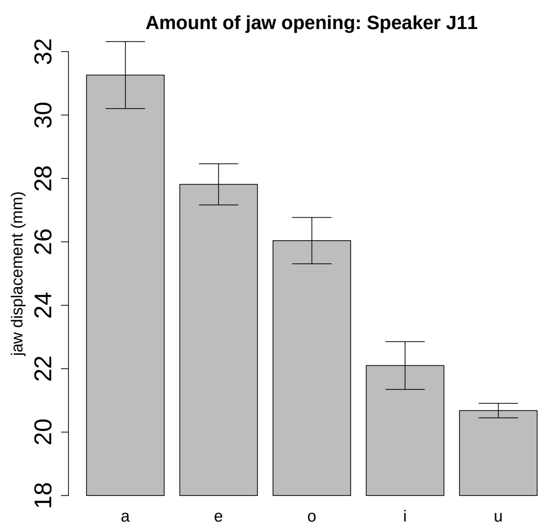

Figure 8: Amount of jaw opening for the five vowels: Speaker J11.

3.2 Dicussion

To be clear, we are not proposing that we should revise the IPA chart. Our data is solely based on the speech of Japanese speakers, and surely in IPA characterizations, some idealization is necessary. Our results, however, do offer something substantial that goes beyond the current IPA description of Japanese (Okada, 1999), in which Japanese [o] is described as more open than [e]. We also reiterate that the IPA chart, as well as Okada's (1999) description, may be based on acoustics rather than articulation (see footnote 2 for discussion); it is also possible that Okada's description is based on tongue height. Even with all of these possibilities, our articulatory findings are still something that is new to our understanding of Japanese phonetics, and we hope that the data offer a useful resource for phonetic theory in general.

Although much of the discussion so far has focused on Japanese, some cross-linguistic comparison is useful. Figure 9 shows jaw displacement of each vowel in English, read in CVC words, such as *peak, kick, cook*, etc (Menezes & Erickson, 2013; Williams et al., 2013). The data are based on a single female native speaker of English (the second author of the paper), and the positions within a sentence are controlled in this study. Each vowel was pronounced about 50 times, except for [ʊ] and [ɔ], which were read about 20 times.

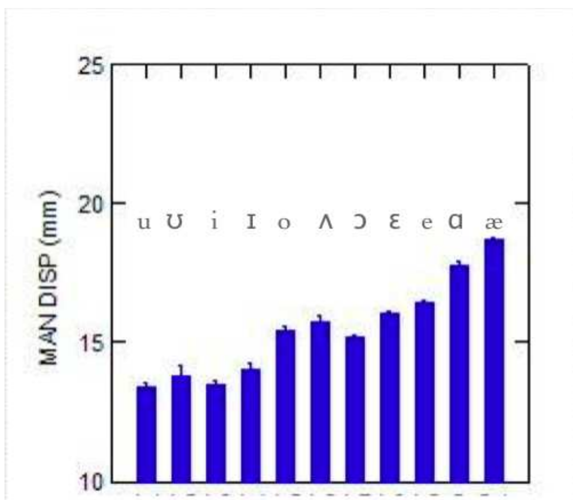

Figure 9: Amount of jaw opening for the English vowels. Based on Williams et al. 2013.

Some pairs show the pattern we observe in Japanese—back vowels are more open given the same openness: for example, [ɛ] shows more opening than [ɔ]. However, not all the same-openness pair shows the same pattern; e.g. [i] and [u] show about the same jaw displacement degree. We hope that more cross-linguistic studies will be carried out on the relationship between vowel opennesss and jaw displacement to examine the universality and language-specificity of jaw displacement patterns.

4 Acoustics

4.1 Results

The results of the acoustic analyses of Speaker J07 are shown in Figure 10. In the result figure of this section, F1 appears on the top left figure, F0 appears on the top right figure, intensity appears bottom left, and duration appears bottom right.[7] We observe that F1 clearly correlates with jaw opening in such a way that the more open vowels have higher F1. The other three acoustic correlates do not seem to show consistent patterns.

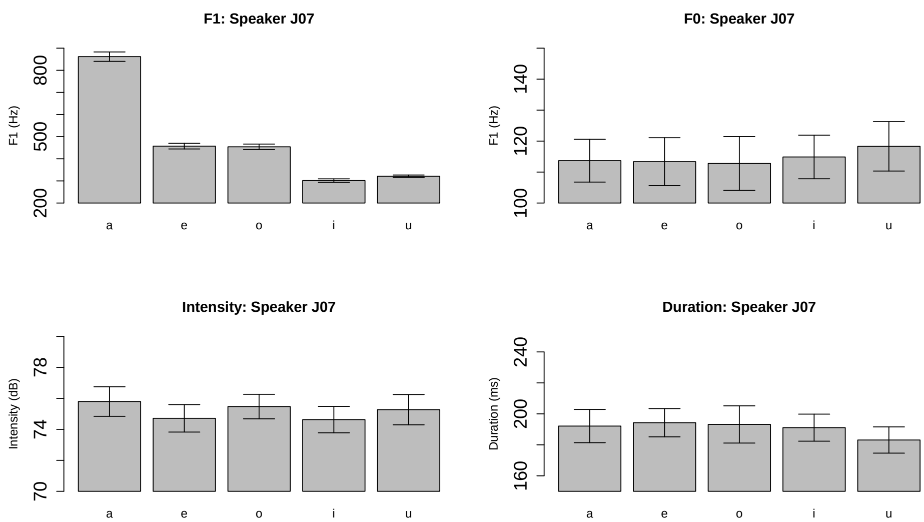

Figure 10: Acoustic properties of the five vowels: Speaker J07.

One interesting reversal found between jaw opening and F1 is between [i] and [u]. Despite that [i] involves more jaw opening than [u] (only slightly for this speaker), F1 is lower for [i] than [u]. We conjecture that this “reversal” occurs because tongue backness affects Helmholtz resonation as well. Recall the equation given in (1) where the Helmholtz resonation is lowered as the length of the back cavity gets longer (Johnson, 2003). The length of the back cavity is longer for /i/ than /u/, because /i/ is a front vowel, resulting in lower F1.

The acoustic results of Speaker J10 are shown in Figure 11. Again the measures other than F1 seem either flat or random, but F1 shows some systematicity. As with Speaker J08, F1 clearly correlates with jaw opening; [a] has the highest F1; [e] and [o] show comparable F1;

[7] The patterns of F1 we obtained in the current experiment are comparable with those obtained in the previous studies on the acoustics of Japanese vowels (Hirahara & Kato, 1992; Keating & Huffman, 1984; Nishi et al., 2008).

[i] and [u] show low F1. However, [i] shows noticeably lower F1 than [u]. These results show that jaw opening crucially affects F1, but is not the only factor that determines F1. Front vowels show lower F1 than back vowels, because of how Helmholtz resonation is determined. These characteristics of the Helmholtz resonation explains why [e] and [i] show lower—or comparable—F1 than [o] and [u], despite the former being more open.

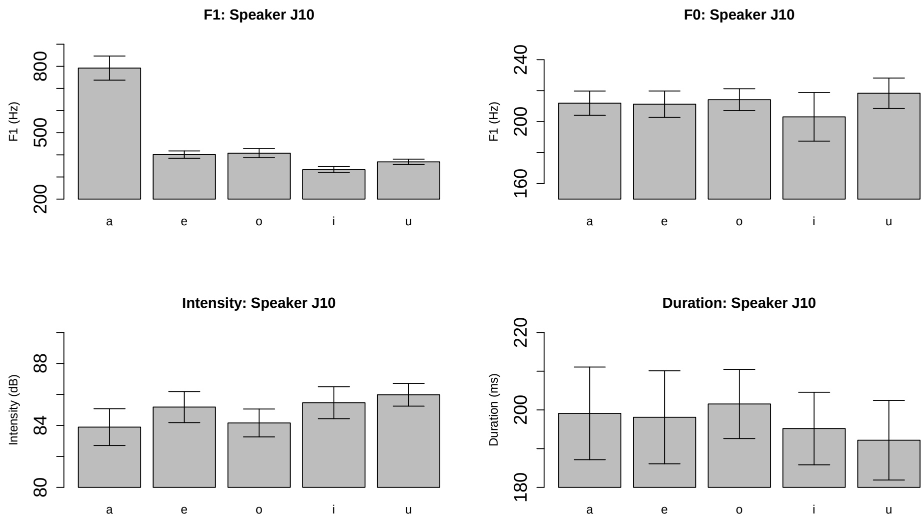

Figure 11: Acoustic properties of the five vowels: Speaker J10.

The results of Speaker J11, which are shown in Figure 12, show the same pattern as the previous two speakers. F1 seems to be the most reliable correlate of vowel opening in Japanese, whereas the other acoustic measures seem to pattern randomly.

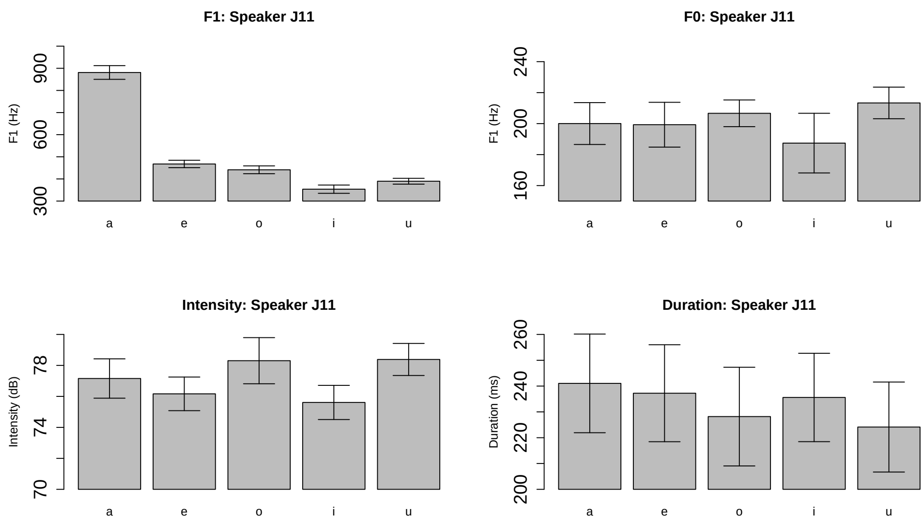

Figure 12: Acoustic properties of the five vowels: Speaker J11. Recall that this speaker put a pause between each vowel only about half of the time.

4.2 Discussion

To summarize, for all the speakers for whom acoustic measurement is possible, it is F1 that closely corresponds to vowel openness, although the differences in articulatory openness between front and back vowels are sometimes neutralized or reversed.

We did not observe the acoustic measures other than F1 to systematically covary as a function of vowel openness, contrary to the previous studies reviewed in the Introduction. The failure to find systematic patterns may be because of our task format: the speakers were simply asked to read vowels with no semantic or informational content. In this speech style, stimuli are often read with a particular rhythmic pattern. As shown in Figure 13, it is read with LHHLLH pitch contour (top panel) and SSSWWS intensity pattern (L=Low, H=High; S=Strong; W=Weak) (bottom panel). These patterns may have obliterated intrinsic differences between the five vowels. Likewise, the presence of pause after each vowel may have placed the vowels phrase-finally, thereby causing some final lengthening, which again may have masked intrinsic durational differences. In short, we suspect that the lack of differences in these acoustic parameters is due to experimental artifacts.

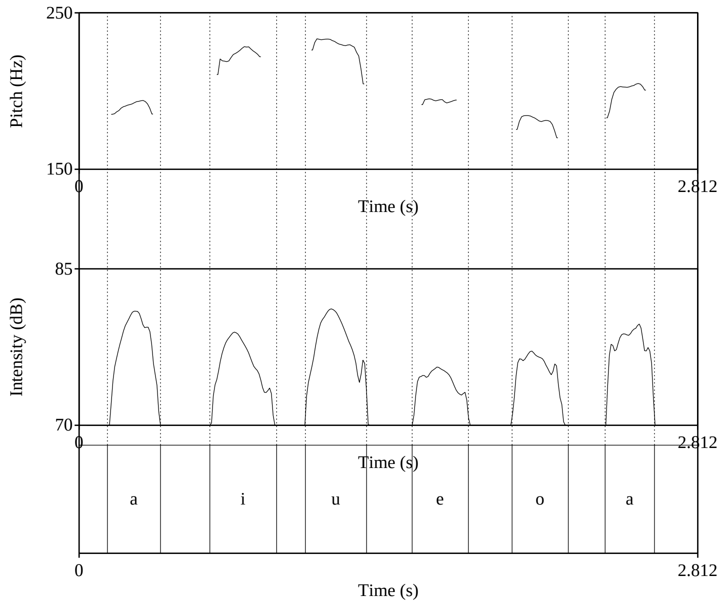

Figure 13: A pitch and intensity contour of [aiueoa] reading.

5 Conclusion

The primary aim of this paper has been descriptive: the current paper has examined how many millimeters the jaw travels for each of the five vowels in Japanese. The results have shown that while the five Japanese vowels can be considered to be classified in terms of three categories ([a]=open; [e] and [o]=mid; [i] and [u]=closed), [o] and [u] systematically showed smaller jaw opening than [e] and [i], respectively. The same tendency was observed in an earlier study on English (Menezes & Erickson, 2013; Williams et al., 2013). We reiterate that we do not challenge the traditional classification system deployed by IPA; neither do we deny the importance of studying the relevant vowel feature—what has been treated as "openness"—in terms of tongue height or acoustics. Instead, we hope to have offered a more realistic picture of how jaw opens for different types of vowels. Building on this research, we also hope to obtain similar measures of vowel opening in other languages (and more English speakers), thereby addressing to what extent the patterns we observed in this paper are Japanese-specific or universal.

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