Synchronies in Mental Development: An Epigenetic Perspective

Early mental development of twins and siblings is analyzed within the framework of evolutionary theory.

Ronald S. Wilson

Recent years have witnessed dramatic advances in such diverse areas as developmental genetics, ethology, evolutionary theory, and behavior genetics. The infusion of data from these areas into psychology—particularly developmental psychology—has revitalized an interest in the biological foundations of behavior. The strong influence of adaptive utility and natural selection is now seen in many aspects of infant behavior, heretofore credited to conditioning (*1*); and the spectrum of infant behavior is increasingly regarded as an epigenetic production which has its roots in the genotype.

The unfolding of behavioral processes during childhood furnishes a natural proving ground for these implications from evolutionary theory. Fishbein (*3*) has coordinated many of the concepts from evolutionary theory with the findings of developmental psychology, and he proposes that behavioral development is guided by epigenetic processes that have been mapped out by evolution in the genetic blueprint. The instructions contained in the genotype are designed for interactions with a particular set of environments—those to which the ancestors were adapted—and the way in which behavior develops is jointly determined by the genotype and the succession of environments encountered.

Summary. Early mental development is analyzed from an evolutionary viewpoint and related to the dynamic interplay of genetic programming, maturational status, and environmental influence. Data are reported from a large sample of twins and siblings who have been tested longitudinally from 3 months to 6 years of age. Monozygotic twins became increasingly concordant with age and also paralleled each other for the spurts and lags in development. Dizygotic twins became less concordant with age and eventually matched their singleton siblings as closely as one another. The overall results suggested that the course of mental development is guided by the intrinsic scheduling of the genetic program acting in concert with maturational status and environmental influence.

Psychology is just beginning to absorb the full implications of evolutionary theory for human development (*1-3*). The distinctive behavioral attributes of *Homo sapiens* must have been molded by adaptation and survival as surely as the physical characters were, and must be as firmly rooted in the phylogenetic history of the species. In Lorenz's phrase (*4*, p. 65), ". . . all behavior, exactly like all bodily structure, can develop in the ontogeny of the individual only along the lines and within the possibilities of species-specific programs which have been mapped out in the course of phylogeny and laid down in the code of the genome."

Epigenesis is a dynamic process with continuous feedback and modulation that assures that development proceeds toward specific targets or end states. It accomplishes this directional stability by means of canalization, described by Fishbein as follows (*3*, p. 7):

> Canalization involves a set of genetic processes which insure that development will proceed in normal ways, that the phenotypic targets will be attained despite the presence of minor abnormal genetic or environmental conditions. Canalization processes operate at each point in development to correct minor deflections from the sought-for phenotypic targets.

At the anatomical level, canalization assures that all species members share the same configuration, and it provides a high degree of buffering against deviant conditions that might introduce defects into the species model. Its occasional lapses, however, become evident in congenital anomalies or malformations.

Fishbein proposes that canalization is responsible for behavioral constancies as well, by furnishing the species-specific behavioral programs that impel each member along a common developmental pathway. The strength of canalization may vary, but those behavioral attributes that have fostered adaptation and survival are likely to be the most strongly canalized.

Canalization means that certain patterns of behavior are easily, almost inevitably, acquired by all species members under the normal circumstances of life. Such behaviors come with a high degree of preorganization and priming laid down in the brain structure by evolution, and they are actuated in straightforward fashion except in the most extreme circumstances. At the human level, the acquisition of language is one illustration of a routinely developed capability which depends on brain structures unique to *Homo sapiens* and which consistently unfolds except in severe circumstances. As Washburn observes, "Clearly, evolution has produced a biological base that makes this learning [language] so easy for humans" (*5*, p. 409).

The dynamic phasing of epigenetic processes is well illustrated by studies of regulator genes that switch on and off the activity of structural genes and control the intensity of their reaction. Gottesman (*6*), who has surveyed several of the studies in molecular genetics that pertain to developmental psychology, suggests that the processes evident in cellular development may also regulate the more molar episodes of body growth and behavioral development. Patterns of acceleration and lag in growth, of precocity or deficit in developmental status, may reflect distinctive cycles of gene action operating in conjunction with the maturational state of the organism. The point has been described by McClearn as follows (*7*, p. 61):

> It is most important to appreciate that the influence of genes is not manifested only at conception or at birth or at any other single time in the individual's life history. Developmental processes are subject to continuing genetic influence, and different genes are effective at different times.

The author is professor of pediatrics at the Child Development Unit, University of Louisville School of Medicine, Louisville, Kentucky 40232.

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The mechanisms of timed gene action are further synchronized by another property of cells—their state of maturation, or competence in Waddington's term (*8*). Before cells are mature, they are not able to react to various agents; but once they mature, they become responsive to and guided by the agents active at that time. Many cells only become competent in the later stages of development, at which time they provide the responsive substrate in which age-linked genes can express themselves.

These characteristics call attention to a prominent feature of epigenetic processes, namely, individual differences in the rate of development and in the timing of particular phases. The variation among individuals is most clearly revealed by the adolescent growth spurt, but these variations ramify throughout every phase of development, and they reflect the unique combination of age-linked genes in each zygote.

Indeed, within each zygote the multitude of chemical reactions going on during differentiation and growth demands precision of linkage to harmonize the course of development among all systems (*9*). For any given child, the growth gradients are not uniform across all systems, but rather progress in a sequence that is fixed in broad outline but idiosyncratic in detail. These variations lead to uneven or nonsynchronized growth rates for different structures of the body and their correlated functions. Eichorn (*10*) has referred to these unevenly phased growth spurts as intraindividual asynchronies.

The mechanisms of timed gene action suggest a biological foundation for such asynchronies, which may then be further modulated by environmental influences. Variations in tempo are an inherent feature of developmental processes, and they must ultimately be reconciled with the differential switching on and off of gene-action systems and maturational processes.

From an epigenetic standpoint, these characteristics should be evident in behavioral development as well. In assessing the individual trends in mental development, Bayley gave a clear description of how these asynchronies might be revealed (*11*, pp. 813–814):

> It becomes evident that the intellectual growth of any given child is a resultant of varied and complex factors. . . . [In] individual growth curves, there may be plateaus, periods of no growth, and occasionally actual decrements. There may be rapid forging ahead. Each child appears to develop at a rate that is unique for him.

Mental Development: An Epigenetic Perspective

Among the capabilities of human beings, none is as distinctive nor as central to his or her adaptive potential as intelligence. It is tied to the recently evolved regions of the brain, particularly the association areas of the neocortex (*12, 13*). It furnishes an enormous integrative capability by which the experiences of the past can be brought to bear adaptively on the problems of the present and the anticipations of the future. As a species characteristic it progresses from the rudimentary sensorimotor coordinations of infancy to the abstract reasoning of the adult, and the transformation is so drastic that the line of continuity is inferential rather than direct. It is perhaps the most widely studied capability of man, and in recent years by far the most controversial.

But if intelligence is rooted in strongly canalized epigenetic processes, then its developmental course from infancy onward should be interpretable within the framework of evolutionary theory. Its manifestations at any given age would be fashioned from the dynamic interplay of genetic programming, maturational status, and environmental influence. It would unfold in accordance with the timetable of brain development—in particular, the gradients of growth which interconnect and functionally activate the brain structures of recent phylogenetic origin, and which render them accessible to the influx of experience.

As a species characteristic, the timetable would advance all children through successive phases of neural interconnections and registration of experience in predetermined order, with a corresponding progression through the stages of mental development. Superimposed on this basic species trend, however, would be individual differences in rate of progress and ultimate level attained.

What is the evidence from the evolutionary record that man's distinctive capabilities are based on the recent phylogenetic additions to his brain? The greatest increase in size seems to have occurred in the association areas of the inferior parietal, temporal, and frontal lobes, plus the speech areas identified as Broca's and Wernicke's areas (*12, 13*). The neuropsychological data strongly implicate these areas for language abilities, spatial understanding, attention, memory consolidation, skilled movements, and planning abilities.

Further, these regions are the slowest to mature and become functional during childhood, lagging behind the sensory and motor projection areas (*9, 14*). Therefore, the brain structures mediating these higher mental processes only gradually become functional, or competent, in Waddington's term; and this fact takes on added significance as one analyzes some of the apparent discontinuities in mental development. These regions also show the greatest degree of growth from birth to maturity (*12*, p. 176), a fact that bears on the slow but progressive elaboration of intellectual functions in the human.

Interpretations of Mental Development

In broad outline, what characteristics of early mental development have been noted in previous research which would suggest a linkage to epigenetic processes? On the one hand, Piaget's (*15*) description of cognitive development, with its emphasis on successive stages unfolding in invariant order and building on the experiences of the preceding stages, highlights the constancies in mental development. It touches on the fundamental operations and transformations accomplished by all human infants, and as such it gives expression to the species-wide regularities in mental development. Indeed, Piaget's detailed microanalysis of cognitive functioning may be regarded as the basic itinerary for the species.

By contrast, the other research area concerned with early mental development has been more in the psychometric tradition, where the assessment of individual differences has been of paramount interest. This approach is best illustrated in the work of Bayley (*11, 16, 17*), who was among the first to demonstrate the low-order correlations between infant mental status and later measures of intelligence. The results were interpreted as follows.

During the early stages of infancy, primitive sensorimotor functions are the major component of mental development, and individual differences in status are primarily a reflection of age-linked spurts and lags in the rate of growth. But as the child matures, his or her mental functions increasingly resemble the analytic and integrative capabilities of the school-age child, and individual differences become a more reliable predictor of later intelligence.

When does this transition occur in the development of mental functions during childhood? After reviewing several studies in this area, Bayley commented (*17*, p. 381):

It would appear that a clear change occurs at some time between 15 months and 2 or 3 years of age. There is evidence . . . that this change is not entirely a result of environmental factors but that it is a function of the changing nature of the intellectual processes after the first year, with accompanying individual differences in children's mental growth rates.

It is also worth noting that Piaget (*15*) identifies the period around 2 years of age as a significant transition period in which symbolic functions are enhanced, enabling the child to draw on internalized memories of past experience as an aid to comprehending the present. And perhaps it is not entirely fortuitous that the newer regions of the brain discussed above display a major growth increment during this period, going from 45 percent of adult surface area at age 1 year to 70 percent at age 2 years (*12*, table 189, p. 378).

Twins and Mental Development

Twins offer an unusually powerful resource to study the course of mental development from an epigenetic perspective. Monozygotic twins provide the rare natural experiment with humans in which two zygotes share exactly the same genotype and are raised in the same family environment.

Dizygotic twins by contrast have a variable number of genes in common (50 percent on the average), proportionally the same as any other pair of siblings from the same family. However, dizygotic twins have further shared the homogeneous experiences of being born and raised as twins, which should enhance their similarity in comparison to siblings. If the collective influences of gene action and pre- and postnatal environment fashion the course of mental development, then the contributions of the various factors may be appraised by comparison of monozygotic twins with dizygotic twins and nontwin siblings.

Previous research from the Louisville Twin Study has shown a significant genetic influence on the course of mental development, and it has also suggested a strong degree of canalization in mental development, as shown by the progressive convergence of monozygotic twins over age, and the opposite trend for dizygotic twins (*18, 19*). With additional data available, perhaps now is the time to reexamine mental development from the broadened perspective of evolutionary theory; to consider it as a species attribute unfolding in programmed stages, but with significant individual differences in rate; to examine how the primitive sensorimotor functions of infancy become transformed into intelligence; and to assess the degree of synchrony in this epigenetic process for monozygotic and dizygotic twins. If there is an underlying ground plan, some of the apparent discontinuities may be resolved into a deeper patterning of growth.

Method and Procedure

Sample. The data reported here are based on a sample of 374 twin pairs and their siblings who have participated in a longitudinal study of mental development during the past 10 years. The twins were recruited from the complete Board of Health birth records for metropolitan Louisville, with particular emphasis being given to securing the cooperation of low socioeconomic families. Recruitment has been an ongoing process, with 35 to 40 twin pairs added each year. The socioeconomic ratings for the twin families showed that all strata were adequately represented in the sample, although the proportion of lower-class families was slightly smaller than in the general population (*20*).

The twins are tested initially at 3 months of age, and they make subsequent visits every 3 months during the first year, every 6 months during the second and third years, and annually thereafter to age 6 years. The ongoing nature of recruitment means that many twins have not completed six full years in the program, but nearly two-thirds of the sample have test data covering at least four consecutive years.

Tests of mental development. The tests used in this program have been selected from the most carefully constructed and best standardized psychometric tests available. These include the Wechsler Preschool and Primary Scale of Intelligence (WPPSI), the Bayley Scales of Infant Development, the restandardized version of the Stanford-Binet Form L-M, and the McCarthy Scales of Children's Abilities (*17, 21*). The characteristics of each test are discussed elsewhere (*19*), but they all share the common properties of exceptional test construction, reliability, and careful standardization on a representative sample. They qualify as benchmarks of mental measurement in an area which has previously been lacking such well-defined standards (*22*).

The Bayley Mental Scale was administered at 3 through 24 months of age, the Stanford-Binet at 30 months and 3 years, and the WPPSI at 4, 5, and 6 years. Recently, the McCarthy scale has been substituted for the WPPSI at 4 years since it gives a broader sample of the child's behavior at that age. Each test converts the raw scores into age-adjusted standard scores with a mean of 100 and standard deviation of 16 (15 for the WPPSI).

At each visit, the twins were tested by separate examiners who also alternated between the twins over successive visits. The test procedures were intensively rehearsed to assure comparability among examiners, and the test scoring was verified by a third examiner before the scores were recorded.

Zygosity determination. Zygosity was established for same-sex pairs by blood-typing 22 or more red cell antigens (*23*). If the results were concordant for all antiserum tests, the twins were classified as monozygotic; if discordant for any test, dizygotic. For technical reasons the blood-typing was deferred until the twins were 3 years old, so the infant tests were completed before zygosity was established. Opposite-sex twins were classifed as dizygotic on the basis of the sex difference.

Results

Since these twins have been tested repeatedly during infancy and childhood, the basic data may be illustrated by plotting the mental development curves for several pairs (Fig. 1). These pairs were selected to illustrate the different trends that may be found, and the degree of congruence within each pair in matching the trend.

The monozygotic twins shown in Fig. 1, A, C, and D, display somewhat different trends in mental development, but there is a high degree of congruence within each pair. Note especially the upward trend for the twins in Fig. 1A and how it contrasts with the downward trend in Fig. 1D. Apparently the inner programming can dictate trends in either direction, and the degree of advancement or lag in the early months has little bearing on the ultimate level reached by school age.

The dizygotic twins in Fig. 1, E and F, show a greater divergence in trend during childhood, although the main directional shifts are much the same. The pair in Fig. 1H exemplifies those dizygotic twins that maintained quite similar trends throughout childhood, perhaps reflecting a high degree of genetic overlap and common experience.

Turning to the full sample, the basic question was whether monozygotic twins as a group were more concordant for mental development than dizygotic twins. However, we first investigated two other sets of variables that would influence the mental development scores and the resulting concordance estimates.

First, Fig. 1 shows that there was a considerable change in scores from age to age for some infants, and it appeared to be more pronounced at the earlier ages. On a sample-wide basis, the extent of this asynchrony in mental development would be revealed by the intercorrelations between test scores at all ages. The correlations were computed for the entire sample and are presented in Table 1.

The results show that the intercorrelations were rather modest in the first year, even for tests given only 3 months apart. But with increasing age, the predictive power steadily increased and the ordering of individual differences progressively stabilized, reaching $r = .86$ for the scores obtained at ages 5 and 6. Each child appeared to move at his or her own distinctive tempo, with age-linked episodes of acceleration and lag, until finally reaching a level that remained relatively stable.

On a sample-wide basis, the turn toward stabilization seemed to occur around 24 months: all subsequent correlations exceeded .60, whereas only three of the preceding correlations reached this level. The point was further clarified by a factor analysis which revealed a large general factor with loadings of 0.78 to 0.85 for every test from 18 months onward; and a second independent factor with substantial loadings around −0.55 for tests during the first year only. No other factor met the conventional criterion of significance (that is, an eigenvalue greater than 1.0). The pattern of correlations and the factor structure reinforced the earlier observations that some significant transition seems to take place around 24 months, in which cognitive functions begin to approximate the characteristics of school-age intelligence.

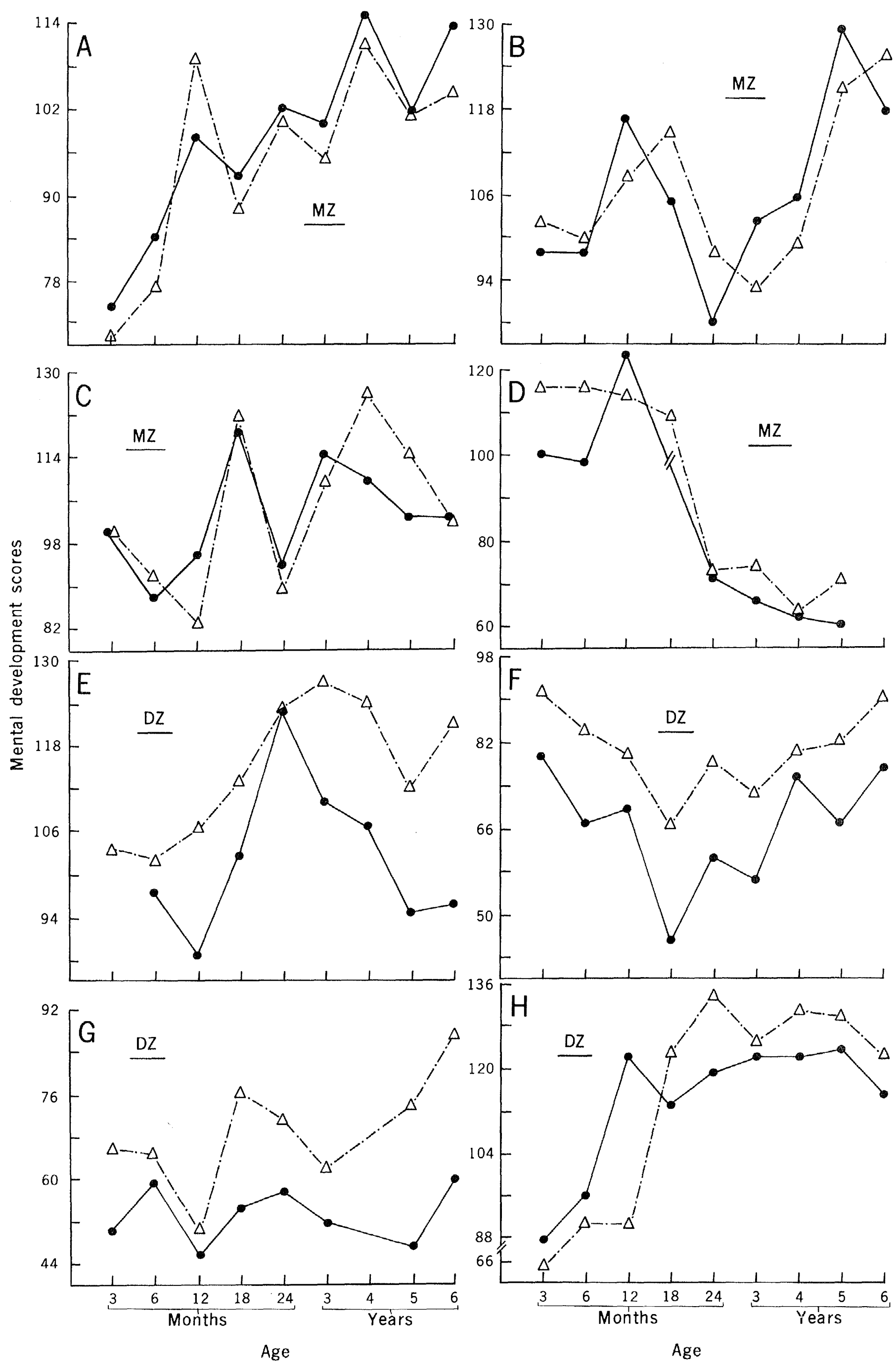

Fig. 1. Illustrative mental development curves for monozygotic (*MZ*) and dizygotic (*DZ*) twins.

Prematurity and Mental Development

The second variable expected to influence early mental development for this sample was prematurity, as calculated from birth weight and gestational age. Many twins fall below the singleton standards for term births, and consequently the measures of early developmental status may be depressed in proportion to the degree of prematurity.

The measures of birth weight and gestational age (completed weeks since menstruation) were correlated with the mental development scores at selected ages, and the results are shown in Table 2. The two indices of prematurity were strongly related to developmental status in the first 6 months of life and remained significant throughout the first year. By 24 months, however, the correlations regressed to a residual value accounting for less than 3 percent of the variance in the test scores, and this relationship remained consistent in subsequent years. Evidently, the effects of prematurity were most pronounced on the sensorimotor coordinations of infancy, but were of much less consequence for the capabilities measured at age 24 months and beyond. The declining influence of prematurity suggests a high degree of resilience and recovery potential for mental development in the face of prenatal deficit, and this prospect will be reconsidered at a later point when twins with large birth-weight differences are analyzed.

For comparison, two other variables

have been correlated with the twins' mental development scores, the first being socioeconomic status as rated from the father's occupation (*24*) and the second being mother's education as measured by the number of years of schooling completed. The results are also shown in Table 2.

Notably, neither of these parental variables correlated significantly with the twins' scores until 24 months, in contrast to the prematurity measures, but they subsequently became significant and remained stable to school age. The correlations presumably arose from cumulative home and environmental influences plus what McClearn describes as "developmental genetic processes that determine the increasing degree of resemblance of offspring and parent on intellectual measures during the first years of life" (*7*, p. 68). The substantial correlation between parents for educational level is worth noting also (r = .66), indicating a considerable degree of assortative mating on this variable.

Concordance in Mental Development

With these results in focus, let us return to the measure of concordance for monozygotic and dizygotic twins, anticipating that they may be initially influenced by prematurity and by individual asynchrony in the tempo of development. The intraclass correlations were computed for the twin pairs at each age (see Table 3). In the first half-year, the concordance values were comparable for monozygotic and dizygotic twins, and closely paralleled the correlations for birth weight (.62 and .67, respectively). But as the effects of prematurity waned, there was a gradual and progressive trend for the monozygotic correlations to become significantly larger than the dizygotic correlations.

By age 6 years the monozygotic correlation had reached R = .85, whereas the dizygotic correlation had receded to R = .63. Aside from some age-to-age fluctuations, the main trends were for monozygotic twins to become more concordant as the individual scores stabilized with age, and for dizygotic twins to become less concordant (*25*). The divergence among dizygotic twins came in the face of continued exposure to the same family environment, so there was a limited extent to which such common influences could compress the variability within dizygotic pairs.

The trends were even more sharply drawn by a comparison of within-pair variances, which depend on the score differences within pairs. The monozygotic score differences were substantially smaller (P < .001) than the dizygotic differences at most ages after the first year, and the range of monozygotic differences also narrowed over age. By way of illustration, the upper-range (90th centile) monozygotic difference score dropped from 22 to 11 by age 6 years, whereas for dizygotic twins the upper-range difference score did not drop below 20. In fact, the median difference score of 4 for monozygotic twins was no larger than the expected difference in test-retest scores for the same child over an 11-week interval.

Concordance for Tempo of Development

The curves in Fig. 1 indicated that some twins were changing in parallel over ages, with synchronized episodes of acceleration and lag. The question was whether monozygotic pairs were more concordant than dizygotic pairs for these synchronies in mental development.

The question was addressed by a repeated-measures analysis of variance that was specifically adapted for twin data (*26*). The analysis appraises both the overall elevation of the score profile and the age-to-age changes that determine the contour of the profile. It yields separate within-pair correlations for

Table 1. Intercorrelations between mental development scores obtained at successive ages. N per correlation ranges from 385 to 142; the median N = 262.

Age	Age									
	Months						Years			
	6	9	12	18	24	30	3	4	5	6
3 months	.57	.43	.44	.39	.24	.28	.26	.26	.37	.34
6 months		.58	.54	.46	.30	.31	.24	.16	.29	.31
9 months			.63	.44	.37	.38	.33	.25	.36	.34
12 months				.54	.47	.40	.36	.24	.43	.42
18 months					.67	.60	.57	.54	.56	.52
24 months						.70	.73	.72	.62	.61
30 months							.81	.72	.67	.70
3 years								.78	.71	.72
4 years									.80	.80
5 years										.86

Table 2. Correlations of twins' mental development scores with birth weight, gestational age, socioeconomic status, and mother's education. $N \leq 350$. Father's education correlates with mother's education, r = .66

Age	Birth weight	Gestational age	Socioeconomic status	Mother's education
3 months	.50	.48	.04	−.01
6 months	.48	.58	.08	.09
12 months	.30	.37	.02	.09
24 months	.14	.12	.29	.27
3 years	.09	.05	.35	.38
6 years	.18	.11	.36	.33

Table 3. Within-pair correlations for monozygotic (MZ) and dizygotic (DZ) twins on measures of mental development.

Age	Number of pairs (MZ/DZ)	Correlations		F-test of within-pair variances
		MZ	DZ	
3 months	73/86	.66	.66	1.58*
6 months	83/90	.74	.72	1.69*
9 months	75/71	.67	.52	2.13†
12 months	81/78	.67	.63	1.73*
18 months	90/100	.83†	.66	2.62‡
24 months	86/101	.80	.72	1.88†
30 months	71/82	.82*	.67	2.64‡
3 years	94/112	.87*	.79	2.24‡
4 years	87/94	.82	.76	1.47*
5 years	105/101	.82†	.66	2.31‡
6 years	117/107	.85‡	.63	3.45‡

For MZ pairs more concordant than DZ pairs: *$P \leq .05$; †$P \leq .01$; ‡$P \leq .001$.

each aspect of the score profile, and also a measure of within-pair variance for the composite trend.

In setting up the analysis, the test ages were grouped into three separate periods so that any shift in patterns of concordance would be evident. The first period included the tests given at 3, 6, 9, and 12 months, when prematurity effects would be pronounced; the second period included the tests at 12, 18, 24, and 36 months, which covered the previously noted transition phase in cognitive functions; and the third period included the tests from 3 through 6 years of age, where individual differences had stabilized and zygosity effects were more sharply drawn.

To preserve the maximum sample size, we included all twin pairs that had complete data for three of the four ages in each period (*27*). The within-pair correlations for overall level and profile contour are presented in Table 4. The results show that the monozygotic correlation for overall level became significantly higher than the dizygotic correlation in the second age period and reached R = .90 in the third period. By combining several tests, the errors of measurement were reduced and a more precise estimate was obtained of the twins' average status during the period.

The results also reveal significantly greater concordance for monozygotic twins in the profile of age-to-age changes, particularly in the second age period. These correlations reflect the degree of synchrony in spurts and lags and presumably arise from age-linked epigenetic processes shared by both twins.

The degree of congruence for both aspects jointly considered is expressed as the variance within pairs for developmental trend. The more closely the twins matched each other for the vector of scores over ages, the smaller the variance within pairs. The results (Table 4, last column) show that the monozygotic twins were significantly more concordant for developmental trend in the first year, and the match became increasingly closer in subsequent years. By contrast, the differences remained substantial in dizygotic pairs and became comparatively larger in relation to the monozygotic differences.

Concordance Among Siblings and Twins

As an adjunct to the research program with twins, other siblings from the same families have been brought in for testing as a matched control group. While the siblings share the same parental heritage and home environment as the twins, they have been raised as singletons and lack the distinctive prenatal and postnatal experiences that affect twins. Therefore, the contribution of these experiences to the mental development of twins may be assessed in relation to this matched control group.

The siblings in this sample were tested on a schedule which yielded age-matched tests for each twin-sibling set. For example, if a pair of 3-year-old twins had a sibling 5 years old, that sibling was given a WPPSI; and when the twins later reached 5 years of age, they were given

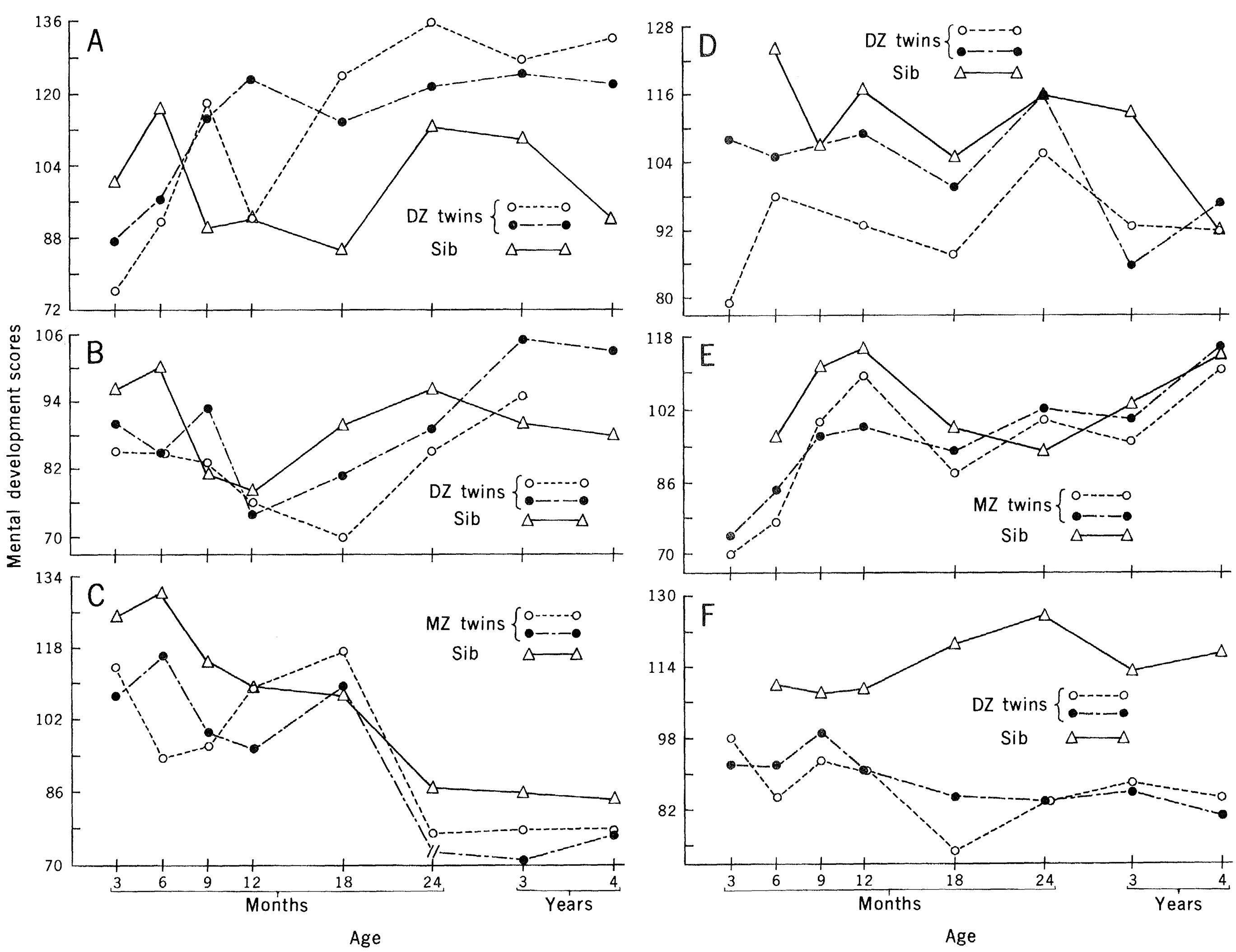

Fig. 2. Mental development curves for twins and younger siblings.

the same test and then compared with the sibling. Age and test matching are crucial procedures for such comparisons to avoid confounding variability from these sources with the actual differences between zygotes.

The intraclass twin-sibling correlations were computed by pairing the sibling first with twin A, then with twin B (designated alphabetically by first name). In most sets the siblings were earlier born than the twins, and the results are presented in Table 5 for those ages where sufficient sets were available to support the analysis.

The average concordance among age-matched twins and siblings moved from near .50 at age 3 years to .60 at age 6 years. This may be contrasted with the downward trend during the same period for dizygotic twins, as also shown in Table 5. The dizygotic twin correlation of .63 at age 6 years was not significantly higher than either of the 6-year twin-sibling correlations. Therefore, it would appear that as individual differences progressively stabilized by age 6 years, the concordance-enhancing experiences unique to twins gradually diminish in influence.

By contrast, these experiences that differentiated between twin and singleton—including prematurity, age, birth order, and parental treatment—may have been initially significant, but their effects did not seem to persist as a permanent and significant source of variance. The fact that the concordance values for dizygotic twins and twin-sibling sets moved toward a common level, which in turn was significantly below the monozygotic correlation, would seem to argue for a powerful age-linked epigenetic determination of mental development. The initial deficit of twins in relation to their siblings was almost fully recovered during this period as well.

Infant siblings. Another source of data is available that bears on the same issue. Whenever a younger sibling was born to one of the participating twin families, that sibling was recruited and tested on exactly the same schedule as the twins. Thus, a sample was created of younger-born siblings whose developmental course during infancy could be compared with that of the twins (see Fig. 2). In some instances, the infant sibling closely followed the trend of the twins, as in Fig. 2, C and E; in some instances the sibling matched one twin more closely than the other, as in Fig. 2D; and in some instances the sibling followed a quite different trend, as in Fig. 2F. The coherence and phasing of the curves is certainly suggestive of correlated devel-

Table 4. Concordance among twins for trends in mental development over ages. The age periods are first year, 3 to 12 months; second to third years, 12 months to 3 years; and fourth to sixth years, 3 to 6 years.

Age period	Zygosity	Number of pairs	Correlations for: Overall level	Correlations for: Age-to-age change	Within-pair variance for trend
First year	MZ	81	.84	.40†	60.6†
First year	DZ	84	.78	.15	112.1
Second to third years	MZ	74	.89†	.67‡	36.8‡
Second to third years	DZ	95	.79	.42	83.7
Fourth to sixth years	MZ	89	.90†	.47*	32.3‡
Fourth to sixth years	DZ	93	.75	.30	75.5

*For MZ pairs more concordant than DZ pairs: *$P \leq .05$; †$P \leq .01$; ‡$P \leq .001$.

Table 5. Concordance within twin-sibling sets for measures of mental development. Four-year correlations were affected by one extremely deviant sib; when omitted, correlations in parentheses were obtained.

Age (years)	Number of sets	Sib-twin A	Sib-twin B	DZ twins	Twin score deficit
3	57	.48	.51	.79	−5.9†
4	44	.44 (.51)	.44 (.55)	.76	−6.0†
5	61	.55	.64	.66	−3.9*
6	79	.57	.63	.63	−2.5

*$P \leq .05$. †$P \leq .01$.

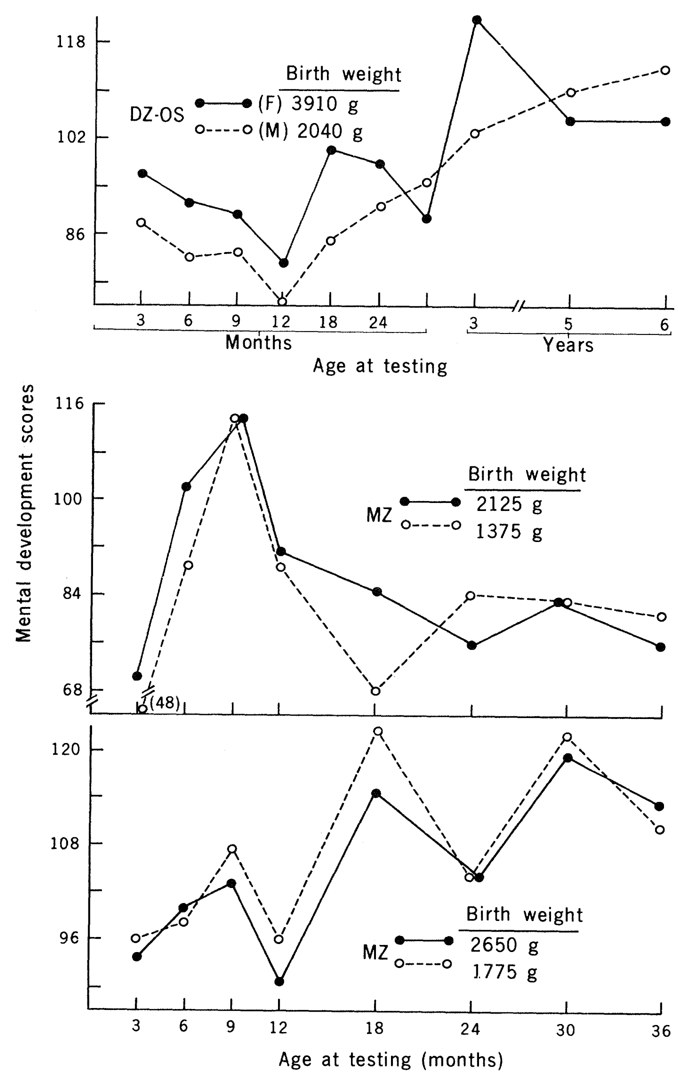

Fig. 3. Mental development curves for two monozygotic pairs of twins of unequal birth size, and the full 6-year data for a dizygotic opposite-sex (*OS*) pair with a birth weight difference of 1870 grams.

opmental trends among these twins and their siblings.

Recruits for the infant sibling sample become available only on an infrequent basis, perhaps understandable after the birth of twins, and consequently the sample size is not fully adequate for statistical analysis. However, for 19 sets of twins and infant siblings, the correlations ranged from .22 to .58 in the first 3 years, with the largest value being obtained for the test at 3 years. That value is consonant with the previous sibling results, and the correlation for twin-sibling congruence in trend over the first years was $R = .44$.

Canalization and Mental Development

These data lead back to an earlier premise from evolutionary theory, namely that a behavioral capability supported by epigenetic processes will be canalized. Canalization means that the behavioral capability will be sustained in the face of nonoptimum conditions or, if temporarily disrupted, restored toward its potential. By implication, the genetic blueprint provides backup capability in the event that the normal sequence of development is deflected, although its restorative power is affected by the stage of development and the compromising agent.

Twins enable one to assess the strength of canalization in mental development in relation to such deviant conditions as premature delivery and low birth weight. In particular, monozygotic twins of unequal birth size offer a rare sample of genetically matched test cases to appraise the extent of recovery from early deficit and subsequent convergence on a common developmental pathway.

To sharpen the comparison, we searched the twin sample for monozygotic pairs in which one twin weighed less than 2000 grams at birth, a frequent criterion for high risk, and the heavier co-twin weighed at least 750 grams more than the lighter twin. The IQ scores at 6 years were designated as the criterion measure of mental development, and the results for the ten available pairs showed an average deficit of only one point for the lightweight twin ($P > .50$). The within-pair correlation was .86, comparable to the full monozygotic sample at this age, and for only two pairs were the difference scores larger than five points.

These results were further amplified by examining the 3-year mental development curves for two monozygotic pairs of unequal birth size, and the full 6-year data for a dizygotic opposite-sex pair that exhibited the largest birth-weight difference in the sample. The curves are shown in Fig. 3.

In the opposite-sex pair, the lighter twin was initially below the heavier twin in developmental status but by six years had moved ahead. The lighter twin in one monozygotic pair was also depressed during the first 6 months, but subsequently recovered and thereafter displayed no systematic deficit. In the second pair, even the initial deficit was not evident for the lighter twin.

These data argue for a strong canalization of mental development, both as a species attribute and as a dimension of individual differences. For monozygotic twins, apparently the common genotype was able to reach through the inequalities of prenatal growth and align both twins along a common developmental pathway. From this perspective, the brain mechanisms underwriting mental development appear to display considerable resilience and recovery potential in the face of nonoptimum conditions, a conclusion also reached by Fujikura and Froehlich (*28*). One might speculate that natural selection has provided a substantial degree of buffering for such a crucial attribute against the recurrently faced hazards of prenatal malnutrition and early delivery (*29*).

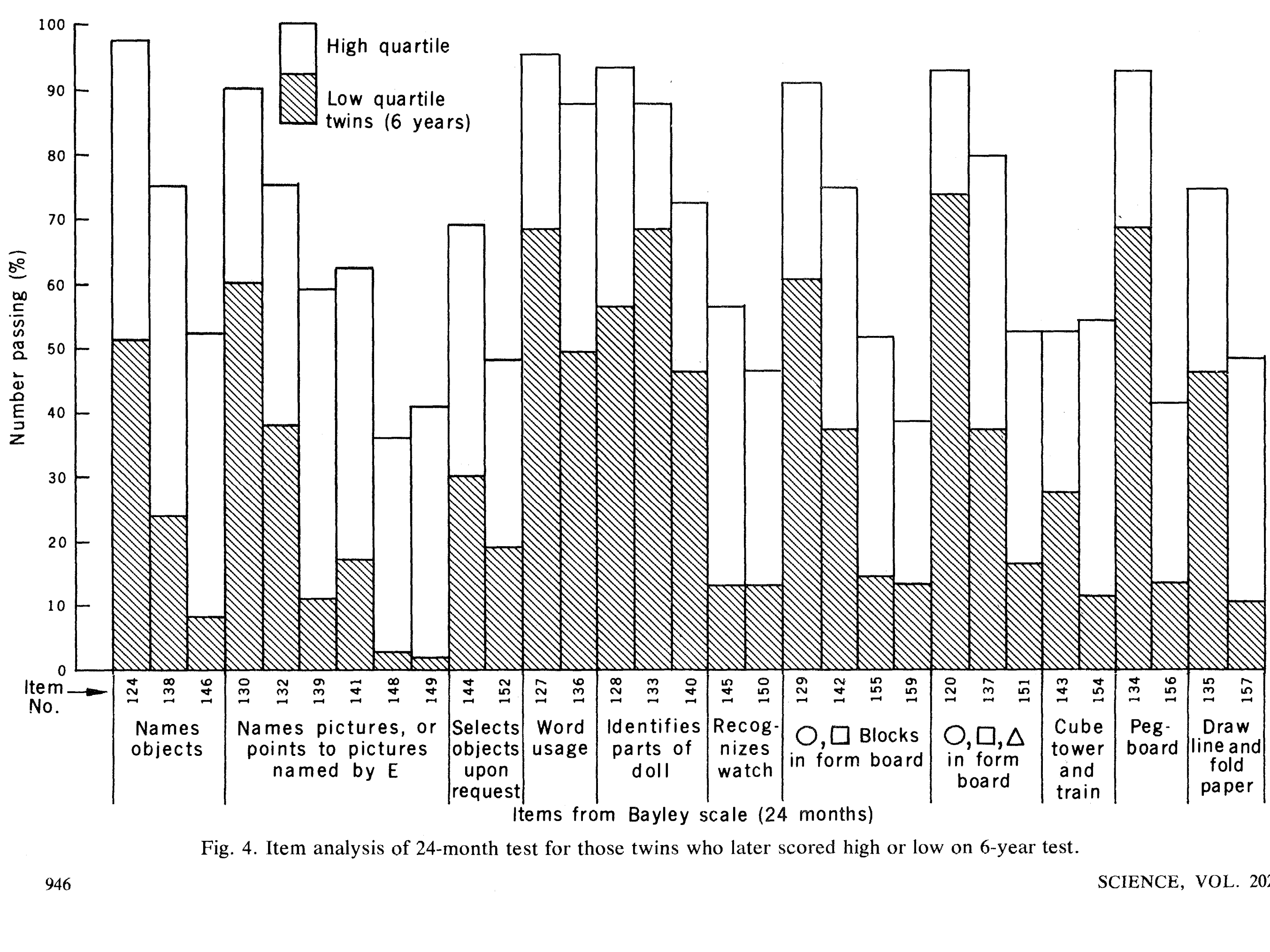

Fig. 4. Item analysis of 24-month test for those twins who later scored high or low on 6-year test.

Mental Development: The Foundation Processes

With this perspective on the synchronies in mental development and their origins in epigenetic processes, let us turn to a consideration of the actual cognitive functions engaged by the test procedures at each age. In particular, what functions become evident during the transition period around 24 months that relate to the later measures of intelligence at 6 years?

To investigate this question, we sorted the sample for all twins that had been tested at both ages ($N = 221$). The distribution of IQ scores at 6 years was separated into quartiles, then an item analysis was performed on the 24-month Bayley tests for the twins in each 6-year quartile group. The item analysis computed the percentage of twins passing each item administered at 24 months, and the data of primary interest are the pass percentages for the high and low quartile groups. Those items showing the maximum difference between groups represent the early predictors of school-age mental status, and thus seem to tap the emerging cognitive functions that become the foundation processes of intelligence.

The pass percentages for the maximum-differentiation items are shown in Fig. 4. The items have been grouped according to the use of common test materials or similarity in task demand, so that the functions tapped by each set of items may be inferred.

The first groups of items involve word knowledge—the correct association of word with object, the ability to vocalize the word, and the ability to comprehend the spoken word. These represent the emergent aspects of language, and the emphasis is less on articulation skills than on comprehending what the word stands for or represents.

The doll and watch items require a percept of an object as being composed of differentiated parts, each of which may be separately identified, but which nevertheless combine into a single entity. The items further require the subject's ability to identify the whole when certain parts are missing, a demonstration that the child's internalized image can make a compensatory adjustment for an incomplete model.

The form-board items require accurate spatial skills and a sensitivity to form differences, plus an awareness of the match between the block outline and the corresponding hole in the form board. The latter becomes crucial when the form board is reversed.

The final three groups of items involve not only psychomotor dexterity but, perhaps more importantly, sustained goal-oriented activities rather than a drift into egocentric play. The infant must retain the instructions in memory and must organize his production to match the examiner's model, with the necessary intermediate steps of comparison and adjustment (*30*).

Discussion. It is evident that infants differ significantly in how they respond to these task demands, and such differences are predictive of later intelligence. The cognitive functions which begin to consolidate around 24 months represent a more advanced mode of central processing than the earlier sensorimotor functions, and within this broad category some infants are more efficient than others.

The focus upon task demand and emergent cognitive functions brings attention back to Piaget's description of cognitive development. As argued elsewhere (*31*), both Bayley and Piaget appear to focus on the same fundamental aspects of early mental development, although their approaches are quite different.

Piaget in particular calls attention to the increasing prominence of symbolization during the 18- to 24-month period, which enables the child to organize and call up memories of past experience in response to such symbols as words or images.

Further, internalized memories play an increasingly important role in the child's construction of time and space, bringing to bear the recollection of past events with the anticipation of future ones. Such recollections gradually create a sense of what is constant and what is permanent among the attributes of the physical world. It makes available an internal monitor for appraisal of current perceptions and prediction of likely outcomes.

Symbolization and brain maturation. The elaboration of this internalized world of reality is perhaps the most significant advance of the 18- to 24-month period. It might be inferred that the transition is jointly determined by the slower maturation rate of the phylogenetically newer areas of the cortex—the association areas—plus the effects of cumulative experience. The association areas make available the massive storage and retrieval facilities in which experience is registered and linked to the memories of prior experience. As these areas become functional through maturation, cognitive functions turn more toward the symbolizing and synthesizing functions that figure so prominently in the growth of intelligence.

And while this is occurring as a main effect for the species, it is also being actualized as a dimension of individual differences. The efficiency and scope of these symbolizing functions become a predictable attribute of each individual's mental status, and the variations in efficiency become translated into the normal distribution of intelligence. Such variations must ultimately have their roots in epigenetic processes that determine the integrative power of the brain. Within the normal range of environments, these processes unfold in accordance with the intrinsic scheduling of the genetic program, and it is at this level that the synchronies in mental development may be found.

Does this suggest that the quality of the home environment is unimportant? Not at all. To quote an earlier conclusion (*19*, p. 326):

> The contribution of the parents is in potentiating the child's inherent capabilities, in creating an atmosphere of enthusiasm for learning, and in adapting their expectations to the child's capability. The wide diversity within families emphasizes the importance of giving each child full opportunity for development, and indeed of making sure that the opportunity is taken. The ultimate goal is the maximum realization of each child's intelligence, coupled with a sense of satisfaction and personal accomplishment in its use. There is no better way to foster such development than by a supportive and appropriately stimulating family environment.

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27. The complete form of the analysis permits no missing data for either twin at any age, or else the pair is excluded. Since this requirement would effectively exclude nearly half the pairs from the repeated-measures analysis, even though only one test might be missing because of illness or a missed visit, some adjustment was needed. Most of the pairs had three complete tests within any given age period (for example, 3, 6, and 12 months, or 6, 9, and 12 months), and the scores were rearranged to align the three scores available for all subjects. If four scores were available, the first one was excluded and the remaining three were selected. The realignment preserves intact the data of central interest—the extent of overall concordance and parallel change for each pair during the period—but it forfeits the test of ages as a main effect. This is of no consequence, however, since the age means are already equalized by the standardization process.
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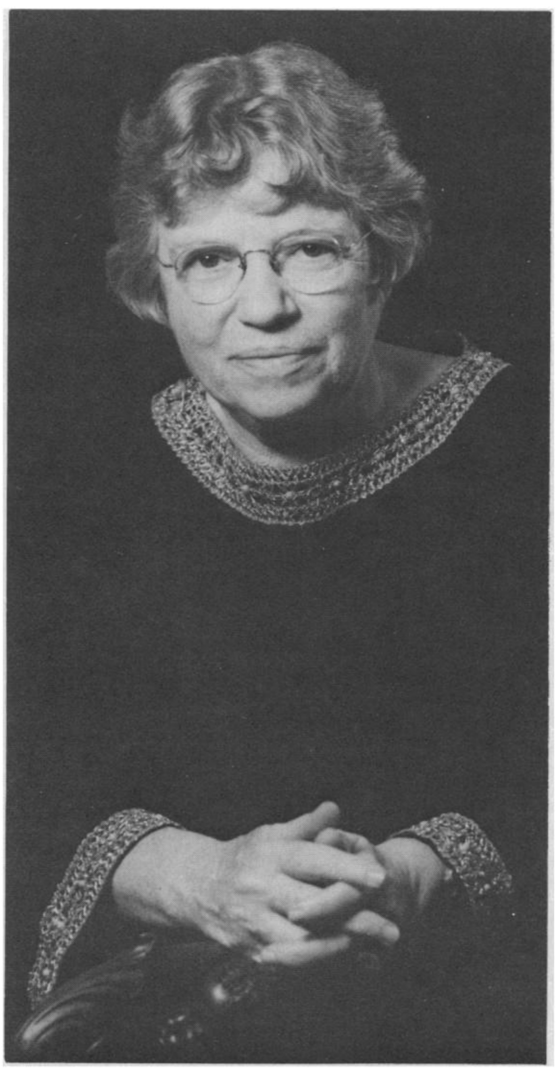
32. This research was supported in part by PHS grants MH 23884, HD 03217, and HD 07200; by NSF grants GB 35578 and BNS 17315; by OCD research grant 90-C-922; and by the Grant Foundation, Inc. I thank A. Matheny, A. Dolan, M. Hinkle, M. Gliessner, B. Slaven, E. Harpring, M. Moseson, J. Parker, H. Dallum, S. Bateman, S. Nuss, and P. Litwin for major contributions to the program.



Margaret Mead
1901-1978

Margaret Mead, world-renowned anthropologist and author, died Wednesday, 15 November 1978, in New York City. News of Margaret Mead's death reached the AAAS Board of Directors during their visit to the People's Republic of China. Dr. Mead was elected president of AAAS in 1973 and retired as Board Chairman in 1976.

In Peking, current Board Chairman Emilio Q. Daddario said, "Margaret Mead's death is hard to accept. She was marvelously vital, filled with a love of action, and tireless in her efforts to create a human science. She touched countless lives and especially the young. There is sadness today in the great cities of the world, and in the faraway villages whose transitions she followed for 50 years and to which she gave her mind and her heart."