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GENETIC AND ENVIRONMENTAL COMPONENTS IN THE COVARIATION OF COGNITIVE ABILITIES: AN ADDITIVE MODEL

For a number of years, geneticists and psychologists have concerned themselves with methods for analyzing the variance of physical or behavioral traits in a population into components reflecting genetic and environmental influences, and various interactions between and among them (Broadhurst and Jinks, 1961; Burt and Howard, 1956; Cattell, 1960; Fisher, 1918; Mather, 1949; Wright, 1952). Only fairly recently, at least among psychologists, has it become recognized that trait covariation (covariances, correlations) can also be subjected to such analysis; a number of recent proposals have been made concerning methods of doing this (Kempthorne and Osborne, 1961; Nichols, 1964; Loehlin, 1965; Vandenberg, 1965; Meredith [see chap. 18, this volume]).

There are some attractive features for the psychologist in working with trait covariation rather than with single traits. First, there is a shift of emphasis away from "heredity versus environment" towards a consideration of the structuring of genetic and environmental influences. And second, while most behavior traits that have been empirically studied appear to reflect both genetic and environmental influence (Fuller and Thompson, 1960; Vandenberg, 1966a), the possibility remains that some *associations* among traits may result solely from common genes or common environment.

The present paper will investigate trait covariation in the realm of cognitive abilities, using data from Thurstone's Primary Mental Abilities test (PMA) administered to two samples of identical and fraternal twin pairs. A simple additive model of the relationship between heredity and environment is employed. One of the writers has elsewhere reported an analysis of some of the same data based on a multiplicative model (Vandenberg, 1965). The relationship between the results of these two approaches will be discussed in a later section of this paper.

Cognitive abilities represent a particularly interesting area for investigation of genetic and environmental components of covariation. Such an investigation may, for example, clarify the question of whether mental abilities are basically general or specific, an issue debated by Spearman (1904), Thomson (1920), Thurstone (1934), Tryon (1935), Cattell (1943), and Guilford (1956), among others. If separation of the covariation of cognitive tests into genetic and environmental portions can be carried out, subsequent factoring of these components should be illuminating. Such a factoring might reveal, for example, a single general factor in the genetic covariation and a number of independent environmental factors; or a general environmental factor tending to pull together relatively independent genetic factors; or an identical factor structure in both realms; or even a different multiple factor structure in each. Any one of these outcomes would have relevance for the generality-specificity question.

The twin method is, of course, not without flaws as a technique for separating genetic and environmental components of variance or covariance, since it leaves together certain sources of variance which would ideally be kept distinct: for example, in the usual application of the twin method (a) any correlated hereditary and environmental influences are grouped with heredity, (b) any gene-environment interaction is grouped with environment, (c) no distinction is made between the prenatal biochemical environment and the postnatal stimulus environment, and (d) genic and additive effects cannot be separated. Not all of these limitations are inherent in every application of the twin method—such as a longitudinal study of twins from birth—but they are characteristic of the method in its usual cross-sectional form. Still, even the conventional twin method does achieve *some* degree of separation of genetic and environmental effects, and if interest is chiefly focused on the pattern of relationships rather than their absolute magnitude, it should be able to provide at least some useful approximations to the true state of affairs.

METHOD

SAMPLES

The first twin sample has been described in detail elsewhere (Sutton, Vandenberg, and Clark, 1962). Briefly, it consists of 82 pairs of like-sexed twins of high school age from four Michigan cities: Ann Arbor, Ypsilanti, Dearborn, and Detroit. Of these, 45 pairs were classified as identical and 37 as fraternal, on the basis of blood typing, eye color, and physical appearance.

The second sample consists of 116 pairs of like-sexed twins of high school age from the metropolitan area around Louisville, Kentucky, 78 identical and 38 fraternal pairs, classified by blood typing (Vandenberg, Stafford, and Brown, Chapter 10, this volume).

The two samples, broken down by zygosity and sex, are described in Table 15-1. Note that dizygotic twins appear to be somewhat undersampled, particularly the males. We believe that in most of the schools from which the twins were recruited a complete list of twins was obtained. There seemed to be no obvious bias in the few refusals to cooperate. The difference, then, would appear to suggest that dizygotic twins, especially males, were less likely to be found in school together at these ages. If the more divergent pairs are the ones most often not in school together, the dizygotic undersampling will tend to lead to an underestimation of genetic effects; however, the focus of the present investigation is on the relationships among effects rather than on their absolute magnitude, so this is not in itself a major problem. The dizygotic sex bias is potentially more serious in view of sex differences to be expected on some of the PMA scales. However, the most critical analyses in the present study are

TABLE 15-1

TWIN SAMPLES BY ZYGOSITY AND SEX, NUMBER OF LIKE-SEXED TWIN PAIRS

Group	Male	Female	Combined
Monozygotic			
Michigan	24	21	45
Louisville	40	38	78
Combined Samples	64	59	123
Dizygotic			
Michigan	14	23	37
Louisville	15	23	38
Combined Samples	29	46	75
All twins	82	116	198

based on within-pair covariance, and sex differences do not present problems here, since only like-sexed pairs are used.

TESTS

The testing procedures have been described in detail elsewhere (Sutton, Vandenberg, and Clark, 1962; Vandenberg, Stafford, and Brown, 1968). In both studies, Thurstone's PMA Tests (Thurstone and Thurstone, 1941) were administered as part of a large battery of psychological tests. In the first study anthropometric and biochemical measures were also obtained. In the Michigan study, 17 subtests of the PMA were administered, three each for the factors of Numerical Ability (N), Verbal Comprehension (V), Spatial Ability (S), Word Fluency (W), and Reasoning Ability (R); and two for Memory (M). At the time of the Louisville study, the Memory subtests were not available and hence not included. In the present paper, therefore, only the five factors N, V, S, W, and R will be considered, each represented by three subtests in both samples.

RESULTS

Means of the PMA scales and subscales for various breakdowns of the total sample are shown in Table 15-2. Analyses of variance indicated that interactions among zygosity, sample, and sex were generally negligible, permitting direct interpretation of the main effects.[1]

It will be seen from Table 15-2 that there was no substantial difference in the mean level of performance between identical and fraternal twin groups on any PMA scale or subscale. There were, however, significant differences for the other classifications, the Michigan sample scoring higher on Number and Word Fluency, and the girls scoring higher on Word Fluency and Reasoning and lower on Space. The sex differences are generally similar to those reported by other investigators using this test in non-twin groups. For example, Herzberg and Lepkin (1954), with 705 17-year-old Pittsburgh high school students, found corresponding significant differences on the same three scales, plus a difference in favor of girls on Verbal Comprehension.

Despite the presence of the differences noted, it was decided to combine the two regional samples and the two sexes to achieve a larger sample for further analyses. Within-pair variance, the main focus of in-

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[1] No interactions involving main scales were significant, and of 60 interactions involving subscales only two reached significance at the .05 level, a result probably safely attributable to sampling fluctuation.

TABLE 15-2
MEANS OF PMA SCALES AND SUBSCALES BY ZYGOSITY, SAMPLE AND SEX

Scale	MZ	DZ	Mich.	Lvle.	Male	Female
1. Addition	19.1	20.3	22.4**	17.5	19.8	19.3
2. Multiplication	40.0	42.0	43.3**	38.9	40.3	41.2
3. 3-higher	46.3	47.3	48.7*	45.2	49.1**	44.6
Number	106.0	110.2	114.6**	102.5	109.3	106.0
4. Sentences	17.9	18.6	19.4**	17.3	18.2	18.1
5. Vocabulary	27.8	28.2	28.7	27.5	27.8	28.1
6. Completion	27.5	27.3	28.2	26.9	28.4*	25.6
Verbal	73.3	74.1	76.1	71.9	74.5	72.9
7. Flags	40.5	40.3	39.8	40.9	43.2**	37.9
8. Figures	37.9	38.5	38.0	38.3	41.1**	35.5
9. Cards Space	34.3	33.3	33.3	34.3	36.0**	32.0
Space	114.4	113.0	111.4	115.7	121.8**	106.6
10. First letters	35.3	36.1	38.0**	33.9	33.2	37.7**
11. 4-letter words	11.1	11.0	11.2	10.9	10.1	11.9**
12. Suffixes	10.4	10.7	11.5**	9.8	9.4	11.5**
Word fluency	57.2	58.0	60.8**	55.2	53.1	61.4**
13. Letter series	15.5	15.5	15.3	15.6	14.7	16.2*
14. Letter groupings	14.5	14.3	13.7	14.9**	13.7	15.1**
15. Pedigrees	23.4	24.5	24.6	23.2	21.7	25.6**
Reasoning	53.4	54.6	53.7	54.0	50.3	56.9**

Note: Total scores were computed only for subjects completing all three subtests, therefore subtest means may not sum exactly to total means.

* Significantly higher at .05 level.
** Significantly higher at .01 level.

terest, should not be appreciably affected by such differences. The variance between pairs should tend to be somewhat inflated by sex and regional differences, but this variance is of secondary interest in any case.

The principal results to be reported are based on intercorrelations among twin sums and twin differences on PMA scales and subscales for the monozygotic (MZ) and dizygotic (DZ) groups, for the total sample. (The basic variance-covariance matrices are contained in Tables A through H in the Appendix.) The correlations among twin sums (or means) are based on between-pairs covariance and should largely reflect between-family influences, both genetic and environmental. The correlations among twin differences are based on within-pair covariance and should reflect within-families influences. As has been noted elsewhere (Vandenberg, 1965), correlations among MZ twin differences are of unique psychological interest, since any such correlations must be due to

common environmental influences on the traits (in some broad sense of the term environment). Correlations among DZ differences, on the other hand, may reflect both common genetic and common environmental influences on the traits in question; the nature of the discrepancies between MZ- and DZ-difference correlations may, therefore, serve to shed some light on genetic effects on the traits.

The intercorrelations of MZ and DZ pair sums and differences on the 15 PMA subscales were factored (principal axes factoring with unities in the diagonal), and the first five factors in each case rotated by the Varimax method (Kaiser, 1958). The rotated factor loadings are shown in Tables 15-3 and 15-4. Loadings of .50 or greater are underlined.

The main question of interest in interpreting these data is whether the structuring of the subtests into Thurstone's five primary mental abilities

TABLE 15-3
ROTATED FACTOR LOADINGS FROM BETWEEN-PAIR COVARIATION*

| | a. Dizygotic Twins | | | | | b. Monozygotic Twins | | | | |
	I	II	III	IV	V	I	II	III	IV	V
1. Addition	70	34	40	18	20	84	20	24	14	10
2. Multiplication	89	18	16	19	19	83	26	08	24	10
3. 3-higher	62	41	35	14	40	71	23	23	08	42
4. Sentences	29	75	22	29	22	29	80	12	22	22
5. Vocabulary	35	76	20	33	26	21	83	06	31	24
6. Completion	22	82	24	20	20	16	85	17	17	21
7. Flags	27	31	80	11	19	26	05	89	07	10
8. Figures	13	08	94	14	07	05	11	93	05	05
9. Cards	15	28	88	13	11	12	12	91	09	13
10. First letters	39	36	08	75	09	16	28	15	82	20
11. 4-letter words	−05	17	19	79	35	07	06	−01	89	21
12. Suffixes	38	35	19	67	15	22	34	08	76	06
13. Letter series	20	36	26	23	78	37	35	12	19	70
14. Letter grouping	42	27	03	29	74	12	22	07	23	82
15. Pedigrees	10	63	29	27	48	18	56	12	18	59

* Note: Decimal points omitted in this and subsequent tables.

TABLE 15-4

ROTATED FACTOR LOADINGS FROM WITHIN-PAIR COVARIATION

	a. Dizygotic Twins					b. Monozygotic Twins				
	I	II	III	IV	V	I	II	III	IV	V
1. Addition	82	02	—02	32	02	79	11	08	—00	24
2. Multiplication	75	22	08	—04	33	80	17	—07	03	—11
3. 3-higher	71	18	36	15	04	17	—13	—01	03	81
4. Sentences	39	74	08	05	—26	04	59	—19	18	—26
5. Vocabulary	21	70	02	37	08	09	77	05	19	—12
6. Completion	—08	70	06	51	13	08	65	17	09	—24
7. Flags	15	18	86	03	00	12	—06	69	03	06
8. Figures	08	05	86	23	02	—07	16	65	—14	—21
9. Cards	04	—02	71	08	49	—06	00	59	31	17
10. First-letters	08	15	37	78	02	03	11	13	71	—24
11. 4-letter words	27	—07	02	81	27	—03	29	—24	61	09
12. Suffixes	12	30	11	77	07	03	05	13	68	07
13. Letter series	23	21	15	27	77	22	48	—00	35	12
14. Letter grouping	36	—02	41	19	33	—28	59	06	—10	46
15. Pedigrees	07	76	14	—12	33	14	51	02	—00	12

factors will appear in the analyses based on various sources of covariation. If we look first at Table 15-3, based on covariation between-pair sums, it is clear that Thurstone's five factors show up here. With the exception of one of the tests assigned to Reasoning, which appears to load at least as heavily on the Verbal Comprehension factor, the high loading for each test is on its designated factor. The general tendency for the tests to be positively correlated is reflected in the generally positive loadings elsewhere in the matrix. No very striking difference is evident between the MZ and DZ loadings. To some extent this is to be expected, since both matrices should reflect both environmental and genetic sources of covariation. One might expect, however, to find some quantitative difference, since the between-pair sum matrix contains all the genetic variation of the MZ twins, but only part of the genetic variation of the DZ twins. We will return to this point later.

Looking next at Table 15-4, it appears that at least four of Thurstone's five factors may be extracted from either MZ or DZ within-pair correlations. The Reasoning factor has been rather badly split apart in the DZ data, but the other four factors are tolerably clear. In the MZ data, Reasoning appears to have merged with Verbal Comprehension, and the fifth factor has split one of the Number tests off from the others, but Number, Verbal, Space, and Word Fluency factors are still fairly clearly identifiable.

One conclusion can immediately be drawn from the MZ data: since any covariation among identical twin differences is necessarily environmentally determined, it follows that—except perhaps for Reasoning—the factor structure of Thurstone's PMA battery reflects the structuring of the environmental influences that have been brought to bear on the development of cognitive abilities in these subjects.

Does the PMA also reflect the structure of genetic influences? For an answer to this, the DZ data do not suffice, since they reflect both genetic and environmental effects. What is needed is DZ data from which the environmental effects reflected in the MZ data have been removed. The approach used in the present study was to subtract the MZ variance-covariance matrix from the DZ variance-covariance matrix, and analyze the resulting difference matrix. Since the environmental effects on within-pair differences may well be somewhat greater for fraternal twins than for identical twins. this procedure may not eliminate environmental effects entirely, but it should markedly reduce them. There is, however, one problem in applying this method to empirical data. A substantial part of the variance of the difference scores is likely to be error variance resulting from test unreliability. If error variances are in fact precisely equal in the MZ and DZ groups, the subtraction of the variance-covariance matrices in effect corrects for attenuation any correlations derived from the resulting difference matrix. But if for some variable the MZ error of measurement happens to exceed the DZ error of measurement, overcorrection, which can lead to absurd correlations, will result; even if this does not occur, the corrected correlations will not be readily comparable with the uncorrected rs on which the analyses in Tables 15-3 and 15-4 are based. One simple solution to this difficulty is to subtract only reliable MZ variance from the DZ variances. For this purpose, a rough estimate of reliability was obtained from the highest correlation involving each subtest; this will tend to be an underestimate of reliability, but with the present data not a very gross one. The variance-covariance matrix of MZ differences. with the variances thus corrected, was subtracted from the variance-covariance matrix of DZ differences. The resulting matrix

was converted to correlations and factored and rotated as before. The rotated factor loadings are shown in Table 15-5. It will be observed that the loadings are somewhat irregular, but on the whole display the same structure observed in the other matrices—once more, with a fragmented Reasoning factor. Granted our assumptions, then, it appears that the basic factor structure of the test battery reflects a characteristic patterning of genetic as well as of environmental influences on cognitive trait development.

The results so far have focused on the loading of the subtests on the PMA factors; possible differences in the relationships among these factors have not been examined. One way to do this is to take the grouping of the subtests as given, and to use the scores on the five regular PMA scales [2] to compute variance-covariance and correlation matrices as before.

[2] The total scale scores are simple sums of the subtest scores.

TABLE 15-5
ROTATED FACTOR LOADINGS FROM WITHIN-FAMILY GENETIC COVARIATION

| | DZ-MZ (corr.) [a] | | | | |
	I	II	III	IV	V
1. Addition	82	06	01	33	−06
2. Multiplication	70	31	15	−07	40
3. 3-higher	59	48	37	25	11
4. Sentences	31	81	12	07	−21
5. Vocabulary	18	60	04	47	−09
6. Completion	−12	47	−01	72	22
7. Flags	06	31	76	08	07
8. Figures	08	04	83	23	07
9. Cards	05	−04	68	02	50
10. First-letters	14	03	51	68	−09
11. 4-letter words	44	−30	14	69	13
12. Suffixes	16	19	09	84	11
13. Letter series	21	−03	23	22	83
14. Letter grouping	46	−13	57	08	17
15. Pedigrees	−13	71	11	00	47

[a] For explanation, see text.

Tables 15-6, 15-7, and 15-8 show the correlation matrices based on twin pair sums, pair differences, and the corrected DZ-MZ difference, respectively. The reliabilities used in correcting the MZ variances of the five scales were estimated by way of the intercorrelations among their subtests, and should therefore be somewhat more accurate than those used in the preceding analysis. Each table shows the original correlations above

TABLE 15-6

PMA SCALE CORRELATIONS FROM BETWEEN-PAIR COVARIATION
(CORRELATIONS ABOVE DIAGONAL, FIRST-FACTOR RESIDUALS BELOW)

| | a. Dizygotic Twins | | | | | b. Monozygotic Twins | | | | |
	N	V	S	W	R		N	V	S	W	R
N	•	73	55	63	69	N	•	57	39	44	58
V	−04	•	54	71	79	V	−07	•	25	54	71
S	05	−00	•	40	49	S	13	−03	•	14	24
W	00	02	−04	•	66	W	−02	06	−05	•	50
R	−02	01	−01	02	•	R	−04	05	−03	03	•

TABLE 15-7

PMA SCALE CORRELATIONS FROM WITHIN-PAIR COVARIATION
(CORRELATIONS ABOVE DIAGONAL, FIRST-FACTOR- RESIDUALS BELOW)

| | a. Dizygotic Twins | | | | | b. Monozygotic Twins | | | | |
	N	V	S	W	R		N	V	S	W	R
N	•	38	38	39	49	N	•	−01	00	−01	15
V	−02	•	18	51	56	V	−01	•	06	33	48
S	05	−13	•	42	41	S	00	−00	•	10	06
W	−04	09	08	•	39	W	−01	07	05	•	27
R	01	09	03	−12	•	R	15	01	−03	−07	•

TABLE 15-8

PMA SCALE CORRELATIONS FROM WITHIN-FAMILY GENETIC COVARIATION
(CORRELATIONS ABOVE DIAGONAL, FIRST-FACTOR RESIDUALS BELOW)

| | DZ-MZ (corr.) | | | | |
	N	V	S	W	R
N	•	51	48	50	54
V	05	•	20	48	36
S	−01	−14	•	48	48
W	−05	10	07	•	32
R	02	01	10	−11	•

the diagonal, and below the diagonal the residuals after extracting a general factor by means of a Spearman formula (DuBois, 1965, p. 462). It will be observed that the one factor accounts for the bulk of the covariation in each case. The general factor loadings are assembled together in Table 15-9.

The contrast of greatest interest is that between the purely environmental effects (Table 15-7b) and the matrix representing mostly genetic effects (Table 15-8), a contrast which may be observed either in the correlations themselves or in the corresponding factor loadings in Table 15-9. Briefly, (a) the "environmental" factors tend to be less intercorrelated than the "genetic" ones, and (b) the correlations in the former case appear to reflect a common factor that mainly involves verbal performance (Verbal Comprehension, Reasoning, Word Fluency), while in the latter case, the correlations suggest a rather uniform second-order factor general to all tests.

By contrast, the correlations based on twin sums (Table 15-6) show a very similar pattern in the MZ and DZ data, with the correlations and factor loadings based on the DZ data consistently somewhat higher. Since, as noted earlier, the MZ between-pair data contain all the genetic variance and the DZ between-pair data only part of it, one might, on the basis of the within-pair findings, have expected a difference in the opposite direction. Interpretation of the between-pair data in both instances is complicated by the fact that the total variance within the DZ group in the present sample materially exceeds that within the MZ group. The difference is not large enough to reach statistical significance, and hence may be attributable to chance differences in sampling. We can merely note that if the DZ group, for whatever reason, actually does include more genetic variability than the MZ group, this fact could account for the anomalies noted.

TABLE 15-9
GENERAL-FACTOR LOADINGS FROM PMA SCALE CORRELATIONS
(BASED ON TABLES 15-6 TO 15-9)

	Between-pair		Within-pair		"Genetic"
	DZ	MZ	DZ	MZ	DZ-MZ
Number	84	78	64	00	81
Verbal	91	82	62	61	57
Space	59	34	51	11	60
Word Fluency	75	59	68	44	68
Reasoning	85	80	75	78	63

The somewhat higher levels of correlation in the between-pair DZ data compared to the within-pair DZ data are quite reasonable: age, sex, socio-economic, and regional differences are contributing to the former and not to the latter, and will enhance correlations. In addition, if assortative mating occurs for these abilities—if like marries like—then within-family genetic variation will tend to be reduced; furthermore, a greater degree of parental similarity probably implies reduced within-family environmental variation as well. Both would further accentuate the observed discrepancy.

THURSTONE'S CHICAGO STUDY

For purposes of comparison, a parallel analysis was made of data from a twin study by Thurstone, Thurstone, and Strandskov (1953, 1955).[a] The data were only available for the five main PMA scales, not for the subscales, so it was possible to check only on the second part of our findings. The Thurstone study involved 48 identical and 55 fraternal twin pairs from Chicago high schools. The test versions and scoring procedures differed in some minor respects from those of the Michigan and Louisville studies, but one would expect at least general comparability of results.

The Chicago data were analyzed in exactly the same fashion as the Michigan-Louisville data, and Tables 15-10 to 15-13 present these results, paralleling Tables 15-6 to 15-9. Since Chicago subscale data were not available, the Michigan-Louisville reliabilities were used in correcting the variances, although this procedure is obviously somewhat hazardous.

Comparison of the results brings out several points of interest. The somewhat lower correlations in the between-pair data (Table 15-10, com-

TABLE 15-10
CHICAGO SAMPLE: BETWEEN-PAIR COVARIATION

| | a. DZ Twins | | | | | | b. MZ Twins | | | | |
	N	V	S	W	R		N	V	S	W	R
N	*	38	05	22	28	N	*	46	16	64	56
V	03	*	35	62	60	V	02	*	29	60	50
S	−03	00	*	25	37	S	−10	02	*	35	44
W	−00	02	01	*	49	W	08	02	00	*	62
R	02	−10	09	−02	*	R	03	−06	11	−09	*

pared to Table 15-6) suggest that the Chicago twin pairs may have been sampled from a less wide range of the population than the Michigan and Louisville twins.

Total variability is somewhat more comparable between the Chicago MZ and DZ groups than it is in the Michigan-Louisville data, and this has improved matters: the Chicago between-pair MZ correlations tend on

TABLE 15-11
CHICAGO SAMPLE: WITHIN-PAIR COVARIATION

| | a. DZ Twins | | | | | | b. MZ Twins | | | |
	N	V	S	W	R		N	V	S	W	R
N	*	36	28	57	55	N	*	17	17	15	21
V	−01	*	31	45	39	V	−06	*	−06	24	40
S	−04	05	*	42	33	S	15	−08	*	07	02
W	00	−02	02	*	64	W	−01	08	06	*	08
R	05	−02	−02	00	*	R	−01	19	00	−07	*

TABLE 15-12
CHICAGO SAMPLE: WITHIN-FAMILY GENETIC CORRELATION

| | DZ-MZ (Corr.) | | | | |
	N	V	S	W	R
N	*	37	27	67	54
V	04	*	39	46	23
S	−09	12	*	48	39
W	01	−03	−04	*	78
R	06	−12	01	09	*

TABLE 15-13
CHICAGO SAMPLE: GENERAL-FACTOR LOADINGS
(BASED ON TABLES 15-10 THROUGH 15-12)

| | Between-pair | | Within-pair | | "Genetic" |
	DZ	MZ	DZ	MZ	DZ-MZ
Number	33	65	67	49	67
Verbal	92	68	55	48	50
Space	37	40	47	04	53
Word Fluency	66	87	85	33	98
Reasoning	77	82	75	44	71

the whole to run somewhat higher than the DZ correlations, as expected, rather than the reverse, as in the Michigan-Louisville data.

Let us look now at the within-pair correlation matrices, both the purely environmental and the largely genetic (Tables 15-7b and 15-11b; Tables 15-8 and 15-12; and the corresponding factors in Tables 15-9 and 15-13). From these we may conclude: (a) the within-family correlations are of the same order of magnitude in the two sets of data; (b) in both sets of data there is less environmental than genetic intercorrelation; (c) there is a difference in the second-order environmental factor, in that Number tends to go along with the verbal tests in the Chicago data, although Space remains independent; and (d) the second-order genetic factor, while still general to all the tests, does not load them as evenly in the Chicago data as in the Michigan-Louisville data. That faulty reliability corrections may be partly to blame is suggested by the suspiciously high loading of Word Fluency.

On the whole, then, the Chicago results tend to support the findings of the present study, except that a question is raised concerning the status of the Numerical Ability factor. What looks in the Michigan-Louisville environmental data like a second-order verbal factor might better be described in the Chicago data as a general educational factor, with Numerical Ability joining the three verbal tests.

It may be worth noting that the Numerical factor has proved erratic in other respects, showing relatively high heritability in the Michigan twin data (Vandenberg, 1962), moderate heritability in the Chicago data (Thurstone, et al., 1955) and close to zero heritability in a study by Blewett in Great Britain (1954)—despite fairly good agreement among the three studies concerning all of the other factors except Reasoning.

DISCUSSION

Summarizing our results, and neglecting a few complications, we can say that (1) the same cognitive ability factors have been found in environmental and in genetic covariation, but that (2) the relationship among these factors differs in the two cases, taking the form of a verbal (educational?) second-order factor in the environmental covariation, and a general factor in the genetic.

In connection with the first of these observations—the similar dimensions found in the genetic and environmental components of cognitive abilities—a few additional comments might be made. First, the case for similar dimensionality in the two realms is not as strong as it would be had the same results emerged from factoring a randomly selected group

of cognitive tests. The three subtests of each factor were after all selected in Thurstone's analyses for their similar correlations with other tests, and might conceivably have been selected simultaneously on quite distinct genetic and environmental dimensions. In this case they would still be expected to hang together in either kind of data, even though for different reasons. This is, of course, hypothetical: a simpler interpretation of the present data is the one suggested earlier—that there are rather similar dimensions in both the genetic and environmental influences which act on cognitive development. It is perhaps worth noting a somewhat parallel finding for personality traits, in a study using a different method (Loehlin, 1965). Separate factoring of groups of personality inventory items of relatively high and low heritability yielded rather similar factors in both groups of items. On general grounds findings such as these are perhaps not unreasonable. Presumably the development of cultural institutions is to some extent influenced by the human biological tendencies they control or exploit. A sex factor, for example, might emerge either from purely sociological or from purely biological data. The case is perhaps less obvious for cognitive traits, but it is at least conceivable that the biological capacities of the human organism have historically had some bearing on what society has tended to recognize, name, and educate as a unit.

The second main finding of this study, and perhaps the more interesting one, is the difference between the second-order factors in the environmental and the genetic components of covariation. In the environmental data the "quantitative" factors, Number and Space, are essentially independent from each other and from the remaining factors—Verbal Comprehension, Word Fluency, and Reasoning. The most plausible basis for the interrelationship of the latter three factors would appear to be their common connection with language and verbal behavior. It is easy to conceive of environmental variables—such as amount of early interaction with adults or number of books in the home—that might have broad effects on verbal development, and clearly language behavior is a major focus of the educational process. The association of Numerical Ability with these factors in the Chicago data would seem most consonant with the last of these.

The second-order factor emerging from the largely genetic component of covariation, on the other hand, involves all five of the primary abilities. This factor may well reflect some general potential for intellectual functioning of the sort Spearman had in view when he proposed his general intellective factor "g." It is highly unlikely that this factor represents even a major effect of a single gene, in view of the continuous distribution of intelligence measures in human populations, and the results of

the animal studies of Tryon (1940), Thompson (1954), and others. However, the factor could conceivably represent a single critical parameter of neural functioning or of cognitive development, under multiple gene control. The data of the present study of course offer little clue to the nature of such a hypothetical neural or biochemical variable, if it exists.

The results of the present investigation also bear some relevance to Cattell's hypothesis of two kinds of intelligence, "fluid" and "crystallized" (Cattell, 1943, 1963). This hypothesis holds that two "general intelligence" factors exist, strongly correlated but functionally distinct, the one reflecting innate ability, the other the effects of educational and cultural processes. These factors are said to be best measured by nonverbal and verbal tests, respectively. In some ways the present study offers more direct support for such a notion than the data Cattell himself presents, although it should be noted that the hereditary factor in this study is a quite general one, and by no means represented only or chiefly in nonverbal tests.

The present results may also be regarded as at least compatible with the findings of Nichols (1965), who examined the heritability of both general and specific abilities in the National Merit Scholarship Qualifying Test with a large twin sample. His method of analysis did not lead to a separate assessment of hereditary and environmental components, but he found evidence for the heritability both of total score and of subtest residual scores with total score partialed out. Because of the high intercorrelation of the subtests the residual scores yielded rather erratic results, but on the whole the data suggested that they were under a substantial degree of separate genetic control. Nichols' total score may perhaps be regarded as comparable to our general factors, his specifics to our subtest groupings.

Finally it is appropriate to compare the present results with those obtained for some of the same data by Vandenberg (1965), using a multiplicative model of the relation between heredity and environment, and analyzing total variation rather than common variation. The evaluation of environmental effects in both analyses was based on the within-pair MZ variance-covariance matrix, but hereditary effects were represented in the earlier study not by a difference matrix, as here, but by finding the matrix which multiplicatively transforms the matrix of MZ differences into that of DZ differences. In the earlier study, four significant latent roots were found in both the "heredity" and "environment" matrices, and interpreted as possibly corresponding approximately to the Number, Verbal, Space, and Word Fluency factors.

Actually, the differences between the results of the previous study and the present one appear to reflect more the difference between analyzing total variation and analyzing common variation than they do the difference between additive and multiplicative models. If specific variance is included in a factor analysis, the number of dimensions obtained tends to approach the number of tests. If common variance alone is analyzed, fewer and broader factors tend to emerge. In this view, one might expect correspondence between the previous study and the first analyses of the present study (those based on subtests), since in both these cases variance specific to the five main scales is included. And, indeed, the results do not differ markedly here. It is only in the second part of the present analysis, with variance specific to the main factors absent, that the present investigation yields general factors not found in the earlier one.

The question of the ultimate usefulness of additive and multiplicative models in this area is thus left open by the present results. For now, all we can suggest is that more experience with both kinds of models is desirable.

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APPENDIX

Tables A–H
Basic variance-covariance matrices
for MZ and DZ twins

TABLE A
VARIANCES AND COVARIANCES, PMA SCALES: MZ PAIR SUMS

	N	V	S	W	R
N	3603.41	1521.73	1449.47	889.60	1034.20
V		2047.49	712.91	837.76	959.43
S			4059.80	304.36	453.67
W				1161.32	497.75
R					937.22

TABLE B
VARIANCES AND COVARIANCES, PMA SCALES: DZ PAIR SUMS

	N	V	S	W	R
N	3943.48	2160.52	2248.69	1282.17	1425.28
V		2161.06	1683.94	1062.12	1199.44
S			4595.79	877.62	1084.55
W				1064.25	682.36
R					1064.74

TABLE C
VARIANCES AND COVARIANCES, PMA SCALES: MZ PAIR DIFFERENCES

	N	V	S	W	R
N	372.74	−1.48	1.36	−2.57	30.04
V		161.25	18.13	58.41	69.88
S			449.28	28.26	13.66
W				196.90	43.60
R					126.89

TABLE D
VARIANCES AND COVARIANCES, PMA SCALES: DZ PAIR DIFFERENCES

	N	V	S	W	R
N	1183.74	242.25	464.66	307.51	226.77
V		325.00	111.14	198.69	132.65
S				478.80	114.34
W			1110.50	313.88	183.25
R					177.84

TABLE E

VARIANCES AND COVARIANCES, PMA SUBSCALES: MZ PAIR SUMS

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Addit.	186.87	233.77	274.20	88.91	115.00	82.08	158.75	99.79	111.22	97.06	25.76	51.82	67.55	28.90	94.37
2. Mult.		567.85	473.11	164.73	229.54	161.82	180.95	100.80	142.42	208.16	64.02	96.93	113.85	58.13	168.76
3. 3-Hi.			902.84	202.66	301.78	225.44	316.61	201.24	257.38	233.65	58.65	101.89	195.30	98.91	272.65
4. Sent.				182.43	214.63	156.59	83.58	85.63	88.50	134.82	37.80	66.71	80.22	45.21	151.62
5. Vocab.					394.14	255.46	98.28	88.89	108.45	224.68	69.16	109.83	113.44	70.06	235.86
6. Compl.						251.72	112.08	92.62	117.09	149.26	38.98	70.50	87.58	50.37	171.61
7. Flags							619.55	466.07	436.14	119.11	25.42	49.92	77.95	30.31	119.58
8. Fig.								589.60	406.70	103.09	12.08	37.39	47.68	28.44	94.09
9. Cards									504.75	133.74	16.91	50.21	67.73	41.86	97.04
10. 1st L.										406.48	125.73	138.21	92.60	59.99	174.70
11. 4-LW.											74.13	49.63	29.61	22.26	47.82
12. Suff.												98.58	42.83	23.54	71.58
13. L. Ser.													101.91	43.68	127.55
14. L. Grp.														47.84	67.26
15. Ped.															313.39

TABLE F

VARIANCES AND COVARIANCES, PMA SUBSCALES: DZ PAIR SUMS

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Addit.	178.96	261.02	315.45	114.07	199.58	111.52	214.68	170.51	173.57	134.45	36.24	76.75	89.72	51.14	140.57
2. Mult.		636.52	565.04	187.89	320.73	167.44	264.49	211.82	213.88	269.76	51.26	132.94	140.26	106.49	193.12
3. 3-Hi.			918.54	300.30	485.20	283.47	525.74	351.73	417.86	356.86	92.65	162.06	252.88	149.16	343.52
4. Sent.				191.02	255.44	146.58	204.87	124.53	158.67	165.95	51.97	80.24	97.98	58.19	174.16
5. Vocab.					457.05	254.76	295.01	189.32	249.88	276.71	84.29	146.44	175.66	94.76	287.05
6. Compl.						199.42	196.30	134.78	173.22	163.85	43.33	78.23	102.95	55.09	176.95
7. Flags							641.25	485.71	478.28	210.47	61.07	116.67	166.90	71.33	235.40
8. Fig.								608.72	483.32	120.39	58.76	81.37	113.01	37.33	182.51
9. Cards									533.67	155.86	53.52	101.51	136.08	48.44	209.86
10. 1st L.										386.11	85.92	148.50	117.44	77.55	183.08
11. 4-LW.											54.72	36.91	42.27	25.52	67.17
12. Suff.												97.02	70.85	38.28	101.93
13. L. Ser.													144.84	64.93	157.14
14. L. Grp.														47.79	69.88
15. Ped.															311.52

TABLE G

VARIANCES AND COVARIANCES, PMA SUBSCALES: MZ PAIR DIFFERENCES

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Addit.	42.72	24.22	16.71	1.78	5.10	1.00	3.53	.68	2.71	1.55	−.80	2.624	7.58	.36	9.26
2. Mult.		86.91	4.14	5.21	15.32	8.62	6.23	−8.55	−3.66	5.74	3.98	1.544	7.26	−1.25	6.31
3. 3-Hi.			159.12	−9.66	−12.37	−8.70	5.08	−11.07	7.67	−13.03	3.23	−1.408	3.53	3.77	−.21
4. Sent.				19.66	13.50	4.93	−4.91	.96	−.69	8.55	4.74	1.591	6.61	2.48	6.56
5. Vocab.					46.44	17.10	−.52	4.52	9.67	12.25	8.97	4.955	12.81	7.92	12.17
6. Compl.						26.12	2.12	8.71	2.67	10.42	4.82	2.097	7.85	3.23	9.96
7. Flags							139.28	23.00	20.78	9.70	−4.10	3.710	1.22	2.01	2.17
8. Fig.								119.18	15.26	4.69	−2.59	.615	2.31	−.04	5.87
9. Cards									74.49	11.15	1.93	5.914	3.26	1.29	−2.73
10. 1st L.										90.89	12.02	13.433	11.16	.95	4.51
11. 4-LW.											22.83	4.698	6.95	1.04	5.80
12. Suff.												20.581	3.67	1.19	5.30
13. L. Scr.													27.64	3.05	5.80
14. L. Grp.														14.86	4.83
15. Ped.															56.39

TABLE H
VARIANCES AND COVARIANCES, PMA SUBSCALES: DZ PAIR DIFFERENCES

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Addit.	95.70	80.94	83.74	19.38	21.08	13.41	25.39	17.08	15.89	30.11	29.84	20.84	14.59	11.98	5.30
2. Mult.		237.55	118.84	26.97	45.75	10.67	66.88	39.69	34.20	29.53	24.84	19.90	33.02	22.71	42.82
3. 3-Hi.			259.57	43.08	34.19	26.49	86.43	86.64	46.06	67.95	31.89	31.25	34.92	34.25	30.56
4. Sent.				37.90	26.63	23.28	19.03	9.50	.50	18.56	3.66	6.80	4.98	4.81	21.49
5. Vocab.					62.97	32.61	19.83	17.77	13.17	41.61	14.02	26.79	13.58	8.23	28.04
6. Compl.						59.09	27.35	17.64	10.38	45.11	16.95	26.19	18.61	3.75	26.81
7. Flags							215.97	131.77	96.58	68.58	7.21	19.61	18.71	22.40	26.47
8. Fig.								202.91	94.40	81.71	21.08	30.66	21.14	23.36	21.81
9. Cards									139.27	46.08	20.94	9.60	27.40	23.29	20.10
10. 1st L.										160.18	50.77	44.88	22.82	23.39	11.12
11. 4-LW.											40.22	22.43	14.26	7.36	2.41
12. Suff.												38.60	10.65	8.95	12.37
13. L. Scr.													29.31	10.27	12.55
14. L. Grp.														24.52	5.40
15. Ped.															65.46