Ann.Bull.RILP(1989)No.23, 85-108

WORD ACCENT, DEVOICING AND DURATION OF VOWELS IN JAPANESE

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1. Introduction

Devoicing of vowels in Japanese is a verbal phenomenon occurring mostly in the Tokyo dialect. It is said that the vowels /i/ and /u/ between voiceless consonants is devoiced if it is in an unaccented or word-final syllable of a word consisting of voiceless consonants and the vowels /i/ or /u/ [1,7,21]. According to Han, the devoicing depends on whether the vowel is accented or not and on which type of voiceless consonants are adjacent to it[4,6]. On the other hand the phenomenon has been investigated by speech physiolosists using a laryngoscopic fiberscope, photoelectric glottograms and electromyography in relation to utterance and laryngeal adjustment[13,14,17,18,28,34-40,43,46-50]. According to Yoshioka, devoicing may be a phonetic variation occurring with probability[48].

Concerning interaction between articulatory movements and vocal pitch control in Japanese word accent, physiological studies by Sawashima, Hirose and Kakita mentions that the activity of cricothyroid muscle increases for pitch-rising[15,16,22,37,41,42].

The relation between devoicing and word accent was investigated using sound spectrograph by Han[4,6]. Han mentioned that the duration of the vowel /u/ was shorter and easier to devoice than /i/ in the condition where the vowel is combined with voiceless consonants in sequences of /C1V1C2V2/ with accentual opposition, and where either of the vowels was /i/ and the other was /u/, or both were /i/ or /u/. Though observation of sound spectrograms and the results of measurements for segmental duration were described, enough data were not found regarding the occurrence of devoicing for each test word, speech rate and the linguistic background of subjects. Studies of bisyllabic words with sequences of the vowel /u/ and voiceless consonants have been seldom reported since the studies by Han[45,20].

Acoustic investigations of segmental duration were initiated by Hiki et. al[11,12]. A series of studies on segmental and mora duration have been reported by Sagisaka, Tohkura and Sato[30-33]. Segmental duration in two-mora words consisting of vowels in a production and perception was analyzed by Higuchi[2,3,8-10]. It was shown that a change in speech rate influenced vowel duration, while the duration of consonants was also influenced in rapid speech. Though words with the accent pattern of 'even type' were taken into account in these studies, vowel or mora duration in other accent patterns was not investigated. Syllables consisting

of the vowel /u/ and segmental environments for devoicing were not discussed. Concerning studies by Han, Sugito and Homma, the duration of the vowel /u/ was not discussed besides a few words used by Sugito[5,20,44]. Consequently, it seems that the data on devoicing and vowel duration are insufficient. In particular, the data for vowel /u/ are still rare.

This study discusses the inter-relation of word accent, the occurrence of devoicing, speech rate, neghboring consonants, the linguistic background of subjects and vowel duration in minimal pairs of bisyllabic words in accentual opposition. Preliminary parts of this study have been reported[23-26].

2. Experiments

2.1 Preparation of test words

Nine pairs of bisyllabic words, both vowels of which were /u/, with opposite accent patterns, one with accent on the first syllable, the other with accent on the second syllable, were used for the experiments. Tables 1.1 and 1.2 give the test words for the experiments. Five differently-accented pairs of test words /huku/, /suku/, /tsuku/, /kuku/ and /muku/ were constructed to discuss the devoicing of vowels, while four pairs of test words /humu/, /sumu/, /tsumu/ and /kumu/ were constructed to compare vowel duration. A dictionary for pronunciation and accent in Japanese language was used to prepare the test words[29]. It was desirable to use meaningful words, consisting of phonemes to make it easy to distinguish the vowels from consonants in the speech wave form and obtain clear pitch patterns. Two carrier sentences were used both in order to define the boundary of the test words exactly and to maintain not only the naturalness but also the consistency of utterances.

2.2 Procedures and method

The subjects were six adult male and female speakers of the Tokyo dialect of Japanese. Table 2 gives the linguistic background of each subject. The test words were inserted into two types of carrier sentence, one of which had the voiced stop /d/ following the test words ['/tsugiwa_____daro:/'('The next will be _____')](1), the other of which had the voiceless stop /t/ following them['/tsugiwa_____toju:/'('We call the next, _____')](2). These were presented to the subjects in list form to read individually, at both a slower and a faster tempo than the subjects' own speech, and more than twenty times for each test word. A pair of lists (A,B) was prepared, one of which had nine test words with accent on the first syllable (A), the other of which had nine test words with accent on the second syllable (B). The procedure consisted of two parts: (I)The subjects inserted the test words on list (A) into the carrier sentence(1) first (List A1), and then into the carrier sentence (2) (List A2) (total 18 words). Then the test words on list (B) were inserted

into the carrier sentence (1) first(List B1), and then into the carrier sentence (2)(List B2)(total 36 words). (II)The subjects read the test words on each list (A1)-(A2)-(B1)-(B2)-(B1)-(B2)-(A1)-(A2) at a slow rate (ten times each) first (total 720 words), and then at a fast rate (ten times each) (total 1440 words for each subject). The recording of 8640 utterances was performed using the TEAC AUDIO SYSTEMS MODEL T-6107 in an anechoic studio. Speech signals low pass filtered with a cut-off frequency of 4.5kHz were passed through A/D converters with a sampling frequency of 10 KHz, 12 bit and entered into a computer.

The boundaries of the vowels and consonants were decided both by observation of the speech wave form displayed on a graphic screen and listening to the speech sounds through D/A converters. In the present study, the duration of a vowel was defined as the time period when a periodic(or quasi-periodic) vibration for the vowel was observable on the speech wave. The measurement unit for duration was 0.1 msec. The normalized duration of each segment of the test words was calculated in each case and examined with the SPSS program on the VAX-11/780 system.

2.3 Decision of the boundaries of vowels and consonants

The point of a positive curve crossing with the baseline in the vicinity of a segment in discussion was defined as the initiating point of that segment. The boundary of each segment was found by means of an observation of the amplitude of the speech wave. This was regarded as a devoiced vowel when some frication without periodic (or quasi-periodic) vibration for the vowel was observable on the speech wave. The fricatives, /h/ and /s/, had their own different fricating wave forms respectively. The nasal /m/ showed a periodic wave form with a small amplitude distinguished from the speech wave form of the preceding or following vowel. The second formants of the nasal /m/ and vowel /u/ were compared when it was difficult to decide the boundary of /u/ from /m/. It was difficult to differentiate the noise of a devoiced vowel from the frication of fricatives, /h/ and /s/. Figures 1.1 , 1.2 and 1.3 give the speech wave form for the words, /mu̥ku/ by subject FK, /ku̥ku/ by subject MS and /ku̥mu/ by subject FK, respectively.

3. Results

3.1 Devoicing of vowels

Devoicing of vowels did not occurred in the test words, /humu/, /sumu/, /tsumu/ and /kumu/. The word final vowel U2 was not devoiced regardless of speech rate when the consonant following it was /d/. In the test word /muku/, the devoicing occurred only for U2 on condition that the consonant /t/ followed it. Table 3 gives the averaged ratio of devoicing for each test word. Fig. 2 shows the averaged ratio of devoicing for four pairs

of test words, /huku/, /suku/, /tsuku/ and /kuku/, for the consonants preceded by U2 (top: /d/, bottom: /t/); vowels(left: U1, right: U2); accents (left of base axis: accented U1, right of base axis: accented U2); and speech rate (S: slow, F: fast).

3.1.1 Slow speech

In case the consonant following the vowel U2 was /d/, the averaged ratio of devoicing for the vowel U1 was 0.21 when the first syllable was accented, and was 0.96 when the first syllable was not accented. The vowel U2 was not devoiced at all.

In case the consonant following the vowel U2 was /t/, the averaged ratio of devoicing for the vowel U1 was 0.19 when the first syllable was accented, and was 0.92 when the first syllable was not accented. The averaged ratio of devoicing for the vowel U2 was 0.43 when the first syllable was accented, and 0.01 when the first syllable was not accented.

3.1.2 Fast speech

In case the consonant following the vowel U2 was /d/, the averaged ratio of devoicing for the vowel U1 was 0.82 when the first syllable was accented, and was 0.99 when the first syllable was not accented. The vowel U2 was not devoiced either.

In case the consonant following the vowel U2 was /t/, the averaged ratio of devoicing for the vowel U1 was 0.62 when the first syllable was accented, and was 0.99 when the first syllable was not accented. The averaged ratio of devoicing for the vowel U2 was 0.63 when the first syllable was accented, and 0.14 when the first syllable was not accented.

3.2 Influence of accent and speech rate on the devoicing of vowels

Devoicing never occurred for vowels preceded or followed by voiced consonants. Devoicing of the vowel /u/ occured less often in accented syllables. The occurrence of devoicing increased in faster speech. U1 accented syllables were much more often devoiced in faster speech, while U2 did not tend to be devoiced under the same accent conditions. There was no considerable difference in the occurrence of devoicing in regard to the type of consonants adjoining to the vowels i.e., fricatives, affricates or stops.

3.3 The effect of personal differences on patterns of devoicing

Tables 4.1 and 4.2 and Figures 3.1, 3.2, 3.3, 3.4, 3.5 and 3.6 show the personal differences in the occurrence of devoicing. In slow speech, the ratio of devoicing for accented U1 was high for subject MS, while it was low for the other subjects. The ratio of unaccented U2s was high for subjects FK and HH,

while it was low for MS, SN, SK and MT. In fast speech, the ratio of devoicing for accented U1 was low for FK, while it was high for the other subjects. It was low for MT when the consonant following U2 was /t/. The ratio of unaccented U2s was high for FK, HH and MT, while it was less high for SN and low for SK and MS. Owing to the increase in speech rate, the ratio of devoicing of accented U1 increased for HH, SN and SK, while it incresed for MT when the consonant following U2 was /d/. The ratio of unaccented U2 incresed for MT, SN and SK.

Regardless of speech rate, the ratio of devoicing was high for unaccented U1, while it was low for accented U2 in all subjects. In slow speech, U2 did not tend to devoice regardless of accent for most of the subjects. The ratio of devoicing for accented U1, regardless of speech rate, was high for MS, while it was low for FK and MT. It increased for SN and SK as the speech rate incresed. The ratio of unaccented U2 was, regardless of speech rate, high for HH and FK, while it was low for MS and SK, though it increased for SN and MT owing to the increase in speech rate. Consequently, it seems that the ratio of devoicing was high for some subjects, while it was low for some others, and increased for others as the speech rate increased.

3.4 Coincidental devoicing of both vowels

The coincidental devoicing of both U1 and U2 increased remarkably in fast speech, whereas it occured seldom in slow speech. Tables 5.1 and 5.2 give details. In slow speech, the devoicing of accented U1 and unaccented U2 coincided in ten cases out of eighty utterances for HH. Coincidental devoicing of unaccented U1 and accented U2 occurred in three cases for FK and in one case for MT out of eighty utterrances for each. On the other hand, in fast speech, coincidental devoicing occurred in 121 cases of the total(480 cases) when U1 was accented, while it occurred in 69 cases of the total(480 cases) when U2 was accented. Thus the coincidental devoicing of both vowels tended to occur more when U1 was accented.

3.5 Influence of speech rate on duration of vowels

Segmental duration was measured to determine the influence of accents and speech rate on segmental duration. Figs. 4.1 and 4.2 give the normalized duration of vowels for four pairs of test words "/humu/, /sumu/, /tsumu/ and /kumu/" with regards to consonants preceded by U2 (top: /d/, bottom: /t/); vowels(left: U1, right: U2); accents (left of base axis: accented U1, right of base axis: accented U2); and speech rate (S: slow, F: fast).

As for subject MS, the duration of each word was reduced by 30%, while the duration of U1 was increased by 30% when it was accented. The duration of U2 was reduced by 10 % when it was accented except in /muku/, while it was reduced by 30% when it was not accented. The duration of the first syllable was

increased by 10%, whereas the duration of the second syllable was reduced by 20 %. It seems that there was a reduction in word duration in fast speech, as supported by the remarkable reduction of the duration of U2.

As for subject FK, in fast speech, both the duration of words and U1 were reduced by 40% and 20-40% except for /muku/ , respectively. The duration of the first syllable was reduced by 10%, whereas the duration of the second syllable was increased by 10%. It seems that there was a reduction in word duration in fast speech, as supported by the reduction of the duration of U1.

4. Discussion

4.1 Summary

The second vowel, the following consonant of which is /d/, was not devoiced. Vowels adjoining to voiceless consonants tended to be devoiced in general.

(1) Accented vowels did not tend to be devoiced compared to unaccented ones.
(2) The Vowel U2 did not tend to be devoiced more than vowel U1 under the same conditions of accent.
(3) The averaged ratio of devoicing increased in faster speech. Especially, even the ratio of devoicing of accented U1 increased.
(4) Accented U2 did not tend to be devoiced. The devoicing of accented U2 induced coincidental devoicing without exception.
(5) Considerable difference was not found in the devoicing of U1 owing to the types of consonants adjoining to it: fricatives, affricates or stops.
(6) The duration of both accented vowels and syllables were longer than unaccented ones.

However, the findings in items (1) and (2) are not conclusive. They depends on the subjects. Accented U1s were almost always devoiced for one subject, while unaccented U2s were almost always devoiced for another one.

4.2 Comparison with the view by Han's work

Concerning the views of Han[4,6], the following phenomena were observed in the sequences of /CVCVCV.../, where C was a voiceless consonant and V was the vowel /i/ or /u/. Han's observations were as follows.

(1) /i/ and /u/ between unaccented voiceless consonants were devoiced. /u/ was devoiced more readily than /i/.
(2) Devoicing was not common when /i/ or /u/ was in an accented syllable.
(3) /i/ and /u/ were more readily devoiced if the tempo was rapid.

(4) Devoicing of vowels in two successive syllables was rare, and the devoicing of three successive vowels did not occur.
(5) When all the voiceless consonants were stops, devoicing occurs in alternative syllables.
(6) Vowels preceded by non-stops were more readily devoiced, while vowels preceded by stops tended to remain voiced. The fricatives showed greater effect on devoicing than affricates.
(7) If there was an accented syllable in the /CVCVCV.../ sequence, the accented vowel remained voiced and the vowels in the neighboring syllables were devoiced.
(8) Patterns of alternation and non-stop voiceless consonants had more effect on devoicing than did the pitch accent.

The results of our study support the first, the second and the third items by Han. However the other items do not always agree with the results of our experiment. Concerning item(4), for instance, coincidental devoicing was found in 2% of the cases even at a slow speech rate, and in 25% for accented first vowels and in 14% for accented second vowels at a fast speech rate. And, yet, whenever an accented U2 was devoiced, coincidental devoicing occurred for U1. As for item (5), the vowels separated by stops from both sides of the test sentence /tsugiwakukutoju:/, were not always voiced, devoiced and voiced alternatively. Even coincidental devoicing occurred in these situations. For item (6), a difference in the devoicing of vowels owing to the type of preceding consonant was not found. In regard to item (7), there were some cases where the accented vowels were devoiced, while the unaccented vowels were still voiced. As for item (8), no comparison was made in our experiments.

4.3 Individual difference in devoicing

Patterns of individual differences in devoicing for the six subjects can be summerized as follows: For four subjects (MT, HH, SK, SN), U1 was devoiced at a slow rate of speech if unaccented, while it was a little devoiced at a fast rate even if accented. U2 did not tend to be devoiced except for besides HH at a slow rate, while the ratio of devoicing increased at a fast rate. On the other hand, as for MS, U1 was devoiced, but U2 did not tend to be devoiced. As for FK, unaccented vowels were devoiced, while accented vowels did not tend to be devoiced.

4.4 Devoicing and accent

The fundamental frequency makes it possible to phonate with accent in Japanese. Accentuation needs a glottal adjustment in which the glottis is closed or nearly closed for voiced sounds by adduction of the interarytenoid (INT) muscle. Then the vocal folds are set into vibration by the transglottal air flow[43]. The muscle has both dynamic and static functions in closing the

glottis and maintaining it thus. The opening and closing of the glottis during speech is controlled by a reciprocal pattern of the posterior cricoarytenoid (PCA) and the interarytenoid (INT) muscles. In principle, the activity of the INT increases, but the activity of the PCA decreases for voiced sounds, whereas the two activities are reversed for voiceless sounds[13,14,17]. It has been supposed that there is a strong activity of the PCA and reciprocally decreased activity of the INT when vowels tend to be devoiced. However, the INT should increase its activity for accentuation. Yoshioka supposes that there is some mechanism to avoid the devoicing of a vowel by the delicate activity of the adductor muscles in accented speech[48,49]. However, further experimental discussions are needed.

4.5 The difference in devoicing between U1 and U2

Voiceless consonants preceded the first vowel of the test words, while the voiceless stop /k/ preceded the second vowel. The consonants following the second vowel were /d/ or /t/. Glottal aperture is definitely larger for word-initial voiceless consonants due to the activity of posterior cricoarytenoid muscle, while it is smaller for the word-medial voiceless stop /k/ in the second syllable. However, the aperture for the voiceless stop /t/, which followed the second vowel, is much smaller than for /k/, and there is no apparent glottal opening[38,40]. The larger glottal opening for word-initial voiceless consonants tends to devocalize their following vowels compared with the glottal opening for the second syllable. This may be the reason that U1 tended to be devoiced more than U2 for these test words. On the other hand, the second vowel does not tend to be devoiced and rather the vocal folds are easily adducted to begin vibration because the maximum glottal aperture is much more smaller in the second syllable.

Concerning acoustic studies, it has been reported that the duration of both consonants and vowels is shorter word-initially, while vowel duration is much longer in word-final position for words in isolation[31]. The duration of U1 was shorter than that of U2 in our experiment. In particular, the difference between unaccented U1s and accented U2s was remarkable. As a result, the first vowels tended to be devoiced, whereas the second were in a condition where the vocal folds were set into vibration.

4.6 Coincidental devoicing of U1 and U2

When the speech rate was fast and the consonant /t/ followed U2, the devoicing ratio was 0.62 for accented U1, 0.99 for unaccented U1, 0.14 for accented U2 and 0.63 for unaccented U2. The ratio of coincidental devoicing was 0.25 for 'high-low' accents (ie, words consisting of an accented u1 and unaccented U2) and 0.14 for 'low-high' accents (ie, a word consisting of an unaccented u1 and accented U2). Unaccented U1s tended to be devoiced, but their probability of coincidental devoicing with

accented U2s was low. Therefore, unaccented U1s were devoiced independently of the accented U2s. However, the accented U2s did not tend to be devoiced, but they were devoied coincidentally with the unaccented U1s, whenever they were devoiced. This means that a preceding unaccented U1 had to be devoiced before an accented U2 was devoiced. Accented U2s were not devoiced unless unaccented U1s were devoiced. On the other hand, as for 'high-low' accent words, the ratio of devoicing was both 0.6 for accented U1s and unaccented U2s. However, the ratio of coincidental devoicing for both of these was 0.25. Consequently the occurrence of coincidental devoicing decreased compared to the independent devoicing of U1 or U2.

4.7 Duration of vowels, syllables and words

In our experiments, there was a significant difference in the duration of vowels, syllables and words according to whether the vowel U1 or U2 was accented or unaccented, regardless of both the speech rate and the type of consonant which followed U2. The difference increased at a fast speech rate, especially for U1. Therefore, the remarkable reduction in the duration of U1 may support the total reduction of the word duration. It seems that the difference in the reduction ratio for duration between MS and FK was due to individual manners of utterance. As for word duration, MS controlled it on U2, while FK controlled it on U1. As for syllable duration, there were two types. One type was where the duration of the first syllable was longer than the second owing to both the accented U1 and the word-initial voiceless consonant.The second was where the accented syllable was always long regardless of its order in a word: the first or the second. It seems that this difference was concerned with the occurrence of devoicing.

Sagisaka et. al. reported that the duration of both consonants and vowels was shorter on word-initials, while the vowel duration was much longer on word-finals in test words[31]. According to the studies by Mayer and Han[5,27], the duration of accented vowels was longer than unaccented ones. Nevertheless the duration of vowel /u/ was not concerned. On the other hand, Sugito mentioned that duration of vowel /a/ was longer for the first mora than for the second one regardless of accents[44]. However the duration of the accented vowels was longer than unaccented ones so far as first vowel /a/ was concerned. On the other hand, Homma mentioned that the duration of unaccented second vowel /a/ was longer than for accented first vowel /a/, owing to pre-boundary lengthening[20]. Hirose and Fujisaki reported that the duration of accented second syllables was longer than of unaccented ones as to [ame] and [ame] in Japanese[19].

As previousely reported[5,11,12,19,23-26], the vowel and syllable duration was controlled by some quantitative relation where the duration of vowels in accented syllables was longer than that in unaccented ones.

5. Conclusion

The ratio of vowel devoicing was different according to whether the vowel was accented or not. It was low for accented vowels and it increased remarkably at a fast speech rate. These results support the description by Han. However, the ratio of devoicing for the first vowels was higher than for the second. This result was not mentioned by Han. It seems reasonable that this result has a relation to the fact that the maximum glottal apertures for the voiceless fricatives, affricates and stops on word-initial are bigger than those for voiceless word-medial stops. It was remarked that the tendencies to word devoicing for the first vowel accented and the second vowel unaccented depend on individuality of each subject. The vowel duration was different whether the vowel was accented or not. It was longer for accented vowels than for unaccented ones.

Acknowledgement

We would like to press our gratitude to Profs. H. Hirose and S. Kiritani for their advice in this study.

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Table 1 Test words

1. Accent on the first syllable

/hu͡ ku/	blow	/hu͡ mu/	hum
/su͡ ku/	like	/su͡ mu/	dwell
/ʦu͡ ku/	arrive	/ʦu͡ mu/	checkmated
/ku͡ ku/	9*9	/ku͡ mu/	set up
/mu͡ ku/	innocence		

2. Accent on the second syllable

/huku͡ /	wipe	/humu͡ /	step
/suku͡ /	empty, hungry	/sumu͡ /	nonsense word
/ʦuku͡ /	prick, touch	/ʦumu͡ /	pick, pile
/kuku͡ /	9*9	/kumu͡ /	draw, drink
/muku͡ /	peel		

Table 2.1 Linguistic background (Subject: male)
(Numbers in double parentheses show age of subjects in each dwelling place)

Subject	MS	HH	SN
Age(recording day)	58	54	46
Birth & dwelling places	Nagasaki(0-11) Yokohama(11-)	Yokohama(0-10) Kamakura(10-20) Yokohama(20-)	Sasebo (0-1) Maizuru (1-2) Yokohama(2-4) Yonezawa(4-7) Kamakura(7-)

Table 2.2 Linguistic background (Subject: female)

Subject	FK	SK	MT
Age(recording day)	44	45	35
Birth & dwelling places	Tokyo (0-33) Israel(33-34) Tokyo (34-36) Israel(36-39) Tokyo (39-)	Tokyo(0-)	Tokyo(0-)

Table 3 Averaged ratio of devoicing for test words

Test word	Speech	Slow /daro:/ u1	Slow /daro:/ u2	Slow /toju:/ u1	Slow /toju:/ u2	Fast /daro:/ u1	Fast /daro:/ u2	Fast /toju:/ u1	Fast /toju:/ u2
/hu̥ku/	120	0.18	0	0.18	0.43	0.78	0	0.58	0.67
/huku̥/	120	0.96	0	0.95	0.01	0.99	0	0.98	0.13
/su̥ku/	120	0.25	0	0.23	0.43	0.85	0	0.65	0.61
/suku̥/	120	0.98	0	0.96	0.02	1.00	0	1.00	0.13
/t̥su̥ku/	120	0.28	0	0.22	0.43	0.85	0	0.61	0.57
/t̥suku̥/	120	1.00	0	0.98	0.01	1.00	0	1.00	0.18
/ku̥ku/	120	0.15	0	0.13	0.44	0.81	0	0.63	0.68
/kuku̥/	120	0.90	0	0.80	0	0.99	0	0.99	0.15
Total									
/Cu̥ku2/	480	0.21	0	0.19	0.43	0.82	0	0.62	0.63
/Cuku2̥/	480	0.96	0	0.92	0.01	0.99	0	0.99	0.14

Table 4.1 Individual devoicing ratios (slow speech rate)

Condition	Test word	Speech for each	MS	HH	SN	FK	SK	MT	Av.
Slow /daro:/ u1	/Cu̥ku2/	80	0.94	0.21	0.08	0	0.05	0	0.21
	/Cuku2̥/	80	1.00	1.00	0.93	0.91	0.94	0.98	0.96
Slow /daro:/ u2	/Cu̥ku2/	80	0	0	0	0	0	0	0
	/Cuku2̥/	80	0	0	0	0	0	0	0
Slow /toju:/ u1	/Cu̥ku2/	80	0.90	0.13	0.10	0	0	0	0.19
	/Cuku2̥/	80	1.00	0.98	0.85	0.99	0.75	0.96	0.92
Slow /toju:/ u2	/Cu̥ku2/	80	0.10	0.99	0.09	1.00	0	0.41	0.43
	/Cuku2̥/	80	0	0	0	0.04	0	0.01	0.01

Table 4.2 Individual devoicing ratios (fast speech rate)

Condition	Test word	Speech for each	MS	HH	SN	FK	SK	MT	Av
Fast /daro:/ u1	/Cu̥ku2/	80	1.00	0.85	0.96	0.19	1.00	0.93	0.81
	/Cuku2̥/	80	1.00	1.00	0.99	0.99	1.00	1.00	0.99
Fast /daro:/ u2	/Cu̥ku2/	80	0	0	0	0	0	0	0
	/Cuku2̥/	80	0	0	0	0	0	0	0
Fast /toju:/ u1	/Cu̥ku2/	80	1.00	0.58	0.85	0.03	1.00	0.26	0.62
	/Cuku2̥/	80	1.00	1.00	1.00	0.98	1.00	0.99	0.99
Fast /toju:/ u2	/Cu̥ku2/	80	0.05	0.93	0.65	1.00	0.23	0.93	0.63
	/Cuku2̥/	80	0	0.38	0.19	0.03	0	0.28	0.14

Table 5.1 Occurrence of coincidence of devoicing for U1, U2 (Slow speech rate)

Test word	Speech for each	Subject MS	HH	SN	FK	SK	MT	Total	Ratio
/hu̥ku/	20	0	1	0	0	0	0	1	0.008
/huku̥/	20	0	0	0	0	0	1	1	0.008
/su̥ku/	20	0	4	0	0	0	0	4	0.033
/suku̥/	20	0	0	0	2	0	0	2	0.017
/t͡su̥ku/	20	0	2	0	0	0	0	2	0.017
/t͡suku̥/	20	0	0	0	1	0	0	1	0.008
/ku̥ku/	20	0	3	0	0	0	0	3	0.025
/kuku̥/	20	0	0	0	0	0	0	0	0
Total									
/Cu̥ku2/	80	0	10	0	0	0	0	10	0.021
/Cuku2̥/	80	0	0	0	3	0	1	4	0.008

Table 5.2 Occurrence of coincidence of devoicing for U1, U2 (Fast speech rate)

Test word	Speech for each	Subject MS	HH	SN	FK	SK	MT	Total	Ratio
/hu̥ku/	20	3	11	8	1	0	8	31	0.258
/huku̥/	20	0	4	4	0	0	7	15	0.125
/su̥ku/	20	1	11	15	0	0	4	31	0.258
/suku̥/	20	0	7	5	1	0	2	15	0.125
/t͡su̥ku/	20	0	8	9	1	0	3	21	0.175
/t͡suku̥/	20	0	8	5	0	0	8	21	0.175
/ku̥ku/	20	0	11	9	0	18	0	38	0.317
/kuku̥/	20	0	11	1	1	0	5	18	0.150
Total									
/Cu̥ku2/	80	4	41	41	2	18	15	121	0.252
/Cuku2̥/	80	0	30	15	2	0	22	69	0.144

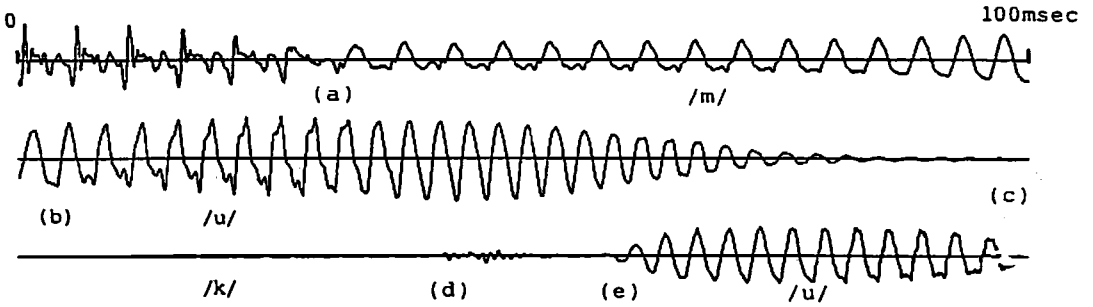

Fig. 1.1 Speech wave form for /mū ku/ (Subject FK).

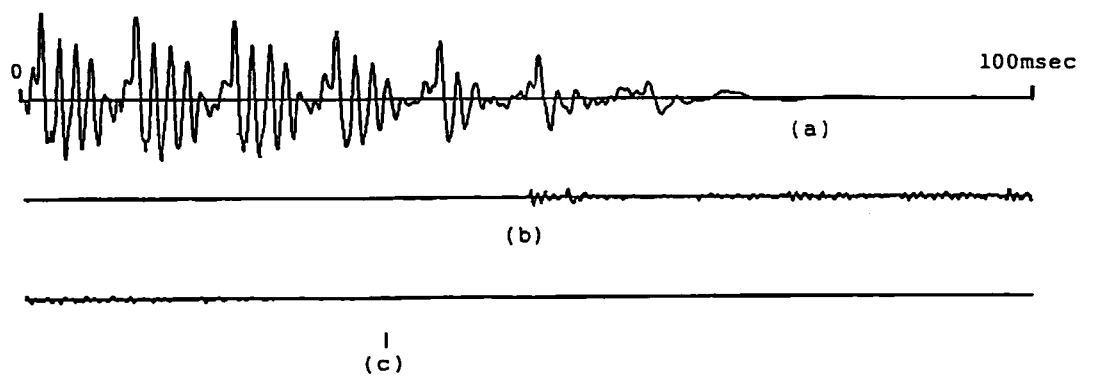

Fig. 1.2 Speech wave form for /kū ku/ (Subject MS).

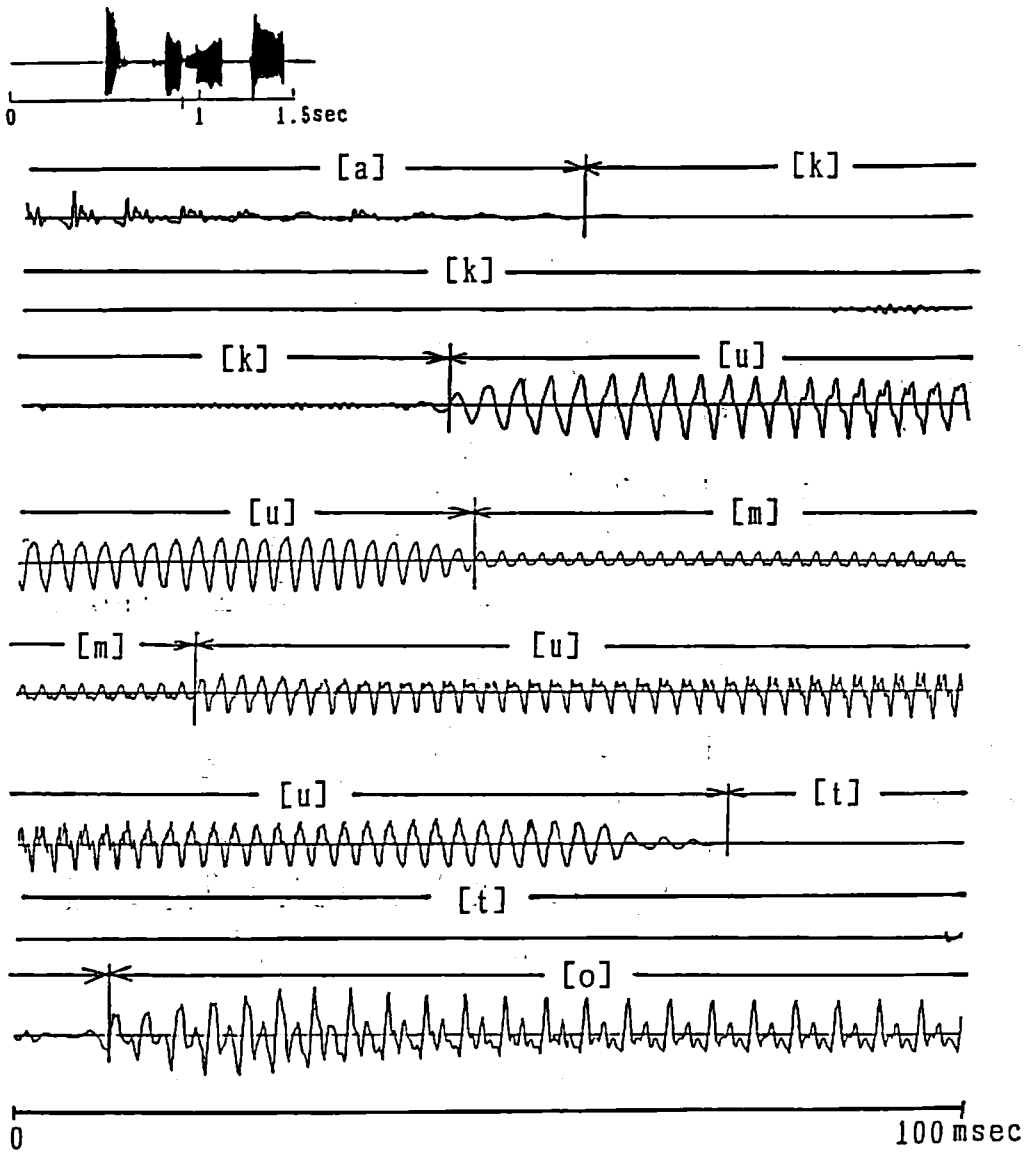

Fig. 1.3 Speech wave form for /kū mu/ (Subject FK).

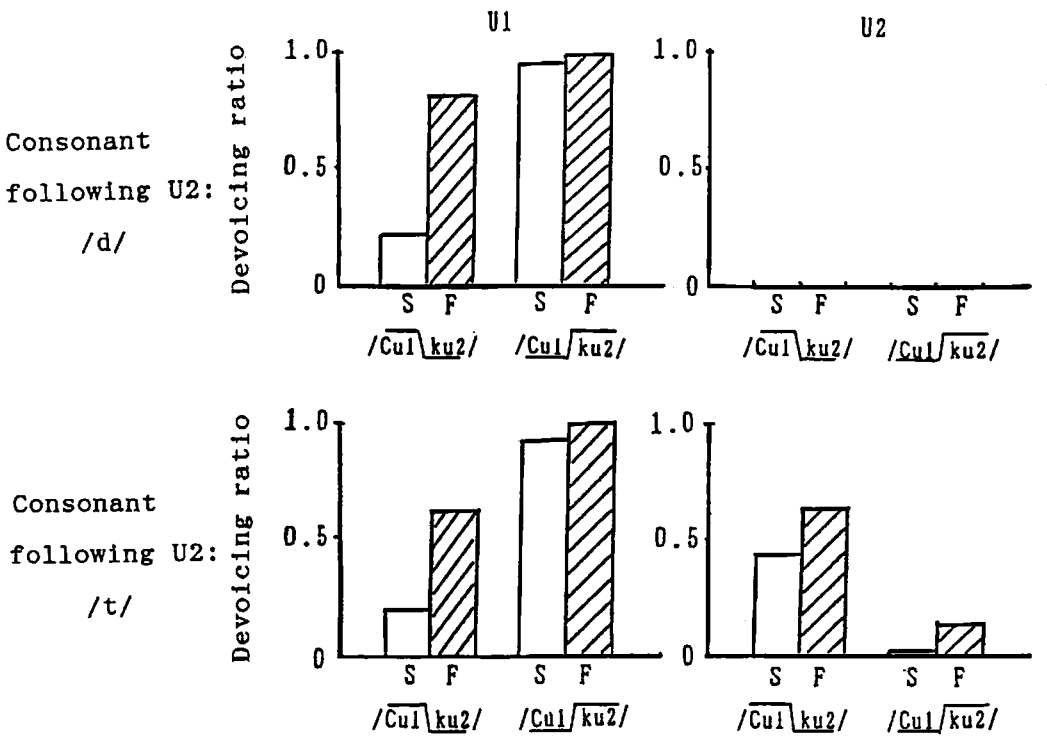

Fig. 2 Averaged ratio of devoicing for six subjects.
S: Slow speech rate F: Fast speech rate

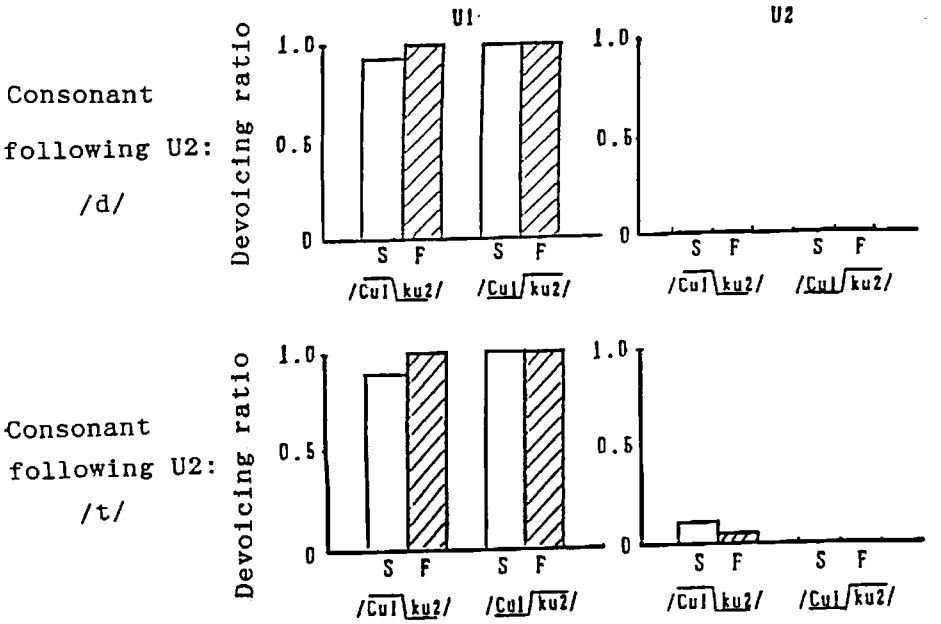

Fig. 3.1 Individual ratio of devoicing(Subject MS).

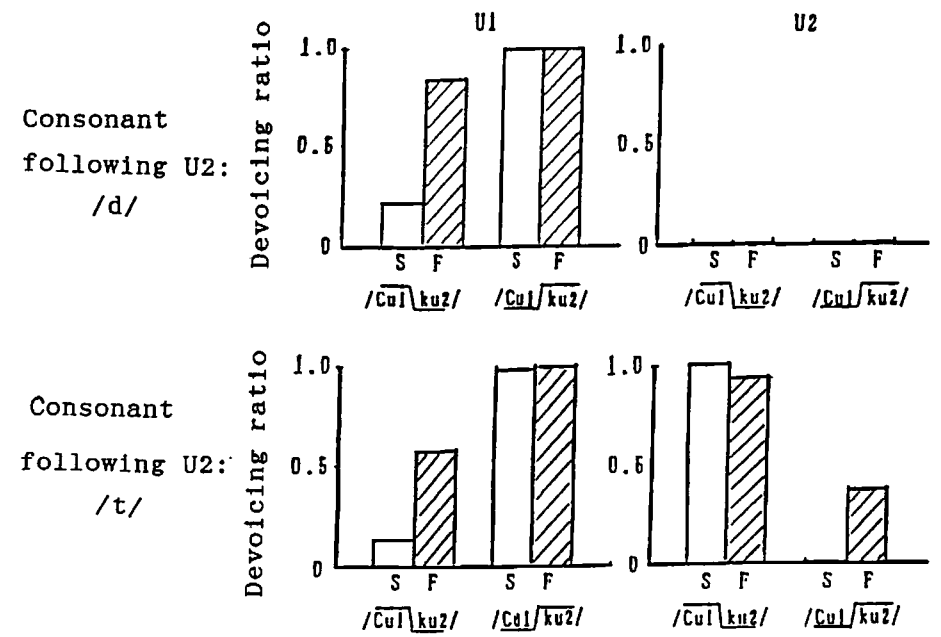

Fig. 3.2 Individual ratio of devoicing(Subject HH).
S: Slow speech rate F: Fast speech rate

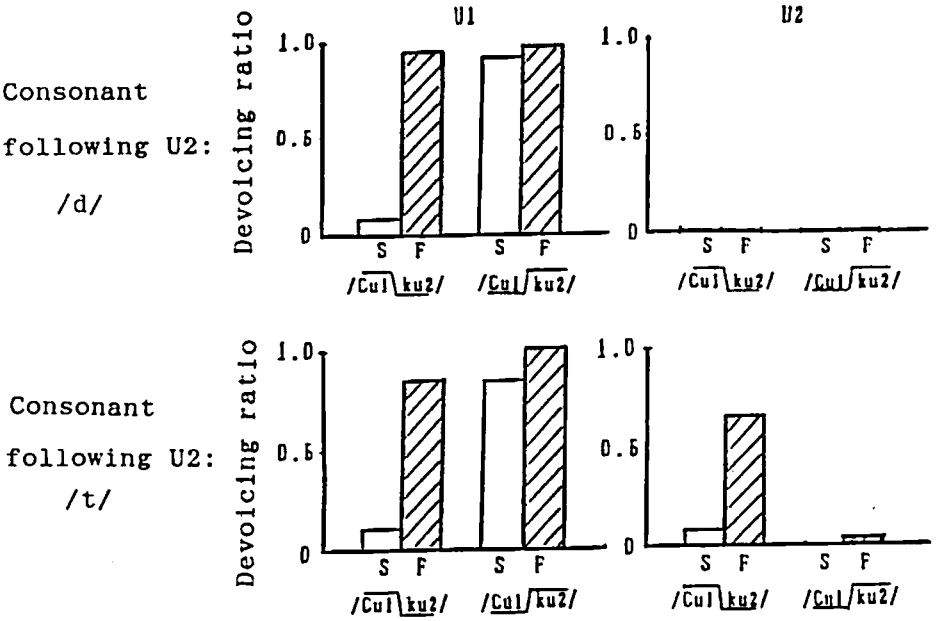

Fig. 3.3 Individual ratio of devoicing(Subject SN).

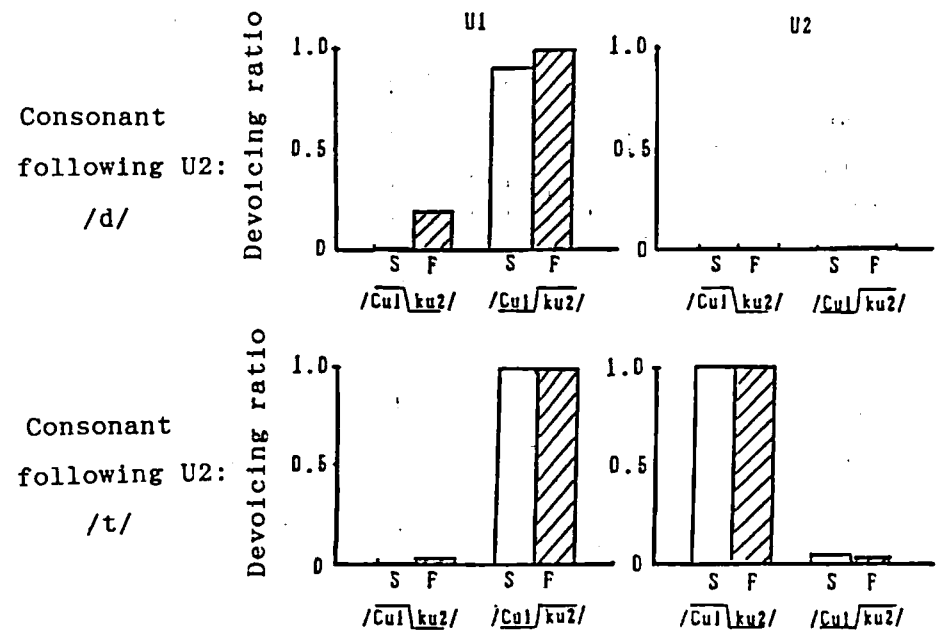

Fig. 3.4 Individual ratio of devoicing(Subject FK).
S: Slow speech rate F: Fast speech rate

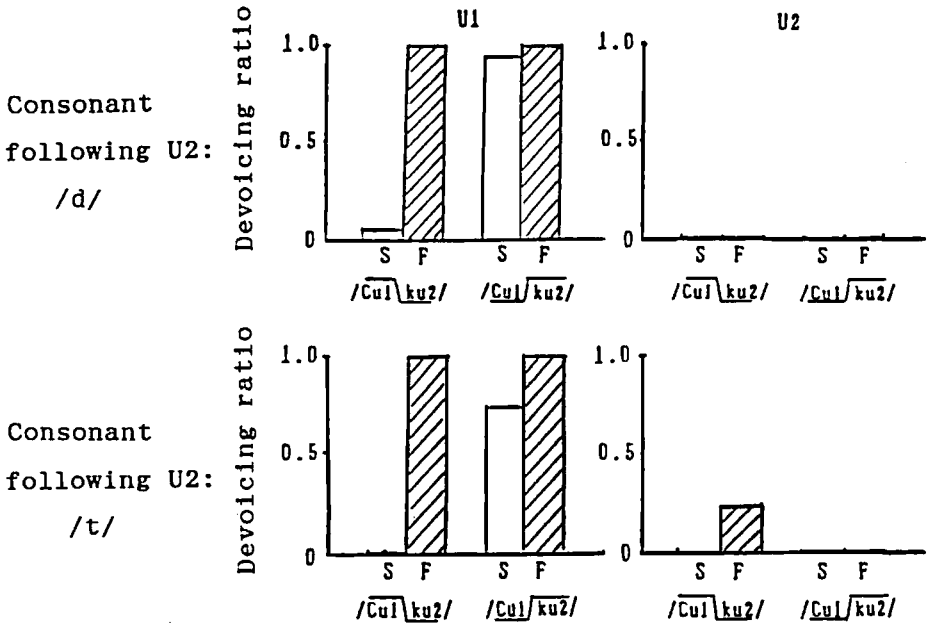

Fig. 3.5 Individual ratio of devoicing(Subject SK).

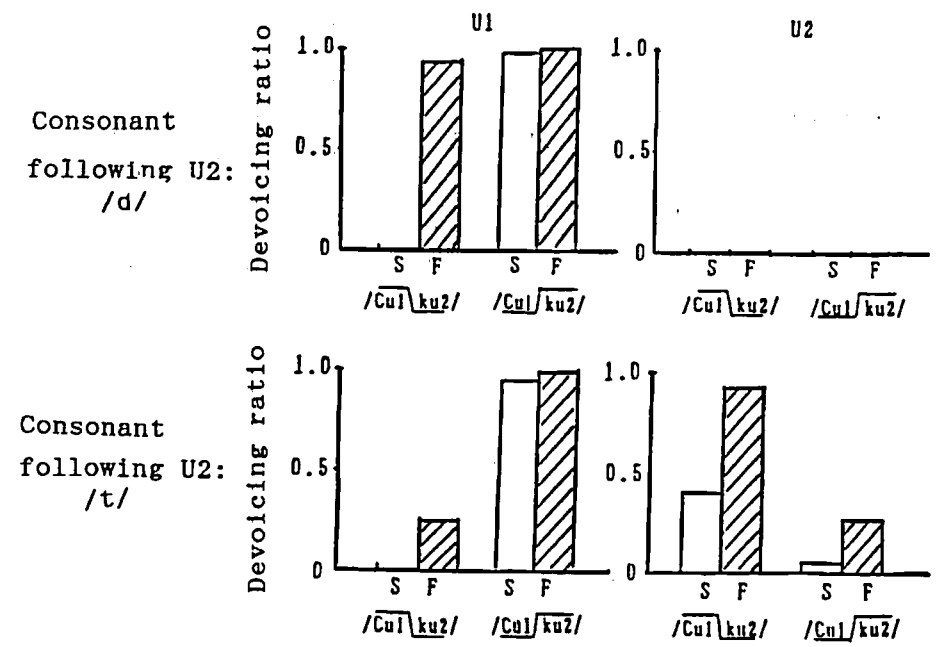

Fig. 3.6 Individual ratio of devoicing(Subject MT).
S: Slow speech rate F: Fast speech rate

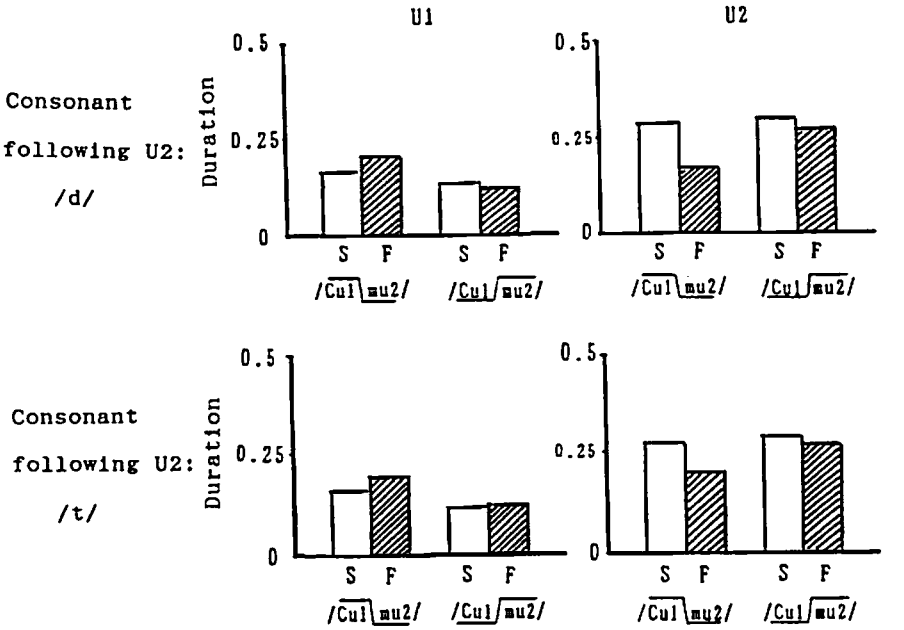

Fig. 4.1 Normalized duration of vowels(Subject MS).

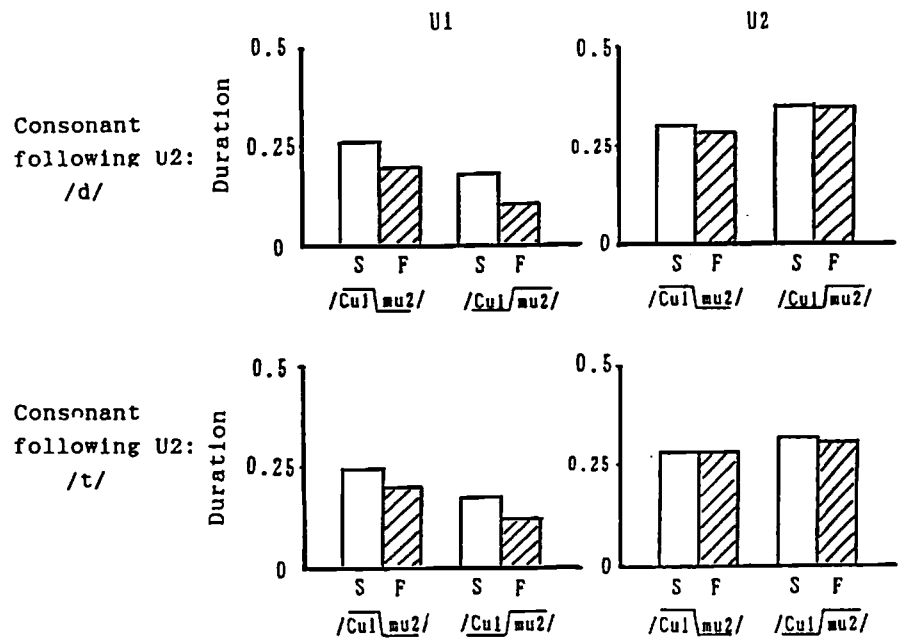

Fig. 4.2 Normalized duration of vowels(Subject FK).

S: Slow speech rate F: Fast speech rate