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Genetic and Environmental Influences on the Development of Piagetian Logico-Mathematical Concepts and Other Specific Cognitive Abilities:
A Twin Study

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CONTENTS

The original version of this work was submitted to the Faculty of the Graduate School of the University of Colorado in partial fulfillment of the requirements for the degree of Doctor of Philosophy, which was awarded in April, 1979 at the Department of Environmental, Population, and Organismic Biology. The Advisory Committee consisted of Drs. James R. Wilson, Steven G. Vandenberg, Jeffry B. Mitton, Gerald E. McClearn, and Robert Plomin.

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The classical twin study method was used to assess the relative contributions of genetic and environmental components to individual variation in several aspects of cognitive functioning. Tests of logico-mathematical concept formation, as well as vocabulary, nonverbal reasoning, and visual memory, were administered to 137 MZ and 72 DZ, same-sex white twin pairs. These children were individually tested on the Piagetian Mathematical Concepts Battery (PMCB), Peabody Picture Vocabulary Test (PPVT), Raven Coloured Progressive Matrices (PM), and a Visual Memory (VM) test. The Attitudes Toward Education (ATE) questionnaire and the Moos [63] Family Environment Scale (FES) were used to collect additional data from the parents. Twins were 4 to 8 years old, with a mean age of 71 months, and most were from middle- and upper-middle-class families. Zygosity was determined from dermatoglyphic information and responses to a questionnaire asking mothers about twin similarities and confusion between the twins by others. These data were analyzed by a simple pair concordance procedure and by a discriminant function analysis. In addition, blood typing was done on 32 pairs for whom zygosity was not possible to determine by these methods.

Previously reported patterns of intercorrelations among the 10 subscales of the FES, as well as the subscale structure, were verified by factor analysis. A factor analysis of the ATE yielded three factors: Basic Academic Education, Parental Participation, and General Utility of Education. These factors correlated significantly ($P < 0.01$) with various environmental indices (including father's occupation and education, Achievement Orientation, Expressiveness, etc). A factor analysis of the PMCB tasks gave some support for the existence of Piaget's underlying concepts of conservation of number, seriation, and classification.

No sex differences were found for any of the specific cognitive abilities or any of the environmental variables. Correlations with age were substantial: 0.75 for PMCB, 0.70 for PPVT, 0.59 for PM, and 0.43 for VM. Because of the high correlations with age, the effect of age on these variables was partialed out in all further analyses. PMCB correlated most highly with PM ($r = 0.41$), and with PPVT ($r = 0.36$). Nonverbal reasoning and vocabulary were relatively independent of each other ($r = 0.23$). Correlations between visual memory and all other tests were low.

MZ and DZ intraclass correlations for height and weight were similar to values reported in other studies. After correcting for test reliability, significant genetic variance ($P < 0.01$) was found for both PMCB and PPVT, and was suggested for VM. Genetic variance for PM was not significant ($P > 0.05$). Correction for reliability could not be employed in this case because an accurate estimate of the PM test–retest reliability is not available. There was no significant effect of age on the magnitude of the MZ or DZ intraclass correlations.

A stepwise multiple regression on the environmental variables was performed for each cognitive test. The environmental variables considered were number of siblings, parental education and occupation, the 10 FES subscales, and the three ATE factors. Age was entered first in the regression equation for each test, and it accounted for 18% to 57% of the total variance in cognitive performance. Parental education accounted for 3% of the total variance in both PMCB and PPVT performance. This was considered as an environmental influence, but the possible confounding with a genetic element in parental IQ was discussed. Achievement Orientation exhibited a significant negative relationship ($R^2 = 0.02$) with PM performance. Cohesion in the Family was positively related to PPVT performance ($R^2 = 0.02$). In addition, Intellectual–Cultural Orientation predicted VM performance ($R^2 = 0.02$). Overall, those environmental variables found to have a small effect suggest the value of a warm, stimulating, supportive (but not "pushy") family environment for normal cognitive development in young children.

Examination of the genetic and environmental results indicated that 49% of the variance in age-corrected PMCB performance was accounted for by the genetic variance (estimated from twin comparisons) and parental education. Similarly, variables identified in this investigation accounted for 60% of the variance in age-corrected PPVT performance, 29% of the age-corrected PM performance, and 32% of age-corrected VM performance.

In conclusion, this was the first large twin study to find both genetic and environmental influences on the development of Piagetian logico-mathematical concepts and other specific cognitive abilities. The results illustrate the feasibility of investigating cognitive development in a theoretical framework such as Piaget's.

Key words: Cognitive development, Abstract thinking, Verbal ability, Visual memory, Piagetian Mathematical Concepts Battery, Peabody Picture Vocabulary Test, Raven Coloured Progressive Matrices, Family Environment Scale, Parental Attitudes Toward Education Questionnaire, Genetic influences, Environmental influences, Twins

1. INTRODUCTION

1.1. Development of Cognitive Functions

Jean Piaget has proposed a theory of the development of cognitive functions as a part of biological development. According to Piaget, cognitive development is an epigenetic process involving adaptation of an organism to its environment. The process includes autoregulations (striving for equilibrium), assimilation of external stimuli, and accommodation to the environment [73]. (For a detailed description of Piaget's theory, see [26,70,73].) Within this realm Piaget has addressed himself to the development of logical thinking [34], the concept of number [72], and the formation of mathematical concepts [71]. Piaget believes that logico-mathematical structures

> essentially involve relations of inclusion, order, and correspondence. Such relations are certainly of biological origin, for they already exist in the genetic (DNA) programming of embryological development as well as in the physiological organization of the mature organism before they appear and are reconstructed at the different levels of behavior itself. They then become fundamental structures of behavior and of intelligence in its very early development before they appear in the field of spontaneous thought and later in reflection. They provide the foundations of those progressively more abstract axiomatizations we call logic and mathematics. . . . the origin of these logico-mathematical structures should be sought in the activities of the subject, that is, in the most general forms of coordinations of his actions, and, finally, in his organic structures themselves. This is the reason why there are fundamental relations among the biological theory of adaptation by self-regulations, developmental psychology, and genetic epistemology [73: p 706].

Piaget believes that logico-mathematical structures (psychological systems of thought) include classification (inclusion into categories), ordering (asymmetrical relations, seriation), and conservation (correspondence or preservation of a quantity or number regardless of contextual changes). He claims that all logical reasoning and mathematical abilities develop from these elementary logical and mathematical structures (concepts). Consequently, overall intellectual functioning is based in part on these structures [73].

Piaget has investigated the development of these logico-mathematical concepts using tasks that require subjects to manipulate objects and give reasons for their actions [72]. Although Piaget has shown little interest in individual differences, standardized forms of his tasks can be used to study individual differences in cognitive development. Standardized tasks based on Piaget's epigenetic theory of cognitive development seem particularly appropriate for an investigation of the genetic and environmental influences on the formation of the logico-mathematical concepts in children. However, no such study has been reported in the literature. In fact, very few researchers other than Piaget have looked at the development of logico-mathematical concepts or the relationship of other cognitive functions to logico-mathematical concept development.

Several studies have focused on the genetics of mathematical or reasoning ability [10,11,48,93,95]. However, with only two exceptions [25,99,101,102], these studies have not measured these abilities in children.

Many researchers have investigated the effects of various general environmental factors, such as socioeconomic status, number of siblings, and crowding, on cognitive abilities [eg, 1,2,23,47,54,82,92,102]. In contrast, very little research has been done on the relationships between cognitive abilities and more specific environmental factors, although they might be more influential than general characteristics of the environment [54,90,94]. The subjects in most of this research were 8 years of age or older. Very few studies have investigated environmental influences on the early development of logico-mathematical concepts, or the possible relationships of verbal, reasoning, and memory functions to such development.

A review of research related to logico-mathematical concept development follows. Most of these studies involve mathematical, reasoning, or general intellectual ability (IQ) in adolescents and adults. All of these abilities are dependent on the elementary logico-mathematical structures described by Piaget [72,73]. Previous studies of logico-mathematical development are, of course, also included in the review.

1.2. Genetic Basis for Mathematical Ability

According to Jean Piaget's theory of the development of logico-mathematical concepts [72], all children, regardless of their cultural background, pass through the same sequence

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of conceptual stages. If this is true, it suggests that such development may have a genetic predisposition as a species-specific characteristic [102]. Indeed, Piaget's sequence of three major logico-mathematical stages (preoperational, transitional, and concrete operational) has been substantiated in studies of 4- through 8-year-olds in both Western and non-Western cultures [1,12,14,15,19–21,30,38–40,43,51,66,76,77,83–87,89,92,104] (see [26] for a review). Wilson [102] has also pointed out that there are likely to be individual differences in the rate of development of such genetically influenced traits and in the ultimate level of ability attained.

A hereditary influence on development of mathematical abilities was claimed by Kosc [44], who defined developmental dyscalculia as a

> structural disorder of mathematical abilities which has its origin in a genetic or congenital disorder of those parts of the brain that are the direct anatomico-physiological substrate of the maturation of the mathematical abilities adequate to age, without simultaneous disorder of general mental functions [44: p 192].

Kosc [45] has cited neurological support for the existence of regions of the brain specific for mathematical operations. This evidence comes from studies of brain damage and tumors. Kosc also reviewed evidence for the existence of a genetic influence on mathematical performance. Most of Kosc's evidence, including monozygotic (MZ) twin correlations for arithmetic scores and family histories of mathematically "gifted" and subnormal children, is based on established mathematical ability in subjects 11 years of age and older. Kosc [44] also classified various types of developmental dyscalculia and designed tests to distinguish between the types in children older than 8½ years.

Additional evidence for a genetic influence on dyscalculia comes from studies of Turner syndrome patients. Money [59–60] reported mild dyscalculia among girls who exhibit Turner syndrome. Money and Alexander [62] also found that Turner subjects performed significantly below average on the Primary Mental Abilities (PMA) numerical ability subtest, even though they performed normally on PMA reasoning. Money [61] concluded that the mathematical deficit in Turner syndrome is one expression of the chromosomal defect basic to the syndrome.

Evidence of a hereditary component in normal mathematical ability has been provided by a number of twin studies (reviewed by Vandenberg [93,95] and by Mittler [58]). The extent of reported genetic contribution varies considerably among the different tests used by various investigators [95]. For example, results of the Michigan and Louisville twin studies [93] indicated a significant hereditary component for the PMA numerical subtest, but not for PMA (verbal) reasoning. Vandenberg [93] cited two Swedish studies that found a significant hereditary component for numerical reasoning [97], for Raven Standard Progressive Matrices (SPM) nonverbal reasoning, and for a number series reasoning test [33]. These studies were limited by the fact that most included fewer than 100 twin pairs, and all subjects were adolescents or adults. Furthermore, as Mittler states, most of

> . . . these studies can be criticized for using an arbitrary assemblage of tests, unrelated to a consistent or satisfactory model of intellectual ability. Quite often the reliability of the measures is not stated [58: p 93].

Similar criticisms have been made by DeVries [13] and Meyers [57].

Results of four recent family studies have shown a familial component for nonverbal reasoning [10,11,68,91,98]. However, since these family studies involved adolescents and adults, they did not address the issue of cognitive development.

Foch and Plomin [25] have conducted the only twin study of specific cognitive abilities in children (5 to 12 years old). After correcting for test–retest reliability, they found no hereditary component for mathematical achievement or nonverbal reasoning as measured by the Raven Coloured Progressive Matrices (Coloured PM).

1.3. Environmental Influences on Mathematical Ability

Piaget [72] contends that age of acquisition of mathematical concepts is associated with various environmental experiences. Effects of environmental variables on the performance of Piagetian tasks have been suggested by the results of several studies. In both a longitudinal and a cross-sectional study, Almy and associates [1,2] found that lower-class children accomplished Piagetian tasks at a later age than middle-class children. Similarly, Figurelli and Keller [23] found that middle-class children scored significantly higher than lower-class children on conservation tasks. Tuddenham [92] observed a significant correlation between father's occupation and child's performance on some Piagetian tasks. Simmons et al [82] found that parental education significantly predicted performance on the Piagetian Mathematical Concepts Battery (PMCB), although father's occupation did not. For their Mexican-American subsample, Simmons et al [82] also found a significant negative correlation between number of siblings and PMCB performance. In a longitudinal twin study of mental development, Wilson [102] obtained modest positive correlations between twins' 6-year-old WPPSI (Wechsler Preschool and Primary Scale of Intelligence) IQ scores and their mother's education and socioeconomic status (0.33 and 0.36, respectively). Marjoribanks [54] found that socioeconomic status (SES) and other family environment variables were more highly correlated with mathematical achievement than with IQ among British children over 7 years of age. Since parental IQ is known to be correlated with SES, and since it is also correlated with offspring cognitive functioning, the effect of this socioeconomic variable could be confounded with hereditary influences [47,80]. Consequently, although SES is an important aspect of environmental influence on the development of logico-mathematical concepts, environmental measures more independent of genetic influences are needed [54].

Although there is an obvious need for such independent measures of the environment, very little research has been done in this area, mostly because of the lack of adequate environmental scales (Vandenberg, personal communication). In addition, all such research has been done on subjects 8 years of age or older. When Spuhler and Vandenberg [90] investigated the relationship between parental attitudes, as measured by Schaefer's parental attitude research instrument (PARI), and cognitive abilities in adolescents and adults, they found less environmental influence on offspring performance than on adult cognitive performance. Wolf [105] found a 0.69 multiple correlation of IQ with three family environment variables (Press for Achievement Motivation, Press for Language Development, and Provision for General Learning) in a study of fifth graders from the full range of socioeconomic strata. SES and IQ were not correlated ($r = 0.02$) in that study.

Similarly, in a large longitudinal study of school-age British children more than 7 years old, Marjoribanks [54] found the influence of various environmental process variables on IQ and mathematical ability to be greater than the influence of SES. His six environmental process variables were (1) Press for Achievement, (2) Educational Aspirations for the Child, (3) Knowledge of Child's School Environment, (4) Press for Intellectuality, (5) Parent–Teacher Interaction, and (6) Parent–Child Activeness. Marjoribanks found that his environmental variables (including SES, sibship size, and crowding) accounted for a larger percentage of the variance in mathematical achievement (average 35%) than in general intelligence (average 13%). However, environmental influences were more stable over time for general intelligence than for academic mathematical achievement. In addition, he reported different patterns of interrelationships among cognitive performance, environmental process variables, SES, and family structure for the different ages and sexes. Marjoribanks found two SES effects on cognitive functioning—a "contextual" effect through the learning environment established by parents, and an "individual" direct SES effect after learning environment intermediaries had been partialed out. His path analyses revealed very complex interrelationships between environment and cognition. For example, for the junior boys (7 to 11 years), mathematical achievement was directly related to IQ and Educational Aspirations for the Child, while IQ was directly related to Educational Aspirations for the Child, sibship size, and crowding. For junior girls, father's occupation was also related to IQ. Marjoribanks [54] concluded that cognitive functioning needs to be studied with more detailed analyses of the influence of family, school, and neighborhood (peer) environments, independent of SES. He suggested that the "individual" SES effect may also be mediated by more subtle aspects of the environment. Thus, there are indications that investigations of the relationship between independent measures of various aspects of the environment and cognitive abilities may lead to enlightening results, especially if such a study is focused specifically on the development of logico-mathematical concepts in young children.

1.4. Verbal, Memory, and Reasoning Interrelationships With Mathematical Ability

Piagetian techniques require verbalization by children in order to assess the development of logico-mathematical concepts. However, previous studies concerned with the influence of verbal ability on Piagetian performance have produced conflicting results. For instance, Little [46] and Winer [103] found that verbal ability was positively related to Piagetian task performance, whereas factor analyses by DeVries [13] and Longeot [49] indicated that verbal abilities were independent of performance on Piagetian reasoning tasks. Tuddenham [92] reported a 0.21 multiple correlation among eight conservation and classification tasks and the Peabody Picture Vocabulary Test (PPVT). An average correlation of 0.31 between Piagetian tasks and the PPVT was obtained by Klippel [42] in a cross-cultural study. A hereditary component in verbal ability has often been found in studies of both adults and children [10,11,25,58,93,95,99,101]. Because of this finding, a genetic component in Piagetian task performance could be related to the verbal ability involved.

Memory ability might also be related to the development of Piagetian logico-mathematical concepts, since recognition of objects is essential for classification. Piaget and Inhelder [75] have recently demonstrated a relationship between memory and cognitive development, as well as a developmental sequence for three types of memory (recognition, reconstruction, and reproduction). Using Piaget's framework, Anooshian and Carlson [3] found low correlations between conservation and mental imagery, with both correlating significantly with IQ. Klippel [42] also found low correlations with memory. However, in a factor analysis, Carlson and Wiedl [5] found that serial recall, short-term visual memory, and class inclusion loaded on one factor, and were independent of a second factor that included equivalence conservation of number, matrices (multiple classification), and Raven Coloured Progressive Matrices. In addition, in reviewing the literature one finds conflicting evidence for a hereditary component in memory [10,11,25,93–95]. Such results call for further study. Considering the memory functions required for Piagetian mathematical conceptualization, a visual memory test (immediate and delayed) would seem appropriate. Using such a visual memory test, DeFries et al [11] found a midchild on midparent regression coefficient (corrected for test reliability) of 0.43 for their memory factor. Foch and Plomin [25] also found a significant hereditary component ($r_{MZ} = 0.69$, $r_{DZ} = 0.19$) for their memory factor (corrected for reliability) in preadolescent twins.

As might be expected from Piaget's theory of logico-mathematical structures, a number of investigators have found that general intelligence is positively correlated with performance on Piagetian logico-mathematical tasks [2,16,46,39]. When Tuddenham [92] used nonverbal reasoning (Coloured PM) as a measure of intelligence, he found a correlation of 0.60 with a composite score on six of his Piagetian tasks. Using the Coloured PM as a defining measure of "simultaneous information integration" (as opposed to "successive synthesis"), Carlson and Wiedl [5] found that it loaded on the same factor as equivalence conservation of number and Piagetian matrices (multiple classification). They concluded that performance on all three measures required a similar mode of "simultaneous information integration." Their results support Inhelder and Piaget's contention [34] that the PM is a multiplicative classification problem. However, Klippel [42] found low correlations between similar Piagetian tasks and the PM ($r = 0.24$). DeVries [13], Kaufman [39], and Garfinkle [26] found that Piagetian tasks and conventional intelligence or academic achievement defined different factors, although correlations among the measures were significant. It is clear that the relationship between reasoning ability and Piagetian logico-mathematical task performance merits further investigation. Since there is no satisfactory non-Piagetian, standardized test of reasoning or mathematical ability for 4- to 8-year-olds, the Coloured PM would seem to provide the best independent assessment of logico-mathematical conceptualization. In addition, a familial component of performance on the Raven Standard Progressive Matrices has been reported [11,31,-68,69], although results from other tests of reasoning have not always indicated familial influence [93,95]. Again, all these genetic studies using the PM have involved subjects over 8 years of age. In a recently completed study of young twins, Foch and Plomin [25] found no hereditary component for Coloured PM performance of children at that age level.

1.5. This Study

This short review of the literature underscores the need for a study such as that which will be reported herein. This research is the first simultaneous investigation of genetic and environmental influences on the development of logico-mathematical concepts in young children, based on the theoretical framework of Jean Piaget's theory of cognitive development. In fact, it is the first large-scale genetic study to use Piagetian tasks. (Munsinger [64] did report a small twin study of 42 pairs using only the Piagetian mountain problem, which is perceptual and not typical of logico-mathematical tasks such as conservation, seriation, and classification.) In addition, this is the first such research to use extensive questionnaires to assess family environment and parental attitudes in relation to Piagetian cognitive development and the development of other specific abilities. Finally, this study may provide further insight into the interrelationships among logico-mathematical concepts and reasoning, verbal, and memory abilities.

2. MATERIALS AND METHODS

2.1. Twin Subjects

Between January, 1976 and March, 1978 cooperation in identifying same-sex twins was secured from all school districts and mothers of twins clubs in the greater Boulder–Denver area, Fort Collins, Greeley, Colorado Springs, and Pueblo, Colorado. In addition, preschools were contacted in the greater Boulder–Denver area, Fort Collins, and Greeley. Letters to parents were distributed by myself or by school district personnel. After

TABLE 1. Age and Sex Distribution of 209 Same-Sex Twin Pairs in the Colorado Piagetian Twin Study

		Age[a] (years)			
Zygosity and sex	N	4	5	6	7
MZ					
Males	58	16	13	20	9
Females	79	19	25	19	16
Total	137	35	38	39	25
DZ					
Males	38	8	9	8	13
Females	34	8	5	13	8
Total	72	16	14	21	21
All pairs					
Males	96	24	22	28	22
Females	113	27	30	32	24
Total	209	51	52	60	46

[a]Mean age is 5 years, 11 months; SD is 13 months; range is 48–95 months.

TABLE 2. Demographic Statistics on 209 Twin Pairs in the Colorado Piagetian Twin Study

Variable	Mean	SD	Range
Number of siblings	1.4	1.2	0–7
Education of father[a]	10.6	2.7	4–16
Education of mother[a]	9.6	1.8	6–16
Provider's occupation[b]	73.0	10.5	20–93

[a]Possible range is 1–16.
[b]According to the Duncan modification of the NORC occupational prestige scale [79]; possible range is 20–93.

receipt of a signed parental consent form postcard, parents were called to arrange an appointment to test their twins in their own home.

The sample was entirely white (non-Mexican–American), same-sex twins. An effort was made to include an equal number of males and females within equal groups of monozygotic (MZ) and dizygotic (DZ) twin pairs. The final decision about zygosity was not made until near the end of data collection (as explained below). When the process was completed, there were fewer DZ than MZ pairs. Apparently it was more difficult to recruit fraternal (DZ) twins, as has been the case in most previous studies [53,94]. The final sample contained 137 MZ (58 male and 79 female) and 72 DZ (38 male and 34 female) pairs (see Table 1). At the time of testing, subjects ranged in age from 48 to 95 months, with a mean age of 71 months. An effort was made to establish a sample of twins relatively equally distributed among 4-, 5-, 6-, and 7-year-old groupings (Table 1).

During the home visit, information was obtained on number of siblings, parental educational levels, and provider's occupation (usually father's). The number of siblings for each twin pair ranged from 0 to 7, with a mean of 1.4 (see Table 2). Parental education was evaluated on a arbitrary scale of 1 to 16 (see Table 3). Education of the fathers and mothers of twin pairs ranged from 4 to 16 and from 6 to 16, respectively, with means of 10.6 (representing a BA or BS degree) and 9.6 (representing three years of college), respectively (Table 3). Distributions of education of the mothers and fathers were similar, although there were more men than women at the upper end of the scale (see Fig. 1). Figure 1 also demonstrates that there were two modes in parental education, such that most parents either completed high school or had a BA or BS degree. Provider's occupation was coded for prestige according to the Duncan modification of the NORC (National Opinion Research Center) scale, which has a possible range of 20 to 93 [79]. In this study, values ranged from 20 to 93, with a mean of 73.0 (representing a technical worker), and a standard deviation (SD) of 10.5 (Fig. 2).

TABLE 3. Coding for Level of Education

Level of education completed	Code
Elementary school grades	
1–2	1
3–4	2
5–6	3
Completed elementary school	4
Secondary school grades	
7–8	5
9–10	6
11–12	7
Completed secondary school	8
College years	
1–2	9
3–4	10
Completed BA, BS	11
5–6	12
Completed MA, MS	13
7–8	14
9–10	15
PhD, MD, etc	16

Although an effort was made to include twins from the full range of socioeconomic status (SES), Figures 1 and 2 illustrate that this strictly volunteer sample was biased toward the higher end of the SES distribution.

2.2. Zygosity Determination

To determine zygosity, a modified form of the Nichols-Bilbro questionnaire (1966) was completed by the parents (usually the mother) during the testing session. In addition, information was recorded on tester observations of twin hair characteristics and eye color similarity, height and weight measurement, and phenylthiourea (PTC) and propylthiouracil (PROP) tasting [37]. Based on the work of Cohen et al [6,7], physical similarities and answers to twin confusion questions were rated on a 5-point scale and were analyzed by both a discriminant analysis and what Cohen et al called the "intuitive" system. In their study, the questionnaire was completed by mothers of twins with a mean age of approximately 8 years. When applying discriminant function zygosity scores to the blood-typed sample from which the function was derived, Cohen et al [6] misclassified only 3 out of 155 pairs (1.9%). In a similar analysis, Klein and Claridge [41] obtained 96% agreement between blood typing and discriminant function zygosity determination (based on self-report questionnaires of 101 twin pairs 14 to 58 years old).

To obtain zygosity scores from the intuitive system, Cohen et al [6,7] equally weighted all questions and simply totalled them. The correlation of zygosity scores based on the discriminant and intuitive analyses was impressive: $r = 0.97$, $P < 0.001$, $N = 155$ pairs [6]. In a later study [7] on a sample of mothers of twins (average age 3 years) from a similar population, the same correlation was 0.96, $P < 0.001$, $N = 275$.

A similar intuitive system was used in this study initially to classify twin pairs as MZ, DZ, or undecided (using the percentages of Cohen et al). In addition, fingerprint ridge counts were calculated [8] and zygosity determined from these [67]. If a twin pair was MZ according to the intuitive analysis but DZ according to dermatoglyphics, or if a pair was of undecided zygosity according to the intuitive analysis, the pair were subjected to blood-typing analysis, with parental permission. (The parents of only two pairs refused permission.) Thirty-two twin pairs had their blood analyzed by the Minneapolis War Memorial Blood Bank for five blood groups (ABO; Rh-C, D, E, c, e, C^w; MNS; Kell; Duffy), six serum proteins (gammaglobulins-azxgfb; haptoglobin; transferrin; Gc; ceruloplasmin; glycerine-rich β-glycoprotein), and five erythrocyte enzymes (esterase-D; acid phosphatase; phosphoglucomutase 1 and 2; adenylate kinase, 6-phosphogluconate dehydrogenase). In cases where twins of a pair differed in only one of these blood markers, that marker was reanalyzed to verify

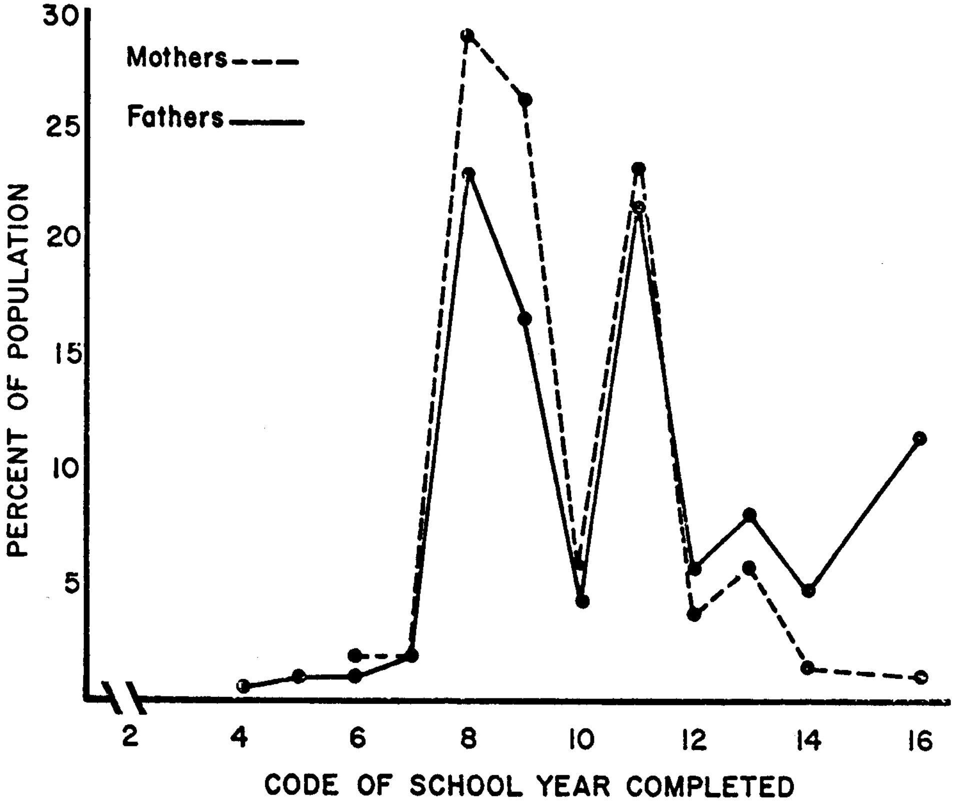

Fig. 1. Distribution of school years completed for fathers and mothers of 209 twin pairs in the Colorado Piagetian Twin Study.

accuracy (two mistakes were found). For these 16 markers, DZs are misclassified only 0.7% of the time [52]. There were three pairs for whom erythrocyte enzymes were accidentally not determined; their blood zygosity determination is still 98% accurate [52]. In addition, parents of four twin pairs had records of previous extensive blood analyses.

Because the blood-typed sample (N = 36 pairs) of twins included only eight DZ pairs, it was not possible to use it to determine discriminant function coefficients (weights) for the 20 less objective physical similarity and "mistakability" questions. Following Cohen et al [6,7], "mistakability" refers to the twins being mistaken for one another. Therefore, the nontyped sample (N = 173 pairs) was subjected to discriminant analysis. The discriminant function coefficients were applied to the blood-typed sample for verification, resulting in the misclassification of 4 out of 36 pairs (11%). This level of error is partly a function of small sample size (36 pairs), but mostly results from the fact that the blood-typed sample was chosen because of its "undecided" character. On the other hand, the intuitive and discriminant zygosity analyses of the nontyped sample disagreed on only two twin pairs (1%). The zygosity of these two pairs was determined on the basis of additional information not available to either analysis (color-blindness and freckles, respectively).

With the probabilities set realistically at 67% MZ and 33% DZ, the resulting standardized discriminant function coefficients are presented in Table 4. Confusion by casual friends of the twins was found to have the greatest discriminative power, with confusion by mother's friends next in order. These results agree with previous findings by Cohen et al [6,7] and Klein and Claridge [41]. Mother's opinion of hair characteristics also had high discriminatory power, with height and weight differences and parents' confusion low in rank. These results are similar to those of Cohen et al, although they also found high predictive power for eye color. Klein and Claridge found height and eye-color differences of high rank, but their study was based on older twins' self-reports.

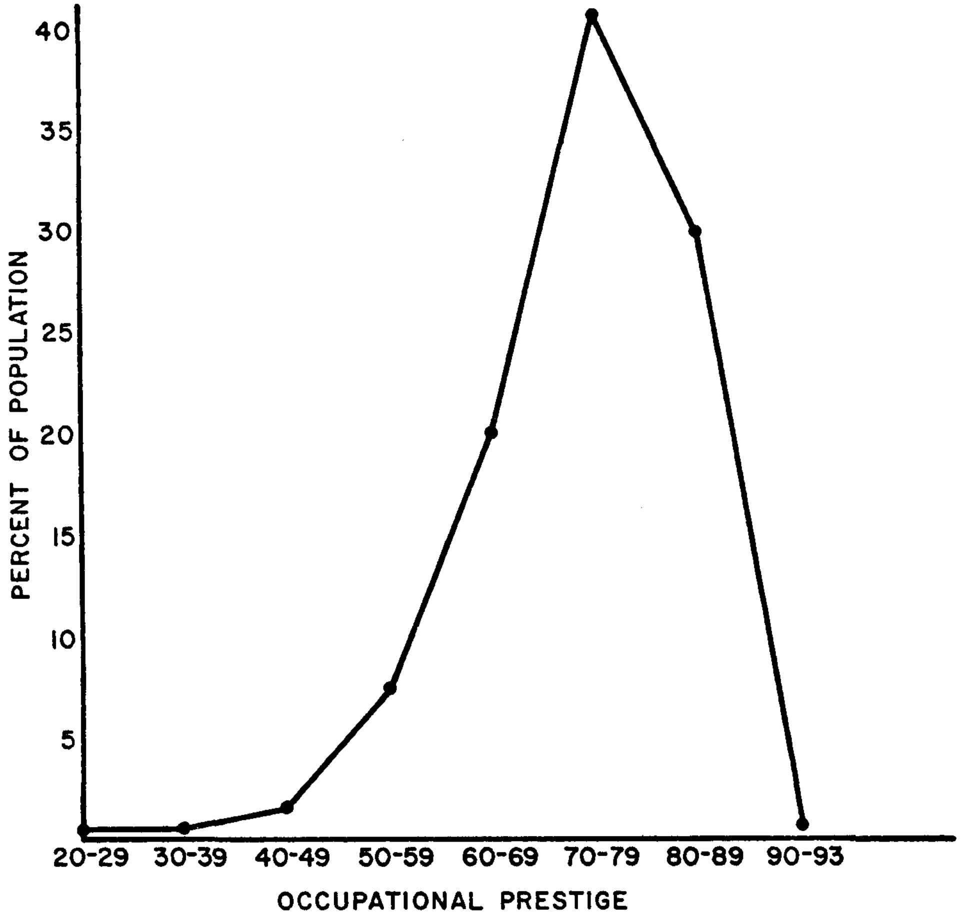

Fig. 2. Distribution of occupational prestige [79] for major income provider of 209 twin pairs in the Colorado Piagetian Twin Study.

2.3. Procedure and Description of Measures

Between February, 1976 and April, 1978, each twin pair was visited by two testers and two recorders in the twins' home. While the twins were being tested, one or both parents verified the twins' birthdate on the consent form and supplied provider's occupation, mother's and father's educational levels, number of siblings in addition to the twin pair, and information about the twins' similarity and "mistakability." Both parents completed the Moos Family Environment Scale [63] and the Attitudes Toward Education questionnaire (see Appendix). If one parent was absent at the time of the visit, his or her responses to these questionnaires were obtained by mail whenever possible. During the home visit, the following physical characteristics of each twin were also recorded: height, weight, fingerprints, and tasting of PTC (nine ½-serial concentrations) and PROP (three ½-serial concentrations), as well as each tester's opinion of differences between the twins in hair characteristics and eye color.

The twins were tested individually in a private room by a tester, accompanied by a recorder of the opposite sex. Over the two and a half years of data collection, there were a number of testers and recorders, all of whom were trained by me. I developed the Piagetian Mathematical Concepts Battery (1975) used in this study (see below). No recorder became a tester until he or she had been a recorder for at least 15 children. This careful training program probably contributed to the absence of tester effects for performance on any of the cognitive tests.

TABLE 4. Discriminant Function Standardized Coefficients From a Discriminant Analysis of Twin Zygosity Based on Physical Similarities and "Mistakability" Questions Concerning 173 Non-Blood-Typed Twin Pairs in the Colorado Piagetian Twin Study

Similarity and mistakability variables	Discriminant function standardized coefficients
Mother's opinion of differences in	
Hair color	0.55
Hair texture and curliness	0.47
Eye color	0.22
"Mistakability" by	
Parents	0.07
Teachers	0.13
Close friends	0.15
Casual friends	0.90
Mother's friends	0.59
Relatives	0.26
Tester-1's opinion of differences in	
Hair color	0.33
Hair texture and curliness	0.33
Eye color	0.09
Tester-2's opinion of differences in	
Hair color	0.12
Hair texture and curliness	0.12
Eye color	0.31
Differences in	
Height	−0.13
Weight	−0.05
PTC	−0.09
PROP	0.24
Fingerprint ridge count	−0.22
Mother's opinion of zygosity	−0.12

The tests administered to the children are described as follows (in the order presented):

2.3.1. Visual Memory (VM). The subject is asked to study and remember a standard set of 40 drawings on blue paper for 1½ minutes. The paper is color coded to make instructions to the children more clear. For immediate recall (VMI), a new set of 40 pictures (on white paper) is presened (1½ minutes), which includes 20 of those previously seen on blue paper. The child is then asked to identify the drawings seen before. For delayed memory (VMD) about 30 to 45 minutes later (after the PMCB), a new set of 40 pictures is presented (1½ minutes), which includes the other 20 of the first set of 40 drawings to be identified. Both VMI and VMD have maximum possible scores of 20 points. VM is the sum of the VMI and VMD scores. This memory task has been used successfully in five other studies [9,11,24,25,68,106], with a split-half reliability for VM of 0.63 among 7- to 18-year-olds (in Colorado), K-R 20 reliabilities of 0.58 (VMI) and 0.62 (VMD) among old subjects (in Hawaii), and a test–retest reliability of 0.52 (VM) among 5- to 12-year-olds (in Colorado). In a small study (N = 50) of 4- to 8-year-olds from middle- and upper-middle-class families, Garfinkle et al [27] found the following test–retest reliabilities: 0.62 for VM, 0.51 for VMI, and 0.55 for VMD.

2.3.2. Piagetian Mathematical Concepts Battery (PMCB). According to Piaget, conservation of number can be demonstrated by the equivalence of sets, ie, knowing that the number of items in two sets remains the same regardless of perceptual transformations on items of one set, as long as no mathematical operation (such as addition or subtraction of items) is performed. Seriation refers to understanding the process of ordering, demonstrated by the ability to arrange a set of proportional objects in a series. Classification is understanding the composition of sets with a knowledge of part-to-part and part-to-whole relations. Piaget claims that an understanding of the sequence of whole numbers, which is essential for the beginning of mathematics, requires the synthesis of classification (which presupposes conservation) and seriation [72].

The PMCB [26] consists of 15 tasks representing the three concepts of conservation of number, seriation, and classification. The battery is administered in 30 to 45 minutes. Since a complete copy of the PMCB is available elsewhere [26], only a brief description of each task is presented here:

1. Conservation of Number. After nine red and nine white poker chips are put in a one-to-one correspondence by the subject, they are compared (same?) once when the red chips are spread out, once when one red chip is removed, and once when the red chips are bunched together.

2. Counting. After counting four and then nine red chips by pointing, the child is asked how many chips there would be if they had been counted in the opposite direction.

3. Seriation-T. The subject is asked to put in order four and then 10 white sticks of various lengths, using slots in a board. If successful, the child is given 10 sticks of equal length painted with different proportions of blue at one end and white at the other. The subject is asked to arrange the sticks such that the amount of blue increases stepwise as the amount of white decreases stepwise on each stick. The examiner helps by identifying the two extreme sticks.

4. Parts and Wholes. The subject is shown three red squares, two yellow squares, and two yellow circles. The examiner then asks once whether all the squares are yellow or red, once if all the yellow blocks are round, once if all the red ones are square, and finally whether all the circles are yellow. After replacing one red square with two red circles, the child is told to take away some blocks so that all the squares are yellow.

5. Transitivity. With the Müller-Lyer illusion as a background, the child compares the length of a brown stick with the length of a black stick and then with the length of another black stick, and is finally asked which black stick is longer (the brown stick is of intermediate length). If successful, essentially the same comparison is repeated three more times. The last time the child is asked to explain his/her answer.

6. Addition and Subtraction. After agreeing that two piles each contain five pennies, the child is asked which pile has more, and why, when (1) one penny is removed from one pile, and (2) one penny is added to one of the equal piles.

7. Conservation of Number-Identity. After the subject agrees that there are four candies on a plate, these candies are poured into a glass and then onto the table; in each case the child is asked how many candies there are after the transformation. Then with 10 candies poured into the glass, the subject is asked how many candies are in the glass and why he/she thinks so.

8. Conservation of Number-Equivalence. This task is essentially the same as task 1, except with candies and pennies. When the candies are spread out, the subject is asked to explain his/her answer.

9. Discrimination. The child is asked to identify the smallest and largest of nine seriated slats scattered randomly.

10. Seriation-K. The subject is asked to arrange five then nine slats in a staircase.

11. Insertion. With the staircase properly assembled, the child is asked to put two sticks, "accidentally" left out, into the staircase one at a time.

12. Numeration. The subject is asked to count 11 steps (in order). A doll climbs to the fourth and then the eighth step; each time the child is asked how many steps the doll climbed. With the doll on the eighth step, the child is asked how many steps the doll has to climb to reach the top.

13. Sorting. The child is asked to sort two green and two red circles and two green and two red triangles onto two plates. With the addition of a blue square, the subject is asked to sort the blocks onto three plates.

14. Some and All-Class Inclusion. The child is shown four red squares and two red and two blue triangles. The subject is asked whether (1) all the blue ones are triangles, (2) all the triangles are blue, (3) all the squares are red, and (4) all the red ones are square. After the first and last questions, the child is asked, "Why?"

15. Multiple Class Membership. Four red squares, and two red and two blue circles are placed before the subject. The child is then asked whether all the squares belong on a plate of red things (shown), whether the blue blocks belong on a plate of squares (various colors, shown), and whether the blue blocks belong on a plate of circles (various colors, shown). Each time the child is asked, "Why?"

Scoring of the PMCB tasks is also described elsewhere [26]. Each task is worth 7 points, with a total of 105 possible. All scoring was initially done by recorders using their own written records, but scoring was then rechecked by me. When the reliability of the PMCB was estimated in terms of internal consistency (coefficient α) using the total sample ($N = 418$), the value of α was found to be 0.89. A test–retest reliability of 0.85 was also obtained using a sample ($N = 50$) similar to the twin sample [27]. The PMCB was factor analyzed using this twin sample to verify previous results [29].

2.3.3. Raven Coloured Progressive Matrices (PM). The SPM is a well-known nonverbal test of reasoning ability which correlates with IQ. The Coloured PM was developed for children 4 to 12 years old. It has 36 possible points. Among 6½- to 12-year-olds, Raven [78] reported a test–retest reliability of 0.90. However,

TABLE 5. Internal Consistency (Kuder-Richardson 20) and Test–Retest Reliabilities of the Moos Family Environment Scale for the Moos [63] Sample (N = 814) and for the Parents of the Colorado Piagetian Twin Study (N = 418)

Subscale	Colorado K-R 20 (N = 418)	Moos sample K-R 20 (N = 814)	Moos sample Test–retest (N = 47)
Cohesion	0.66	0.78	0.86
Expressiveness	0.57	0.71	0.73
Conflict	0.67	0.75	0.85
Independence	0.28	0.64	0.68
Achievement Orientation	0.54	0.65	0.74
Intellectual–Cultural Orientation	0.68	0.78	0.82
Active–Recreational Orientation	0.65	0.68	0.77
Moral Religious Orientation	0.73	0.79	0.80
Organization	0.69	0.78	0.76
Control	0.53	0.70	0.77

Foch and Plomin [25] recently reported test–retest reliability of 0.26 in a sample of 30 twins 5 to 12 years old.

2.3.4. Peabody Picture Vocabulary Test (PPVT). The PPVT is also a well-known standardized test, which correlates with verbal IQ, and has a parallel forms reliability of 0.77 [17]. This test was designed for 2- through 18-year-olds, and has a possible 150 points, although no 8-year-old would be expected to score as high as 150.

The parental questionnaires are described below:

2.3.5. Attitudes Toward Education (ATE). The ATE scale was constructed by Vandenberg, Garfinkle, and Claussner for use in this twin study, and has undergone no previous analysis. For the parents of this twin sample (N = 384) the ATE internal consistency (or coefficient α) reliability is 0.61 (excluding items 5 and 13; see Results). A copy of the ATE is available in the Appendix.

2.3.6. Family Environment Scale (FES). The FES is a 90-item true/false questionnaire empirically developed by Moos [63] using 1,000 individuals in 285 families of mostly middle- and upper-middle-class and various ethnic backgrounds. The questionnaire contains 10 sets of items. Each set assesses a specific aspect of the family environment. These 10 subscales are listed in Table 5. In Moos's sample (N = 814) the K-R 20 (or internal consistency) reliabilities of these subscales ranged from 0.65 to 0.79. Moos reported test–retest reliabilities between 0.68 and 0.86 for a sample of 47 persons (Table 5). As seen in Table 5, the K-R 20 reliabilities for this study (N = 418) are comparable (except for Independence), considering the somewhat smaller sample size. In addition, a factor analysis was performed on the 90 items, which generally verified the assignment of items to their own subscales (see Results). Therefore, scores on the 10 existing subscales were used to analyze their relationships with cognitive performance.

2.4. Methods of Analysis

Genetic analyses were performed utilizing intraclass correlations (t) for MZ and DZ twin pairs. "Broad" heritability was estimated by $2(t_{MZ} - t_{DZ})$ [22]. "Broad" heritability is the proportion of the phenotypic variance in a trait due to genetic influences, which include additive genetic, dominance, and epistatic variances [56]. These values were calculated for performance on the PMCB, as well as for the other tests, and for height and weight as a check on the representativeness of this twin sample. In addition, the MZ and DZ intraclass correlations for performance on each cognitive test were analyzed for possible age trends.

Using multiple regression, the sample was analyzed for the effects of sex, age, number of siblings, parents' education, attitudes and occupation, and family environment on performance on each test (PMCB, PPVT, PM, VM). Intercorrelations among the PMCB, Peabody, Raven , and Memory measures were also calculated, with age partialed out. The PMCB tasks, PPVT, PM, VMI, and VMD were factor analyzed together to further investigate their relationships.

Using the information gained from the above analyses, the variance in age-corrected PMCB performance was partitioned into genetic and environmental components such that $V_P = V_G + V_E$, where V_P is the phenotypic variance, V_G is the genetic variance, and V_E is the environmental variance [22]. This model assumes no genotype–environment covariance (covGE) nor interaction (G × E), or at least that these components are included in either the genetic or environmental components [48]. This type of analysis was also performed for the variance in age-corrected PPVT, PM, and VM performance.

3. RESULTS

3.1. Introductory Note

Since there were no significant ($P < 0.01$) mean or variance differences between sexes in cognitive performance, all data were pooled across sex for the subsequent analyses. There were also no significant ($P < 0.01$) mean or variance differences in test performance, in age, or in any of the environmental variables between the MZ and DZ samples. Therefore, except for the MZ and DZ intraclass correlational analyses, results were determined for the whole sample.

3.2. Factor Analysis of the PMCB

A factor analysis was performed on the raw scores of the 15 tasks of the PMCB in order to verify the previously reported factor structure for the tasks [26,29]. Squared multiple correlations of each variable with all other variables were inserted into the main diagonal of the correlation matrix as initial estimates of communalities. Since three major concepts (classification, seriation, conservation) were expected, the factor analysis was preset to three factors. A Varimax rotation of the three principal factors was performed to produce orthogonal factors and a simple factor structure. Table 6 shows that the correlations among the 15 tasks were all positive and moderate (Mean $r = 0.36$). The Varimax rotated factor matrix is presented in Table 7.

Factor I is characterized by a combination of classification and conservation of number. Parts and Wholes, Some and All-Class Inclusion, and Multiple Class Membership are classification tasks that load highly on this factor. Another classification task, Sorting, also has its highest loading here. Counting, Addition and Subtraction, and Conservation of Number-Identity are conservation tasks that have high loadings on this factor. Numeration also loaded above 0.50. However, it is worth noting that some seriation tasks (Discrimination, Seriation-K, and Insertion) also load highly on factor I, indicating its rather general nature despite Varimax rotation.

Factor II is a conservation factor with high loadings for the two conservation of number equivalence tasks, and for Seriation-T. Equivalence conservation and seriation develop at the same time, according to Piaget [72], and these particular tasks are also of similar difficulty [26]. Thus, it is not surprising that Seriation-T also loads highly on this factor. In addition, Insertion has its second highest loading on this factor. These tasks also appeared on the same factor in the development of the PMCB [26]. Transitivity (akin to conservation of length) has its highest loading on this factor.

Factor III represents size relations, or seriation, and is defined by Seriation-K and Insertion. Seriation-T has its second highest loading on this factor.

This factor matrix is consistent with analyses made on this battery in earlier work [29]. As pointed out in that previous report, there are slight differences between these results and the factor matrix found in the original 1975 analysis [26]. However, the present results may be considered more accurate since the 1975 sample was considerably smaller ($N = 144$).

*TABLE 6. Correlations Among the Tasks in the PMCB for 418 Twins in the Colorado Piagetian Twin Study**

Task	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	—														
2	.47														
3	.60	.55													
4	.27	.38	.38												
5	.29	.21	.33	.21											
6	.23	.40	.34	.32	.14										
7	.39	.49	.44	.40	.27	.52									
8	.67	.38	.57	.27	.26	.22	.32								
9	.20	.25	.24	.32	.11	.34	.33	.10							
10	.49	.56	.62	.40	.21	.45	.52	.44	.27						
11	.51	.57	.69	.48	.30	.42	.49	.49	.28	.76					
12	.35	.56	.48	.44	.26	.41	.57	.32	.32	.56	.51				
13	.21	.23	.20	.20	.12	.25	.32	.14	.15	.28	.24	.20			
14	.24	.36	.32	.44	.17	.35	.34	.20	.22	.31	.38	.37	.15		
15	.34	.44	.42	.41	.13	.43	.42	.28	.29	.45	.44	.41	.19	.36	—

*Mean r = 0.36. For N = 418, the critical value ($P < 0.01$) of the correlation coefficient is 0.13. The numerals represent the following PMCB tasks: 1, Conservation of Number; 2, Counting; 3, Seriation-T; 4, Parts and Wholes; 5, Transitivity; 6, Addition and Subtraction; 7, Conservation of Number-Identity; 8, Conservation of Number-Equivalence; 9, Discrimination; 10, Seriation-K; 11, Insertion; 12, Numeration; 13, Sorting; 14, Some and All-Class Inclusion; 15, Multiple Class Membership.

Although the results of this factor analysis suggest that three major concepts are indeed being measured by the PMCB, the structure of the factor matrix indicates considerable overlap. Piaget [72] has said that conservation of number (equivalence), classification, and seriation develop to some extent at separate rates (décalage), although they all occur between the ages of 4 and 8 years. At the same time, the generality of factor I demonstrates considerable interdependence of number, classes, and relations, which has also been described by Piaget [72]. In fact, the unrotated first principal factor accounted for 82% of the common variance. Because both the theory and these empirical findings support the interdependence of the development of the three concepts, the total PMCB score was used in the analyses as a measure of the global development of logico-mathematical concepts.

3.3. Factor Analysis of the Attitudes Toward Education Scale (ATE)

A factor analysis was performed on the 15 items of the ATE scale to identify the major attitudes measured. Squared multiple correlations of each item with all the others were inserted into the main diagonal of the correlation matrix (Table 8) as initial estimates of communalities. Examination of the correlation matrix (Table 8) and a preliminary factor analysis revealed that items 5 and 13 had communalities less than 0.09. Hence, they were eliminated from further analyses. The Guttman Scree criterion [32] indicated three meaningful factors. A Varimax rotation of the three principal factors produced three orthogonal factors (Table 9) interpretable as follows.

The first factor, Basic Academic Education, emphasizes the need for satisfactory teaching of the "three Rs"—reading, writing, and arithmetic. The second factor represents Parental Participation in their children's education. There is also a high loading for the item that emphasizes gym, music, and art for preadolescents in school. The third factor represents General Utility of Education, with an emphasis on success in life.

TABLE 7. Varimax Rotated Factor Matrix of the Tasks in the PMCB for 418 Children in the Colorado Piagetian Twin Study

Task	Factor[a] I	II	III	C[b]
Conservation of Number	.20	.78	.17	.68
Counting	.50	.38	.34	.50
Seration-T	.34	.62	39	.66
Parts and Wholes	.56	.21	.15	.38
Transitivity	.20	.32	.07	.15
Addition and Subtraction	.61	.10	.22	.43
Conservation of Number-Identity	.64	.26	.23	.53
Conservation of Number-Equivalence	.12	.76	.17	.62
Discrimination	.46	.07	.08	.23
Seriation-K	.40	.34	.75	.84
Insertion	.43	.46	.57	.72
Numeration	.60	.27	.29	.51
Sorting	.29	.12	.14	.12
Some and All-Class Inclusion	.52	.17	.08	.31
Multiple Class Membership	.54	.24	.20	.39
Percentage of Common Variance	44.2	34.5	21.3	

[a]A factor loading is a correlation coefficient of a variable and the factor. Factor loadings of 0.50 or more are underlined.
[b]Communality, the squared multiple correlation of each variable with all other variables.

3.4. Factor Analysis of the Family Environment Scale (FES)

The 90 items of the FES were factor analyzed to verify the nature of the 10 subscales described by Moos [63]. Squared multiple correlations of each item with all others were inserted into the main diagonal of the correlation matrix as initial estimates of communalities. Since 10 subscales were expected, the preliminary factor analysis was preset for 10 factors. A Varimax rotation of the 10 principal factors produced seven well-defined factors, which were interpreted as follows: (1) Cohesion and Expressiveness; (2) Organization and Control; (3) Intellectual–Cultural Orientation; (4) Conflict; (5) Moral–Religious Emphasis; (6) Achievement Orientation; and (7) Active–Recreational Orientation. This factor solution produced all of Moos's 10 subscales except Independence, which was not well represented. This is understandable because of the low internal consistency reliability (coefficient $\alpha = 0.28$) associated with the Independence subscale.

Since three factors were vague, and the Guttman Scree criterion indicated only eight meaningful factors, the analysis was repeated presetting eight factors. The resulting Varimax rotated factor matrix is presented in Table 10. The first factor represents the Organization and Control subscales. The second factor represents Cohesion and Expressiveness. Factor III is defined by the Intellectual–Cultural Orientation items. The fourth factor represents the Conflict subscale, while the fifth factor is defined by the Moral–Religious Orientation items. The sixth and seventh factors represent the Active–Recreational Orientation and Achievement Orientation subscales, respectively. Finally, although weak, the last factor represents Independence.

The clustering of items can be clearly seen by looking at the factor loadings of 0.30 or more, which are underlined in Table 10. As a quantitative verification of the factor definitions, the mean factor loading of the theoretical defining items was compared to the

*TABLE 8. Correlations Among Responses to 15 Items of the Attitudes Toward Education Scale (ATE) for 384 Parents of Children in the Colorado Piagetian Twin Study**

Item	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	—														
2	.12														
3	.11	.15													
4	−.01	.04	.04												
5	−.12	−.01	−.03	.03											
6	.13	.21	.10	.03	.02										
7	−.09	−.06	.00	.54	.00	.10									
8	.01	.20	.17	.17	−.01	.17	.08								
9	.23	.03	.10	.06	−.06	.09	−.08	.05							
10	.29	.07	.13	−.02	.01	.23	−.07	.12	.17						
11	−.06	.05	.03	.41	.02	.06	.43	.08	−.01	−.08					
12	.03	.15	.06	.00	−.02	.17	.00	.10	.06	−.04	.05				
13	−.01	.02	−.08	.02	.09	.07	−.02	.08	.02	.03	−.08	.02			
14	.24	.06	.09	.15	−.01	.32	.06	.13	.19	.24	.01	.19	.03		
15	−.01	−.07	.04	.27	−.01	.13	.35	.06	.22	.01	.43	.14	.02	.08	—

*For N = 384, the critical value ($P < 0.01$) of the correlation coefficient is 0.14. The numerals represent the ATE items listed on the ATE questionnaire in the Appendix. Abbreviations of the items are available in Table 9.

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TABLE 9. Varimax Rotated Factor Matrix of 13 Items of the ATE for 384 Parents of Children in the Colorado Piagetian Twin Study*

Item		Factor[a]			
		I	II	III	C[b]
1	Meet teachers	−.06	.51	.07	.27
2	Education–good life	−.06	.03	.49	.25
3	Help get along with others	.02	.16	.25	.09
4	Basic three Rs	.65	.05	.06	.43
6	Second language	.10	.30	.42	.28
7	Too many frills	.73	−.07	.00	.54
8	Do well in school	.11	.08	.38	.17
9	Read frequently to twins	−.00	.37	.05	.14
10	Gym, music, and art	−.06	.51	.11	.28
11	Cannot even do arithmetic	.64	−.09	.10	.43
12	Read and write–success	.05	.05	.31	.10
14	Reading important pastime	.17	.48	.25	.30
15	Don't teach arithmetic well	.51	.04	.07	.27
Percent of Common Variance		47.7	29.1	23.2	

*Items 5 and 13 are excluded due to very low communalities.

[a]A factor loading is a correlation coefficient of a variable and the factor. Factor loadings of 0.31 or more are underlined.

[b]Communality, the squared multiple correlation of each variable with all other variables.

mean factor loading of the remaining items, using a t-test. For example, for factor I, the mean factor loading for the defining items (those ending in the 9s and 0s, ie, 9, 19, . . . 89; 10, 20, . . . 90) was compared with the mean factor loading for the remaining 72 items. For all eight factors (including the weak Independence factor) the mean factor loading of the defining items was significantly ($P < 0.01$) higher than the mean factor loading of the remaining items. The critical value ($P < 0.01$) of t is 2.635, for 88 degrees of freedom. The values of t for each factor were as follows: (I) $t = 8.51$; (II) $t = 7.57$; (III) $t = 10.31$; (IV) $t = 8.18$; (V) $t = 11.53$; (VI) $t = 11.52$; (VII) $t = 6.78$; (VIII) $t = 3.46$.

The results of this factor analysis support the theoretical basis of the 10 subscales of the Moos FES. However, it is interesting that the Cohesion and Expressiveness items were essentially inseparable in this factor analysis, as were the Organization and Control items. If this result can be replicated with a larger, more representative sample, then it might be appropriate to regroup the FES items into eight subscales. However, for the present, this author has accepted the 10 subscales as defined by Moos [63], and used them accordingly in further analyses of these twin data.

3.5. Cognitive Performance and Relationships Among Tests

Table 11 lists the means, standard deviations, and ranges of performance on the four cognitive tests for the four age groups and for the total sample. The statistics for the PMCB, PM, and PPVT were all reasonable. The findings for the PMCB were comparable to the results of an earlier analysis [26]. Since the PPVT is meant for persons up to 18 years old, this PPVT mean was not particularly low. The mean for the VM indicated that these young children did not do very well on this visual memory task. In fact, very young children tended to point to pictures they liked, and not necessarily to ones they remembered. However, the mean of 16.3 for the 7-year-olds ($N = 92$) was somewhat higher, and comparable to previous findings among 7- to 10-year-olds in Colorado [24].

TABLE 10. Varimax Rotated Factor Matrix of the Items in the Family Environment Scale (FES) for 384 Parents of Children in the Colorado Piagetian Twin Study*

Item	Factor[a]								
	I	II	III	IV	V	VI	VII	VIII	C[b]
1	.05	.40	.05	.17	.09	.16	.14	.08	.25
11	−.01	.24	.24	.27	.06	.20	−.02	.17	.26
21	.22	.05	.18	.22	.00	.16	.25	.11	.24
31	.05	.54	−.01	.03	.09	.04	.14	.04	.33
41	.04	.22	.16	.27	−.01	.15	.15	.04	.19
51	−.05	.35	.06	.10	.01	−.01	.16	.00	.16
61	.04	.45	.08	.11	.17	.05	.13	.11	.29
71	.02	.50	.10	.24	.03	−.13	−.02	.07	.34
81	.09	.28	.12	.36	−.07	.08	.06	.00	.25
2	−.10	.31	.21	−.01	.06	.15	.00	.07	.18
12	−.19	.18	.15	.02	−.09	.13	−.03	−.23	.17
22	−.12	.41	.12	.11	−.04	.12	−.09	.03	.23
32	.00	.39	.26	.01	.09	.19	.16	.06	.30
42	−.10	.06	.02	−.02	−.04	.23	.06	−.18	.11
52	−.02	.40	−.03	.23	−.04	.16	−.11	.04	.25
62	−.09	.35	.12	.01	.01	.08	.08	−.10	.17
72	−.09	.11	.12	−.25	−.10	.02	−.14	−.09	.14
82	−.11	.32	.34	.00	.06	.09	−.04	−.08	.25
3	−.18	−.35	.03	−.47	.00	.00	−.06	.04	.38
13	.02	−.05	.11	−.49	−.03	.09	−.02	.15	.29
23	−.09	−.18	.01	−.39	−.07	.01	.03	.00	.20
33	−.01	−.01	−.03	−.57	−.04	.05	−.02	.18	.36
43	.00	−.27	.03	−.45	−.03	−.03	.03	−.22	.33
53	−.02	.01	.05	−.38	.02	−.06	.01	−.01	.16
63	−.01	−.12	.16	−.11	−.05	.09	−.28	.04	.14
73	.05	−.26	−.13	−.43	−.03	.03	.04	−.17	.30
83	−.09	.05	−.09	−.26	−.15	.12	−.02	.28	.20
4	−.13	−.10	.19	.00	−.04	.13	.14	.01	.10
14	.02	.09	.23	−.04	−.05	.07	.14	−.09	.10
24	−.09	.14	.13	.20	.02	−.05	.03	−.02	.09
34	−.17	−.09	.13	.06	−.14	.10	−.02	−.41	.26
44	.08	.06	.08	.24	−.08	.05	.03	.25	.14
54	−.02	−.15	−.02	.04	−.07	−.09	−.03	−.20	.08
64	−.03	.08	.05	.10	−.11	.14	.32	−.11	.16
74	.14	.35	.06	.21	−.13	.01	−.06	.20	.25
84	.08	.27	.06	.09	−.11	−.04	.05	−.10	.19
5	.22	.05	−.01	.06	.05	−.07	.27	−.11	.15
15	.18	.06	−.11	.04	.00	−.05	.45	−.23	.30
25	.09	−.19	−.13	−.04	−.10	−.11	.20	−.03	.13
35	.20	.12	−.08	−.05	.06	.03	.22	−.34	.23
45	.17	.04	−.03	.04	.18	−.05	.44	.11	.27
55	.10	−.03	−.03	−.01	−.05	.14	−.31	.08	.24
65	.08	.09	.10	−.01	.07	−.08	.42	.06	.21
75	.42	−.11	−.13	.00	.15	−.09	.12	.03	.25
85	.22	.02	−.13	−.14	−.09	−.05	−.09	−.36	.25

Table continues

TABLE 10. Varimax Rotated Factor Matrix of the Items in the Family Environment Scale (FES) for 384 Parents of Children in the Colorado Piagetian Twin Study (continued)*

6	.03	.21	.42	−.10	−.05	−.02	−.04	−.08	.25
16	−.01	−.01	.52	.06	−.05	.11	−.23	.01	.34
26	.04	.12	.33	.05	.04	.13	.27	.06	.22
36	.00	.02	.53	.14	−.06	.20	−.03	.11	.35
46	.06	.37	.50	.05	.00	.16	.03	−.01	.41
56	.01	−.04	.37	−.20	.11	−.04	−.11	−.14	.24
66	−.04	.14	.35	−.02	.00	−.10	−.13	−.02	.17
76	.01	.11	.36	.19	.06	.13	−.10	.13	.22
86	−.10	.02	.49	.01	.11	.00	.17	.04	.29
7	−.15	−.06	.07	.16	.05	.34	−.08	.07	.19
17	.02	.12	.24	.10	−.04	.37	.00	.06	.22
27	.09	.12	.06	−.03	.07	.39	−.01	.05	.19
37	.13	.20	.07	−.10	.03	.43	.00	−.08	.26
47	.05	.10	.34	.02	.05	.23	.18	−.07	.22
57	.15	.14	.23	.02	−.07	.44	.03	.02	.30
67	.05	.09	.43	.04	−.04	.11	.03	−.03	.21
77	−.14	−.08	.15	−.01	.00	.50	−.08	−.07	.30
87	.00	.03	.38	.11	.04	.24	−.06	.07	.22
8	.13	−.02	.10	.09	.61	.09	−.19	.08	.46
18	.18	.03	.14	.03	.67	.07	.07	.16	.54
28	.16	.15	.08	.03	.59	.08	.05	.05	.41
38	.17	.03	−.22	−.06	.54	−.02	.06	−.03	.38
48	.40	.00	.03	.05	.23	−.07	.20	.11	.28
58	.20	.20	−.07	.01	.34	−.03	−.01	−.03	.20
68	.10	.21	.09	.11	.08	−.06	−.05	.17	.11
78	.11	−.04	.07	.14	.59	−.10	−.02	.08	.40
88	.18	.06	−.19	−.09	.38	.00	.21	−.15	.29
9	.31	−.03	.04	.16	.23	.03	.05	.14	.20
19	.53	.04	.04	.25	.09	.05	.19	.03	.39
29	.28	.12	.03	.35	−.06	.13	.04	.24	.29
39	.39	−.07	.05	−.03	.00	.07	−.04	−.13	.18
49	.28	.20	.11	.21	.00	−.07	.00	.19	.22
59	.44	.00	.10	.29	.03	.12	.17	.17	.36
69	.52	.00	.00	.10	.07	.02	.19	−.06	.32
79	.25	.27	.04	.07	.06	−.02	−.04	.00	.14
89	.40	.07	.01	.07	.13	.11	−.07	−.03	.21
10	.13	−.16	−.12	−.38	.05	.01	−.08	.03	.22
20	.40	.05	.04	−.09	.18	.01	.04	.30	.30
30	.15	−.14	−.16	−.19	.03	−.02	−.06	−.07	.11
40	.56	−.03	−.06	−.01	.02	−.07	.06	.03	.32
50	.62	.09	−.04	−.11	.13	.02	.14	.10	.45
60	−.06	−.07	.01	−.26	−.11	−.16	−.01	.11	.14
70	.06	.18	−.18	−.18	.02	−.11	−.09	.35	.24
80	.23	−.15	−.23	.01	.07	.11	.00	−.06	.15
90	.39	−.03	−.10	−.12	.15	−.10	.06	−.05	.21
Percent of Common Variance	16.8	15.8	15.4	14.7	12.2	8.8	8.6	7.7	

*According to Moos [63], items 1, 11, 21 . . . 81 represent Cohesion; 2, 12, . . . 82 represent Expressiveness; 3s represent Conflict; 4s are Independence; 5s are Achievement; 6s are Intellectual–Cultural; 7s are Recreational; 8s are Moral–Religious; 9s are Organization; 10s are Control.

[a]A factor loading is a correlation coefficient of a variable and the factor. Factor loadings of 0.30 or more are underlined.

[b]Communality, the squared multiple correlation of each variable with all other variables.

TABLE 11. Performance on the Cognitive Tests for Each Age Group, and Correlation With Age for 418 Children in the Colorado Piagetian Twin Study

		Mean (SD)							
Age (years)	N	PMCB[a]		PM[b]		PPVT[c]		VM[d]	
4	102	53.2	(16.0)	13.1	(4.8)	50.0	(7.8)	7.4	(6.4)
5	104	70.1	(13.9)	15.6	(4.6)	58.0	(6.2)	11.7	(7.5)
6	120	85.6	(11.1)	19.5	(4.4)	63.9	(6.8)	13.6	(6.6)
7	92	90.2	(8.8)	21.7	(5.5)	66.6	(6.3)	16.3	(7.5)
Total sample	418	74.9	(19.1)	17.5	(5.8)	59.7	(9.2)	12.2	(9.6)
Total possible		105		36		150		40	
Total range		19–105		0–33		24–87		−4–35	
Correlation with age		0.75		0.59		0.70		0.43	

[a]Piagetian Mathematical Concepts Battery.
[b]Progressive Matrices (Coloured).
[c]Peabody Picture Vocabulary Test.
[d]Visual Memory, the sum of the Immediate and Delayed Visual Memory scores.

As expected, the PMCB had the highest correlation with age (r = 0.75), followed by the PPVT (r = 0.70), the PM (r = 0.59), and finally VM (r = 0.43). Because of such high correlations with age (Table 11), age was partialed out of performance on all tests in further analyses (except where indicated).

After partialing out age, correlations among the tests were calculated, and are presented in Table 12. For N = 418, the critical value (P < 0.01) of the correlation coefficient is 0.13. As expected, PMCB and PM performances correlated most highly (r = 0.41), since both are thought to measure nonverbal reasoning abilities. However, there is also a verbal element to performance on the PMCB, as indicated by its correlation of 0.36 with the vocabulary test (PPVT). The correlation of 0.23 between the PM and the PPVT indicates that these tests do indeed measure relatively separate abilities, which are differentially related to performance on the Piagetian battery. Visual memory ability is only slightly related to performance on the other three tests, as indicated by the smaller, although significant, correlations (Table 12).

For a different look at these interrelationships, a factor analysis was performed using the 15 PMCB tasks, PM, PPVT, VMI, and VMD. Squared multiple correlations of each variable with all other variables were inserted into the main diagonal of the correlation matrix as initial estimates of communalities. The Guttman Scree criterion [32] indicated

*TABLE 12. Correlations Among the PMCB, PM, PPVT, and VM, With Age Partialed Out, for 418 Children in the Colorado Piagetian Twin Study**

	PMCB[a]	PM[b]	PPVT[c]	VM[d]
PMCB	—			
PM	0.41			
PPVT	0.36	0.23		
VM	0.22	0.19	0.19	—
Correlation with age	0.75	0.59	0.70	0.43

*For N = 418, the critical value (P < .01) of the correlation coefficient is 0.13.
[a]Piagetian Mathematical Concepts Battery.
[b]Progressive Matrices (Coloured).
[c]Peabody Picture Vocabulary Test.
[d]Visual Memory.

TABLE 13. Varimax Rotated Factor Matrix of 15 PMCB Tasks, PM, PPVT, VMI, and VMD for 418 Children in the Colorado Piagetian Twin Study

Task	Factor[a] I	II	III	C[b]
Conservation of Number	.18	.76	.11	.62
Counting	.52	.44	.19	.50
Seriation-T	.35	.72	.23	.70
Parts and Wholes	.53	.22	.23	.38
Transitivity	.17	.32	.10	.14
Addition and Subtraction	.64	.14	.09	.44
Conservation of Number-Identity	.65	.29	.12	.52
Conservation of Number-Equivalence	.13	.75	.06	.58
Discrimination	.46	.08	.08	.22
Seriation-K	.54	.53	.16	.60
Insertion	.52	.59	.18	.66
Numeration	.61	.33	.18	.51
Sorting	.32	.15	.01	.13
Some and All-Class Inclusion	.47	.15	.27	.31
Multiple Class Membership	.53	.27	.21	.40
Progressive Matrices (PM)	.41	.51	.26	.50
Peabody Vocabulary (PPVT)	.51	.42	.31	.54
Visual Memory-Immediate (VMI)	.17	.29	.70	.61
Visual Memory-Delayed (VMD)	.19	.07	.73	.58
Percent of Common Variance	42.9	39.2	17.8	

[a]A factor loading is a correlation coefficient of a variable and the factor. Factor loadings of 0.46 or more are underlined.

[b]Communality, the squared multiple correlation of each variable with all other variables.

three meaningful factors. A Varimax rotation of the three principal factors produced three orthogonal factors (Table 13) interpretable as follows.

Factor I represents conservation of number and classification with additional high loadings for the two easier seriation tasks (Seriation-K and Insertion) and Numeration. The PPVT also has its highest loading on this factor. This might be expected because of the importance of vocabulary for classification tasks. The PM also has a substantial secondary loading on this factor. Factor II represents conservation of number and seriation. The PM has its highest loading on this factor. The most difficult and abstract Piagetian tasks define this factor, which explains this PM loading. In addition, the PPVT has its second highest loading on this factor. Factor III represents visual memory almost exclusively. This illustrates the marked independence of visual memory ability. This is consistent with previous results using this VM test [11,25,68], and with the results of other tests of visual memory reported by Carlson and Wiedl [5]. This independence of memory can also be seen in the low VM correlations presented in Table 12.

At the same time, the PM and PPVT factor loadings are symmetrical on the two Piagetian factors. Yet, both tests have high loadings on both factors, illustrating that total PMCB performance is indeed related to performance on both the PM and the PPVT, as indicated by the intercorrelations presented in Table 12.

3.6. Intraclass Correlations

With age partialed out of test performance, the residual scores were used to calculate the MZ and DZ intraclass correlations presented in Table 14, and the within- and between-pair variances in Table 15. As a check on the sample, the same calculations were included for height and weight. All the MZ–DZ within-pair variance comparisons were in the expected direction (Table 15). The PMCB between-pair variance for MZ twin pairs is

*TABLE 14. Intraclass Correlations (t) and Estimates of "Broad" Heritability (h^2) for the Cognitive Tests, and for Height and Weight, for 137 MZ and 72 DZ Twin Pairs in the Colorado Piagetian Twin Study**

	Intraclass correlation (t)		
Measure	MZ	DZ	h^{2a}
PMCB	.73 ± .04 (.86)	.56 ± .08 (.66)	$.34^{b,c}$ ± .18 $(.40)^{d}$
PM	.49 ± .07	.39 ± .10	.20 ± .24
PPVT	.69 ± .04 (.90)	.52 ± .09 (.68)	$.34^{c}$ ± .19 $(.44)^{d}$
VM	.17 ± .08 (.27)	−.08 ± .12 (−.13)	
Height	.94 ± .01	.54 ± .09	$.80^{d}$ ± .17
Weight	.91 ± .01	.67 ± .06	$.48^{d}$ ± .13

*Numbers in parentheses are the appropriate values corrected for test reliability. The reliability estimates used in these corrections are as follows: PMCB 0.85 test–retest; PPVT 0.77 Form A–Form B; VM 0.62 test–retest. All calculations are based on age-corrected scores.

[a]"Broad" heritability, $h^2 = 2(t_{MZ} - t_{DZ})$, from Falconer [22]. The approximate standard error of the heritability estimate for 137 MZ and 72 DZ twin pairs was calculated from a formula given by Loehlin and Nichols [48], originally from Jensen [36].

[b]There were two MZ twin pairs with extremely large within-pair differences in PMCB score (more than 30 points different), even larger than any DZ within-pair difference. If these two pairs are excluded, the PMCB MZ intraclass correlation is 0.77, and the h^2 is 0.42. Their exclusion does not effect the other results. However, since no appropriate reason has been found for excluding these two MZ pairs, they are included in all analyses.

[c]$P < 0.05$.

[d]$P < 0.01$.

the only between-pair variance that seems considerably larger than the DZ between-pair variance. However, there were no significant differences between the MZ and DZ between-pair variances for any of the cognitive tests, or for height and weight. The intraclass correlations for height and weight were within the range of previously reported values [100]. However, the intraclass correlations for weight seemed a little high compared to Wilson's results [100].

The DZ intraclass correlation for VM was not significantly different from zero. In fact, the DZ intraclass correlation was negative (Table 14), which results from the fact that the within-pair mean square was greater than the between-pair mean square (Table 15). The MZ intraclass correlation (uncorrected) was, however, significantly different from zero ($P < 0.05$) and, therefore, from the DZ intraclass correlation. In addition, the MZ–DZ within-pair variance comparison was in the expected direction (Table 15). This result suggests at best a small amount of genetic variance in VM performance, which increased somewhat when the intraclass correlations were corrected for test–retest reliability (Table 14). This VM result is in line with that of Foch and Plomin [25] for their 5- to 12-year-old sample (N = 101 pairs). For their VM factor there was no significant difference between the MZ and DZ intraclass correlations (0.36 and 0.10, respectively), uncorrected for test–retest reliability, which was 0.52. However, after correcting for reliability, they did find significant genetic variance for their memory factor. In addition, previous studies using this VM test with older subjects have consistently found modest familial resemblance [11,68].

It was considered that these VM results might be partly a function of the validity problem among the youngest children mentioned earlier. In fact, Table 11 shows that the

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*TABLE 15. Within- and Between-Pair Variances for the Four Cognitive Tests and for Height and Weight for 137 MZ and 72 DZ Twin Pairs in the Colorado Piagetian Twin Study**

	Within-pair variance		Between-pair variance	
Measure	MZ	DZ	MZ	DZ
PMCB	48.29	54.69	129.57	69.45
PM	11.03	13.38	10.72	8.66
PPVT	13.77	21.33	31.18	22.90
VM	40.34	50.82	8.11	−3.69[a]
Height	0.25	2.02	3.82	2.38
Weight	2.92	16.29	28.35	32.63

*These calculations are based on age-corrected scores.
[a]The negative value is the result of using the following formula

$$V_B = \frac{MS_B - MS_W}{2}$$

where V_B is the between-pair variance, MS_B is the between-pair mean square, and MS_W is the within-pair mean square.

4-year-olds performed quite poorly on the VM (mean = 7.4). Consequently, the intraclass correlations were recalculated without the 4-year-olds. For 102 MZ and 56 DZ twin pairs, the MZ and DZ intraclass correlations were 0.21 and −0.07, respectively, which was not significantly different from the results obtained with the whole sample. Thus, the poor 4-year-old VM performance was not biasing the intraclass correlation results.

For the PM, there was no significant difference between the MZ and DZ intraclass correlations (Table 14). Foch and Plomin [25] also reported no genetic variance for the PM, which in their sample had a test–retest reliability of only 0.26. Perhaps the test–retest reliability for the Coloured PM is considerably lower than Raven [78] initially reported, which would make the Coloured PM inappropriate for this type of analysis. If the MZ and DZ intraclass correlations are corrected using Foch and Plomin's [25] PM test–retest reliability estimate of 0.26, the correlations become 1.88 and 1.50, respectively, which suggest that this estimate is inappropriate for this study. Further, the PM correlated highly with the PMCB (r = 0.41, with age partialed out). Since ". . . the index of reliability cannot be less than any validity coefficient of a test" [50], the PM–PMCB correlation (0.41) can be used as a lower-bound estimate of the PM reliability. Then the corrected MZ and DZ intraclass correlations would be 1.20 and 0.95, respectively, which would result in a genetic variance of 0.50. In addition, the reliability ought to be at least of the magnitude of the MZ intraclass correlation [99], which was 0.49. If this MZ intraclass correlation is used as a lower-bound estimate of the PM reliability, then the corrected MZ and DZ correlations become 1.00 and 0.80, respectively, with a resultant genetic variance of 0.40. Since these two lower-bound estimates are of similar magnitude, they are probably closer to the Coloured PM test–retest reliability for this sample than the 0.26 reported above. These calculations are indirect, of course, but the reason for reporting them is to emphasize the need for further investigation of the Coloured PM test–retest reliability among preadolescents.

Aside from the problem of test reliability, there may be, in fact, less genetic variance in the ability measured by the Coloured PM for this age group than might have been anticipated by previous results with the Standard PM among older groups [11,31,68, 69,81]. For example, DeFries et al [11] found a midchild on midparent regression coefficient of 0.60 (corrected for test reliability) for SPM performance among adolescents and adults, whereas Scarr and Weinberg [81] found a broad heritability of 0.88 for SPM performance among twins 10 to 16 years old. The genetic variance of 0.20 for PM performance of this sample of 4- to 8-year-old twins is considerably lower than these previously reported values.

There was a significant ($P < 0.05$) difference between the MZ and DZ intraclass correlations for both PMCB and PPVT performance. Since the standard errors for the heritability estimate are $\pm$ 0.19 (PPVT; $\pm$ 0.18 for PMCB) for this twin sample (calculated using a formula reported by Loehlin and Nichols [48]), the genetic variance for both the PMCB and the PPVT ranges between 0.15 and 0.53. These results are comparable to those obtained by Wilson [102] for WPPSI IQ among twins 5 ($h^2 = 0.32$) and 6 ($h^2 = 0.44$) years old (206 and 224 pairs, respectively). Wilson did not report Verbal and Performance IQ intraclass correlations for his 5- and 6-year-old twins. However, Verbal and Performance IQ information was available for 130 pairs of 7- and 8-year-old twins [101]; and the results for the PPVT and the PMCB are again within range. Foch and Plomin [25] also found genetic variance for vocabulary but not for math achievement. However, their math test had a considerably lower test–retest reliability (0.64) than the PMCB (0.85) and was achievement- rather than concept-oriented. As indicated in the introduction, significant genetic variance has consistently been found for both vocabulary and math ability among adolescents and adults. But this is the first study to find genetic variance in Piagetian mathematical conceptualization tasks in young children.

3.7. Age Trends in Intraclass Correlations

Although this was not a longitudinal study, the age span did allow for an investigation of possible age trends in the MZ and DZ concordances for the cognitive tests. For each cognitive test, the within-pair difference in test scores was plotted against age for the MZ and DZ samples separately. For all four tests, there was no MZ or DZ relationship between within-pair score difference and age (all correlation and regression coefficients were less than 0.09). These results indicate no changes with age in the MZ and DZ intraclass correlations. This was verified by the following stepwise multiple regression analyses, performed separately on the MZ and DZ samples.

For the PMCB, three regression coefficients (b_1, b_2, and b_3) were calculated for the following stepwise multiple regression equation

$$PMCB_i = b_1 age + b_2 PMCB_j + b_3(PMCB_j \times age) + constant,$$

where $PMCB_i$ and $PMCB_j$ are the scores for the two twins. A double-entry procedure was used, that is, each twin was entered once as $twin_i$ while the twin partner was entered as $twin_j$, and vice versa. Therefore, in the first step of the regression analysis, b_1 was the regression coefficient for PMCB performance on age for the whole MZ or DZ sample. In the second step, b_2 was the intraclass correlation with age partialed out. And, in the third step, b_3 was a measure of any interaction between age and the relationship between $PMCB_i$ and $PMCB_j$ (ie, the intraclass correlation), after controlling for the effects of age and the size of the intraclass correlation. Since the relationships representing b_1 and b_2 have already been examined, b_3 was the coefficient of interest in this analysis. For both the MZ and DZ samples, b_3 was not significant at the 0.01 level. In other words, the within-pair relationship on PMCB performance did not change as a function of age.

Regression coefficients and constants were also calculated by similar stepwise multiple regression equations for the PPVT, PM, and VM. Again, b_3 was not significant ($P > 0.05$) for any of these three tests in either the MZ or the DZ sample.

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Thus, the intraclass correlations for the MZ and DZ samples were not different across age for all four cognitive tests. These results generally agree with what Wilson [102] found for WPPSI IQ among 4- through 6-year-olds (N ≈ 200 pairs) and for a smaller sample (N = 130 pairs) of combined 7- and 8-year-olds [101]. However, the DZ intraclass correlations Wilson reported did tend to decline slightly between 4 and 8 years of age. Age-to-age intraclass correlations are not presented in this report because the DZ samples were too small for meaningful results: the DZ samples range from 16 pairs (4-year-olds) to 22 pairs (6-year-olds).

3.8. Environmental Analyses

Although significant genetic variance was reported above for age-corrected PMCB and PPVT performance, the degree of genetic variance determined was not large. In addition, genetic variance was only found for the age-corrected PM after speculatively correcting for test reliability, and age-corrected VM genetic variance was based on a DZ intraclass correlation that was not significantly different from zero. Furthermore, the magnitude of the PMCB and PPVT corrected intraclass correlations and between-pair variances indicated the presence of considerable between-family environmental variance (see Tables 14 and 15). The PM between- and within-pair variances were similar and the genetic variance was small, indicating some between-family environmental variance (Table 15). However, the VM showed considerable within-pair variance (Table 15), and the DZ intraclass correlation was close to zero, suggesting very little between-family environmental variance. These results suggest the possible value of examining specific between-family environmental influences on PMCB and PPVT performance, and possibly on VM and PM performance. Hence, the following between-family environmental analyses were performed.

Since there were no significant ($P > 0.05$) mean or variance differences in any of the environmental variables between MZs and DZs, the environmental analyses were performed on the whole sample. There were no mean or variance sex differences in performance on cognitive tests (for the entire sample). There were also no significant sex differences in any of the environmental variables (except for Conflict, which could have occurred by chance, given the number of variables). Therefore, sex was included in these analyses because of possible correlations between sex and the environmental variables. The environmental variables considered were number of siblings, provider's occupational status, father's and mother's educational levels, average family scores on the 10 subscales of the FES, and average family factor scores on the three ATE factors. Table 16 presents the correlation matrix between the four cognitive tests, sex, and these environmental variables, with age partialed out. For N = 358 (some parents did not return the ATE), the critical value ($P < 0.01$) of the correlation coefficient is 0.14. Any minor differences between Tables 12 and 16 are due to the fact that Table 16 only included twins with complete environmental information, while Table 12 was based on the entire twin sample.

The pattern of correlations between the 10 FES subscales was similar for this sample and the Moos [63] sample (N = 814). There was one interesting discrepancy: the correlation between Intellectual–Cultural and Achievement Orientation was −0.20 (Table 16), whereas the same correlation was 0.02 for the Moos [63] sample. For this twin sample, Achievement Orientation was also significantly negatively correlated with Expressiveness, father's education, and performance on the PMCB and the PM. The parents of these twins for the most part had at least two years of college education and were intellectually–culturally oriented ($r = 0.47$). Apparently, these parents did not emphasize

*TABLE 16. Correlations Among the PMCB, PM, PPVT, and VM, Sex and Independent Environmental Variables for 358 Children in the Colorado Piagetian Twin Study**

Variable	PMCB	PM	PPVT	VM	Sex	Sib	Occ	EdF	EdM	Cohes
PMCB	—									
PM	.41									
PPVT	.37	.23								
VM	.23	.18	.19							
Sex	.07	−.06	−.17	−.06						
Number of Sibs	.01	−.06	−.10	−.04	−.06					
Provider's Occupation	.18	.10	.13	−.05	.01	−.04				
Father's Education	.22	.10	.24	.04	.01	−.03	.60			
Mother's Education	.26	.12	.19	.09	.13	−.04	.32	.61		
Cohesion	.10	−.03	.19	.08	−.07	−.16	.17	.16	.19	
Expressiveness	.02	−.03	.13	−.01	.05	−.21	.04	.15	.17	.28
Conflict	.05	.04	.02	−.01	−.24	.16	.00	.05	.04	−.29
Independence	.08	−.06	.04	.01	.07	−.14	.13	.18	.21	.18
Achievement	−.14	−.16	−.07	−.03	−.07	.10	−.15	−.22	−.16	.06
Intellectual-Cultural	.16	.06	.20	.13	.15	.05	.23	.47	.46	.29
Recreation	.11	.01	.05	.03	.07	−.07	.15	.17	.17	.23
Moral-Religious	−.01	.02	−.07	−.05	.03	.21	−.08	−.18	−.11	.15
Organization	−.02	−.06	−.04	.00	−.02	.00	.06	−.06	−.05	.31
Control	−.07	.01	−.09	−.05	−.17	.23	−.12	−.21	−.23	−.09
ATE I	.10	−.02	.13	−.06	.07	−.11	.25	.30	.18	.05
ATE II	−.13	.02	−.09	−.02	−.14	.11	−.11	−.23	−.19	−.30
ATE III	−.10	−.07	−.08	−.07	.01	−.12	.13	−.04	−.02	−.02
Age	.75	.60	.69	.43	.01	.06	−.12	−.13	−.12	−.07

*For N = 358, the critical value ($P < 0.01$) of the correlation coefficient is 0.14. All correlations are with age partialed out.

Express	Conflict	Indep	Ach	IntCult	Recreat	MorRel	Organ	Control	ATE I	ATE II	ATE III
−.04											
.19	−.19										
−.20	−.10	−.04									
.39	−.03	.20	−.20								
.39	−.04	.06	−.17	.44							
−.08	−.19	−.11	.20	.00	.01						
−.09	−.32	.06	.32	.04	.11	.41					
−.37	.20	−.25	.31	−.23	−.14	.29	.35				
.24	−.02	.16	−.31	.12	.17	−.24	−.13	−.28			
−.20	.10	−.05	.04	−.29	−.13	−.08	−.10	.15	−.04		
.00	−.00	.01	−.15	−.07	.13	.05	.08	.01	.07	.29	
−.03	.08	−.02	.05	−.03	−.08	−.01	−.05	−.07	.05	−.03	−.04

achievement as defined by the Moos subscale, which is competition-oriented [63]. And, when achievement was strongly emphasized, it was inversely related to abstract reasoning performance among the twins and expressiveness within the family. This is understandable considering the offspring of these parents were preadolescent, and somewhat young for strong achievement and competitive pressure. This result is also in line with Piaget's contention that a child is capable of developmental advancement only when he or she is ready for it, and premature prompting can, in fact, do more harm than good [74].

It is worth noting that parental educational levels were highly correlated (r = 0.61). This was consistent with previous results [102], r = 0.66. In addition, father's education and occupation correlated 0.60 (Table 16). Parental education and father's occupation were positively related to PMCB and PPVT performance, with correlations ranging from 0.13 to 0.26 (correlations with the PM were considerably lower). However, these correlational results were somewhat lower than those obtained by Wilson [102] for 6-year-old WPPSI IQ (r = 0.36 for occupation; r = 0.33 for mother's education). Scores on the PMCB, PM, and PPVT were apparently less related to environmental influences represented by parental education and occupation than is IQ. They were also less affected by assortative marriage for education, which could result in lower estimates of genetic variance for these cognitive tests. This is consistent with the fact that the WPPSI is more information- and achievement-oriented than these specific ability measures. At the same time, a child's IQ may be more related to parental occupation and education because of the association of parental IQ with these variables [47], and the possible higher assortative marriage for IQ than for specific cognitive abilities [48]. In other words, WPPSI IQ may be more related to parental IQ than are performances on the PMCB, PM, and PPVT. And, of course, parental IQ has its own genetic variance [47]. Thus, the higher correlation between WPPSI IQ and parental occupation and education may indirectly represent a greater genetic influence on IQ and achievement than on these specific cognitive abilities. Since there was no direct measure of parental intellectual functioning, this issue cannot be untangled from the results of this study.

The inverse relationship between ATE I and Achievement Orientation (r = −0.31) suggests an emphasis on the "three Rs" in education. This emphasis is not on the competitive aspects of achievement, but is more individually and personally oriented. However, the more highly educated and intellectually oriented the parents were, the less they participated in their twins' academic education, and the more cohesive the family was, with less parental control. Thus, it seems that this educated parental sample was less "pushy" about formal education and more concerned with individual competence in reading, writing, and arithmetic for these young twins. It is interesting that the third ATE factor did not correlate very highly with anything (except the second ATE factor). Of course, all these ATE results are dependent on the actual items of the ATE (see Appendix), which could certainly be improved upon and expanded.

An overall look at the pattern of correlations between the FES and ATE measures and the cognitive tests supports previous findings. The pattern of results suggests that "a stimulating and supportive atmosphere enhances mental development, whereas a dull or punitive atmosphere may have a suppressive effect" [99: p 586].

The significant correlations in Table 16 indicate that mother's and father's educations, provider's occupational status, and Intellectual–Cultural and Achievement Orientations might predict PMCB performance. Similarly, Achievement Orientation might negatively predict PM performance. Also, mother's and father's educational levels, Cohesion in the family, Intellectual–Cultural Orientation, and sex might predict PPVT performance in this sample of 358 twins. None of the environmental variables significantly correlated with memory (VM).

A stepwise multiple regression technique was used four separate times to determine the significant amounts of unique variance in cognitive performance for each test accounted for by the independent between-family environmental variables listed. Stepwise regression "chooses" independent variables that provide the best possible prediction of the dependent variable (test performance) by the fewest independent variables. In each of the stepwise multiple regression analyses, the significance of an independent variable referred to the significance of the F of the partial correlation of the independent variable (with the dependent variable) that entered the regression equation next. The 0.01 level of significance was chosen as meaningful for the sample of 358 children. In addition, R was the multiple correlation of the independent variables with the dependent variable, while R^2 was the squared multiple correlation or the percent of the total variance in the dependent variable accounted for by the independent variables in the regression equation.

The results of the four stepwise multiple regression analyses are presented in Tables 17 through 20. For all four tests, age was partialed out first and was the single most important independent variable. Age accounted for 57% of the total variance (R^2) in PMCB (Table 17), 35% in PM (Table 18), 48% in PPVT (Table 19), and 18% in VM (Table 20) performances. These results confirm the high correlations between age and the cognitive tests (Tables 12 and 16).

For the Piagetian battery, the only other significant ($P < 0.01$) effect was mother's education, accounting for 3% of the total variance in PMCB performance (Table 17). However, this was considered to be a general parental education factor because the parental educations correlated 0.61 ($P < 0.01$) and there was no significant ($P < 0.01$) difference between the correlation coefficients of the PMCB with father's and mother's educational levels (as shown by a test of homogeneity between two nonindependent correlation coefficients [18: p 186]). This same effect of mother's education was also found during the development of the PMCB [26], and was similarly interpreted as a general parental education factor. This result also agrees with previous findings of SES differences in Piagetian task performance [1,2,23,92]. Thus, age and parental education accounted for 60% of the total variance in PMCB performance (Table 17).

Achievement Orientation was inversely related to PM performance ($P < 0.01$), accounting for 2% of the total variance (Table 18). This result confirms the correlational results previously discussed. Thus, age and Achievement Orientation accounted for 37% of the total variance in PM performance (Table 18).

For the PPVT, father's education accrued an R^2 of 0.03 (Table 19). This was again considered as a general parental education factor for the same reasons just mentioned. Again, this result agrees with previous findings relating SES to cognitive performance, and particularly verbal ability [4,35,47,54,81,102]. In addition to this parental influence, the twins' sex (girls performed better) accounted for 2% of the total PPVT variance (Table 19). Parental education and twins' sex were not significantly ($P < 0.01$) correlated (Table 16). Therefore, this sex effect was probably an artifact of this particular subsample of 358 children, since there were no significant ($P < 0.01$) sex differences in PPVT performance for the total sample of 418 children. Cohesion in the family was the only other variable significantly ($P < 0.01$) predicting PPVT performance, accounting for 1% of the total variance (Table 19). These results (excluding sex) are easily interpreted, since family cohesion probably facilitates verbal communication (Cohesion and Expressiveness correlated 0.38), and more educated parents have more extensive vocabularies to which their children are exposed. Furthermore, the Cohesion subscale represents a warm, sup-

*TABLE 17. Stepwise Multiple Regression of PMCB Performance on Environmental Variables for 358 Children in the Colorado Piagetian Twin Study**

Step	Variable entered	Significance of F for variable to enter equation	R^2
1	Age	<0.001	0.57
2	Mother's Education	<0.001	0.60
3	Achievement Orientation	0.05	0.60
4	ATE III—General Education	0.02	0.61
5	Provider's Occupation	0.05	0.61
6	Active—Recreational Orientation	0.25	0.61
7	Expressiveness	0.20	0.62

	Analysis of variance for final step				
Source	df	SS	MS	F	Significance
Regression	7	80,797.42	11,542.49	80.25	<0.001
Residual	350	50,341.39	143.83		
R = 0.78					
R^2 = 0.62					
Standard error of multiple regression = 11.99					

*Significance of F for variable to enter equation is the significance of the F of the partial correlation of the independent variable (with the dependent variable) to enter the regression equation. R is the multiple correlation of the independent variables with the dependent variable. R^2 is the squared multiple correlation, or the percent of the total variance in the dependent variable accounted for by the independent variables in the regression equation. Standard error of the regression is the square root of the Residual Mean Square (MS).

portive family environment [63] in which vocabulary could develop naturally. Thus, age, parental education, sex (a probable artifact), and family Cohesion accounted for 54% of the total variance in PPVT performance (Table 19).

Finally, Table 20 indicates that age was the only significant ($P < 0.01$) predictor of VM performance, accounting for 18% of the total variance. Intellectual–Cultural Orientation bordered on significance ($P = 0.013$), accounting for 2% of the total variance in VM performance. Apparently a family Intellectual–Cultural Orientation is conducive to visual memory, perhaps by providing stimulating things to retain in the mind's eye, such as concerts, museums, and art exhibits. Thus, age and Intellectual–Cultural Orientation accounted for 20% of the total variance in VM performance (Table 20). It must be kept in mind, however, that at least 75% of the variance in VM performance was within-family variance, which could not be identified in this between-family environmental analysis. In fact, about 38% of VM variance was due to test–retest unreliability ($1 - 0.62 = 0.38$), which could be considered part of the within-family variance.

In summary, the significant between-family variables predicting cognitive performance accounted for substantial amounts of total variances. The R^2 for each final step in each regression analysis was considerable: 0.62 for PMCB; 0.41 for PM; 0.56 for PPVT; and 0.22 for VM performance (Tables 17 through 20). However, it must be remembered that age accounted for the majority of the variance in each regression equation.

*TABLE 18. Stepwise Multiple Regression of PM Performance on Environmental Variables for 358 Children in the Colorado Piagetian Twin Study**

Step	Variable entered	Significance of F for variable to enter equation	R^2
1	Age	<0.001	0.35
2	Achievement Orientation	<0.01	0.37
3	ATE III—General Education	0.06	0.38
4	Mother's Education	0.08	0.38
5	Control	0.08	0.39
6	Sex	0.15	0.39
7	Number of Sibs	0.15	0.39
8	Independence	0.15	0.40
9	ATE II—Participation	0.15	0.40
10	Moral–Religious Orientation	0.13	0.41

Source	Analysis of variance for final step: df	SS	MS	F	Significance
Regression	10	4,884.97	488.50	23.66	<.001
Residual	347	7,164.42	20.65		

$R = 0.64$
$R^2 = 0.41$
Standard error of multiple regression = 4.54

*See footnote to Table 17 for explanation.

4. DISCUSSION

In evaluating the results of this twin study, it is important to keep in mind that the sample was somewhat biased since the twins came from middle- and upper-middle-class families. Thus, the sample was not entirely representative of the population of same-sex, Anglo twin pairs in the United States. However, keeping this in mind, a number of important findings merit discussion.

4.1. Zygosity Determination

The results of this study have again shown the value of a questionnaire concerning twin physical similarities and questions of confusion by others for determining twin pair zygosity. In this case, as in the studies by Cohen et al [6,7], the questionnaire was usually completed by the mothers of young twins (although a few fathers did respond). Additional information was provided by test administrator observations; height, weight, and fingerprint ridge measurements; and PTC and PROP tasting. The "intuitive" method of zygosity determination proposed by Cohen et al [6,7], along with blood-typing analysis of "undecided" pairs, correctly classified at least 89% of the sample, and most likely closer to 98%. The exact percentage was impossible to determine because the blood-typed verification sample was the "undecided" group, not a randomly chosen representative sample. At the same time, the "intuitive" and discriminant function analyses were in 99% agreement. Consequently, for future studies of this nature, I would recommend that the "intuitive" method of zygosity determination used in this study be employed in conjunction

*TABLE 19. Stepwise Multiple Regression of PPVT Performance on Environmental Variables for 358 Children in the Colorado Piagetian Twin Study**

Step	Variable entered	Significance of F for variable to enter equation	R^2
1	Age	<0.001	0.48
2	Father's Education	<0.001	0.51
3	Sex	<0.01	0.53
4	Cohesion	<0.01	0.54
5	Intellectual–Cultural Orientation	0.05	0.54
6	Organization	0.09	0.55
7	Number of Sibs	0.14	0.55
8	ATE I—Basic 3 Rs	0.19	0.55
9	ATE III—General Education	0.16	0.55
10	Mother's Education	0.30	0.56

Source	Analysis of variance for final step				
	df	SS	MS	F	Significance
Regression	10	17,002.44	1,700.24	43.29	<0.001
Residual	347	13,629.39	39.28		

R = 0.75
R^2 = 0.56
Standard error of multiple regression = 6.27

*See footnote to Table 17 for explanation.

*TABLE 20. Stepwise Multiple Regression of VM Performance on Environmental Variables for 358 Children in the Colorado Piagetian Twin Study**

Step	Variable entered	Significance of F for variable to enter equation	R^2
1	Age	<0.001	0.18
2	Intellectual–Cultural Orientation	<0.013	0.20
3	Provider's Occupation	0.11	0.20
4	Sex	0.14	0.21
5	Expressiveness	0.15	0.21
6	Moral–Religious Orientation	0.23	0.22
7	Cohesion	0.18	0.22

Source	Analysis of variance for final step				
	df	SS	MS	F	Significance
Regression	7	4,583.87	654.84	14.04	<0.001
Residual	350	16,324.85	46.64		

R = 0.47
R^2 = 0.22
Standard error of multiple regression = 6.83

*See footnote to Table 17 for explanation.

with fingerprint analysis, and blood-typing verification for those twin pairs which would be diagnosed as "undecided" on the basis of the questionnaire and dermatoglyphics. A discriminant analysis does not seem necessary if this combined methodology is used.

The discriminant analysis of this twin sample again confirmed the high predictive value of frequency of confusion by casual friends in determining twin zygosity [6,7,41]. This analysis also points out that parents were poor predictors of actual twin zygosity (Table 4). This was largely due to their blind faith in the zygosity diagnosis of the delivering obstetrician, who usually based his/her diagnosis on the number of placentas. Furthermore, parents of MZ pairs seemed to look hard for distinguishing characteristics, and therefore rarely confused their twins. In addition, for this sample PTC tasting and weight differences were also very poor predictors of zygosity (Table 4). These results suggest that PTC tasting could be eliminated in future uses of this method while retaining PROP tasting. However, researchers at the University of Indiana have found PTC tasting to be an effective discriminator of zygosity (Rose, personal communication, 1976), but they use a few more PTC solutions than were used in this study.

4.2. The Environmental Questionnaires

The ATE was constructed for use in this study. Although it had an internal consistency (or coefficient α) reliability of 0.61 and a relatively well-defined factor structure (Table 9), the ATE did not relate significantly to any of the cognitive tests. However, none of the other environmental variables related very strongly to performance on the cognitive tests. In addition, the ATE factors did relate sufficiently to show up in a number of the steps in the various multiple regression analyses (Tables 17 through 20). Furthermore, the Basic Academic Education (ATE I) and Parental Participation (ATE II) factors exhibited a number of significant correlations with other environmental variables (Table 16). In comparison, in Marjoribanks' [54] study, Press for Intellectuality, which was similar to the Parental Participation factor, correlated significantly with 7-year-old nonverbal intelligence. Therefore, the ATE seems to have some value in measuring parental attitudes toward education as a method of evaluating a child's environment. However, the ATE needs some improvements. First, expanding the ATE to 20 or 25 items would increase its α reliability. Secondly, the new items would need to be carefully chosen with the intent of more clearly defining the three factors. The new ATE would then need reanalysis of its psychometric characteristics, such as coefficient α and test–retest reliability, validity and item-factor correlations, along with standardization on a large representative sample.

On the other hand, the FES has been previously standardized by Moos [63], who reported high K-R 20 and test–retest reliabilities for the 10 subscales (Table 5). This study was the first verification of his K-R 20 reliabilities (Table 5), and the first factor analysis of the 90-item scale (Table 10). In this study, the pattern of K-R 20 reliabilities was similar to that of Moos, but the magnitude of the reliabilities was somewhat lower, although acceptable, except for the Independence subscale (Table 5). The patterns of correlations between the 10 subscales were also similar to those of Moos (Table 16), except for the Achievement Orientation subscale, which has already been discussed. On the whole, the Varimax rotated factor structure matrix verified Moos's theoretical 10 subscale structure quite well. It seems that the Independence subscale might need improvement. In addition, the simultaneous factor loadings of the Cohesion and Expressiveness, and the Organization and Control items, need to be verified on a larger, more representative sample. Perhaps these four subscales could be combined into two large subscales (the two former and the two latter subscales, respectively). But, for these analyses, the 10 subscale structure was accepted and used in relation to the cognitive performance for the first time. A few of the subscales showed significant influences on cognitive performance in this sample (Tables 17 through 20). Because of the young, still developing nature of these twins, the majority of the variance in cognitive performance was due to the effect of age. Possibly the FES subscales might be more predictive of cognitive performance among adolescents or adults. They might also be more predictive of academic achievement or IQ than of these particular abilities. For example, Marjoribanks [54] found that his environmental press variable, Educational Aspirations for the Child, which was similar to FES Achievement Orientation, correlated significantly with 7-year-old nonverbal intelligence, but correlated even more highly with intelligence and math achievement of 11-year-olds. He also found that his Press for Achievement, which was similar to FES Intellectual–Cultural Orientation, correlated highly with intelligence and math achievement of 15-year-olds. Thus, it is hoped that future research will expand the use of the FES as a measure of environmental influences on various types of cognitive performance in diverse age groups, and possibly in heterogeneous ethnic groups.

4.3. The PMCB

The PMCB has been shown to be a reliable measure of Piagetian logico-mathematical concepts, with an internal consistency (or coefficient α) reliability of 0.89 and a test–retest reliability of 0.85 [27]. This α reliability agrees with previous results found when the predictive validity of the PMCB was also shown [26]. The factor structure of the PMCB supported the importance of the three Piagetian concepts of classification, conservation of number, and seriation. Although the same three concepts were present, the distribution of the factor loadings was somewhat different from the results of the original 1975 analysis [26]. Perhaps these results are more accurate because the sample size is so much greater (144 vs 418). To date 614 children have taken the PMCB. In the future a factor analysis of the task scores for all these children should be performed.

At the same time, the intercorrelations among the tasks (Table 6) and the Varimax factor structure matrix (Table 7) suggest the interdependence of number, classes, and relations attested to by Piaget [72]. In fact, in the PMCB these three concepts are not independent enough to be considered three separate subtests. Perhaps the tasks within each concept could be improved to increase their discriminatory power, or some additional tasks could be added. However, this suggests a whole new test construction. Presently, the PMCB as a whole is quite acceptable as a single measure of global logico-mathematical concept development.

4.4. Sex Differences

For the whole sample of 418 children there were no significant ($P < 0.01$) sex differences in cognitive performance on any of the four tests. For the PMCB, this result was also found when the test was developed [26]. Tuddenham [92] also reported no significant sex differences on his Piagetian tasks, for 100 first through third graders. Tuddenham's results are important here because tasks 1 through 5 of the PMCB are basically his, while tasks 6 through 15 are taken from Kaufman [38]. On the other hand, Kaufman [38,39] found that girls scored significantly higher than boys on his Piagetian Battery. Kaufman's sample ($N = 103$) consisted of all kindergarten children. Almy et al [1,2] found no sex differences in conservation of number among kindergarten through second graders, whereas Klippel [42] found a sex effect for class inclusion and conservation of number among 5-year-olds. Thus, previous results for Piagetian tasks are contradictory. However, the PMCB has consistently demonstrated no sex differences [26,27], indicating its applicability across sexes. This may be partly due to its administration with both a male and a female present, and to strong administrative emphasis on treating all children exactly alike. These administrative procedures would have allowed for the expression of any "true," unbiased sex effects, which apparently do not exist. Thus, studies using the PMCB have shown that any "sex roles" that may influence logico-mathematical conceptualization do not develop until after 7 years of age.

In addition, Klippel [42] reported sex effects for Stanford-Binet Memory and the Coloured Progressive Matrices, but none for the PPVT. However, Foch and Plomin [25] found no sex effects for the PM (Coloured), and also none for vocabulary and Visual Memory (VM) tests. The PPVT has no history of sex effects in children [17], and neither does the VM [24]. Furthermore, Scarr and Weinberg [81] found no sex differences in Standard PM and PPVT performance for 10- to 15-year-old twins (N = 224 pairs). Klippel's sex difference in PM performance may have been partly due to sample size (N = 60), and partly due to the fact that her sample consisted of three different ethnic groups of New Zealand children (she also found an ethnic effect for PM). Therefore, except for Klippel's results, this study supports previous findings of no sex differences in PM, PPVT, and VM performance for young children. Again, any "sex roles" in these abilities apparently develop after the age of 7.

However, Wilson [99] has found sex differences ($P < 0.05$) in WPPSI IQ for 4- and 5-year-old twins; but these sex differences disappeared at the age of 6, which is more comparable to the overall sample in this study (mean age 5 years, 11 months, see Table 1). It is interesting that IQ shows sex differences at some ages while these specific ability measures do not. This is possibly one good reason for using more specific ability tests in the future and fewer measures of general intelligence.

4.5. Relationships Among Tests

As expected, PPVT and PM performance were found to be relatively independent after age was partialed out (Table 12). This result agrees with previous factor analytic results [10,11,25,106] and with Klippel's [42] correlation of 0.26. The factor matrix reported in this study (Table 13) might seem to imply a higher correlation between the PPVT and the PM. However, this factor analysis was done without partialing out age, and therefore is based on a PPVT-PM correlation of 0.55. Similarly, VM performance was shown to be basically independent of performance on the other cognitive tests (Tables 12 and 13). As mentioned earlier, this is consistent with previous results [3,5,10,11,25,42,68,106].

The PMCB was most highly correlated with PM performance ($r = 0.41$, age partialed out, see Table 12). As previously noted, this was expected, since the PM was included in the study as a "control" measure of nonverbal mathematical reasoning. In addition, this result agrees with Tuddenham's [92] multiple correlation of 0.60 between the Coloured PM and six Piagetian tasks (covering conservation of number, seriation, and classification), keeping in mind that Tuddenham did not partial out age. In fact, before partialing age out, the PMCB and PM correlated 0.66. Klippel [42] obtained a lower, average correlation of 0.35 between the Coloured PM and her conservation of number, seriation, and class inclusion tasks. However, her sample was considerably smaller and demonstrated ethnic effects on the PPVT, PM, and Stanford-Binet IQ tests [42]. In addition, she did not calculate an overall multiple correlation of all her tasks with PM performance.

PMCB performance was also related to level of vocabulary (r = 0.36, age partialed out, see Table 12). This result agrees with most previous correlational results [42,46, 55,103]. Tuddenham [92] found a lower multiple correlation (0.21) between the PPVT and eight conservation and classification tasks. However, his correlation did not include his seriation task, which was included in the PMCB (Task 3). This particular task happens to have the highest correlation with the total PMCB score [26]. Therefore, I suspect that if he had included this and other seriation tasks in his correlation with the PPVT, the multiple correlation would have been higher.

The factor analysis (Table 13) reported herein further illustrates the PMCB relationship to both PPVT and PM performance. The highest loading for the PM was among the highest loadings for seriation and conservation tasks, which are the most difficult abstract Piagetian tasks in the PMCB. As mentioned earlier, this supports the findings of Carlson and Wiedl [5]. They factor analyzed the PM in conjunction with measures of visual and serial memory, and Piagetian conservation, class inclusion, and matrices tasks. Carlson and Wiedl found that the PM, conservation, and matrices loaded on one factor, whereas the memory tasks and class inclusion were associated with a second factor. Similar correlational results were reported by Tuddenham [92]. At the same time, the highest PPVT loading in the present study was among the high loadings for conservation and classification. This result agrees with Klippel's [42] correlation of 0.41 between a classification task (class inclusion) and the PPVT (although Klippel's ethnic effects must be kept in mind). On the other hand, Tuddenham [92] reported a correlation of 0.35 between the PPVT and conservation, which was higher than with his classification tasks. I suspect that, had Carlson and Wiedl [5] included the PPVT in their factor analysis, they might have found a relationship similar to the one reported herein. As it was, they did find class inclusion on a factor separate from PM and conservation. DeVries [18] found her Piagetian tasks and vocabulary achievement on entirely separate factors, but her results may have been due to the stronger interrelationships among all the achievement subtests. Because Tuddenham and Klippel have not factor analyzed their data, the present study is the first to report a factor analysis with the simultaneous use of the PPVT, PM, visual memory, and Piagetian tasks.

4.6. Genetic Influences

The intraclass correlations for height and weight suggest that this sample was indeed representative of same-sex, Anglo twin pairs in the United States [100]. Therefore, the intraclass correlational results for the cognitive tests can also be considered generally representative. However, socioeconomic differences have a stronger influence on cognitive performance than on height and weight [47]. Because this sample was not as heterogeneous in socioeconomic status as one would have preferred, it is possible that the variance between families, and therefore the intraclass correlations, may have been less than expected in a random sample. This was apparently true for VM, and possibly for PM performance, but was perhaps not true for the PMCB and PPVT (Tables 14 and 15). These observations are in line with the low, nonsignificant correlations between PM and VM and the socioeconomic indices (provider's occupation and parental education, Table 16), possibly due to insufficient variance in the socioeconomic indices with respect to these two tests. However, parental education did correlate significantly with PMCB and PPVT performance, and provider's occupation correlated significantly with the PMCB (Table 16), indicating sufficient variance in these socioeconomic indices with respect to Piagetian logico-mathematical conceptualization and vocabulary. In other words, it is possible that the degree of variance in SES has differential effects on the relationships between SES and performance on various congitive tests. This hypothesis is supported by the fact that Scarr and Weinberg [81] did find significant ($P < 0.01$) correlations between SES and SPM, PPVT, and Benton Figural Memory performance for 224 pairs of white twins from the full SES range.

Thus, the small amount of genetic variance (uncorrected) found in this study for VM and PM performance (Table 14) may have been deflated by the restriction in SES variance (Table 2). Parental education and provider's occupation are correlated with parental intelligence, which exhibits genetic variance [47]. Therefore, it is possible that the genetic variance in VM and PM performance was deflated by a restriction in the genetic variance of intellectual functioning in the parental sample. However, as already mentioned, it is also possible that there is in fact less genetic variance in VM and PM performance in children than previous results with adolescents and adults would have indicated. Further research is needed to resolve this issue. However, for definitive results, future research must determine the test–retest reliability of the Coloured PM, use a larger sample of twins from the full range of SES, and make a concerted effort to locate more DZ twin pairs than this study was able to include.

Similarly, it is possible that this somewhat biased sample had deflated the actual genetic variance for PMCB and PPVT performance. This reasoning is supported by higher levels of genetic variance found among less biased samples of adolescents and adults for vocabulary, arithmetic, and Progressive Matrices [11,68,81,95,98]. At the same time, there was sufficient SES variance in this sample to produce significant correlations with PMCB and PPVT performance (Table 16) and, as just mentioned, sufficient variance between families for these two tests. Hence, it is possible that the intraclass correlations for PMCB and PPVT reported herein are unbiased estimates. This conclusion would imply that a considerable amount of both between- and within-family environmental variance exists for performance on these two tests in children. This conforms with Piaget's contention that interaction with the environment promotes cognitive development [73]. Such interaction with the environment might be more important for cognitive development in children than among adults. Wilson [102] has also found genetic variance for WPPSI IQ of the magnitude reported herein for PMCB and PPVT performance. However, this is the first twin study using Piagetian tasks, and the first large twin study of specific cognitive abilities in young children. Therefore, further research needs to be conducted to verify these results.

It should be pointed out that parental assortative marriage could also have deflated the genetic variance for these four tests by inflating the DZ intraclass correlations [48]. However, this effect could have been balanced by nonadditive genetic influences (dominance and epistasis), which could have inflated the heritability estimates [56]. Loehlin and Nichols [48] suggest that both assortative mating and nonadditive genetic influences may be less significant for specific cognitive abilities than for IQ. In fact, DeFries et al [11] have recently found relatively low estimates of assortative marriage for specific cognitive abilities. And results of this study indicate low correlations between children's performance on these four tests and parental education, which exhibited a high spouse correlation. Thus, assortative marriage and nonadditive genetic factors may not be significantly biasing the heritability estimates.

In addition, calculation of broad heritability using Falconer's [22] formula assumes that environmental factors are not more similar for MZ than for DZ twin pairs. If MZ twins are in fact treated more similarly, the resulting heritability will be an overestimate [56].

However, recent evidence indicates that the "equal environments (MZ vs DZ) assumption" is valid for specific cognitive abilities [48,96].

The results of this study indicate no change in MZ and DZ intraclass correlations as a function of age for these four cognitive tests. However, this was not a longitudinal study. The field of individual differences in specific cognitive abilities in young children is relatively unexplored. It is hoped that the results of this project will inspire a large longitudinal twin study using the PPVT, PM, VM, PMCB, and possibly other measures of specific cognitive abilities, especially some based on Piaget's theory (such as Piagetian tasks of spatial and memory ability).

4.7. Environmental Influences

As discussed in Results, parental education and father's occupation correlated significantly with PMCB and PPVT performance. In this study, these parental variables were considered as measures of the twins' environment. However, it has already been pointed out that parental education and occupation have a genetic component that is confounded with environmental variation. This idea is supported by the significant ($P < 0.01$) genetic variance found for PMCB and PPVT in the intraclass correlational analysis. The only way to separate the genetic and environmental influences represented by these parental variables may be to have an independent measure of parental intellectual functioning, such as the Standard PM. Thus, inclusion of parental SPM scores is recommended for future twin studies of specific cognitive abilities in young children. Perhaps the parents could also take a vocabulary test, the VM, and some Piagetian tasks of formal operations. Then, of course, the investigators would have a combined family and twin study, which could be very informative.

The four multiple regression analyses all found age to be the most significant influence on cognitive performance for this sample of 4- to 8-year-old twins. This was expected since these children were tested during a crucial developmental period. However, what does this age effect mean? Does it represent genetic or environmental influences on cognitive development, or both? Wilson [102] has begun to answer this question in a large longitudinal twin study of IQ. He has investigated twin concordance in developmental trends in IQ ("spurts and lags"), as well as overall levels of IQ [102]. However, Wilson has not reported any environmental information except father's occupation and parental education. Further research is necessary to address this issue for specific cognitive abilities, particularly those with a theoretical development framework, such as Piaget's.

Parental education accounted for 3% of the total variance in PMCB performance, while age accounted for 57%. These results can be compared with the 1975 results of 11% and 35%, respectively [26]. The age effect in the present study was larger because of the inclusion of 4-year-olds. At the same time, the parental education effect was smaller, possibly partly because of the restricted SES range in the twin study, as compared to the full SES range in the 1975 study. Wilson [102] also found that mother's education accounted for 11% of the variance in 6-year-old WPPSI IQ ($r = 0.33$, $r^2 = 0.11$). However, Marjoribanks [54] found that father's education only accounted for 3% of the variance in nonverbal intelligence in 7-year-old boys and 0.5% of the variance in girls. Thus, further research on samples with a wider SES range is necessary to verify the extent of the influence of parental education on logico-mathematical conceptualization. This is also true for PPVT performance, since the PMCB and PPVT exhibited somewhat parallel results with respect to parental education.

It is interesting that Achievement Orientation, as defined by the Moos [63] subscale, was inversely related to PM performance. Achievement Orientation also had a significant, although small, negative correlation with PMCB performance (Table 16). On the surface, this result seems to be in direct conflict with Marjoribanks' findings [54] for his similar factor (Educational Aspirations for the Child). However, his factor mainly emphasized maximal education and a professional occupation; it did not include competition or a more general achievement pressure. Furthermore, his factor was much more predictive for subjects aged 11 years and above. Thus, the results of this study suggest that pressure for competitive achievement inhibits abstract reasoning and possibly other aspects of cognitive development in young children [74].

What aspects of the environment influence visual memory still remain somewhat of a mystery. There is some effect of Intellectual–Cultural Orientation in the family ($R^2 = 0.02$). However, further research is needed in this area. In particular, perhaps a more reliable measure of visual memory could be developed for this age group, possibly based on Piaget and Inhelder's [75] recent studies of memory and cognitive development. Since the variance due to test reliability is part of the unknown within-pair variance, increasing test reliability might decrease within-pair environmental variance, and therefore possibly increase the proportion of between-family environmental variance that could be investigated.

The results of this study indicate that the FES and ATE questionnaires do not sufficiently measure those aspects of a child's environment that influence cognitive development in these four specific abilities. However, this study has opened the door to further research in this area. More refined measures of different aspects of the environment need to be applied to larger, random samples. Although the FES and the ATE need further study, these scales could serve as a beginning.

4.8. A Synthesis

Using the results of this study, the variance in test performance can be partitioned into various components, using the following general formula [22]:

$$V_P = V_G + V_E, \tag{1}$$

where V_P is the phenotypic variance, V_G is the genetic variance, and V_E is the environmental variance. However, since this was not a longitudinal study, this formula can only be applied to the variance in age-corrected test scores. Therefore, in this synthesis, the results of the multiple regression analyses (Tables 17 through 20) have been modified to express percentages of the variance in age-corrected scores. These modifications were calculated by dividing the percentage of the total variance for a variable by the actual residual variance left after age was partialed out of the total variance in test performance. In the PMCB, for example, after partialing out age, 43% of the total variance is left as the residual, age-corrected variance. Education of the mother accounted for 3% of the total PMCB variance, and therefore accounted for 7% (ie, 0.03/0.43) of the variance in age-corrected scores. Thus, for the discussion that follows, the phenotypic variance being partitioned is the V_P for the age-corrected test scores.

In this study the environmental measures elucidated between-family environmental variance. However, since genetic influences were not included in the stepwise multiple regression equations, it must be kept in mind that the between-family environmental influences identified may be confounded with genetic factors. As already mentioned, this is particularly true of the influence of parental education.

For the phenotypic variance in age-corrected PMCB performance, V_{PMCB}, the empirical results are as follows:

$$V_{PMCB} = V_G + V_{EDM} + V_{ENV} + V_{ERR}, \quad (2)$$

where V_G is the genetic variance or "broad heritability," h^2, corrected for test reliability (Table 14); V_{EDM} is the variance accounted for by Education of the Mother; V_{ENV} is the variance accounted for by the remaining environmental variables listed in Table 17; and V_{ERR} is the variance due to other unknown factors (including both between- and within-family variances). Therefore,

$$V_{PMCB} = .40 + .07 + .02 + V_{ERR} = .49 + V_{ERR}. \quad (3)$$

Thus, theoretically this study has accounted for 49% of the phenotypic variance in age-corrected PMCB performance. However, as was just discussed, further research is needed to separate the confounding of genetic and environmental factors in the effect of parental education. In addition, the genetic variance had a standard error of $\pm$ 0.18 (Table 14), exemplifying the need for a larger twin sample. Nonetheless, the results of this study, illustrated by equations (2) and (3), certainly indicate the value of further research in this area of genetic and environmental influences on the development of Piagetian logico-mathematical concepts.

The phenotypic variance in age-corrected PM performance, V_{PM}, can be expressed as follows:

$$V_{PM} = V_G + V_{REL} + V_{ACH} + V_{ENV} + V_{ERR}, \quad (4)$$

where V_{REL} is the variance due to the unreliability of the test, which has an unknown reliability; V_{ACH} is the variance accounted for by FES Achievement Orientation; V_{ENV} is the variance accounted for by the remaining environmental variables listed in Table 18; and V_{ERR} is the variance due to other unknown factors. Therefore,

$$V_{PM} = .20 + V_{REL} + .03 + .06 + V_{ERR}, \quad (5)$$

and

$$V_{PM} = .29 + V_{REL} + V_{ERR}. \quad (6)$$

Thus, theoretically this study has accounted for 29% of the phenotypic variance in age-corrected PM performance. However, as previously mentioned, the true test–retest reliability of the Coloured PM must be determined. Precise knowledge of this reliability would probably change all the percentages given in equation (5), increasing their accuracy. In addition, the results of this study, as illustrated by equation (6), particularly demonstrate the need for further research into other environmental influences on PM performance not yet identified.

Similarly, the phenotypic variance in age-corrected PPVT performance, V_{PPVT}, can be expressed as follows:

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$$V_{PPVT} = V_G + V_{EDF} + V_{COH} + V_{ENV} + V_{ERR}, \quad (7)$$

where V_{EDF} is the variance accounted for by Education of the Father, V_{COH} is the variance due to FES Cohesion in the family, V_{ENV} is the variance accounted for by the remaining variables listed in Table 19, and V_{ERR} is the variance due to other unknown factors. Therefore,

$$V_{PPVT} = .44 + .06 + .02 + .08 + V_{ERR} = .60 + V_{ERR}. \quad (8)$$

Thus, theoretically this study has also accounted for 60% of the phenotypic variance in age-corrected PPVT performance. However, again the same comments can be made regarding further research on parental education factors, and the use of larger samples to decrease the standard error ($\pm$ 0.19) of the genetic variance. On the other hand, the importance of Cohesion in the family and the combined effect of the other family environment variables listed in Table 19, give food for thought to psychologists, educators, social workers, and other professionals dealing with a child's home environment. Furthermore, these results suggest the value of future programs of parental education, and possibly therapy, in an effort to provide a warm, supportive atmosphere in which the child can develop.

Finally, the phenotypic variance in age-corrected VM performance, V_{VM}, can be expressed as follows:

$$V_{VM} = V_G + V_{I\text{-}CULT} + V_{ENV} + V_{ERR}, \quad (9)$$

where $V_{I\text{-}CULT}$ is the variance accounted for by FES Intellectual–Cultural Orientation, V_{ENV} is the variance accounted for by the remaining environmental variables listed in Table 20, and V_{ERR} is the variance due to other unknown factors. Therefore,

$$V_{VM} = .27 + .024 + .024 + V_{ERR} = .318 + V_{ERR}. \quad (10)$$

The genetic variance in equation (10) is based on the MZ intraclass correlation corrected for test reliability, assuming that the DZ correlation is zero. This estimate of the genetic variance in VM performance is not very satisfactory and needs further study. In addition, it suggests considerable within-pair environmental variance, as opposed to the between-family environmental factors studied. However, based on this estimate, 32% of the phenotypic variance in age-corrected VM performance has been accounted for in this study. But, exactly how does intellectual–cultural orientation affect visual memory? The same question can be asked of the other environmental variables listed in Table 20. This study has provided evidence that suggests the need for further research into other environmental influences on visual memory ability.

5. SUMMARY AND CONCLUSIONS

In summary, this study has demonstrated the value of using independent environmental questionnaires for determining specific environmental influences on cognitive abilities. Specifically, the ATE (with some improvements) has the potential for becoming a useful measure of three particular aspects of parental attitudes toward education. The FES subscales have basically maintained their reliabilities, patterns of intercorrelations, and theoretical structure. Consequently, the FES appears to be a valuable instrument for helping us identify aspects of the family environment, other than SES, that affect specific cognitive abilities in young children. However, the FES may prove more valuable for families with older children. It would be interesting to use the FES, and an improved ATE, in a longitudinal twin study to determine whether the influences of these particular environmental variables change over time with respect to the development of specific cognitive abilities.

The value of the PMCB as a general measure of logico-mathematical concept development has been reaffirmed. The PMCB has continued to exhibit a high α reliability (0.89), and the general factor structure of the three underlying concepts of conservation of number, classification, and seriation has been verified. The exact factor matrix structure remains to be elucidated, perhaps by using the task scores of all the 614 children who have now taken the PMCB. At the same time, a complete standardization analysis could be undertaken, including publication of norms.

There were no sex differences in cognitive performance on any of the four tests. This is a socially significant finding, since it suggests that any "sex roles" in these specific abilities develop after the age of 7.

The PMCB was the only test used which was based on a theory (Piaget's) of cognitive development. Hence, it is not surprising that it was this test that correlated most highly with age, while PPVT, PM, and VM followed in rank order (Table 11). Age also accounted for the most variance in performance on any of the four cognitive tests (see Tables 17 through 20). Obviously, these twins were tested during a crucial developmental period. This result strongly emphasizes the need for a longitudinal twin study of specific cognitive abilities. Such a study could also verify that MZ and DZ intracorrelations for these abilities do not change between 4 and 8 years of age. Changes over time in environmental influences on cognitive performance also could be investigated.

The present study has reaffirmed the relative independence of vocabulary (PPVT) and reasoning ability (PM), and the virtual independence of visual memory (VM). As expected, logico-mathematical conceptualization (PMCB) was found to be more highly related to abstract reasoning (PM) than to vocabulary (PPVT). However, PMCB performance correlated significantly with both, and PMCB tasks were associated with both in a factor analysis. On the other hand, the PMCB correlations with PM and PPVT indicate that the PMCB is also measuring something other than vocabulary and reasoning ability (as defined by PPVT and PM). Other aspects of PMCB performance remain to be elucidated in future research.

The intraclass correlations for height and weight indicated that this was a relatively representative twin sample. Significant amounts of genetic variance were found for age-corrected PMCB and PPVT performance, the magnitude (0.40 to 0.44) of which was in line with Wilson's results [102] for WPPSI IQ. At the same time, no significant genetic variance was found for age-corrected PM performance, without speculatively correcting for test reliability. However, when a lower-bound estimate of test–retest reliability (0.41 or 0.49) was used as a correction, significant genetic variance for age-corrected PM performance resulted. Finally, for the VM, the DZ intraclass correlation was negative (within-pair was greater than between-pair mean square) and close to zero, although the MZ intraclass correlation was significantly different from zero, but small. This result implies that, at best, little genetic variance was present in the VM, and that the variance was mostly due to within-family environmental factors.

Three conclusions are obvious from these results. First, a better estimate of the PM test–retest reliability is needed. Second, the within-pair variance in age-corrected VM performance needs to be decreased in relation to the between-pair variance, in order to obtain a reasonable estimate of genetic variance. Improvements in the VM reliability and validity might help solve this problem. And, finally, these results suggest considerable environmental variance for these four tests.

Parental education and occupation were significantly correlated with PMCB and PPVT performance. Parental education also accounted for a significant amount of the total variance in both PMCB and PPVT performance. In this study parental education and occupation were considered as environmental variables. However, as previously discussed, they also have a genetic component. To separate the genetic and environmental aspects of the parental influences, separate measures of parental intellectual functioning must be incorporated into future studies of this type. In addition, the true extent of this parental education influence needs to be verified with a sample from the full SES range.

A competitive achievement orientation, as defined by the Moos [63] FES subscale, was inversely related to abstract reasoning (PM), and had a negative correlation with the PMCB. This result supports Piaget's [76] contention that undue pressure inhibits cognitive development. Cohesion in the family was the only FES subscale that significantly predicted vocabulary (PPVT). This finding suggests the importance of a warm, supportive family environment for natural cognitive development, and is in agreement with the negative effect of a "pushy" achievement orientation. Finally, an intellectual–cultural orientation in the family positively influenced visual memory (VM), possibly through the mechanism of the child being exposed to stimulating experiences. However, this orientation accounted for 2% of the total variance in VM performance. Much more research is needed to identify other environmental influences on visual memory.

A synthesis was made of the genetic and environmental findings for the four tests. Theoretically, 49% of the variance in age-corrected PMCB performance was accounted for by the genetic, parental education, and a few other combined between-family environmental variables. Similarly, 60% of the variance in age-corrected PPVT performance was theoretically accounted for by the genetic, parental education, cohesion in the family, and combination of a few other between-family environmental factors. This is a remarkably high value. However, further research is needed to elucidate the meaning of the variance due to age, which was partialed out (for all four tests), and to separate the genetic and environmental influences inherent in parental education. In addition, 29% of the variance in age-corrected PM performance was accounted for by genetic, achievement orientation, and a combination of other between-family environmental factors. In the future, this percentage may increase when a better estimate of the test–retest reliability of the PM is available. Finally, 32% of the variance in age-corrected VM performance was accounted for by genetic, intellectual–cultural orientation, and a combination of other between-family environmental variables. Similarly, this percentage should increase somewhat in the future if an improved test of visual memory for children becomes available. These results emphasize the need for further research into other between- and within-family environmental influences on Piagetian logico-mathematical concept formation (PMCB), abstract reasoning (PM), vocabulary (PPVT), and visual memory (VM) abilities.

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APPENDIX: ATTITUDES TOWARD EDUCATION SCALE

Please circle the number indicating how much you agree or disagree with the statement. For instance, if you agree somewhat, you would circle number 2:

	agree strongly		neutral		disagree strongly
	1	(2)	3	4	5

	agree strongly		neutral		disagree strongly
1. We made it a point to meet the teachers when the twins first went to school.	1	2	3	4	5
2. The more education a person has, the better chance at a good life.	1	2	3	4	5
3. Schools should help children to get along with one another.	1	2	3	4	5
4. Schools should go back to teaching the basic three R's: reading, writing and arithmetic.	1	2	3	4	5
5. At first the twins were fearful of going to school.	1	2	3	4	5
6. Everyone should learn a second language.	1	2	3	4	5
7. There are too many frills and fads in today's schools.	1	2	3	4	5
8. We would be very unhappy if the twins do not do well in school.	1	2	3	4	5
9. We read frequently to the twins.	1	2	3	4	5
10. Gym, music and art should be taught to every child in elementary school.	1	2	3	4	5
11. The way schools teach today, children cannot even do simple arithmetic.	1	2	3	4	5
12. People who can read fast and write well are more successful.	1	2	3	4	5
13. The average person can get along fine without learning much math.	1	2	3	4	5
14. Reading should be an important pastime for everyone.	1	2	3	4	5
15. Many stores can find no clerks that can make change because the schools don't teach arithmetic well enough.	1	2	3	4	5

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