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Substantial Genetic Influence on Cognitive Abilities in Twins 80 or More Years Old
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hibiting the nepovirus recovery phenotype and was not a general property of virus-infected tissue.

Through this analysis of nepovirus-induced recovery, we have demonstrated that a natural virus-induced effect and transgene-induced gene silencing are similar. Both phenomena are potentially virus-inducible and are associated with strain-specific virus resistance that is targeted against RNA. On the basis of these similarities, we propose that the same RNA-based mechanism underlies both phenomena. Gene silencing may occur when the plant erroneously perceives a transgene or its RNA product to be part of a virus. Transgene-induced gene silencing is normally displayed by only a small proportion of lines produced with any one construct (6, 13). It may be possible to increase the incidence of gene silencing by ensuring that transgene transcripts have features, such as double-strandedness, that resemble replicative forms of viral RNA. Conversely, if it is necessary to evade gene silencing to achieve very high levels of transgene expression, it may be appropriate to produce transgenes specifying transcripts in which features resembling viral RNA are removed.

Why do nepoviruses and members of a few other virus groups elicit such pronounced recovery? One explanation, at least for nepoviruses, may follow from an earlier suggestion that there is an association between recovery and the potential of the virus to be transmitted through the seed of the infected plant (14). Normally, transmission through seed does not take place because viruses are excluded from the meristem and surrounding area of the plant in which gametes are produced. When seed transmission does take place, it is probably because this exclusion from the meristem has been overcome. Perhaps recovery is initiated when the nepovirus penetrates the meristem. This possible association of meristems, nepoviral recovery, and gene silencing suggests that there may be an increased likelihood of gene silencing when transgenes are expressed in meristems.

Recovery is not the only resistance phenomenon in plants that is specifically targeted against the inducing virus and close relatives. "Green islands" and mosaics that are induced by non–seed transmitted viruses are examples of localized areas of virus-specific resistance in infected plants (15). The relatedness of these other resistance responses and nepoviral recovery could indicate that gene silencing is a manifestation of a ubiquitous defense in plants against viruses.

Note added in proof: A recent report (21) also describes a recovery phenomenon in virus-infected plants that has similarity to gene silencing.

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16. The primary inoculations were to 4-week-old seedlings maintained in a glasshouse under added artificial illumination at a temperature between 20° and 25°C.
17. Cultures of tomato black ring nepovirus and of tomato ringspot nepovirus (Wisconsin strain) were obtained from the Scottish Crop Research Institute, Dundee, UK. They were propagated by inoculation to *Nicotiana* sp. The crude sap of infected plants was used as inoculum for these viruses. PVX inocula consisted of sap of plants infected with in vitro transcripts of a full-length cDNA clone (pTXS) (11).
18. The probe for PVX was ^{32}P-labeled cDNA from the 3′ terminal 1.5 kb of the PVX genome. For tomato black ring nepovirus strains W22 and BUK, the probes were ^{32}P-labeled polymerase chain reaction (PCR)–amplified cDNAs. The primers for PCR amplification of these probes were from nucleotides 1470 to 1498 and 2625 to 2650 of the RNA2 of W22 that are conserved in both strains (9). The probe for tomato ringspot nepovirus was ^{32}P-labeled cDNA produced by oligo dT–primed reverse transcription of purified tomato ringspot viral RNA. RNA isolation and Northern analysis were done as described previously (11). The Northern analysis images were generated on a Fuji BAS1000 phosphorimager.
19. The construct pPVX.W22 was obtained by transfer of a cDNA fragment of W22 into the Eco RV site of PVX vector cDNA in pP2C2S (11). This cDNA fragment was obtained by PCR amplification of W22 RNA1 between nucleotide positions 4431 and 5409 of the sequence of RNA1 (9).
20. PVX.GFP and PVX.W22 were inoculated directly as transcripts of the cDNA clones pTXS.GFP (11) or pPVX.W22. Each plant was inoculated with the equivalent of a 5-μl transcription reaction. The probes for PVX.W22 and PVX.GFP were ^{32}P-labeled cDNA from the 3′ terminal 1.5 kb of the PVX genome.
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Substantial Genetic Influence on Cognitive Abilities in Twins 80 or More Years Old

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General and specific cognitive abilities were studied in intact Swedish same-sex twin pairs 80 or more years old for whom neither twin had major cognitive, sensory, or motor impairment. Resemblance for 110 identical twin pairs significantly exceeded resemblance for 130 fraternal same-sex twin pairs for all abilities. Maximum-likelihood model-fitting estimates of heritability were 62 percent for general cognitive ability, 55 percent for verbal ability, 32 percent for spatial ability, 62 percent for speed of processing, and 52 percent for memory. There was also evidence for the significant influence of idiosyncratic experience as the environmental component that most determines individual differences in cognitive abilities late in life.

Individuals aged 80 and older, whose prevalence is increasing at nearly twice the rate of the rest of the population in developed countries throughout the world (1), vary immensely in health and functional capabilities. Little is known about the genetic and environmental origins of this wide range of individuality (2–4). A particularly crucial aspect of quality of life in the elderly is cognitive functioning, which includes general and specific cognitive abilities. General cognitive ability, which represents that which diverse cognitive abilities have in common, is frequently measured by a

Table 1. Means, standard deviations (SD), and correlations with age and gender for each of the component tests. All correlations with age are significant ($P < 0.01$) with the exception of Verbal Meaning, with older subjects performing less well. The only significant correlation with gender is for Information, with women performing less well than men.

Cognitive test	Mean (SD)	Correlation	
		Age	Gender
Verbal Meaning	15.64 (7.04)	−0.06	0.01
Figure Logic	14.31 (5.53)	−0.16	0
Block Design	11.63 (7.13)	−0.18	0.03
Digit Span	8.79 (2.31)	−0.19	−0.02
Picture Memory	18.46 (4.85)	−0.13	0.09
Information	27.82 (11.53)	−0.21	−0.23
Symbol Digit	24.44 (11.10)	−0.18	0.01

Fig. 1. Distributions of general cognitive ability as indexed by (**A**) first principal component (PC) scores for subjects in the twin analysis and (**B**) WAIS short-form scores consisting of WAIS Information and WAIS Block Design. PC scores were standardized for subjects with a mean of 0 and a standard deviation of 1.0. The WAIS scores were standardized separately for the two constituent subtests and then summed.

total score on intelligence tests or derived as a first principal component from diverse tests of cognitive abilities (5). In the hierarchical model of cognitive abilities, specific cognitive abilities include group factors—such as spatial, verbal, and memory abilities—each determined from what is in common among several tests of each ability (6).

Twin and adoption studies converge on the conclusion that cognitive abilities are among the most heritable behavioral traits (7–9). Model-fitting meta-analyses based on dozens of adoption and twin studies, involving more than 10,000 pairs of twins, estimate that about half of the variance of general cognitive ability scores can be accounted for by genetic differences among individuals (10, 11). Specific cognitive abilities, less well studied than general cognitive ability, also show substantial genetic influence, although less than for general cognitive ability (12, 13). Developmental comparisons have yielded the intriguing finding that, for general cognitive ability, heritability increases from infancy (about 20%) to childhood (40%) to adolescence (50%) to adulthood (60%)

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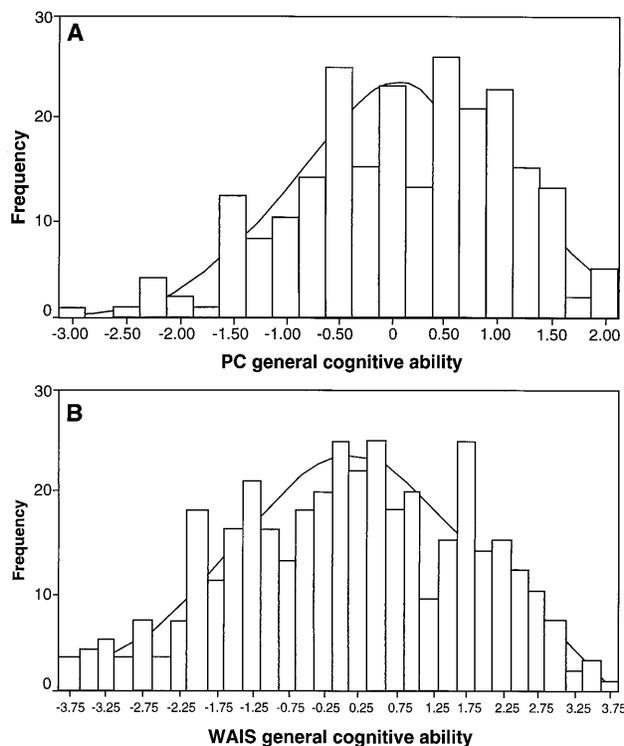
(14, 15). Recent studies of middle-aged twins also report substantial heritability for general and specific cognitive abilities (16–19). This finding is especially interesting because it contradicts a prevailing assumption in gerontology that environmental influence increases throughout the life-span with nonnormative environmental influences (20). This previous evidence for increasing heritability from infancy to middle age leads to the prediction that the heritability of cognitive abilities is substantial even for the very old.

The Swedish Twin Registry (21), consisting of 96% of all twins in Sweden, was used to select twins for the first twin analyses of individual differences in normal cognitive functioning in the very old. Both members of the pair not only had to be 80 or more years old and alive during the testing period (1991 to 1993) but both also had to be functioning sufficiently well to complete most of the cognitive tests in the demanding 1.5-hour battery (22). However, the twin pairs surviving into very late life do not differ significantly from a representative sample of nontwin individuals of the same age in cognitive functioning (23). The final sample consisted of 110 pairs of identical twins and 130 pairs of same-sex fraternal twins.

The median age of the twins was 82.3; 74% were between 80 and 84, 22% between 85 and 89, 3% between 90 and 94, and 1% over 95 years of age. The twins are representative of similarly aged individuals in Sweden in gender (64% female), years

of education (7.2 ± 2.4), and ethnicity (100% Caucasian). Concerning their living arrangements, 89% lived in conventional housing; 13% were in service apartments in which some housekeeping, meals, and social and health services are available; and 13% were in institutional settings.

Subjects were tested individually in their place of residence by licensed nurses. The members of a twin pair were tested by different nurses. Tests of cognitive abilities were chosen to include tests used in previous aging research, especially the H-70 [Hälsa (health)-70] study (24), a prospective longitudinal assessment of individuals initially 70 years old. Other tests were selected to sample across diverse specific cognitive abilities, including verbal, spatial, speed of processing, and memory abilities. Five of the tests are part of the most widely used battery in Sweden (25), which was based on Thurstone's (26) theory of primary mental abilities: Verbal Meaning (synonyms), Figure Logic (identifying one figure from five that are different), Block Design (making colored cubes match patterns presented on cards), Digit Span (forward and backward), and Picture Memory (recognizing pictures shown earlier). Other tests include the Information subtest from the Wechsler Adult Intelligence Scale (WAIS) (27), as translated and modified for use in Sweden (28), and the speeded Symbol Digit test (matching digits to patterns), which is a reversed format of the WAIS Digit Symbol test. Tests such as these generally show

reasonable reliability in studies of elderly individuals (*16*). Three of the tests have two parts, which permitted analyses of reliability in the present sample. Reliabilities comparable to other studies were found: 0.88 for Verbal Meaning, 0.77 for Figure Logic, and 0.86 for Information.

Table 1 presents means, standard deviations, and correlations with age and gender for the seven tests. The means and standard deviations indicate a wide range of variability for each of the tests. Age accounts for a significant amount of variance in performance on six of the seven cognitive tests for these individuals from 80 to 97 years of age. Gender is significantly related to only one of the tests. Because age and gender effects inflate twin resemblance for same-sex twins, all scores were adjusted for age and gender with a multiple regression procedure (*29*).

Factor analyses of these diverse tests yielded a strong general cognitive ability factor that accounted for 50% of the variance, consistent with other studies in middle age (*16*). All tests correlated above 0.52 with the first principal component used as an index of general cognitive ability. Because such principal component scores can be assigned only for subjects with complete data on all tests (52 identical and 65 fraternal twin pairs), we also indexed general cognitive ability with a short form of the WAIS (*30*), which adds scores on Information and Block Design (90 identical and 104 fraternal twin pairs). We also examined specific cognitive abilities constructed by standardizing and adding tests to represent verbal ability (Verbal Meaning and Information; 78 and 93 pairs of identical and fraternal twins, respectively), spatial ability (Figure Logic and Block Design; 86 and 89 twin pairs, respectively), speed of processing (Symbol Digit; 73 and 92 twin pairs); and memory (Digit Span and Picture Memory; 63 and 82 twin pairs). In addition to con-

ducting model-fitting twin analyses using only pairs for whom data were available for both twins, we also employed pedigree analysis (*31*), which utilizes all available information, including data in which one twin is missing. We also analyzed pairs with complete data for comparison purposes.

Distributions of scores for general cognitive ability as indexed by the first principal component (PC; Fig. 1A) and the WAIS short form score (Fig. 1B) were nearly normal, especially for the WAIS short form. Similar distributions were found for the scales of specific cognitive abilities.

For general and specific cognitive abilities, identical twin correlations were significantly greater than fraternal twin correlations, indicating genetic influence (Fig. 2). Twin correlations were similar when only those twin pairs with complete data on all tests were included (*32*). The data were submitted to standard maximum likelihood model-fitting analysis for twin data (*33*) to estimate genetic and environmental components of variance. We report model-fitting results using data for pairs for whom data were available for both twins, although similar results were obtained when we employed pedigree analysis (*34*).

Estimates of heritability—the proportion of total phenotypic variance attributable to genetic variance—and their 95% confidence intervals were 62% (29 to 73%) for general cognitive ability as indexed by the PC and 53% (19 to 76%) as indexed by the WAIS short form, 55% (24 to 81%) for verbal ability, 32% (0 to 58%) for spatial ability, 62% (29 to 73%) for speed of processing, and 52% (7 to 67%) for memory ability (Fig. 3). In all cases, dropping the genetic parameter from the model resulted in a significant reduction in the fit of the model, demonstrating the significance of the heritability estimates. If variance due to error of measurement (about 10%) was removed from the total phenotypic variance, heritability estimates would account for a larger proportion of the remaining phenotypic variance.

The shared environment parameter, or twin resemblance not explained by heritability, accounted for 11% (0 to 47%) of the variance for PC and 15% (0 to 43%) for WAIS general cognitive ability, 20% (0 to 47%) for verbal ability, 13% (0 to 48%) for spatial ability, 0% (0 to 27%) for speed of processing, and 0% (0 to 32%) for memory ability. Dropping the shared environment parameter from the model did not result in a significant reduction of fit for any of the cognitive abilities, indicating that shared environment does not account for significant variance. However, the classical twin method of comparing identical and fraternal twin correlations is not a powerful design for

Fig. 2. Intraclass correlations for identical twins (MZ; black bars) and fraternal twins (DZ; gray bars) for general cognitive ability (PC and WAIS) and specific cognitive abilities.
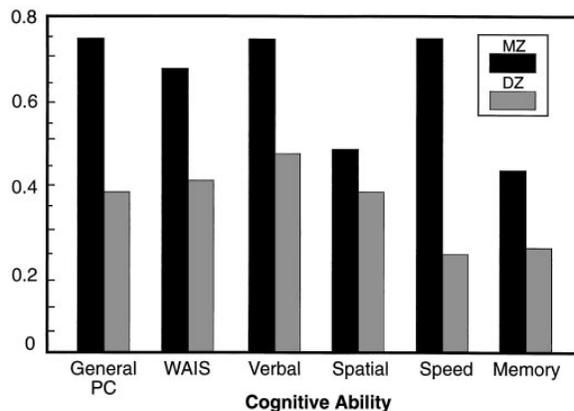
Fig. 3. Estimates of proportions of variance due to genetic influence (black), shared environment (gray), and nonshared environment (white), as derived from maximum likelihood, model-fitting twin analyses. For each measure, the full model fit well. Chi-squares with 3 degrees of freedom were 1.22 ($P = 0.75$) for PC general cognitive ability, 0.92 ($P = 0.75$) for WAIS general cognitive ability, 0.89 ($P = 0.83$) for verbal ability, 3.38 ($P = 0.34$) for spatial ability, 0.66 ($P = 0.76$) for speed of processing, and 2.8 ($P = 0.42$) for memory.
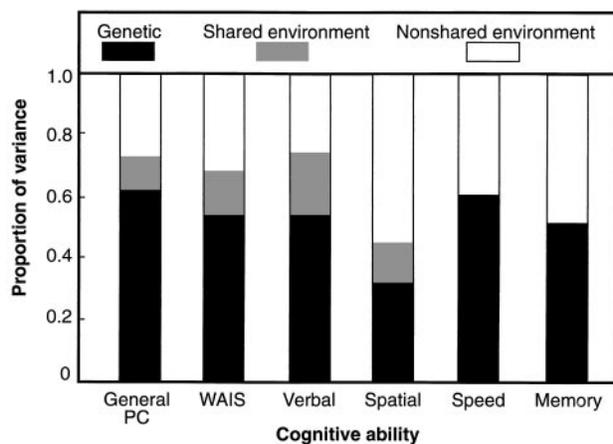
Akaike fit indices also indicate that the full model fits well for each measure: −4.78, −5.08, −5.11, −2.62, −4.34, and −3.21, respectively. For each measure, the best-fitting model was one that only included genetic and nonshared environment parameters, with the following chi-squares with 4 degrees of freedom: 1.45, 1.72, 2.36, 3.70, 1.66, and 2.80, respectively. In other words, dropping the shared environment component of variance from the full model did not significantly reduce the fit of the model. In contrast, dropping the genetic parameter from the model significantly worsened the fit, with the following chi-squares with 4 degrees of freedom for the above measures: 9.64, 10.14, 12.74, 5.03, 12.30, and 7.54, respectively.

detecting shared environment influence (*35*). Most of the nongenetic variance is due to nonshared environment and error of measurement. If the measures are about 90% reliable, then the amount of variance resulting from nonshared environment would be 17% for PC and 22% for WAIS general cognitive ability, 15% for verbal ability, 45% for spatial ability, 28% for speed of processing, and 38% for memory.

Although genetic influence on cognitive functioning late in life appears to be substantial, these data also demonstrate considerable environmental influence. About 40% of the variance for general cognitive ability and even more of the variance for specific cognitive abilities is environmental in origin. Moreover, consistent with results from studies of younger adults, our results indicate that, for the most part, these environmental influences are not shared by twins growing up in the same family nor are they due to adult experiences shared by twins. In other words, environmental influences that contribute to individual differences in cognitive abilities are those that make family members, in this case twins, different (*36*). The most direct evidence for this conclusion is that identical twin correlations are considerably less than the reliability of the measures (usually given as 0.80 to 0.95), even though identical twins are genetically identical. Differences within pairs of identical twins provide a tool with great potential for identifying these nonshared environmental factors.

It is now becoming possible to identify some of the specific genes responsible for the substantial heritability of individual differences in cognitive abilities (*9*) and cognitive disabilities (*37*). For example, the gene for apolipoprotein-E has not only been associated with late onset Alzheimer's disease but also with cognitive decline in an unselected sample of elderly individuals (*38*). Other genes that are related to general aging, such as the genes for telomerase or helicases, might also account for some of the heritable differences in cognitive functioning late in life. However, it is also possible that genes that contribute to individual differences in cognitive abilities late in life may be the same genes that contribute to individual differences earlier in the life span. This hypothesis is supported by longitudinal twin analyses that indicate that genetic effects largely contribute to continuity rather than to change in individual differences in cognitive abilities during the adult years (*3*, *15*). Even if such genes individually account for only a small amount of variance, they could provide handholds in the climb toward understanding the developmental pathways between genes and cognitive abilities.

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22. The Swedish Twin Registry was used to identify 947 same-sex twin pairs who were 80 years old or older and both alive during the 3-year period of testing that began in 1991. Research funds permitted us to contact 737 of these pairs. Of these 737 pairs, 188 pairs could not participate because one or both twins had died before the onset of testing and 198 pairs were excluded because one or both twins declined to participate, usually for reasons of frailty or incapacity. In-person testing was conducted for 351 intact pairs, although for 111 pairs one or both members of the pair were unable to complete the tests for reasons of suspected dementia (88 pairs) or major sensory or motor handicaps (23 pairs). Suspected dementia was diagnosed as described [*American Psychiatric Association Diagnostic and Statistical Manual of Mental Disorders* (American Psychiatric Association, Washington, DC, ed. 3 revised, 1987)]. The preliminary diagnosis was made on the basis of performance on a battery of tests for dementia and cognitive impairment, including the Mini-Mental State Examination [M. F. Folstein, S. E. Folstein, P. R. McHugh, *J. Psychiatr. Res.* **17**, 189 (1975)]. A diagnostic work-up of all suspected dementia cases is under way. The final sample for these analyses of individual differences in normal cognitive functioning includes 240 pairs (110 identical pairs and 130 fraternal pairs) who were able to complete most of the tests in the 1.5-hour battery; 51% of these individuals 80 years old and older completed all of the tests. Zygosity was diagnosed from physical similarity information, with the exception of nine pairs for whom zygosity was uncertain; for these, DNA fingerprinting revealed one pair to be identical and eight pairs to be fraternal.
23. S. F. Simmons *et al.*, *J. Aging Health*, in press. For example, although there is only a weak genetic contribution to longevity (*2*), it is possible that fraternal twins who both survive past 80 years of age are more similar in their cognitive functioning than fraternal pairs in which only one twin survives. This could lead to a lower estimate of heritability in analyses of intact pairs 80 or more years old, a hypothesis that could be tested in a longitudinal twin study that began before 80 years of age. The sample is also limited to the cohort born between 1894 and 1913 in Sweden.
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32. For twins with complete data on all tests, correlations were similar to those shown in Fig. 2. For example, for general cognitive ability as indexed by the WAIS short form, the monozygotic (MZ) and dizygotic (DZ) correlations in Fig. 2 were 0.68 and 0.41, respectively, and the correlations for twins with complete data on all tests were 0.73 and 0.41. The largest discrepancy, still far from statistically significant, emerged for speed of processing. In Fig. 2, the MZ and DZ correlations were 0.49 and 0.24, and the correlations for twins with complete data on all tests were 0.58 and 0.27.
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