Role of Genes and Environments for Explaining Alzheimer Disease

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Context: Twin studies using selected samples have shown high heritability for Alzheimer disease (AD).

Objective: To evaluate genetic and environmental influences on AD in a fully ascertained population of older twins, including like- and unlike-sex pairs.


Setting and Participants: All twins in the Swedish Twin Registry aged 65 years and older. The study included 11,884 twin pairs, among whom were 392 pairs in which 1 or both members had AD.

Main Outcome Measures: All individuals were screened for cognitive dysfunction. Suspected cases of dementia and their co-twins received complete clinical diagnostic evaluations for AD. Estimates of heritability, shared environmental influences, and nonshared environmental influences, adjusting for age, were derived from the twin data.

Results: Heritability for AD was estimated to be 58% in the full model and 79% in the best-fitting model, with the balance of variation explained by nonshared environmental influences. There were no significant differences between men and women in prevalence or heritability after controlling for age. Within pairs concordant for AD, intrapair difference in age at onset was significantly greater in dizygotic than in monozygotic pairs, suggesting genetic influences on timing of the disease.

Conclusions: In the largest twin study to date, we confirmed that heritability for AD is high and that the same genetic factors are influential for both men and women. However, nongenetic risk factors also play an important role and might be the focus for interventions to reduce disease risk or delay disease onset.

Arch Gen Psychiatry. 2006;63:168-174

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ing genes. Evidence for the role of the environment comes from MZ twin pairs who are discordant for the disease. Differences between the twin with the disease and the twin without the disease can provide clues regarding biological markers of AD that differentiate the affected from the unaffected twin or provide information related to which environmental risk factors might have led one twin to have the disorder while sparing the other.6,15

Studies of rates of concordance in twins who have volunteered for research can be biased if, for example, pairs who are concordant or MZ pairs are more likely to volunteer. For this reason, use of a twin registry that was compiled from a population from which cases were ascertained in an unbiased fashion is essential. Age effects are also critical to address in twin studies, particularly for age-dependent traits such as AD. If age is not appropriately handled, inflated shared (ie, familial) environmental effects will be obtained.16

Including unlike-sex twin pairs in the study permits asking additional questions. Not only can heritability and environmental influences be quantitatively compared for men and for women, but also comparing similarity for like- and unlike-sex pairs tests whether the same genes and the same environments play a role for men and for women. The possibility that genetic influences may differ for men and for women is supported by a meta-analysis that indicated moderation of the effect of the apo-lipoprotein E gene by sex on risk of AD.17

In this article, we use biometrical twin analyses to address the following: (1) to verify in a population-based twin registry the extent of heritability of AD, (2) to evaluate possible differences between men and women in heritability of AD, and (3) to examine similarity between members of MZ vs DZ twin pairs in their age at onset of dementia.

METHODS

PARTICIPANTS

Swedish Twin Registry

The compilation of the Swedish Twin Registry is described in detail elsewhere.18 In 1961, a questionnaire was sent to all like-sex twin pairs born between 1886 and 1925 in which both twins were alive, with twin births having been identified from parish records. Unlike-sex pairs were not included in the questionnaire; however, using the stored parish records, pairs born between 1906 and 1925 have now been added to the computerized twin registry. In 1970, the cohort of twins born between 1926 and 1967 was identified using the nationalized birth registration system then in place, and in 1973, like-sex twins in the new cohort were sent a questionnaire. The registry is regularly matched to other national health care registries to update address and vital status information. No contact with the entire registry took place for the next 25 years. In 1998-2001, all living twins in the twin registry who were born in 1935 and earlier, both like- and unlike-sex twins, were requested to participate in a telephone screening interview. This interview included screening for cognitive dysfunction to identify potential cases for a study of dementia. If the twin were unable to be interviewed, a brief interview that included questions about cognitive status was carried out with an informant. The study of dementia in Swedish twins is known as HARMONY.

HARMONY Sample

We have recently presented detailed information about case identification for HARMONY.19 A 2-phase procedure was followed, with a screening phase and a clinical phase. Individual participation rate was 71.3% for the screening phase and 69.7% for the clinical phase.

The data set for the analyses presented here includes all pairs where one or both members of the pair participated in either phase. After excluding 131 pairs where zygosity was indeterminate, the total number of pairs was 11,884 (10% MZ male, 14% MZ female, 18% DZ male, 26% DZ female, and 32% unlike-sex pairs). For 127 individuals whose twin partner was dead and hence did not participate in the first phase, information was available from medical records and informants or from pilot work with subsamples of the twin registry, enabling the diagnostic board to ascertain dementia status so that the pair data could be complete. Sample size for complete pairs and for individuals from complete and incomplete pairs, by sex and zygosity, appears in Table 1.

Individuals were classified as demented based on clinical diagnoses or as nondemented if either the clinical evaluation determined that the individual did not meet diagnostic criteria for dementia or if the individual screened negative. The resulting data set included 680 individuals with a diagnosis of dementia and 12,546 individuals who were nondemented. Among those with dementia were 428 with probable or possible AD, 168 with vascular dementia or mixed AD and vascular dementia; 31 with dementia secondary to another medical condition; and 33 other or type not specified. The total number of pairs where one or both had AD was 392. For analyses of AD, individuals with a different type of dementia were treated as missing. Average age at onset of dementia is listed in Table 1.

PROCEDURES

The screening phase was conducted by telephone and was designed to identify anyone with cognitive dysfunction using a screening tool with high sensitivity so that false negatives would be minimized. For the twins themselves, telephone cognitive screening used the TELE questionnaire.20 Informants were given the Blessed Dementia Rating Scale.21 The TELE has been demonstrated to have a specificity of 0.95 in an unselected community sample, with specificity set low (0.52) to minimize false negatives, and to perform well relative to other telephone screening protocols.22

The clinical phase entailed complete in-person diagnostic evaluations for dementia for individuals who screened positive, their co-twins, and a sample of twins where both had screened negative. Clinical diagnoses used information collected by an assessment team comprising a physician and a nurse. Assessments included neuropsychological testing, a semistructured interview with a knowledgeable informant, and a physical examination with blood panel. A diagnostic review board took the assessment information and independently formulated a clinical dementia diagnosis and differential diagnosis of type of dementia, following Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition (DSM-IV) criteria for dementia.23 NINCDS/ADRSA criteria (National Institute of Neurological and Communicative Disorders and Stroke–Alzheimer’s Disease and Related Disorders Association) for AD,24 NINDS-AIREN criteria (Neuroepidemiology Branch of the National Institute of Neurological Disorders and Stroke–Association Internationale pour la Recherche et l’Enseignement en Neurosciences) for vascular dementia,25 Lund and Manchester criteria for frontal temporal dementia,26 and consensus criteria for dementia with Lewy bodies.27 Individuals were first classified as demented, questionable (meeting some but not all DSM-IV criteria), or nondemented and then given a differen-
shared factors is 1.00 for both twin types. Monozygotic twins and 0.5 for dizygotic twins and that the correlation of additive genetic components is 1 for correlation. The 1.00, 1, and 0.5 notations represent the assumptions of the agreement between the 2 members of the diagnostic review board monozygotic; Pt1; twin 1’s phenotype; Pt2, twin 2’s phenotype; rg, genetic influences; e, nonshared environmental loadings; f, female; m, male; MZ, environment; DZ, dizygotic; E, nonshared environmental influences; a, genetic loadings; C, shared environmental influences; c, shared environmental influences; cm, men; cm, women. For different diagnoses was 0.86 for 204 individuals. Prevalence of Alzheimer disease calculated after removing other cases of dementia from the denominator.

Table 1. Prevalence of Total Dementia and Alzheimer Disease, Probandwise Concordance Rates, and Tetrachoric Correlations (With 95% Confidence Intervals) by Zygosity and Sex

<table>
<thead>
<tr>
<th></th>
<th>MZ Men</th>
<th>MZ Women</th>
<th>DZ Men</th>
<th>DZ Women</th>
<th>Unlikely-Sex Twins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete pairs, No.*</td>
<td>428</td>
<td>655</td>
<td>679</td>
<td>1009</td>
<td>1454</td>
</tr>
<tr>
<td>Individuals, No.</td>
<td>1355</td>
<td>1884</td>
<td>2333</td>
<td>3247</td>
<td>2121</td>
</tr>
<tr>
<td>Prevalence</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total dementia, No., %†</td>
<td>68 (5.02)</td>
<td>143 (7.59)</td>
<td>94 (4.03)</td>
<td>245 (7.55)</td>
<td>60 (2.83)</td>
</tr>
<tr>
<td>AD, %‡</td>
<td>2.65</td>
<td>5.74</td>
<td>2.44</td>
<td>5.93</td>
<td>1.26</td>
</tr>
<tr>
<td>Age at onset of dementia, mean ± SD, y</td>
<td>76.6 ± 7.1</td>
<td>78.2 ± 7.6</td>
<td>75.1 ± 9.2</td>
<td>79.0 ± 7.8</td>
<td>76.2 ± 7.2</td>
</tr>
<tr>
<td>Probandwise concordance, %</td>
<td>44</td>
<td>58</td>
<td>25</td>
<td>45</td>
<td>26</td>
</tr>
<tr>
<td>Tetrachoric correlation (95% CI)</td>
<td>0.73 (0.52-0.87)</td>
<td>0.83 (0.72-0.90)</td>
<td>0.53 (0.29-0.73)</td>
<td>0.70 (0.59-0.79)</td>
<td>0.63 (0.46-0.76)</td>
</tr>
</tbody>
</table>

Abbreviations: AD, Alzheimer disease; CI, confidence interval; DZ, dizygotic; MZ, monozygotic.
*Complete pairs are those in which both members of the pair participated.
†Prevalence of dementia calculated as number of cases divided by number of individuals.‡Prevalence of Alzheimer disease calculated after removing other cases of dementia from the denominator.

![Figure 1](https://example.com/figure1.png)

Figure 1. Model of sex limitation of genetic effects. A indicates genetic influences; C, shared environmental influences; E, nonshared environmental influences; f, female; m, male; MZ, monozygotic; Pt1, twin 1’s phenotype; Pt2, twin 2’s phenotype; rg, genetic correlation. The 1.00, 1, and 0.5 notations represent the assumptions of the twin model that the correlation of additive genetic components is 1 for monozygotic twins and 0.5 for dizygotic twins and that the correlation of shared factors is 1.00 for both twin types.

Within each of the 5 groups. Probandwise concordance is the ratio of the number of affected twin partners of independently ascertained cases to the total number of cases. Tetrachoric correlations represent the correlation of liability for the disorder between twins in a pair. For AD, individuals with other dementias were excluded from the analyses. Results for total dementia include all dementias. Pairs were included if either member of the pair was in the HARMONY sample.

Biometrical twin analyses were conducted on raw ordinal data using the Mx data program (Department of Psychiatry, Virginia Commonwealth University, Richmond, Va), in which twin resemblance was compared for 5 groups of twins: male and female MZ and DZ twins as well as unlike-sex pairs. In ordinal models, each individual is coded as having the disease or not having the disease, and the threshold is the z score that corresponds to the rate of the disease. Thus, the model assumes an underlying normally distributed liability. Using the raw data option in Mx permits including incomplete pairs who contributed information for the estimation of thresholds but not for twin resemblance. Model fitting used the method of maximum likelihood.

The sex-limitation twin model is shown in Figure 1. Variance is partitioned into 3 components: A (additive genetic), C (shared environmental effects common to both members of a twin pair), and E (nonshared or unique environmental effects). The observed data are fit based on assuming that genetic similarity is half as great for DZ as for MZ twin pairs, ie, 0.5 vs 1.0, while environmental influences shared by twins in a pair contribute equally to making MZ and DZ pairs similar and are correlated 1.0. Unlike-sex twins contribute to resolving whether sex limitation is present, ie, whether different genes may be influential for men and women. As indicated in Figure 1, if different genetic influences are important for the disease in men and in women, then unlike-sex twins will be less genetically similar for the trait than DZ twins, and the genetic correlation (rg) will be less than 0.5. Alternatively, if different environments are more influential in one sex than the other, then one can test whether the correlation between environments shared by twins (rg) is less than 1.0 in unlike-sex pairs. If neither were supported, one can test whether the magnitudes of genetic and environmental sources of variance differed significantly by sex comparing the fit of the 3-group unconstrained model with a model where genetic and environmental loadings were sex specific.
environmental influences were set to be the same for men and women. In addition, a series of models were tested, successively dropping either the $A$ or the $C$ parameter. Alternative nested models were compared by taking the difference in log likelihood between the full and reduced model, which is distributed as a $\chi^2$ with degrees of freedom equal to the difference in the number of parameters estimated in each model.

Finally, with an age-related disease, twin similarity for age is confounded with twin similarity for disease. This leads to inflation of C. Therefore, we adjusted the estimated thresholds (ie, rate of the disease) according to age of the twin. The adjustment is expressed as $\beta_{age}$.\textsuperscript{14}

Comparison of ages at onset within concordant MZ and DZ twin pairs relied on a Wilcoxon 2-sample test. This statistic reduces the effect of isolated extreme scores when data are not normally distributed.

Sample sizes, unadjusted prevalence rates, proband-wise concordance rates, and tetrachoric correlations are listed in Table 1 for both AD and total dementia for all 5 groups. Prevalence tended to be higher for women than for men, and rates of disease were higher among those who were older than those who were younger (Figure 2). As shown by both concordance rates and tetrachoric correlations, resemblance was greater for MZ than for DZ and for women than for men. Concordance for vascular dementia (not listed in the table) was very low, with only 1 MZ pair, 3 DZ pairs, and 3 unlike-sex pairs in which both twins had vascular dementia or mixed vascular and AD.

Model-fitting results for AD are summarized in Table 2. Findings for total dementia were similar and are therefore not shown. The top section of Table 2 provides results of the 5-group model without including $\beta_{age}$. These results are included because the method corresponds to how other twin studies have calculated heritability. Thresholds could be equated for twins in a pair, in MZ and DZ men, and for MZ and DZ women, but not for men and women and not for like-sex and unlike-sex pairs. Therefore, thresholds were allowed to differ for men and women in like-sex pairs and for unlike-sex pairs. In the results presented in Table 2, the amount of variance assigned to C is substantial, especially for women.

The bottom sections of Table 2 list results of the 5-group model with age-adjusted thresholds. With $\beta_{age}$ in the model and allowed to differ for men and women, sex differences in thresholds were no longer significant, indicating that the differences in thresholds likely reflected the greater longevity of women compared with men and hence their greater opportunity to have become demented. Although allowed freely to vary, the genetic correlation ($r_g$) for unlike-sex pairs was estimated to be 0.5, providing no evidence that different sets of genes are important for men and women. Similarly, the correlation between environments shared by twins ($r_c$) was not significantly less than 1.0 in unlike-sex pairs, providing no evidence for sex differences in the nature of shared environmental factors. The lower threshold for unlike-sex pairs may reflect the historical difference in how unlike-sex pairs were enrolled in the twin registry, in which those born the ear-

<table>
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<th>RESULTS</th>
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Figure 2. Prevalence of Alzheimer disease by age group and sex.
ence in age at onset was 3.66±3.63 years. Among 20 DZ pairs where both had AD, the average±SD difference in age at onset was 8.12±7.04 years. A Wilcoxon 2-sample test normal approximation resulted in a z score of 2.73, which corresponds to a 1-sided probability of .003. There was no relationship between the intrapair difference in age at onset and the age at which the first twin became affected.

In the largest population-based twin study of dementia to date, with like- and unlike-sex pairs and using advancements in twin methodology, we have confirmed that heritability of AD is high and does not differ by sex. The same genetic effects are operating in men and women. Genes also seem to have a role in disease timing because age at onset of AD is significantly more similar for concordant MZ pairs than for DZ pairs where both had AD. The average±SD difference in age at onset was 8.12±7.04 years. A Wilcoxon 2-sample test normal approximation resulted in a z score of 2.73, which corresponds to a 1-sided probability of .003. There was no relationship between the intrapair difference in age at onset and the age at which the first twin became affected.

### Table 2. Parameter Estimates (With 95% Confidence Intervals) From Model Fitting Results for Alzheimer Disease: Full Model Without Adjusting for Age and Full and Reduced Models Adjusting for Age

<table>
<thead>
<tr>
<th>Group</th>
<th>A*</th>
<th>C*</th>
<th>E*</th>
<th>f_g for Unlike-Sex Pairs</th>
<th>Threshold†</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Full Model Without Adjusting for Age</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men</td>
<td>0.59 (0.00-0.89)</td>
<td>0.21 (0.00-0.72)</td>
<td>0.20 (0.07-0.46)</td>
<td></td>
<td>1.96</td>
</tr>
<tr>
<td>Women</td>
<td>0.37 (0.11-0.63)</td>
<td>0.53 (0.29-0.73)</td>
<td>0.10 (0.05-0.20)</td>
<td></td>
<td>1.47</td>
</tr>
<tr>
<td>Unlike sex</td>
<td></td>
<td></td>
<td></td>
<td>0.50</td>
<td>2.14</td>
</tr>
<tr>
<td><strong>Full Model Adjusting for Age</strong></td>
<td></td>
<td></td>
<td></td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>Men</td>
<td>0.58 (0.00-0.86)</td>
<td>0.07 (0.00-0.59)</td>
<td>0.36 (0.14-0.69)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Women</td>
<td>0.45 (0.02-0.88)</td>
<td>0.36 (0.00-0.71)</td>
<td>0.19 (0.09-0.35)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduced Models Adjusting for Age</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men and women equalled</td>
<td>0.58 (0.19-0.87)</td>
<td>0.19 (0.00-0.49)</td>
<td>0.23 (0.13-0.37)</td>
<td>0.50</td>
<td>−0.09</td>
</tr>
<tr>
<td>Men and women equalled, C parameter dropped</td>
<td>0.79 (0.67-0.88)</td>
<td>NA</td>
<td>0.21 (0.12-0.33)</td>
<td>0.50</td>
<td>−0.09</td>
</tr>
</tbody>
</table>

Abbreviations: A, additive genetic influences; C, shared environmental influences; E, nonshared environmental influences; NA, not applicable; f_g, genetic correlation.

*All values are parameter estimate (confidence interval).

†Threshold is the z score corresponding to prevalence.
results from the best-fitting model in the present study. As was also reported by the Norwegian study, substantial influence from shared environmental factors was suggested (24%). Findings for the shared environmental factors illustrate how, if a disorder is age-related, that parameter may be overestimated. In the present study, controlling for age reduced the magnitude of the shared environment parameter.

Both the SATSA subsample and a second subsample from the OCTO (Octogenarian)-Twin study were able to be followed longitudinally, and those findings have been previously reported. Individuals who were nondemented at baseline were ascertained again for dementia at follow-up. Results based on 77 incident cases of AD, with no correction for age, found somewhat lower heritability compared with estimates based on prevalent disease (48%) and no influence from shared environment. The reason that results for the analyses of incident cases showed lower heritability than results for analyses of prevalent cases reflects essential differences between the 2 designs; namely, for the incident design, the cases include only those who developed dementia over a 5-year period. If the incident sample were followed longer, more cases of dementia and more concordant pairs would be likely. Finally, in contrast to the present study, none of the previous reports based on the Swedish Twin Registry represent comprehensive ascertainment of the whole registry nor do they include unlike-sex pairs.

Previous twin studies of AD have not been able to evaluate sex differences. In the present analyses, we found that more women than men in the population had AD; however, women and men did not differ in prevalence once age was taken into account. Concordance was higher in women, reflecting their greater longevity. For these reasons, the shared environment parameter was larger for women than for men, especially in models that did not take age into account. There was no significant moderation of genetic effects by sex. With age taken into account, models for men and women could be equated. For this latter reason, the apparent difference in shared environmental effects for women and men after controlling for age should not be overinterpreted. Nonetheless, it is possible that female siblings might be more similar in their environments than male siblings. Previous analyses with the SATSA sample from the Swedish Twin Registry also found influences for shared environment for Mini-Mental State Examination scores for women but not for men.

The most important differences between past twin studies and the present report are (1) the size of the study, in which the number of cases is from 4-fold to more than 10-fold greater than those reported earlier; (2) representativeness of the sample; (3) inclusion of unlike-sex pairs to test for evidence of sex limitation; and (4) incorporation of an age correction to the disease threshold in the biometrical twin models that statistically controls for spurious twin resemblance because of their shared age.

The present study also has a number of limitations, including the following:

- This is a prevalence study, and it is not possible to distinguish whether discordant twin pairs will ultimately differ in presence of disease or whether they are only different in age at onset. In evaluating genetic variability for having AD, influences related to age at onset are included, and it is not possible to separate susceptibility to AD from age at onset for AD. Ideally, all of these twins could be followed up longitudinally. Nonetheless, the range of ages included in the present study ensures that the sample was not limited to individuals too young to be at risk for developing dementia. Still, more definitive results will only become available as repeated examinations are undertaken of this and other twin registries.
- Not all twins agreed to participate, with refusal both at screening and clinical phases. We have previously noted that prevalence of dementia in the present study was comparable with several major epidemiological studies of dementia prevalence. To test how nonparticipation might be affecting the results, we used information available in the twin registry from linking to the national Inpatient Discharge Registry and Cause of Death Registry, which contain diagnoses for hospital stays and causes of death, respectively, recorded using the ICD revision current at the time of the event. Thus, we determined whether nonparticipants had any dementia diagnosis recorded. When we added this information to our data, the analyses showed that heritability of dementia was within 1% for men and 2% for women, compared with the results based only on cases identified by our protocol.
- In twin studies, estimates of the influence of genes and environment are relative. When variation due to environmental factors is low, estimates of the role of genetic effects will be higher. Moreover, both sets of influences are “anonymous”; that is, we cannot use the results to infer what genes may be involved or what environmental factors might be important.

The results of the present study also provide important evidence for the extent to which environment influences disease occurrence. Concordance is not perfect, there is important influence due to nonshared environment, and age at onset in concordant pairs varies, all suggesting that there are nongenetic lifestyle factors that can affect the risk and timing of AD.

Submitted for Publication: December 8, 2004; final revision received April 29, 2005; accepted August 18, 2005.

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Funding/Support: This work was supported by grant R01-AG08724 from the National Institute on Aging, Bethesda, Md. Dr Gatz held a Zenith Award (ZEN-02-3895) from the Alzheimer’s Association, Chicago, Ill.

Acknowledgment: The name HARMONY comes from the Swedish words for “health” (helso), “genes” (arv), “environment” (miljo), and “new” (ny). We thank Charles O. Gardner for making available his Mx script for incorporating age thresholds into an ordinal model. All protocols are available online at http://www.usc.edu/dept/LAS/psychology/SCRAP. Age-at-onset questions are shown in the protocol named Debut.

REFERENCES