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Evaluation of the Speaker-Factor in Japanese VCV Utterances

Koh-ichi TABATA and Toshiyuki SAKAI

Summary

In order to evaluate the speaker-factor in uttered words, multivariate analysis of variance for four-factor design with repeated measurements has been applied to the analysis of the spectral vectors obtained from Japanese V_1CV_2 utterances by 10 adult male speakers, where V_1, V_2=/a, i, u, e, o/ and C=/m, n, η/. The speaker, the vowel V_1, the consonant C, and the vowel V_2 have been assigned to the four factors, respectively, and the interaction between speaker-factor and V_1, C, or V_2-factor has been especially interesting in the analysis.

As the results, what we should take into account as to the co-articulation of a certain phoneme are (1) the main effect of the phoneme, (2) the main effect of just preceding (or following) phoneme, (3) the interaction between the phoneme and just preceding (or following) phoneme, and (4) the main effect of the speaker-factor. The interactions between the speaker-factor and these phonemes are relatively small, and the influence of the speaker-factor to the co-articulation is not so complicated. These facts imply the possibility of the speaker-independent description about the phoneme and the rule of co-articulation.

1. Introduction

Multivariate analysis of variance had, for the first time, been applied to the analysis of speech sounds by the authors, considering the frequency components of speech spectra as the components of multi-dimensional vectors[1~4]. It has been found useful for the investigation of the co-articulation of phonemes or the difference of speakers in the analysis of uttered phoneme sequences.

In order to investigate the effect of speakers on the spectra, as reported in the authors' literatures (1) and (2), multivariate analysis of variance for four-factor design with single observation was applied to the Japanese V_1VC_2 (vowel-consonant-vowel) utterances like/ame/. Choosing one of /a, i, u, e, o/ for the initial vowel V_1 and the final vowel V_2, and one of /m, n, η/ for the consonant C, 75 kinds of words are obtained as all combinations. 375 utterances of these

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75 kinds of words by 5 adult male speakers were used for analysis. Four factors of the analysis of variance were assigned to speaker, V_1, C, and V_2, respectively. The results of the analysis will be shown in Fig. 4, from which we found the interesting properties of the speaker-factor.

In this paper, we have investigated and evaluated the properties of the speaker factor in further detail[5]. Multivariate analysis of variance for four-factor design with repeated measurements has been applied to the analysis of 2,250 utterances of the same 75 kinds of words as the above by 10 adult male speakers. The design with repeated measurements has been applied in order to reveal the "interaction" between the speaker-factor and the factors of phonemes.

2. Interaction

We had better understand the important role of the interaction in the analysis of variance.

In the field test of the crops by the analysis of variance, for example, it may be rather desirable to detect the large interaction between two kinds of artificial manures because it means the discovery of new effect by the combination of artificial manures.

From the viewpoint of the speech recognition, on the other hand, it may be desirable that the interaction between the factors of phonemes themselves, especially between the speaker factor and them, is smaller.

We will take the (multivariate) analysis of variance for two-factor design with repeated measurements in order to show the meaning of the interaction. Consider two factors — A and B, and assume $A_1 \sim A_a$ and $B_1 \sim B_b$ to be their levels or categories. Let x_{ijk} be the k-th observation under the i-th treatment (or level) of the factor A and j-th treatment of the factor B, then we have the linear model for the design,

$$x_{ijk}(1\times p)=\mu+\alpha_i+\beta_j+\gamma_{ij}+\varepsilon_{ijk}, \qquad (i=1, \ldots, a,\ j=1, \ldots, b,\ k=1, \ldots, r) \tag{1}$$

where,

$$\sum_{i=1}^{a}\alpha_i=\sum_{j=1}^{b}\beta_j=\sum_{i=1}^{a}\gamma_{ij}=\sum_{j=1}^{b}\gamma_{ij}=0, \tag{2}$$

and

$$\varepsilon_{ijk}\sim N(0, \Lambda): \text{multi-dimensional normal distribution.} \tag{3}$$

ε_{ijk} called the residual may be relatively small, and we do not mention it further here. α_i represents "main effect" of the treatment A_i, and β_i also represents "main effect" of the treatment B_j. γ_{ij} represents the effect specific to the combination of the treatment A_i and the treatment B_j, that is, the "interaction" between the factor A and the factor B.

If γ_{ij} is null or very small, we may provide a set of b patterns $\{\beta_1, \ldots, \beta_b\}$*

* The number of the independent patterns is $b-1$.

in order to explain x_{ijk} with respect to the factor B. Otherwise, we must provide another set of a•b patterns $\{\gamma_{11}, \ldots, \gamma_{ab}\}$* in addition to the above set, then the total number of the patterns becomes ab+b.

Now, we can discuss the role of the interaction from the viewpoint of speech sounds.

First, assume that the design is applied to the analysis of the co-articulation of CV utterances consisting of two successive phonemes, consonant (C) and vowel (V). Let x_{ijk} represent the spectral vector at the time point corresponding to the vowel portion of the CV utterances. In order to inspect the influence of the consonant C to the vowel V, the consonant C and the vowel V may be assigned to the factor A and the factor B, respectively, where the number of kinds of C is a, and that of V is b. If there were no interaction between C and V, γ_{ij} would be null, then we might provide b patterns $\beta_1, \ldots, \beta_b$ in order to explain the vowel component of x_{ijk}, where β_j represents j-th kind of vowel. On the other hand, if the interaction between C and V is not small, we must provide ab+b patterns. The number ab+b, however, is not terrible, for the kinds of both consonants and vowels are fixed.

Secondly, assume that the design is applied to the analysis of the speaker's effect on vowel utterances. The speaker S and the vowel V may be assigned to the factor A and the factor B, respectively, where the number of speakers is a, and the number of kinds of V is b. If there were no interaction between S and V, γ_{ij} would be null, then we might also provide b patterns $\beta_1, \ldots, \beta_b$ in order to explain the vowel component of x_{ijk}. Otherwise, we must provide ab+b patterns. In this case the number ab+b may become very large, because the number of speakers a is not finite in practical meaning. If γ_{ij}'s were much greater than β_j's, we might consider that each speaker had his own pattern of vowel not common to the all speakers. Conversely, if β_j's is much greater than γ_{ij}'s, then it may be considered that every speaker has the common pattern of vowel.

3. VCV UTTERANCES AND THEIR SPECTRA

Multivariate analysis of variance for four-factor design with repeated measurements has been applied to the analysis of speech spectra obtained from 2,250 Japanese V_1CV_2 utterances by 10 adult male speakers. The V_1CV_2 words consist of 75 combinations in which /a, i, u, e, o/ are chosen for the V_1 and V_2, and /m, n, η/ are chosen for the C. The speakers uttered the 75 words, three times each.

We will give a definition of speech spectra and procedure of segmentation.

When let $b_1(t), \cdots, b_p(t)$ (p=20) represent, in order, amplitude outputs of 20-channel 1/4-octave filters (bank of 20 filters whose center frequencies cover 210

* The number of the independent patterns is ab−a−b+1, then the total number of the independent patterns is (ab−a−b+1)+(b−1).

up to 5660 Hz) at time t, they are considered to represent speech spectra at that time. After normalizing the square sum of these components at 1, we establish p-dimensional vector x(t) by taking logarithm of its components. That is,

$$x_i(t) = \log \{b_i(t) / \sqrt{\sum_{j=1}^{p} b_j^2(t)}\}. \tag{4}$$

We define p-dimensional vector $x(t) = (x_1(t), \ldots, x_p(t))$ with Eq. (4) which would be used for the analysis $(p=20)$, and be called the spectral vector.

Amplitude outputs of the filter analyzer are A-D converted at intervals of 10 ms, then put into the computer in real time. On the paper of the line-printer we represent the speech spectrum patterns of the input with which we observe to determine the stationary parts or transition ones.

We define times $t_1, t_2, \ldots, t_9$ as Fig. 1, corresponding to the stationary or transition parts in each word.

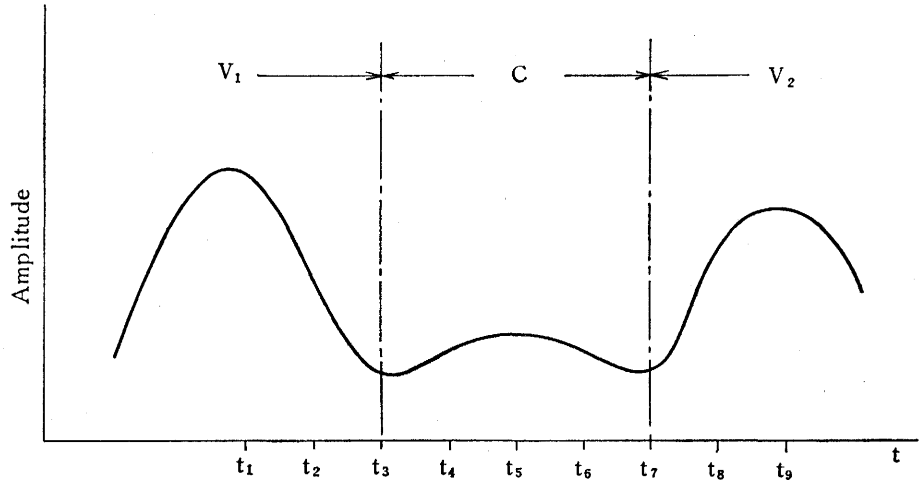


Fig. 1. Schematic representation of V_1CV_2 word and definition of t_i. $t=t_1$: stationary part of V_1, $t=t_3$: boundary of V_1-C, $t=t_5$: stationary part of C, $t=t_7$: boundary of $C-V_2$, $t=t_9$: stationary part of V_2. If i is even, $t_i=(t_{i+1}+t_{i-1})/2$.

4. Multivariate Analysis of Variance for Four-factor Design

Let $x(1\times p)$ be a p-dimensional random vector. The model and the statistical test for the multivariate analysis of variance for four-factor design with repeated measurements are shown as follows.

The linear model of multivariate analysis of variance for four-factor design with repeated measurements

$x_{ijklm}(1\times p) = \kappa$	general level
$+\alpha_i+\beta_j+\gamma_k+\delta_l$	main effect
$+\varepsilon_{ij}+\zeta_{ik}+\eta_{il}+\theta_{jk}+\lambda_{jl}+\mu_{kl}$	two-factor interaction

$+\nu_{ijk}+\rho_{ijl}+\sigma_{ikl}+\tau_{jkl}$ three-factor interaction
$+\varphi_{ijkl}$ four-factor interaction
$+\chi_{ijklm},$ residual (5)

where $1\leqq i\leqq a$, $1\leqq j\leqq b$, $1\leqq k\leqq c$, $1\leqq l\leqq d$ and $1\leqq m\leqq e$ (See Table 1). The constants a, b, c and d are the numbers of levels of the factor A, B, C and D, respectively. The constant e is the number of repetitions.

Table 1. Multivariate analysis of variance for four-factor design with repeated measurements.

	Factor	Effect vector	Q_i
Main effect	A	α_i	Q_1
	B	β_j	Q_2
	C	γ_k	Q_3
	D	δ_l	Q_4
Two-factor interaction	AB	ε_{ij}	Q_5
	AC	ζ_{ik}	Q_6
	AD	η_{il}	Q_7
	BC	θ_{jk}	Q_8
	BD	λ_{jl}	Q_9
	CD	μ_{kl}	Q_{10}
Three-factor interaction	ABC	ν_{ijk}	Q_{11}
	ABD	ρ_{ijl}	Q_{12}
	ACD	σ_{ikl}	Q_{13}
	BCD	τ_{jkl}	Q_{14}
Four-factor interaction	ABCD	φ_{ijkl}	Q_{15}

The general level vector $\kappa(1\times p)$ is determined in order that effect vectors $\alpha_i(1\times p)\sim\varphi_{ijkl}(1\times p)$ satisfy the following conditions:

$$\sum_{i=1}^{a}\alpha_i=0,\ \sum_{j=1}^{b}\beta_j=0,\ \sum_{k=1}^{c}\gamma_k=0,\ \sum_{l=1}^{d}\delta_l=0,$$
$$\sum_{i=1}^{a}\varepsilon_{ij}=\sum_{j=1}^{b}\varepsilon_{ij}=0,\ \sum_{i=1}^{a}\zeta_{ik}=\sum_{k=1}^{c}\zeta_{ik}=0,\ \sum_{i=1}^{a}\eta_{il}=\sum_{l=1}^{d}\eta_{il}=0,$$
$$\sum_{j=1}^{b}\theta_{jk}=\sum_{k=1}^{c}\theta_{jk}=0,\ \sum_{j=1}^{b}\lambda_{jl}=\sum_{l=1}^{d}\lambda_{jl}=0,\ \sum_{k=1}^{c}\mu_{kl}=\sum_{l=1}^{d}\mu_{kl}=0,$$
$$\sum_{i=1}^{a}\nu_{ijk}=\sum_{j=1}^{b}\nu_{ijk}=\sum_{k=1}^{c}\nu_{ijk}=0,\ \sum_{i=1}^{a}\rho_{ijl}=\sum_{j=1}^{b}\rho_{ijl}=\sum_{l=1}^{d}\rho_{ijl}=0,$$
$$\sum_{i=1}^{a}\sigma_{ikl}=\sum_{k=1}^{c}\sigma_{ikl}=\sum_{l=1}^{d}\sigma_{ikl}=0,\ \sum_{j=1}^{b}\tau_{jkl}=\sum_{k=1}^{c}\tau_{jkl}=\sum_{l=1}^{d}\tau_{jkl}=0,$$
$$\sum_{i=1}^{a}\varphi_{ijkl}=\sum_{j=1}^{b}\varphi_{ijkl}=\sum_{k=1}^{c}\varphi_{ijkl}=\sum_{l=1}^{d}\varphi_{ijkl}=0. \tag{6}$$

Besides, assume that

$$\chi_{ijklm}\sim N(0,\Lambda), \tag{7}$$

that is, χ_{ijklm} is assumed to be independently distributed according to the p-dimensional normal distribution $N(0,\Lambda)$.

The breakdown of total variance

Let "$'$" denote the transposed matrix, then the breakdown of total variance $Q(p\times p)$ (matrix of sums of squares and cross products) is as follows: (See Table 1.)

$$\begin{aligned}Q=&Q_1+Q_2+Q_3+Q_4+Q_5+Q_6+Q_7+Q_8+Q_9+Q_{10}\\&+Q_{11}+Q_{12}+Q_{13}+Q_{14}+Q_{15}+R,\end{aligned}\tag{8}$$

where

$$Q=\sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{c}\sum_{l=1}^{d}\sum_{m=1}^{e}(x_{ijklm}-x_{.....})'(x_{ijklm}-x_{.....}),$$

$$Q_1=bcde\sum_{i=1}^{a}(x_{i....}-x_{.....})'(x_{i....}-x_{.....}),$$

$$Q_2=acde\sum_{j=1}^{b}(x_{.j...}-x_{.....})'(x_{.j...}-x_{.....}),$$

$$Q_3=abde\sum_{k=1}^{c}(x_{..k..}-x_{.....})'(x_{..k..}-x_{.....}),$$

$$Q_4=abce\sum_{l=1}^{d}(x_{...l.}-x_{.....})'(x_{...l.}-x_{.....}),$$

$$Q_5=cde\sum_{i=1}^{a}\sum_{j=1}^{b}(x_{ij...}-x_{i....}-x_{.j...}+x_{.....})'(x_{ij...}-x_{i....}-x_{.j...}+x_{.....}),$$

$$Q_6=bde\sum_{i=1}^{a}\sum_{k=1}^{c}(x_{i.k..}-x_{i....}-x_{..k..}+x_{.....})'(x_{i.k..}-x_{i....}-x_{..k..}+x_{.....}),$$

$$Q_7=bce\sum_{i=1}^{a}\sum_{l=1}^{d}(x_{i..l.}-x_{i....}-x_{...l.}+x_{.....})'(x_{i..l.}-x_{i....}-x_{...l.}+x_{.....}),$$

$$Q_8=ade\sum_{j=1}^{b}\sum_{k=1}^{c}(x_{.jk..}-x_{.j...}-x_{..k..}+x_{.....})'(x_{.jk..}-x_{.j...}-x_{..k..}+x_{.....}),$$

$$Q_9=ace\sum_{j=1}^{b}\sum_{l=1}^{d}(x_{.j.l.}-x_{.j...}-x_{...l.}+x_{.....})'(x_{.j.l.}-x_{.j...}-x_{...l.}+x_{.....}),$$

$$Q_{10}=abe\sum_{k=1}^{c}\sum_{l=1}^{d}(x_{..kl.}-x_{..k..}-x_{...l.}+x_{.....})'(x_{..kl.}-x_{..k..}-x_{...l.}+x_{.....}),$$

$$\begin{aligned}Q_{11}=de\sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{c}&(x_{ijk..}-x_{ij...}-x_{i.k..}-x_{.jk..}+x_{i....}+x_{.j...}+x_{..k..}-x_{.....})'\\&\cdot(x_{ijk..}-x_{ij...}-x_{i.k..}-x_{.jk..}+x_{i....}+x_{.j...}+x_{..k..}-x_{.....}),\end{aligned}$$

$$\begin{aligned}Q_{12}=ce\sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{l=1}^{d}&(x_{ij.l.}-x_{ij...}-x_{i..l.}-x_{.j.l.}+x_{i....}+x_{.j...}+x_{...l.}-x_{.....})'\\&\cdot(x_{ij.l.}-x_{ij...}-x_{i..l.}-x_{.j.l.}+x_{i....}+x_{.j...}+x_{...l.}-x_{.....}),\end{aligned}$$

$$\begin{aligned}Q_{13}=be\sum_{i=1}^{a}\sum_{k=1}^{c}\sum_{l=1}^{d}&(x_{i.kl.}-x_{i.k..}-x_{i..l.}-x_{..kl.}+x_{i....}+x_{..k..}+x_{...l.}-x_{.....})'\\&\cdot(x_{i.kl.}-x_{i.k..}-x_{i..l.}-x_{..kl.}+x_{i....}+x_{..k..}+x_{...l.}-x_{.....}),\end{aligned}$$

$$\begin{aligned}Q_{14}=ae\sum_{j=1}^{b}\sum_{k=1}^{c}\sum_{l=1}^{d}&(x_{.jkl.}-x_{.jk..}-x_{.j.l.}-x_{..kl.}+x_{.j...}+x_{..k..}+x_{...l.}-x_{.....})'\\&\cdot(x_{.jkl.}-x_{.jk..}-x_{.j.l.}-x_{..kl.}+x_{.j...}+x_{..k..}+x_{...l.}-x_{.....}),\end{aligned}$$

$$\begin{aligned}Q_{15}=e\sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{c}\sum_{l=1}^{d}&(x_{ijkl.}-x_{ijk..}-x_{ij.l.}-x_{i.kl.}-x_{.jkl.}+x_{ij...}+x_{i.k..}\\&+x_{i..l.}+x_{.jk..}+x_{.j.l.}+x_{..kl.}-x_{i....}-x_{.j...}-x_{..k..}-x_{...l.}+x_{.....})'\\&\cdot(x_{ijkl.}-x_{ijk..}-x_{ij.l.}-x_{i.kl.}-x_{.jkl.}+x_{ij...}+x_{i.k..}+x_{i..l.}+x_{.jk..}\end{aligned}$$

$$+x_{.j.l.}+x_{..kl.}-x_{i....}-x_{.j...}-x_{..k..}-x_{...l.}+x_{.....}),$$

$$R=\sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{c}\sum_{l=1}^{d}\sum_{m=1}^{e}(x_{ijklm}-x_{ijkl.})'(x_{ijklm}-x_{ijkl.}),$$

and

$$x_{.....}=\frac{1}{abcde}\sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{c}\sum_{l=1}^{d}\sum_{m=1}^{e}x_{ijklm},$$

$$x_{i....}=\frac{1}{bcde}\sum_{j=1}^{b}\sum_{k=1}^{c}\sum_{l=1}^{d}\sum_{m=1}^{e}x_{ijklm},\ \ldots,\ x_{...l.}=\frac{1}{abce}\sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{c}\sum_{m=1}^{e}x_{ijklm},$$

$$x_{ij...}=\frac{1}{cde}\sum_{k=1}^{c}\sum_{l=1}^{d}\sum_{m=1}^{e}x_{ijklm},\ \ldots,\qquad x_{.j.l.}=\frac{1}{ace}\sum_{i=1}^{a}\sum_{k=1}^{c}\sum_{m=1}^{e}x_{ijklm},\ \ldots,$$

$$x_{ijk..}=\frac{1}{de}\sum_{l=1}^{d}\sum_{m=1}^{e}x_{ijklm},\ \ldots,\qquad x_{i.kl.}=\frac{1}{be}\sum_{j=1}^{b}\sum_{m=1}^{e}x_{ijklm},\ \ldots,$$

$$x_{ijkl.}=\frac{1}{e}\sum_{m=1}^{e}x_{ijklm}.$$

The likelihood ratio test for null hypothesis

Let us consider a test of the hypothesis for the main effect of factor A that all the effects of A's levels are equal (there is no effect of A);

$$H_A(t):\ \alpha_1=\ \ldots\ =\alpha_a=0 \tag{9}$$

We can test the hypothesis since it is possible to prove that the likelihood ratio criterion

$$\nu=\left\{n-l_2-\frac{1}{2}(p+l_1+1)\right\}\log\frac{|Q_1+R|}{|R|} \tag{10}$$

is distributed asymptotically according to χ^2-distribution with pl_1 degrees of freedom under the conditions—$n=a\cdot b\cdot c\cdot d\cdot e$, $l_1=a-1$, $l_1+l_2=abcd$, and $n-abcd \geqq p$—when n is sufficiently large.

Table 2. Degrees of freedom of Q_i; $l_1+l_2=abcd$, and degrees of freedom of R is $n-abcd$ ($n=abcde$).

Factor	Q_i	l_1
A	Q_1	$a-1$
B	Q_2	$b-1$
C	Q_3	$c-1$
D	Q_4	$d-1$
AB	Q_5	$ab-a-b+1$
AC	Q_6	$ac-a-c+1$
AD	Q_7	$ad-a-d+1$
BC	Q_8	$bc-b-c+1$
BD	Q_9	$bd-b-d+1$
CD	Q_{10}	$cd-c-d+1$
ABC	Q_{11}	$abc-ab-ac-bc+a+b+c-1$
ABD	Q_{12}	$abd-ab-ad-bd+a+b+d-1$
ACD	Q_{13}	$acd-ac-ad-cd+a+c+d-1$
BCD	Q_{14}	$bcd-bc-bd-cd+b+c+d-1$
ABCD	Q_{15}	$abcd-abc-abd-acd-bcd+ab+ac+ad+bc+bd+cd-a-b-c-d+1$

The hypotheses concerned with the other factors or interactions may be tested in the similar way with the each corresponding Q_1, l_1, and l_2 shown in Table 2.

5. The Evaluation of the Speaker-factor in VCV Utterances

Multivariate analysis of variance for four-factor design with repeated measurements mentioned in the section 4 has been applied to the analysis of the spectral vectors at the each time point t_i obtained from the 2,250 utterances mentioned in the section 3 (As $i=1, \ldots, 9$, the total number of the analyses is 9).

The speaker S, the vowel V_1, the consonant C, and the vowel V_2 have been assigned to the factor A, B, C, and D, respectively, where $a=10$, $b=5$, $c=3$, $d=5$, and $e=3$. Then, we have computed respectively the test criterion ν (Eq. (10)) for the hypothesis that there is no effect of each factor or no interaction between each factor. We have normalized ν by the value of significant level as the following equation, because the degrees of freedom corresponding to main effects and interactions are different from each other and so are the values of 1% significant level of χ^2 test different from each other (See Table 2).

$$\nu' = \frac{\nu}{\text{(Value of 1\% significant level of } \chi^2 \text{ test corresponding to the degrees of freedom of } \nu)} \tag{11}$$

The value of the normalized criterion ν' is shown in Fig. 2.

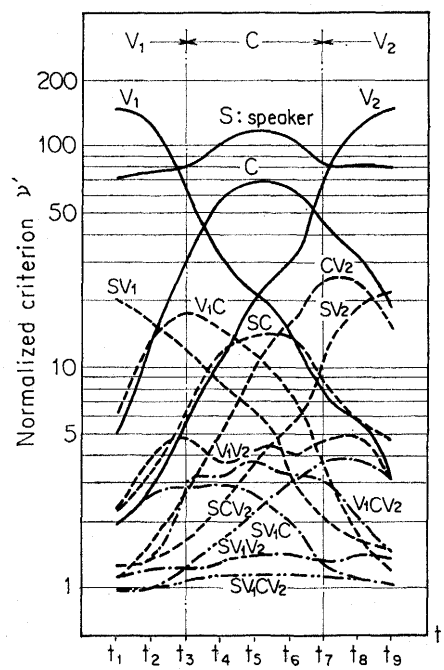


Fig. 2. Multivariate analysis of variance for four-factor design with repeated measurements (S: speaker).

From Fig. 2, it may be said that

(1) The main effect of the speaker-factor is relatively large at overall time points, especially larger than that of the consonant-factor at the stationary part of the nasal consonant. It is the second largest factor at the stationary part of the vowel:

(2) The interaction between the speaker-factor and the vowel (V_1 or V_2)-factor is much smaller than the main effect of the speaker-factor or the vowel-factor:

(3) The interaction between the speaker-factor and the consonant-factor is much smaller than the main effect of the speaker-factor or the consonant-factor:

(4) The interaction between the speaker-factor and the vowel-factor is larger than the main effect of the consonant-factor at the stationary part of the vowel, while it is smaller than the interaction between the consonant-factor and the vowel-factor at the boundary between the consonant and the vowel ($t=t_7$) where the important information about the consonant seems to exist. (See the next section.):

(5) The stationary part of the consonant may be almost explained by the main effects of the four factors.

In conclusion, what we should take into account as to the co-articulation of a certain phoneme are (1) the main effect of the phoneme, (2) the main effect of the just preceding (or following) phoneme, (3) the interaction between the phoneme and the just preceding (or following) phoneme, and (4) the main effect of the speaker-factor. The interactions between the speaker-factor and these phonemes are relatively small, and the influence of the speaker-factor to the co-articulation is not so complicated. These facts imply the possibility of the speaker-independent description about the phoneme and the rule of co-articulation.

6. DISCUSSION

In order to make sure of the results, we compare them with our other results obtained previously.

Fig. 3 shows the multivariate analysis of variance for four-factor design with repeated measurements applied to Japanese $C_1V_1C_2V_2$ utterances by one adult male speaker, where C_1, C_2=/p, t, k, b, d, g, m, n, η/ and V_1, V_2=/a, e, o/[4]. The major behavior of Fig. 3 is similar to that of Fig. 2 except for the speaker-factor.

Fig. 4 shows the multivariate analysis of variance for four-factor design with single observation applied to Japanese V_1CV_2 utterances by 5 adult male speakers, where V_1, V_2=/a, i, u, e, o/ and C=/m, n, η/[1~3]. The behavior of Fig. 4 is similar to that of Fig. 2 except for the interactions.

Fig. 5 shows the multivariate analysis of variance for three-factor design

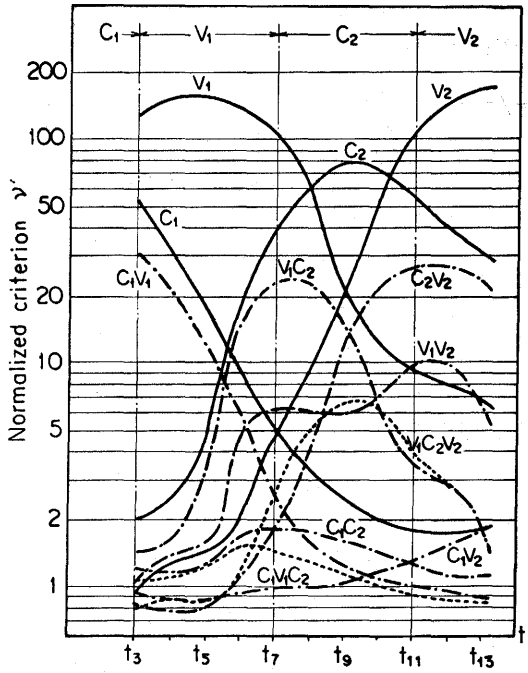


Fig. 3. Multivariate analysis of variance for four-factor design with repeated measurements.

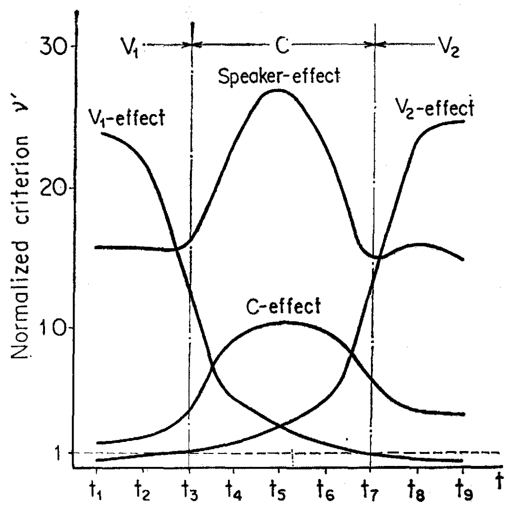
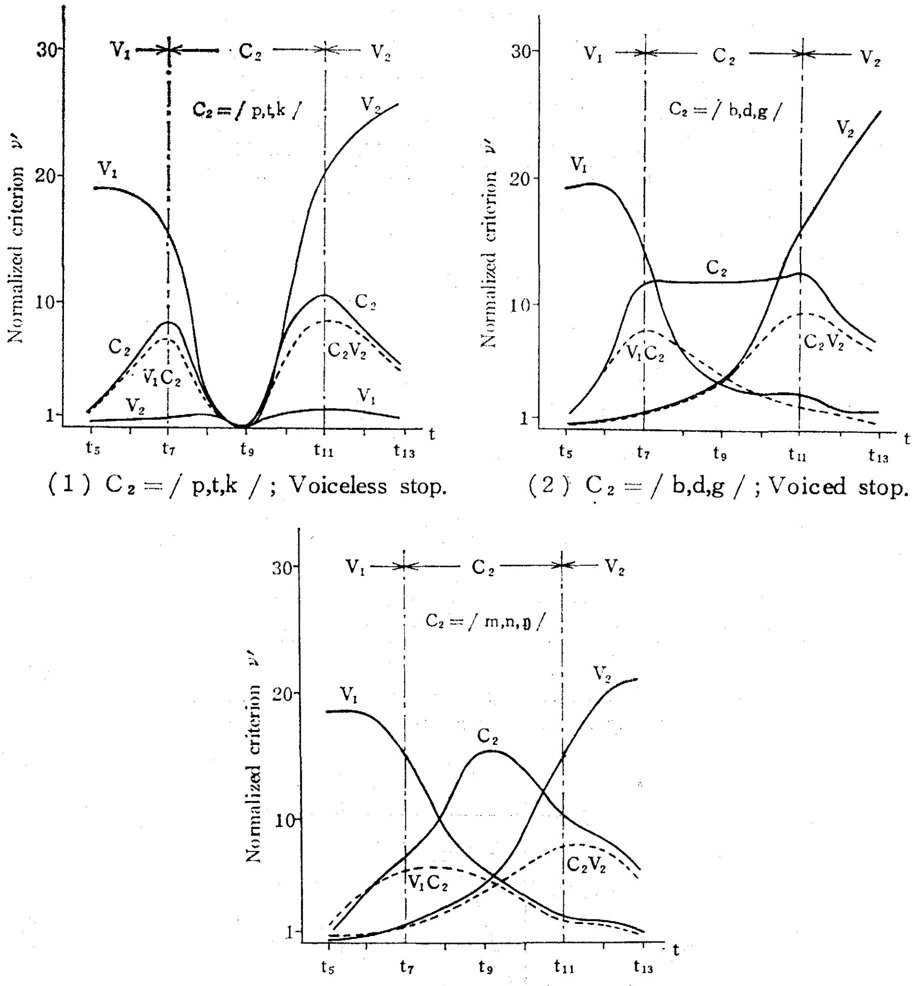


Fig. 4. Multivariate analysis of variance for four-factor design with single observation.

with repeated measurements applied to the same utterances as Fig. 3 by ignoring C_1[4]. It shows that there may be the important imformation about the consonant at the boundary between the consonant and the vowel. (See (4) in the section 5.)



(1) $C_2 = / p,t,k /$; Voiceless stop. (2) $C_2 = / b,d,g /$; Voiced stop.

(3) $C_2 = / m,n,\eta /$; Nasal.

Fig. 5. Multivariate analysis of variance for three-factor design with repeated measurements. V_1, V_2=/a, e, o/.

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