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Factor Analysis of Environmental Variation in the Permanent Dentition

By

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We have at present several hypotheses attempting to explain how the morphological conditions observed in our dentition have been gained, *e.g.*, the field hypothesis (BUTLER, 1939; DAHLBERG, 1945, 1951), the "terminale Reduktion" hypothesis extended from BOLK's one (FUJITA, 1958, 1973), the clone model (OSBORN, 1978), *etc.* These hypotheses concern phylogenetic or ontogenetic formation of a dental system, but not the practical condition of the causes, genetic and environmental, acting on the dental system. On the other hand, there are many studies on the genetic and environmental factors influencing dental formation. Among others, OSBORNE *et al.* (1958) discussed the possibility of the dependency of genetic size differences between the teeth upon the differential developmental periods. SOFAER *et al.* (1971, 1972) discussed the relationships of the developmental timing to the genetic and environmental variabilities in human teeth. MOSS and MOSS-SALENTIJN (1977) and MOSS (1978) suggested that the between-sex difference of the periods for amelogenesis caused a sexual dimorphism in size of human canines. MIZOGUCHI (1977b) demonstrated that the genetic variability in small components of the crowns of the upper and lower first molars was lower than that of the whole crown size, and discussed the possible existence of a developmental pathway or a process for the integration between the small components and the whole crown in the same tooth. All these studies suggest that there must remain some influences of the differential developmental periods on the completed dental system.

However, it is still unknown how genetic and environmental factors and their interactions influence the forming dental system as a whole with the differential developmental periods of the teeth. This paper presents an attempt to find correspondency, if any, of the differential developmental periods with the factors, especially environmental ones, extracted from a set of completed tooth crown diameters.

Materials

Dental plaster casts from 272 Japanese monozygous (MZ) twin pairs of nine to sixteen years of age, of which 137 pairs were males and 135 pairs were females, were used. These casts were collected in 1950's by the project team for general twin studies supported by the grant in aid for scientific research of the Ministry of Education of Japan, and are stored in the Department of Anatomy, the University of Tokyo. Perma-

nent teeth, the central incisors through the second molars, on the right side of both jaws were measured on the casts by the present writer. The method of measurements adopted is that of FUJITA (1949). The mesiodistal diameters of tooth crowns were measured with a sliding caliper with an accuracy of 0.05 mm.

The list of the mesiodistal crown diameters of a sample of Japanese consisting of 50 males and 50 females presented by HANIHARA and KOIZUMI (1979) afforded additional data for this study.

Methods

In order to clarify the complicated condition of genetic and environmental factor interactions behind a dental system, the following statistical methods were successively used under some simple assumptions.

Estimation of heritability

An unbiased estimate of the intraclass correlation coefficient, r, was obtained by the following formula on the basis of the analysis of variance in one-way classification for the MZ twin sample (KEMPTHORNE, 1969).

$$r=\frac{(V_B-V_W)/2}{(V_B-V_W)/2+V_W}, \tag{1}$$

where V_B is an unbiased estimate of the between-class variance and V_W is that of the within-class variance. The sampling variance of r, $V(r)$, is as follows (KEMPTHORNE, 1969).

$$V(r)=\frac{V(X)}{Y^2}-\frac{2X\cdot Cov(X,Y)}{Y^3}+\frac{X^2V(Y)}{Y^4}, \tag{2}$$

where

$$X=(V_B-V_W)/2\,, \qquad Y=(V_B-V_W)/2+V_W\,,$$
$$V(X)=V(Y)=Cov(X,Y)=\frac{1}{2}\left[\frac{{V_B}^2}{n+1}+\frac{{V_W}^2}{n+2}\right],$$

in which n is the number of twin pairs.

For an intraclass correlation coefficient between MZ twins to be regarded as a heritability estimate in a broad sense, it should at least be assumed, first, that many genetic and environmental factors with a subtle effect influence a character in question and their effects of all kinds are additive; second, that there is no genotype-environment interaction; and third, that there is no common environmental variance within twin pairs.

Genetic and environmental correlations based on a cross twin analysis

Phenotypic correlations between characters can be partitioned into genetic and environmental correlations (FALCONER, 1960) using a cross twin analysis (OSBORNE *et al.*, 1958), at least, under the assumption that there is no genotype-environment inter-

action. The genetic correlation between two characters is supposed to be caused mainly by pleiotropic action of genes, and the environmental correlations, to be due to the influence of the same differences of environmental conditions on two characters (FALCONER, 1960). The formula for a genetic correlation coefficient, r_G, used here is as follows (FALCONER, 1954, 1960; REEVE, 1955).

$$r_G = \frac{r_{XY}}{\sqrt{r_{XX} r_{YY}}} , \tag{3}$$

where r_{XX} and r_{YY} are the intraclass correlation coefficients on the characters X and Y, respectively, between MZ twins, and r_{XY} is the cross twin correlation, *i.e.*, PEARSON's product-moment correlation coefficient between X of twin A and Y of twin B. An environmental correlation coefficient, r_E, between two characters was obtained by the use of the following formula (FALCONER, 1954, 1960).

$$r_E = \frac{r_P - h_X h_Y r_G}{e_X e_Y} , \tag{4}$$

where r_P is the phenotypic correlation, *i.e.* PEARSON's product-moment correlation coefficient between two characters, X and Y, and h_X^2 and h_Y^2 are the heritabilities for X and Y, respectively. The relationship of h_X^2 and e_X^2 or of h_Y^2 and e_Y^2 is as follows.

$$h_X^2 + e_X^2 = 1 , \qquad h_Y^2 + e_Y^2 = 1 .$$

Of the above quantities, two estimates obtained for each of r_P and r_{XY} from the MZ twin sample were averaged by the method using FISHER's z-transformation (MATHER, 1951; RAO, 1952).

Factor analysis

There are two types of factor analysis: exploratory and confirmatory (JÖRESKOG and LAWLEY, 1968).

In the present study, JÖRESKOG's (1967) maximum likelihood factor analysis of exploratory type was first used in order to determine the number of common factors needed to account adequately for a set of variables on the human dentition. In this case, the factor correlation matrix was assumed to be a unit matrix, or the common factors were assumed to be orthogonal or uncorrelated. The solution obtained was then transformed by KAISER's normal varimax rotation method (OKUNO *et al.*, 1971; ASANO, 1971) to find a more meaningful interpretation.

Secondly, the restricted factor analysis of confirmatory type was employed to test a simple structure hypothesis (JÖRESKOG, 1966) formulated on the basis of the rotated solution mentioned above. In this case, it was assumed that the common factors might be correlated or oblique. The method used here is, in practice, LAWLEY and MAXWELL's (1963) approximate method for estimating the factor loadings on the correlated factors.

In addition, the combination of principal component analysis (LAWLEY and MAXWELL, 1963; OKUNO *et al.*, 1971, 1976; TAKEUCHI and YANAI, 1972) and KAISER's

normal varimax method was employed chiefly to examine the difference in efficiency between the exploratory maximum likelihood factor analysis and the principal component analysis in the case of searching for a simple structure of factors behind a system of characters.

Methods of calculation

Calculations for the analysis of variance, the intraclass correlation coefficients as well as the genetic and environmental correlations were processed using the computer program, MIVCRL, written in FORTRAN, in which the subroutine subprogram NORMAL contained in PLAS[1] was utilized. The maximum likelihood factor analysis of exploratory type and the principal component analysis were performed using the FORTRAN programs, MLFAEP and PCAFPP, respectively. The above calculations were carried out by a HITAC 8800/8700 (OS-7) computer of the University of Tokyo Computer Centre.

The approximate restricted factor analysis of confirmatory type was processed by the use of the program, AEF, written in BASIC with SORD M223-MARK II microcomputer in the Department of Anthropology, National Science Museum, Tokyo.

All the programs used here were coded by the present writer.

Results and Discussion

Preparatory to factor analyses, it was tested whether there was any sexual dimorphism for the variance and the intraclass correlation coefficient within MZ twin pairs on each of the mesiodistal diameters as well as for each of the inter-character correlation coefficients between the teeth.

Between-sex difference

It has been reported that there are significant between-sex differences in the means of some mesiodistal crown diameters of the permanent dentition (HANIHARA and KOIZUMI, 1979). MIZOGUCHI (1977a), observing a twin sample which is almost the same with the present sample, also recognized such differences in all the teeth from the central incisors to the first molars of both jaws except for the upper first and second premolars and for the lower lateral incisor.

As regards the phenotypic variances of the mesiodistal diameters, only the upper and lower first molars exhibited significant sexual dimorphism (Table 1). Further, Table 2 shows that there are significant between-sex differences of the intraclass correlation coefficients between MZ twins in the upper and lower first molars and in the lower canines at the level of 5% or less, and in the upper canines at the 10% level. These four teeth have no significant between-sex difference at the 5% level in the mean intrapair variance within MZ twin pairs except for the lower canine in which the male variance is greater than the female one (Table 1).

[1] Program Library for Anthropological Statistics (ed. K. HANIHARA, 1974).

Table 1. Between-sex differences in variance of the mesiodistal diameters on the MZ twin sample[1].

	Total var. (d.f.)		*F*-ratio	Intrapair var. (d.f.)		*F*-ratio
	Male	Female		Male	Female	
I^1	.2139 (241)	.2130 (235)	1.0042	.0448 (121)	.0362 (118)	1.2376
I^2	.3741 (243)	.4462 (245)	1.1927	.0623 (122)	.0877 (123)	1.4077*
C^-	.1597 (159)	.1797 (195)	1.1252	.0639 (80)	.0512 (98)	1.2480
P^1	.1519 (185)	.1748 (209)	1.1508	.0248 (93)	.0340 (105)	1.3710
P^2	.1486 (127)	.1676 (159)	1.1279	.0258 (64)	.0382 (80)	1.4806
M^1	.2711 (221)	.3516 (223)	1.2969**	.0699 (111)	.0633 (112)	1.1043
M^2	.2129 (31)	.2352 (51)	1.1047	.0719 (16)	.0592 (26)	1.2145
I_1	.0970 (187)	.1016 (209)	1.0474	.0174 (94)	.0242 (105)	1.3908
I_2	.1290 (217)	.1454 (225)	1.1271	.0199 (109)	.0253 (113)	1.2714
C_-	.1416 (189)	.1586 (231)	1.1201	.0474 (95)	.0295 (116)	1.6068**
P_1	.1811 (173)	.1706 (231)	1.0615	.0348 (87)	.0332 (116)	1.0482
P_2	.1920 (113)	.1595 (165)	1.2038	.0515 (57)	.0439 (83)	1.1731
M_1	.2460 (173)	.3663 (171)	1.4890***	.0784 (87)	.0713 (86)	1.0996
M_2	.4802 (23)	.2760 (51)	1.7399	.1375 (12)	.0738 (26)	1.8631

[1] Total variance and the mean intrapair variance from the analysis of variance in one-way classification.

* $P<0.10$; ** $P<0.05$; *** $P<0.01$, by two-tailed *F*-test.

Table 2. Intraclass correlation coefficients within MZ twin pairs as rough estimates of heritabilities (h^2) for the mesiodistal diameters.

	$h^2 \pm$S.E. (No. of pairs)		Normal deviate[1]
	Male	Female	
I^1	0.7912 ± 0.0241 (121)	0.8305 ± 0.0202 (118)	1.2498
I^2	0.8342 ± 0.0195 (122)	0.8041 ± 0.0226 (123)	1.0084
C^-	0.6011 ± 0.0517 (80)	0.7163 ± 0.0351 (98)	1.8435*
P^1	0.8372 ± 0.0219 (93)	0.8062 ± 0.0242 (105)	0.9498
P^2	0.8276 ± 0.0278 (64)	0.7733 ± 0.0318 (80)	1.2856
M^1	0.7431 ± 0.0302 (111)	0.8208 ± 0.0218 (112)	2.0861**
M^2	0.6697 ± 0.0963 (16)	0.7519 ± 0.0597 (26)	0.7255
I_1	0.8214 ± 0.0237 (94)	0.7628 ± 0.0290 (105)	1.5646
I_2	0.8466 ± 0.0192 (109)	0.8269 ± 0.0210 (113)	0.6923
C_-	0.6663 ± 0.0409 (95)	0.8145 ± 0.0221 (116)	3.1879***
P_1	0.8089 ± 0.0262 (87)	0.8061 ± 0.0230 (116)	0.0803
P_2	0.7335 ± 0.0434 (57)	0.7262 ± 0.0369 (83)	0.1281
M_1	0.6827 ± 0.0410 (87)	0.8062 ± 0.0267 (86)	2.5241**
M_2	0.7227 ± 0.0948 (12)	0.7363 ± 0.0630 (26)	0.1195

[1] Normal deviate for the between-sex difference of h^2 was directly obtained using unbiased estimates of h^2 and their standard errors.

* $P<0.10$; ** $P<0.05$; *** $P<0.01$.

From the above, it is most likely that the mean mesiodistal crown size is greater in males than in females, but the variances, especially genetic variances, at least of the canines and the first molars of both jaws, are lesser in males than in females. It should be noted, however, that there is a possibility of the intraclass correlation coefficients between MZ twins or rough estimates of relative genetic variance containing considerable amount of environmental variance, as was pointed out by MIZOGUCHI (1977a). HANIHARA and KOIZUMI's (1979) data, however, revealed no significant difference in variance between sexes for any of the teeth from the central incisors to the second molars of both jaws.

LUNDSTRÖM (1977) reported that the sister-sister correlations were greater than the brother-brother or sister-brother correlations, but BOWDEN and GOOSE (1969) and TOWNSEND and BROWN (1978) found no evidence of sexual dimorphism in the correlations between relatives. This is not surprising because, if the populations treated were different, the conditions would be different from one another, both genetically and environmentally, as shown by HANIHARA (1978).

Although TOWNSEND and BROWN (1978) reported for Australian Aboriginals that there was no trend of the inter-character correlations in females exceeding those in males, eight of 66 inter-character correlation coefficient pairs in the present sample showed such between-sex differences significant at the level of 5% or less. HANIHARA and KOIZUMI's (1979) data also exhibited significant differences of the same kind in four of 66 correlation pairs.

After all, the succeeding analyses were performed on the basis of sexually segregated data because of the statistically significant between-sex differences of mean values, variances, intraclass correlations and inter-character correlations in some of the teeth.

Methodological problems

Before discussing the results of the factor analyses, some comments will be given on the methodological problems. The most fundamental one is that the indices based on the variances, *e.g.*, an *F*-ratio, a variety of correlation coefficients, or heritabilities, never present any information on the basic and stable part of the characters (EDWARDS, 1969; CAVALLI-SFORZA and BODMER, 1971) as represented by the mean values. The results based on such indices, therefore, should be interpreted always keeping our mind on this restriction. This is also imposed on most of the multivariate analyses including a factor analysis and a principal component analysis used in biological studies.

The next problem is concerned with a factor analysis. Its usefulness has long been debated and the controversy is not yet settled completely. Among a variety of procedures called "factor analysis," only the maximum likelihood factor analysis presents efficient estimates of factor loadings (LAWLEY and MAXWELL, 1963). Of the maximum likelihood factor analyses, the JÖRESKOG's (1967) method, which was used here, is highly evaluated as an excellent one with the rapid convergence (OKUNO *et al.*, 1976). However, even this method has a few drawbacks such as arriving sometimes

at different solutions depending on the choice of initial values or at improper solutions more often than usually expected (JÖRESKOG, 1967; TUMURA, 1971). One of the greatest disadvantages in the factor analysis is that the sufficient conditions for uniqueness of a factor model is not yet known (JÖRESKOG and LAWLEY, 1968; OKUNO *et al.*, 1971). Therefore, TUMURA (1971) recommended the combined method of a principal component analysis and transformation of the solution in stead of the factor analysis. The principal component analysis is surely a powerful method for data reduction problems (ZEGURA, 1978), but is at best an approximate method for searching a factor structure concealed in a set of variables. If the estimated correlations from the factor loadings obtained were verified to be extremely close to the observed correlations, it might be said that the factor analysis is the most appropriate procedure for finding a factor structure, as was stated by OKUNO *et al.* (1976). This could hardly be achieved by the principal component analysis unless almost all the principal components were taken into account. The improper solutions in the exploratory maximum likelihood factor analysis may, in fact, not be a solution (TUMURA, 1971), but this problem seems to be derived mainly from the assumption that there is no interaction between factors. In most biological data, this assumption appears to be far away from the fact. It is the case also in the principal component analysis. In order to gain an insight into the simple factor structure, however, it seems that the use of such a factor analysis should be allowed at an early stage of investigation.

The orthogonal solutions obtained by an exploratory procedure are usually transformed by a variety of transformation methods, orthogonal or oblique, for finding more easily interpretable solutions. It should be noted here, however, that the most commonly used Kaiser's normal varimax rotation method, for example, uniquely determines the solution for convenience' sake but do not necessarily show a true factor structure (LAWLEY and MAXWELL, 1964).

At the final stage, the results obtained by the above procedures should be ascertained by the confirmatory factor analysis using another sample. The confirmatory factor analysis has also deficiency similar to that of the exploratory one, but can be used even for the hypotheses with the correlated factors.

Genetic and environmental factors in a dental system

Based on the MZ twin sample, first of all, genetic and environmental correlations were estimated by a cross twin analysis between the permanent teeth from the central incisors to the first molars of both jaws. The upper and lower second molars were excluded from the analyses because the sample sizes were too small. Inter-character correlations were obtained on the basis of the samples of different size because not all the teeth were available for measurements in some individuals. Sample sizes, necessary for a chi-square test in the maximum likelihood factor analysis, were assumed to be 114 and 136 for the male and female phenotypic correlation matrices, and 111 and 132 for the male and female genetic or environmental correlation matrices for convenience' sake, based on the minimum value of the amounts of information (MATHER,

1951) for 66 correlation coefficients in each matrix.

First, the number of common genetic factors inherent in the mesiodistal diameters was tentatively determined on the basis of the informations from the previous works. LOMBARDI (1975) reported, applying the iterative principal factor analysis to his data combined for sexes, that four common factors accounted for 69% of the total phenotypic variance of the mesiodistal diameters of the central incisors to the second molars of both jaws. HANIHARA (1976, 1977) showed by the use of principal component analysis that five principal components explained 78% of the total phenotypic variance of the mesiodistal diameters of the permanent teeth. Based on these works, it seemed likely that there were four major common factors independently influencing the four morphological tooth classes, *i.e.*, the incisor, the canine, the premolar and the molar classes, and that there was a major specific factor related only to the upper lateral incisor. On the other hand, the relative genetic variabilities of the mesiodistal diameters had been known to be considerably high (LUNDSTRÖM, 1948; POTTER and NANCE, 1976; MIZOGUCHI, 1977a). It is also shown in Table 2. Thus, the four major common factors causing the phenotypic variation were considered to be genetic ones. The result of the maximum likelihood factor analysis on the genetic correlations for females seems to confirm this supposition (Table 3). The principal component analysis on the same data also revealed similar pattern, but, even when five principal components were taken into account, it did not arrive at any better solution than the maximum likelihood factor analysis did. Namely, four differences were recognized to be significant at the 5% level of 66 differences between the estimated and the original correlation coefficients in the former, while only two were significant in the latter. The factor

Table 3. Varimax rotated solution of the genetic correlations between the mesiodistal diameters in females.

	Factor loading				Communality	Residual variance
	I	II	III	IV		
I^1	0.27	0.26	0.20	0.78*	0.7918	0.2082
I^2	0.15	0.22	0.23	0.33*	0.2326	0.7674
C^-	0.28	0.85*	0.33*	0.32*	1.0000	0.0000
P^1	0.13	0.23	0.89*	0.34*	0.9819	0.0181
P^2	0.20	0.19	0.78*	0.30	0.7727	0.2273
M^1	0.68*	0.26	0.36*	0.34*	0.7713	0.2287
I_1	0.18	0.12	0.18	0.87*	0.8376	0.1624
I_2	0.13	0.27	0.33*	0.78*	0.8030	0.1970
C_-	0.25	0.63*	0.36*	0.44*	0.7865	0.2135
P_1	0.24	0.39*	0.81*	0.32*	0.9693	0.0307
P_2	0.35*	0.15	0.76*	0.09	0.7268	0.2732
M_1	0.91*	0.21	0.27	0.24	1.0000	0.0000
V.F.[1)]	15.09	14.15	27.60	23.77	80.61	19.39

[1)] Contribution of each factor to the total variance (%).

* Factor loading of greater than 0.30 in absolute value.

analysis of the genetic correlation matrix for males, unfortunately, could not be executed because the determinant of the matrix took a negative value, probably due to some kinds of errors.

Tables 4 and 5 show the results of the exploratory factor analyses of the environ-

Table 4. Varimax rotated solution of the environmental correlations between the mesiodistal diameters in males.

	Factor loading				Communality	Residual variance
	I	II	III	IV		
I^1	−0.11	−0.02	0.06	0.31*	0.1083	0.8917
I^2	−0.02	0.03	0.32*	0.15	0.1249	0.8751
C^-	0.03	−0.20	0.24	0.07	0.1034	0.8966
P^1	0.01	−0.12	0.55*	0.13	0.3368	0.6632
P^2	−0.10	−0.44*	0.10	−0.01	0.2146	0.7854
M^1	0.09	0.12	0.00	0.61*	0.3927	0.6073
I_1	0.23	−0.07	0.09	−0.12	0.0816	0.9184
I_2	−0.07	0.98*	0.11	0.12	1.0000	0.0000
C_-	0.26	0.16	0.26	0.10	0.1650	0.8350
P_1	0.37*	0.01	0.82*	−0.43*	1.0000	0.0000
P_2	0.05	−0.02	0.32*	0.56*	0.4191	0.5809
M_1	0.98*	0.15	−0.06	0.09	1.0000	0.0000
V.F.[1)]	10.53	10.68	11.24	8.77	41.22	58.78

1) Contribution of each factor to the total variance (%).
* Factor loading of greater than 0.30 in absolute value.

Table 5. Varimax rotated solution of the environmental correlations between the mesiodistal diameters in females.

	Factor loading			Communality	Residual variance
	I	II	III		
I^1	0.09	0.23	0.05	0.0640	0.9360
I^2	−0.19	−0.11	0.40*	0.2126	0.7874
C^-	−0.13	0.07	0.35*	0.1454	0.8546
P^1	0.07	0.07	0.53*	0.2918	0.7082
P^2	0.15	−0.05	0.52*	0.2998	0.7002
M^1	0.19	0.18	0.23	0.1224	0.8776
I_1	0.25	−0.15	−0.01	0.0867	0.9133
I_2	0.26	0.22	−0.07	0.1186	0.8814
C_-	0.27	0.02	0.01	0.0707	0.9293
P_1	−0.08	0.40*	−0.02	0.1632	0.8368
P_2	−0.10	0.99*	0.02	1.0000	0.0000
M_1	0.99*	0.03	0.00	1.0000	0.0000
V.F.[1)]	11.18	11.07	7.55	29.79	70.21

1) Contribution of each factor to the total variance (%).
* Factor loading of greater than 0.30 in absolute value.

mental correlation matrices for males and females, respectively. As regards the number of environmental common factors for the mesiodistal diameters, no information was available. Therefore, it was determined by the exploratory procedure. As a result, the number of "four" was assigned to the male correlation matrix, and the number of "three," to the female one. The hypothesis for males was not rejected ($\chi^2=35.20$, d.f.$=27$, $P=0.13$). For females, the hypothesis was rejected ($\chi^2=55.40$, d.f.$=35$, $P=0.02$), but the number, three, selected here was the most appropriate for explaining the environmental correlations among the possible numbers of the common factors. After some considerations on the meanings of environmental common factors, it was found that a few of the factors probably corresponded to the developmental period before commencement of calcification of the teeth and to the period for the calcification itself. These correspondencies are shown in Table 6 and Figs. 1 and 2. The importance of the calcification periods for the tooth crown size itself was pointed out by MOSS and MOSS-SALENTIJN (1977) and MOSS (1978), but, for the environmental variation of the crown size, it seems from the present results that the periods before commencement of calcification are much more important.

After all, it is likely that there are at least four major genetic factors and two major environmental factors influencing a dental system in common. Each of these factors should be regarded as a group of genes or of minor environmental factors behaving in the same way.

In the next place, it was ascertained whether or not these genetic and environmental

Table 6. Comparisons of the relative developmental periods with the relative contributions of the environmental factors to each mesiodistal diameter.

	Developmental period[1)]		Contribution of environmental factor					
			Male			Female		
	T_1	T_2	I	III	IV	I	II	III
I^1	0.112	0.266	0.011	0.003	0.093	0.008	0.054	0.002
I^2	0.189	0.210	0.000	0.102	0.022	0.038	0.011	0.163
C^-	0.118	0.290	0.001	0.059	0.005	0.017	0.005	0.123
P^1	0.241	0.183	0.000	0.305	0.017	0.005	0.004	0.283
P^2	0.270	0.161	0.010	0.011	0.000	0.022	0.003	0.275
M^1	0.054	0.357	0.009	0.000	0.370	0.036	0.032	0.054
I_1	0.117	0.230	0.053	0.008	0.016	0.064	0.023	0.000
I_2	0.113	0.257	0.005	0.012	0.015	0.066	0.048	0.004
C_-	0.119	0.284	0.066	0.066	0.009	0.070	0.000	0.000
P_1	0.259	0.160	0.138	0.680	0.181	0.006	0.157	0.000
P_2	0.283	0.147	0.002	0.100	0.316	0.010	0.990	0.001
M_1	0.055	0.343	0.966	0.003	0.008	0.999	0.001	0.000

[1)] $T_1=(\ln Y-\ln X)/\ln Z$; $T_2=(\ln Z-\ln Y)/\ln Z$, where X is the time in week, after fertilization, when a tooth germ is fully formed, Y is the time when the calcification commences, and Z is the time when the crown is completed. They are all the median values obtained from the data of SCHOUR and MASSLER (SCOTT and SYMONS, 1974); of LOGAN and KRONFELD (LOWREY, 1973); and of NOLLA (LOWREY, 1973).

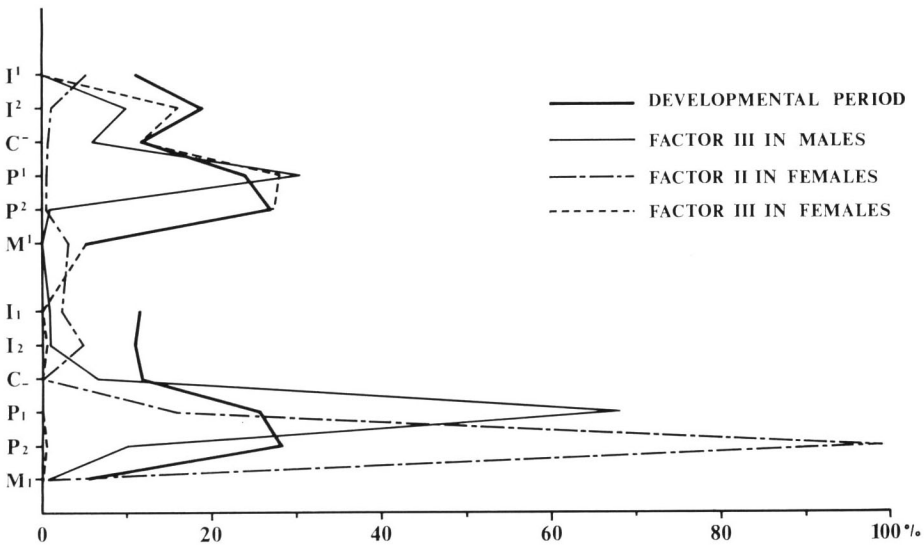

Fig. 1. Comparison of the relative developmental periods before commencement of calcification with the contributions of an environmental factor to the mesiodistal diameters.

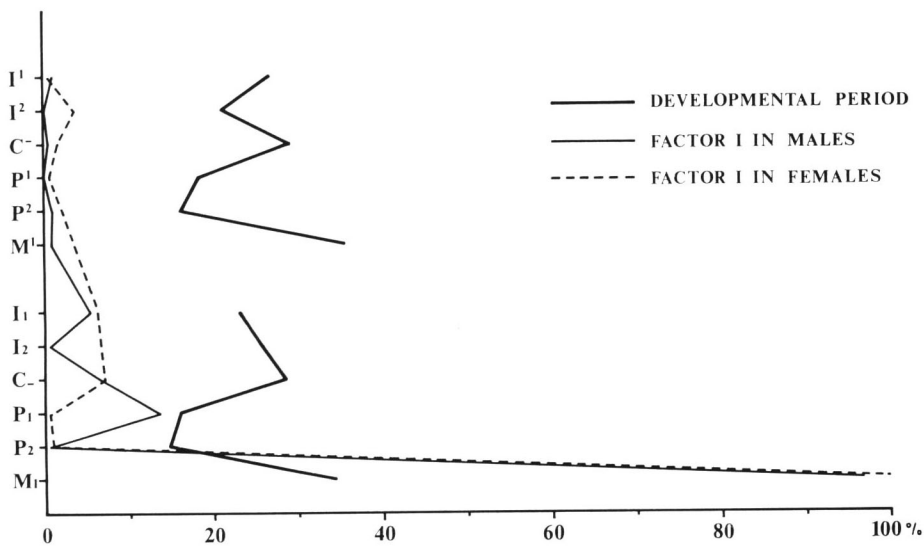

Fig. 2. Comparison of the relative developmental periods of calcification with the contributions of an environmental factor to the mesiodistal diameters.

factors could simultaneously be detected among the factors extracted from the phenotypic correlation matrices. The results of the exploratory factor analyses for males and females are shown in Tables 7 and 8, respectively. The hypothesis that the number of common factors was six was not rejected in males ($\chi^2=8.70$, d.f.$=13$, $P=0.80$) nor in females ($\chi^2=5.33$, d.f.$=9$, $P=0.80$). In Table 7, Factor V may be regarded as an environmental factor acting for the periods before commencement of calcification, which seems to correspond to Factor III in Table 4, on the basis of the pattern of the contributions of each factor to the individual teeth. In Table 8, Factor I may be inferred as an environmental factor acting before calcification, which appears to be comparable to Factors II and III in Table 5. It is difficult to identify Factor V in Table 8. All the other factors than the above in Tables 7 and 8 would be regarded as genetic factors for the four morphological tooth classes stated previously. Thus it seems to be possible to extract a few environmental factors common to the dental system based on the phenotypic correlations. It should be noted here, however, that a possible genetic factor affecting only the upper lateral incisors was not extracted as a common factor in males nor in females. Also at this point, the maximum likelihood factor analysis differs from the principal component analysis which always generates such a factor when more than four factors are taken into account (HANIHARA, 1976, 1977).

Many authors have attempted to search the sources of variation in a dental system of man or the other animals by the use of factor analytical methods (WALLACE and BADER, 1967; POTTER *et al.*, 1968, 1976; HENDERSON and GREENE, 1975; LOMBARDI, 1975; TOWNSEND and BROWN, 1979). Although most of the authors have dealt with the phenotypic correlations between the tooth crown diameters, POTTER *et al.* (1976) discussed the genetic and environmental factors extracted from the genetic and environmental covariance matrices obtained by the use of the method of BOCK and VANDENBERG for the multivariate analysis of twin data (NAKATA *et al.*, 1974). They stated that environmental effects were localized among the teeth. This condition was also observed in this study when the principal component analysis was used.

Further investigation

The above discussion has been done under many assumptions, of which the most serious one is that there are no interactions between factors. A phenotype seems, in fact, to be produced by genotype-environment interactions within the "norm of reaction" (DOBZHANSKY, 1955). Furthermore, it is possible for the internal or cellular environment itself of a certain character to be controlled by some other genes (STERN, 1960).

In this section, therefore, the phenotypic correlations will be analyzed by the restricted factor analysis of confirmatory type (LAWLEY and MAXWELL, 1963) without the assumption of no interactions between factors. However, there are a few restrictions for simplification of the model. First, it is assumed that there are four genetic and two environmental factors influencing the twelve permanent teeth of both jaws. Another assumption is the following target matrix of factor pattern:

Table 7. Varimax rotated solution of the phenotypic correlations between the mesiodistal diameters in males.

	Factor loading						Communality	Residual variance
	I	II	III	IV	V	VI		
I^1	−0.10	−0.09	−0.18	−0.23	−0.01	−0.74*	0.6455	0.3545
I^2	−0.18	−0.05	−0.26	0.00	−0.11	−0.53*	0.3955	0.6045
C^-	−0.47*	−0.18	−0.30	−0.04	−0.22	−0.37*	0.5337	0.4663
P^1	−0.19	−0.16	−0.90*	−0.13	−0.16	−0.28	1.0000	0.0000
P^2	−0.16	0.06	−0.57*	−0.13	−0.24	−0.28	0.5046	0.4954
M^1	−0.10	−0.24	−0.21	−0.90*	−0.18	−0.21	1.0000	0.0000
I_1	−0.18	−0.17	−0.13	−0.07	−0.15	−0.76*	0.6780	0.3220
I_2	−0.28	−0.16	−0.20	−0.13	−0.13	−0.69*	0.6594	0.3406
C_-	−0.85*	−0.11	−0.27	−0.13	−0.12	−0.40*	1.0000	0.0000
P_1	−0.25	−0.17	−0.54*	−0.14	−0.39*	−0.17	0.5895	0.4105
P_2	−0.14	−0.08	−0.38*	−0.17	−0.79*	−0.16	0.8556	0.1444
M_1	−0.14	−0.92*	−0.10	−0.23	−0.08	−0.26	1.0000	0.0000
V.F.[1)]	10.63	8.97	16.28	8.63	8.51	20.82	73.85	26.15

1) Contribution of each factor to the total variance (%).
* Factor loading of greater than 0.30 in absolute value.

Table 8. Varimax rotated solution of the phenotypic correlations between the mesiodistal diameters in females.

	Factor loading						Communality	Residual variance
	I	II	III	IV	V	VI		
I^1	0.14	−0.56*	−0.22	0.16	−0.76*	0.13	0.9995	0.0005
I^2	−0.03	−0.14	−0.10	0.14	−0.34*	0.33*	0.2743	0.7273
C^-	0.15	−0.22	−0.20	0.81*	−0.18	0.30	0.8792	0.1829
P^1	0.29	−0.23	−0.17	0.21	−0.14	0.74*	0.7792	0.2110
P^2	0.28	−0.19	−0.22	0.20	−0.11	0.67*	0.6647	0.3378
M^1	0.11	−0.21	−0.60*	0.26	−0.22	0.30	0.6201	0.3801
I_1	0.03	−0.68*	−0.21	0.13	−0.24	0.17	0.6086	0.3899
I_2	0.13	−0.79*	−0.16	0.22	−0.15	0.27	0.8091	0.1973
C_-	0.06	−0.37*	−0.30	0.48*	−0.10	0.38*	0.6225	0.3719
P_1	0.40*	−0.27	−0.21	0.31*	−0.14	0.61*	0.7713	0.2294
P_2	0.90*	−0.08	−0.19	0.11	−0.04	0.37*	0.9995	0.0005
M_1	0.17	−0.21	−0.94*	0.13	−0.09	0.15	0.9995	0.0005
V.F.[1)]	10.24	15.51	13.77	10.57	7.69	17.45	75.23	25.24

1) Contribution of each factor to the total variance (%).
* Factor loading of greater than 0.30 in absolute value.

$$\begin{bmatrix} x\,x\,x\,o\,o\,o\,x\,x\,x\,o\,o\,o \\ o\,x\,x\,x\,o\,o\,o\,x\,x\,x\,o\,o \\ o\,o\,x\,x\,x\,o\,o\,o\,x\,x\,x\,o \\ o\,o\,o\,o\,x\,x\,o\,o\,o\,o\,x\,x \\ o\,x\,o\,x\,x\,o\,o\,o\,o\,x\,x\,o \\ x\,o\,x\,o\,o\,x\,x\,x\,x\,o\,o\,x \end{bmatrix}',$$

where x is a non-zero factor loading and o is a zero loading. To carry out this confirmatory factor analysis, HANIHARA and KOIZUMI's (1979) data were utilized. The results are shown in Tables 9 and 10 for males and females, separately. Although the LAWLEY and MAXWELL's (1963) approximate chi-square tests for this factor analysis rejected the hypotheses for both sexes ($P<0.001$), another chi-square test for the significance of difference between two sample correlation matices (LAWLEY and MAXWELL, 1963) showed no significant difference between the estimated and the observed correlation matrices in either of males ($\chi^2=38.63$, d.f.$=78$, $P=0.99$) and females ($\chi^2=19.62$, d.f.$=78$, $P=0.99$). Strictly speaking, these results are not so exact, but, in practice, appear to be available. From Tables 9 and 10, it is clear that there are considerably high contributions of genetic interactions and of genotype-environment interactions. It should be noted here that the first two highest genetic joint contributions were concerned with upper and lower canines in both males and females, and that, in females, the upper lateral incisors received the highest genotype-environment contributions among the dentition. Although these results appear to be very suggestive, final conclusions should be drawn from much more evidence.

Summary and conclusions

In order to clarify how genetic and environmental factors act on a dental system, the genetic and environmental correlations between the mesiodistal diameters of twelve permanent teeth were analyzed by the exploratory maximum likelihood factor analysis under the assumption of no interaction of the factors. The extracted genetic factors are most likely comparable to four major factors usually derived from the phenotypic correlations. One of two environmental factors obtained appears to be concerned with the developmental periods before calcification, and the other, with the calcification periods. It should be noted that the environmental variation of the mesiodistal crown diameters is likely caused chiefly through the periods before calcification. Further, the approximate factor analysis for the correlated factors of confirmatory type showed the complicated conditions of the factors influencing the dental system. It is emphasized here that the contributions of factor interactions are of great importance.

Table 9. Contributions of the supposed genetic and environmental factors to the mesiodistal diameters in males[1].

	Direct contribution						Joint contribution[2]			Commu-nality	Residual variance
	Genetic				Environ.						
	I	II	III	IV	V	VI	G-G	E-E	G-E		
I^1	9.36	0	0	0	0	7.67	0	0	−16.29	0.74	0.26
I^2	0.10	2.17	0	0	1.09	0	−0.15	0	−2.26	0.94	0.06
C^-	0.60	0.68	0.41	0	0	1.41	1.08	0	−3.23	0.95	0.05
P^1	0	0.04	0.47	0	1.16	0	−0.13	0	−0.68	0.86	0.14
P^2	0	0	0.50	0.39	0.25	0	−0.52	0	0.02	0.63	0.37
M^1	0	0	0	0.53	0	0.77	0	0	−0.32	0.98	0.02
I_1	10.48	0	0	0	0	7.91	0	0	−17.50	0.89	0.11
I_2	0.50	0.26	0	0	0	0.01	−0.12	0	0.08	0.73	0.26
C_-	1.57	0.38	0.47	0	0	3.62	1.31	0	−6.73	0.63	0.37
P_1	0	0.03	0.44	0	1.86	0	0.10	0	−1.60	0.83	0.17
P_2	0	0	0.08	1.12	0.00	0	−0.35	0	−0.08	0.77	0.23
M_1	0	0	0	0.44	0	0.05	0	0	−0.07	0.42	0.58
Total	22.61	3.56	2.36	2.48	4.36	21.44	1.23	0	−48.67	9.38	2.62

[1] Source of data: HANIHARA and KOIZUMI (1979).

[2] "G-G," "E-E" and "G-E" designate the contributions due to the interactions between genetic factors, between environmental factors, and between genetic and environmental factors, respectively.

Table 10. Contributions of the supposed genetic and environmental factors to the mesiodistal diameters in females[1].

	Direct contribution						Joint contribution[2]			Commu-nality	Residual variance
	Genetic				Environ.						
	I	II	III	IV	V	VI	G-G	E-E	G-E		
I^1	0.78	0	0	0	0	0.04	0	0	−0.13	0.69	0.31
I^2	0.60	4.34	0	0	0.87	0	−2.94	0	−1.94	0.94	0.06
C^-	1.76	3.76	0.15	0	0	0.03	−5.08	0	−0.03	0.58	0.42
P^1	0	0.03	0.30	0	0.26	0	0.06	0	0.24	0.88	0.12
P^2	0	0	0.17	0.70	0.02	0	0.24	0	−0.22	0.90	0.10
M^1	0	0	0	0.59	0	0.01	0	0	0.02	0.62	0.38
I_1	1.01	0	0	0	0	0.28	0	0	−0.41	0.88	0.12
I_2	0.00	0.84	0	0	0	0.17	−0.06	0	−0.18	0.78	0.22
C_-	2.03	5.37	0.50	0	0	0.09	−6.90	0	−0.15	0.94	0.06
P_1	0	0.02	0.06	0	0.37	0	0.02	0	0.16	0.62	0.38
P_2	0	0	0.00	0.79	0.01	0	0.01	0	−0.11	0.70	0.30
M_1	0	0	0	0.32	0	0.48	0	0	0.12	0.92	0.08
Total	6.18	14.37	1.18	2.40	1.52	1.10	−14.66	0	−2.63	9.46	2.54

[1] and [2] See the footnote to Table 9.

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