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Twins, Families, and the Psychology of Individual Differences: The Legacy of Steven G. Vandenberg

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To honor the retirement of Steven G. Vandenberg, his contributions to multivariate behavioral genetics are reviewed. During Professor Vandenberg's prolific career, he made substantial contributions to three general areas: twin research, family studies, and research on individual differences. In the area of twin research, two large-scale studies, the Hereditary Abilities Study and the Louisville Twin Study, are reviewed. His contributions to the analysis of twin data, with particular reference to the canonical generalization of Bartlett's F *ratio, are also noted. In the area of family studies, Professor Vandenberg was principal or co-principal investigator of the Boulder Family Study, the Hawaii Family Study of Cognition, the Colorado Adoption Project, and a twin-family study of smoking behavior; his papers on ethnic comparisons, assortative marriage, and kinship analyses are reviewed. In his research on individual differences, Professor Vandenberg conducted studies of the cross-ethnic factorial invariance of primary mental abilities in Chinese and South American students and took an early interest in automated methods for factor analysis. Over the course of his career, Professor Vandenberg has made a variety of tangible and intangible contributions to behavioral genetics, and his personal humility and scientific outlook have provided an important role model for his colleagues and students.*

KEY WORDS: twin studies; family studies; individual differences; multivariate analysis; cognitive abilities.

INTRODUCTION

I want to make it clear that I am, by profession, not a mathematical statistician, but a lawyer turned psychologist with an interest in biological correlates of behavior

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> and especially interested in hereditary factors in human behavior. (Vandenberg, 1966a, p. 526)

Steven G. Vandenberg's career as a psychologist and behavioral geneticist has spanned more than three decades. Now, in honor of his retirement as Professor of Psychology at the University of Colorado, I attempt to review some of his many scientific contributions to multivariate behavioral genetics. It is fitting that this tribute appears in *Behavior Genetics* because Professor Vandenberg played a significant role in founding this journal and served as its first editor with John DeFries. Their hopes for the journal as a medium of exchange among behavior geneticists clearly summarize Professor Vandenberg's ideals as a scientist and researcher:

> In our view, behavior genetics is simply the intersection between genetics and the behavioral sciences. We are particularly interested in the role of heredity as it has affected the past, is affecting the present, and will affect the future of mankind. . . . It is most clear from recent events that the misunderstandings inherent in the old nature-nurture controversy are not dead and buried, but alive and well. In fact, this topic seems to generate today as much emotional reaction with as little information as in the past. Perhaps when appreciation of the substantive and methodological information of behavior genetics becomes more widespread, people will be able to cope more effectively with such issues. (Vandenberg and DeFries, 1970, pp. 1–2)

In many respects this review was a far more difficult task than I first envisioned. Professor Vandenberg's far-ranging interests and his multidisciplinary approach to research in multivariate, developmental behavioral genetics make a simple summary of his work nearly impossible. What makes this review even more difficult is that he did not constrain himself to examining one particular phenotypic model. He examined phenotypes derived from nearly every physical and behavioral system in the human body. Over the past three decades, Professor Vandenberg has published over 170 papers on topics ranging from physical growth measures to personality inventories and, of course, cognitive abilities. Although Professor Vandenberg is most widely recognized in the area of twin research, he has also made important contributions to other areas by promoting the consideration of individual differences in social perception, vocational preference, aggressive tendencies, personality development, and anthropometric measures.

The products of the wide variety of his interests have generally fallen into one of three areas: twin research, family studies, and research on individual differences. Many of us were first introduced to Professor Vandenberg's research through the published results of his twin studies, and those must be the logical starting point for a review of his work.

TWIN RESEARCH

The Hereditary Abilities Study, University of Michigan

The Hereditary Abilities Study, Professor Vandenberg's first large-scale twin analysis, probably marks the beginning of the contemporary era of such studies. Clearly, this study was not the first to use twins. By 1956, when the results of this study were first published in *Eugenics Quarterly*, a wide variety of twin studies had already been performed. What marked the initiation of contemporary methods was the use of standardized measures of anthropometric characteristics, perception, personality, and cognitive abilities combined with serological, dermatoglyphic, and craniometric X-ray evidence for zygosity diagnosis. Although other studies may have collected more twin pairs, none collected a greater variety of data, and none since the earlier study by Newman *et al.* (1937) combined as many interdisciplinary interests. In many respects, these preliminary results (Vandenberg, 1956) presage many issues and research topics which are still of interest:

> It may be asked if all of these measures are separately controlled by heredity. It may be that some of them are highly correlated, so that we are repeatedly measuring the same underlying traits [and] the effect of the environmental influences might well be to attenuate and obscure correlations due to genetic interrelationships. . . . [Concerning] the various theories about the nature and organization of human intelligence, [some] hold that it is most profitable to regard intelligence as a general capacity [while others feel] that specific abilities like verbal ability, spatial visualization, or reasoning ability are much more concrete entities. A comparison of heritability estimates of these special abilities with heritability estimates of general intelligence will be of great help to ascertain the relative merits of these competing theories. It is a long-standing tradition in psychology to regard intelligence and personality as two separate aspects of an individual which at most exert some slight influence on one another. . . . It may be that the distinction reflects in part a philosophical tradition rather than empirical facts. (Vandenberg, 1956, pp. 97–99)

The Hereditary Abilities Study yielded a number of papers. In 1961, Professor Vandenberg examined the relationships among some of the psychological tests, intrapair birth order, and anthropometric measures (Vandenberg *et al.*, 1961). In the following year, he used these data in support of Lyon's hypothesis (Vandenberg *et al.*, 1962b) and published the details of the sample selection and zygosity diagnosis, including the raw serological and background data (Sutton *et al.*, 1962).

The battery of psychological tests used in the Hereditary Abilities Study was comprised of 117 separate tests representing five general areas of interest: cognitive abilities (35 variables), motor skills (14 variables), perceptual skills (17 variables), sensory and musical aptitude (24 variables), and personality (28 variables). Data were collected from 82 pairs of like-sexed twins, 45 pairs of monozygous (MZ) twins, and 37 pairs of

dizygous (DZ) twins. Vandenberg (1962a) reports the heritability estimates for all of these tests. Eleven of the 17 subtests of the Primary Mental Abilities test battery had significant heritabilities. Of Thurstone's six primary abilities (number, verbal, spatial, word fluency, reasoning, and memory), significant subtest heritabilities were found in all areas except for memory. When the subtests were combined into separate measures of each primary ability, significant heritabilities were found for the number, verbal, spatial, and word fluency abilities.

Of the remaining 18 tests of cognitive abilities, 7 had significant heritabilities; 7 of the 17 tests of perceptual skill (tests representative of Thurstone's "closure" factor) had significant heritabilities; and 6 of the 14 tests of motor skill had significant heritabilities. Two personality inventories were administered, the Thurstone Temperament Schedule (7 scales) and the Cattell Junior Personality Quiz (12 scales). Seven of the 17 personality scales had significant heritabilities: Factors A, B, C, and F (Active, Vigorous, Impulsive, and Sociable) from the Thurstone Temperament Schedule and Factors B, C, and D from the Cattell Junior Personality Quiz (Nervous Tension, Neuroticism, and Will Control).

During this period, Professor Vandenberg also wrote extensively on the heritability of various anthropometric measures and their consistency in different studies. For example, in Vandenberg (1961) he summarized the heritability F ratios for 31 anthropometric and 16 cranial measures from six twin studies and noted the high degree of agreement among the different studies. In 1962, he published a more extensive discussion of these data (Vandenberg, 1962b), which were summarized in a biological handbook on growth (Vandenberg, 1962c). These papers cite yet another paper that did not appear until 1964 (Vandenberg and Strandskov, 1964) in which the anthropometric measurements of the twins collected by Thurstone and Strandskov were analyzed.

At first glance it may appear somewhat unusual for a psychologist who is interested primarily in cognitive abilities and personality disposition to be acting in the role of a physical anthropologist. However, it is quite sensible taken in context. Physical measurements are reliable and are thus useful for examining whether heritability estimates are stable under varying conditions and at different periods during the life span, particularly childhood. Perhaps most significantly, these studies pointed to the lack of a consistently planned investigation of the connection between growth and heredity in humans.

The Louisville Twin Study, University of Louisville

The Louisville Twin Study filled this need. Although Professor Vandenberg did not join this study until 1960, 3 years after its initiation, he

served as its director until 1967. As Vandenberg *et al.* (1968) noted, the Louisville Twin Study was the first twin study designed specifically with planned replications. Moreover, it was the first study of the influence of heredity on rates of growth and age-related behavioral changes. As initially proposed in 1957, the study was designed to exploit methodological progress in zygosity diagnosis such as those methods already used in the Hereditary Abilities Study and multivariate statistical advances such as those applied by Professor Vandenberg in several of his earlier papers.

The combination of Professor Vandenberg's multivariate sophistication and a rich source of longitudinal data on twins was indeed profitable. A number of papers were published using the Louisville data. Vandenberg and Falkner (1965) presented results for the growth measures on 60 pairs of twins (29 MZ, 31 same-sex DZ) with at least six repeated measurements (first at 1 month, then at 3, 6, 9, 12, 18, and 24 months, and every year thereafter). They showed that a polynomial regression on height with a linear and quadratic term for age (birth through 4 years of age) satisfactorily fit these data. Moreover, hereditary influences were found for both the linear and the quadratic terms (rate and acceleration) but not for the constant term (initial status).

Brown *et al.* (1967) examined behavioral differences in a sample of 140 pairs of Louisville twins and found that the putative relationship between birth weight and birth order was not replicated in their community-based sample; they also reported larger behavioral differences between fraternal twins than between identical twins. Vandenberg (1967a) reported further results for the cognitive battery and found considerable similarity with his earlier study of Michigan twins. Shipe *et al.* (1968) showed that low neonatal Apgar ratings were unrelated to subsequent cognitive test results or to personality scale scores. Bock *et al.* (1970) examined the relationship between blood types and Wechsler Adult Intelligence Scale (WAIS) scores among adolescent twins from the Louisville study and found evidence for a possible linkage between a major gene for verbal ability and the *Rh* locus.

Multivariate Analysis

An important methodological contribution which Professor Vandenberg nurtured through both the Michigan and the Louisville studies, with occasional digressions using other sets of data, was the relationship of results within and between studies using multivariate analysis. Early on, Professor Vandenberg recognized that results from hundreds of separate psychological tests were not necessarily independent and that to present them as such could be quite misleading. Consequently, he turned to mul-

tivariate analyses as a method for summarizing these results and as a method for summarizing the lack of independence among the measures.

The development of methods for examining multivariate data in the context of behavioral genetic studies is found in two edited collections of papers, *Methods and Goals in Human Behavior Genetics* (Vandenberg, 1965a) and *Progress in Human Behavior Genetics* (Vandenberg, 1968a). The former contains one of the first complete descriptions of the problem and its solution using data from the Michigan study (Vandenberg, 1965b). The latter collection contains 18 papers, of which 6 directly concern statistical methods and 4 concern twin studies. Professor Vandenberg authored or coauthored 4 of these papers (Bock and Vandenberg, 1968; Loehlin and Vandenberg, 1968; Vandenberg and Johnson, 1968; Vandenberg *et al.*, 1968). Many of the ideas published in these papers had their genesis in a variety of earlier papers, some of which have been cited already (Vandenberg, 1964, 1966a,b, 1967a, 1968b,c; Vandenberg and Strandskov, 1964).

The gist of the method for connecting results within studies is a multivariate generalization of Bartlett's F ratio for testing the difference between two variances. In the extension to canonical form, univariate MZ and DZ within-pair variances are replaced by within-pair covariance matrices, and linear combinations of variables which best discriminate MZ twins from DZ twins are sought. This kind of multivariate partitioning also led to estimates of separate genetic and environmental covariance matrices, as well as their comparisons.

Methods for comparing results between studies were quite limited and usually consisted of examining the similarities between factor pattern matrices. Professor Vandenberg was among the first to adopt Tucker's "phi" coefficient as a way for comparing two factor solutions. In his search for these methods, he also discovered techniques for rotating factor matrices to congruence as a way to judge factorial invariance. Although some of these methods have been surpassed by direct tests for invariance, his early interest demonstrated the demand for this capability.

FAMILY STUDIES

In 1967, Professor Vandenberg accepted a position at the University of Colorado as Professor of Psychology and Fellow of the Institute for Behavioral Genetics. Although his interest in twins was undiminished, his relocation coincided with a change in focus toward family studies. He was involved in two parallel family studies, both of which used the same battery of cognitive tests. In addition, he became a coinvestigator of the Colorado Adoption Project (DeFries *et al.*, 1981) and of a study of smoking behavior that employed a complicated twin-family sampling design.

In the first family study, the Hawaii Family Study of Cognition, he was one coinvestigator among eight in a cooperative venture between the Institute for Behavioral Genetics in Colorado and the Behavioral Biology Laboratory in Hawaii. In the second, the Boulder Family Study, he was the principal investigator. The primary purpose of the Hawaii study was to compare the familialities (familial resemblances due to genetic or environmental influences) of cognitive abilities among families with different ethnic backgrounds. Several different ethnic groups were sampled, the two largest of which were Americans of European ancestry (AEA) and Americans of Japanese ancestry (AJA). In addition to collecting a sample from the mainland, the primary goal of the Boulder study was to gather data on specific parental child-rearing attitudes and behaviors, as well as more detailed information regarding assortative marriage.

The Colorado Adoption Project, begun in 1975, is a longitudinal, prospective adoption study consisting of over 200 adoptive families and matched nonadoptive families. The goal of this continuing study is to assess genetic and environmental influences on individual differences in behavioral development. Analyses of adult data indicate that selective placement is minimal and that the biological, adoptive, and nonadoptive parents are highly similar with regard to various demographic variables, test reliabilities, factor structures, and mate correlations (DeFries *et al.*, 1981). A detailed description of this landmark study and analyses of the infant data have recently been published by Plomin and DeFries (1985).

The study of smoking behavior (Crumpacker *et al.*, 1979) consisted of two parts. The first was a nongenetic pilot study of the Denver metropolitan area in which the questionnaires were validated; this study also collected spouse data that were used in analyses of assortative mating. The second and main part of the study consisted of a twin-family study using the Swedish twin registry as the basis for identifying twins living in southern and central Sweden. In addition to collecting data on smoking, this study also measured a variety of personality, cognitive, medical, and environmental variables. Chief among these measures were the Comrey Personality Scales, the Eysenck Personality Questionnaire, and Raven's Progressive Matrices test.

These studies yielded papers in three broadly defined, but not mutually exclusive areas: ethnic comparisons, assortative marriage, and kinship analyses.

Ethnic Comparisons

DeFries *et al.* (1974) presented the results of separate factor analyses of the battery of 15 cognitive tests for AEAs and AJAs from the Hawaii Family Study. Separate components analyses followed by Varimax ro-

tation yielded nearly identical factor loadings. Four factors were interpreted: Verbal Ability, Spatial Visualization, Perceptual Speed and Accuracy, and Visual Memory. Coefficients of congruence between the two factor matrices were all greater than 0.96, indicating an essentially identical structure of intellect in the two ethnic groups.

Assortative Marriage

Accounting for the extent of assortative marriage (spouse resemblances) and assortative mating (genetic correlations between spouses) is important in estimating parent–offspring resemblances. Professor Vandenberg provided a review of this topic in 1972. In that review, he discussed two reasons why assortative mating should be considered in the analysis of data from family studies. The first concerns specific genetic consequences; the second, marital adjustment, which influences the social climate of the marriage.

Subsequently, he coauthored several papers which presented empirical evidence for assortative marriage in several different ethnic groups. Johnson *et al.* (1976a) presented spouse correlations for 555 AEA couples and 148 AJA couples, Johnson *et al.* (1976b) presented spouse correlations for 209 Korean couples, and Zonderman *et al.* (1977) presented spouse correlations for 123 AEA couples from the Boulder Family Study.

In addition, Price and Vandenberg (1979) presented spouse correlations for physical attractiveness for 72 couples from the Hawaii and 55 couples from the Boulder Family Study. They found that assortment for physical attractiveness was largely independent of age and was of a moderate magnitude (0.25 in Hawaii, 0.39 in Boulder). Price and Vandenberg (1980) also presented spouse correlations for physical, social, and behavioral measures in two samples from the United States and Sweden. They found considerable similarities between these samples in the extent of spouse correlations and provided preliminary evidence that the resemblance between spouses is due to initial assortment, not phenotypic convergence over time.

Kinship Analyses

One of the first papers on parent–offspring resemblance for cognitive abilities in the Hawaii Family Study appeared in 1976 (DeFries *et al.*, 1976). This paper presented midchild on midparent regressions (upper-bound estimates of heritability) as well as single-parent, single-child correlations (as a check for possible sex linkage). Among AEA families, their results showed moderately high regression coefficients for verbal and

spatial abilities (approximately 0.6) and somewhat smaller regression coefficients for memory and perceptual speed (approximately 0.4). They found no evidence for a sex-linked pattern of correlations between parents and offspring for any of the cognitive abilities.

Park *et al.* (1978) administered the same battery of cognitive tests to Korean families and found considerably larger parent–offspring regressions than those found in the Hawaiian AEA and AJA families. They attributed the greater parent–offspring resemblance in Korea to differences in test administration procedures (the family's home in Korea vs. group administration in Hawaii) and to larger genetic variability due to assortative mating. In their sample of Korean families, Park *et al.* replicated earlier findings of the absence of a sex-linked, recessive pattern of parent–child correlations.

DeFries *et al.* (1979a) presented parent–offspring regressions for the complete Hawaii data set and replicated their earlier findings based on only a partial data set. In particular, the results supported earlier evidence for differential heritability among their tests of cognitive ability. They also presented a more rigorous test for the presence of sex linkage. Using a hierarchical multiple regression, they found no evidence for sex linkage in any of their spatial tests.

Ashton *et al.* (1979) provided evidence for an autosomal dominant gene which accounted for approximately one-third of the phenotypic variance in the Hidden Patterns Test and Raven's Progressive Matrices, and for a sex-limited autosomal dominant gene which accounted for approximately one-half of the phenotypic variance in the Mental Rotations test. DeFries *et al.* (1979b) presented genetic and environmental correlations among the 15 cognitive tests for AEA families in the Hawaii study and replicated findings from animal studies regarding the congruence between genetic and environmental factors.

Spuhler and Vandenberg (1980) presented parent–offspring resemblances from the Boulder Family Study and compared their results to four studies which used the same or similar cognitive tests. They concluded that although these studies provided strong evidence for the heritability of specific cognitive abilities, they precluded a definitive conclusion about their differential heritability.

Price *et al.* (1982) presented the results of a random-effects linear model applied to the personality data collected in the Swedish twin-family study. Using a sophisticated path analytic procedure, they failed to find evidence for a simple additive mode of transmission for normal personality traits. Their results provided evidence for a moderate nonadditive genetic effect as well as a significant effect due to environmental sources of variance, particularly influences outside the home.

INDIVIDUAL DIFFERENCES

The study of individual differences is, of course, a generic interest for most behavioral geneticists. Professor Vandenberg performed several explicit methodological and substantive studies focusing exclusively on the nature and extent of variability in measures of personality and cognitive abilities. The paper by Vandenberg and Sutton (1953), Professor Vandenberg's first publication, was on variation in human urinary excretion patterns. Individual differences were also the focus of several subsequent publications (Vandenberg, 1959a,b, 1960a). Perhaps the most important of these papers (Vandenberg, 1959b) concerned the primary mental abilities of Chinese students. In this study Professor Vandenberg performed a multiple-groups factor analysis on 20 of Thurstone's 57 tests. A tetrachoric correlation matrix was computed by hand using the relative weights of two stacks of scoring cards as the basis for group percentages. Following factor analysis, orthogonalization, and rotation, these factors were compared to Thurstone's factors using a method for rotation to maximal congruence. Considerable resemblance between the two samples was found for five factors: Spatial, Verbal, Number, Memory, and Perceptual Speed.

These early papers clearly reveal Professor Vandenberg's interest in and proficiency with multivariate methods. He published a number of other papers in which factor analysis was the highlighted method. Not surprisingly, Professor Vandenberg was also interested in the techniques for automated analyses, and he published several papers on the use of computers in psychology and medicine (Vandenberg, 1960b, 1965c; Vandenberg *et al.*, 1962a).

Professor Vandenberg's interest in the cross-cultural generality of findings from factor analytic studies also yielded a study of the structure of cognitive abilities in South American students (Vandenberg, 1967b). The results revealed considerable similarity between the factors in Chinese and the factors in South American students, suggesting that these factors are invariant across cultures. Another study (Vandenberg, 1968d) demonstrated the factorial invariance of garment measures in American and Dutch women.

PARTING TRIBUTE

Professor Vandenberg's career is a difficult one to summarize in a single sentence or even in a single paragraph. Some of his accomplishments, although tangibly available in print, are omitted from this review for reasons of brevity. Over the course of his career he received international recognition and, most recently, was elected president of the Be-

havior Genetics Association. Other of his accomplishments have been intangible and have had more to do with his personal style and temperament. As a teacher and advisor, he is widely respected as an incomparable source of open-minded advice and good leads into difficult topics. As a colleague and fellow researcher, he is an invaluable source of useful techniques and insights. As a friend, he is a warm and good-natured individual, well read in several languages on nearly every classical and contemporary subject.

Over the past several decades, Professor Vandenberg has made several profound contributions to behavioral genetics. His prolific output of published papers has significantly influenced the way in which we study the connection between heredity and behavior. Perhaps his most important contribution was through the introduction and pursuit of multivariate methods. However, he also strongly influenced the way in which we think of the relationships among cognitive abilities and the manner in which they are developed, utilized, and transmitted. An equally important contribution has been his emphasis on the connection between cognitive abilities and other phenotypes, including, for example, handedness, vocational preference, and personality.

Perhaps the best way to summarize his personal humility and his scientific outlook is to let him speak for himself:

> [There are] *stages* or degrees of knowledge about hereditary mechanisms in man. . . . In the most advanced stage, we would have knowledge about a condition due to one gene located in a known region on a given chromosome; in general, human genetics has not reached this state yet. . . . The next best stage of knowledge is one in which the gene can be assigned to a specific chromosome although not to a definite location on it. . . . A stage of yet less exact knowledge is where we can only distinguish between autosomal and sex-linked traits. . . . Then we might distinguish situations where more than one gene is involved. If it turns out that there are only two or three genes, pedigree studies might still be useful, and we can try to build various models for combinations of genes and test how well such models fit actual data. . . . Finally we may have conditions controlled by many genes. Here we have to revert to the methods of biometrical genetics: analysis of variance, regression analysis, path coefficients, and heritability estimates and this is where twin studies come in. . . . My own background and temperament has led me to choose problems near the bottom of this list rather than near the top and this is dictated in part by previous work I have done, some familiarity with statistical techniques, and other things in my personal history, but in no way reflects a value judgment about what is more important. (Vandenberg, 1965a, pp. 29–31)

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