A Replicated Molecular Genetic Basis for Subtyping Antisocial Behavior in Children With Attention-Deficit/Hyperactivity Disorder

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Context: Attention-deficit/hyperactivity disorder (ADHD) is a heterogeneous neurodevelopmental disorder that in some cases is accompanied by antisocial behavior.

Objective: To test if variations in the catechol O-methyltransferase gene (COMT) would prove useful in identifying the subset of children with ADHD who exhibit antisocial behavior.

Design: Three independent samples composed of 1 clinical sample of ADHD cases and 2 birth cohort studies.


Main Outcome Measures: Diagnosis of ADHD and measures of antisocial behavior.

Results: We present replicated evidence that the COMT valine/methionine polymorphism at codon 158 (COMT Val<sup>158</sup>Met) was associated with phenotypic variation among children with ADHD. Across the 3 samples, valine/methionine homozygotes had more symptoms of conduct disorder, were more aggressive, and were more likely to be convicted of criminal offenses compared with methionine carriers.

Conclusions: The findings confirm the presence of genetic heterogeneity in ADHD and illustrate how genetic information may provide biological evidence pointing to clinical subtypes.

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morphism at codon 158 (Val158Met; codon numbering based on the largest known protein isoform). The Met allele is associated with a 40% reduction in enzymatic activity in the PFC13 and (it is inferred) a higher level of PFC dopamine as a consequence. The biochemical consequences of this polymorphism in COMT may be of broad functional relevance, as carriers of the Val allele have been shown to exhibit less efficient PFC processing as indicated by a worse performance on measures of executive functioning.14 These findings led us to test whether individuals with ADHD who are carriers of the Val allele would be at greater risk of developing early-onset antisocial behavior and its sequelae. In 3 independent studies of children with ADHD, we confirmed that children homozygous for the high-activity Val allele exhibited early-onset, pervasive, and persistent antisocial behavior and were convicted of a disproportionate share of crimes as adults.

METHODS

SAMPLES

Participants in the first sample were drawn from the Cardiff ADHD Genetic Study. This sample of 376 children of white British origin had been drawn from child psychiatry and pediatric clinics across northwest and southwest England and Wales between 1997 and 2003.17 Genotyping for COMT was completed for the first set of individuals collected, which consisted of 241 children (214 boys and 27 girls [the expected sex distribution for clinic cases with this diagnosis]) aged 5 to 14 years (mean age, 9 years 3 months [SD, 2 years 2 months]) who met DSM-IV18 criteria for ADHD or International Statistical Classification of Diseases, 10th Revision (ICD-10),19 criteria for hyperkinetic disorder. Data on COMT and antisocial behavior in the Cardiff ADHD Genetic Study have been previously reported,12 but were reanalyzed herein to facilitate cross-study comparisons and pooled analysis.

Participants in the second sample were members of the Environmental Risk (E-Risk) Study, which tracks the development of a birth cohort of 2232 British children. This E-Risk sample was drawn from a larger 1994-1995 birth registry of twins born in England and Wales.20 The E-Risk sample was constructed in 1999-2000, when 1116 families with same-sex 5-year-old twins (93% of those eligible) participated in home assessment when the children were aged 5 years, with parents’ permission, questionnaires were posted to the children’s parents. The children were aged 7 years and teacher questionnaires were obtained for 91% of the 2232 E-Risk twins (93% of those followed up). Because each study family contains 2 children, all statistical analyses in this report were corrected conservatively for the nonindependence of the twin observations by using tests based on the sandwich or Huber-White variance estimator (Stata, version 8.2: Stata Corp, College Station, Texas).

Participants in the third study were members of a New Zealand birth cohort study (the Dunedin Longitudinal Study), which tracks the development of 1037 children. This sample was constituted at age 3 years when the investigators enrolled 91% of consecutive 1972-1973 births in Dunedin, New Zealand. Co-
aggressive behavior problems were totaled to create a measure that reflects pervasive aggressive behavior across settings. Sample items from the aggression subscale include “physically attacks people,” “destroys things that belong to others,” and “gets in many fights.”

In the Dunedin Longitudinal Study, we analyzed a composite index of antisocial behavior in adolescence and in adulthood (aged ≤26 years) that counts the number of antisocial outcomes observed for each study member, including whether a study member (1) met diagnostic criteria for adolescent conduct disorder, (2) was convicted of a violent crime, (3) had elevated scores on a self-reported disposition toward violence measure, or (4) had elevated scores on informant reports of antisocial symptoms. Details about this index are provided in an article by Caspi et al. In addition, the Dunedin cohort has now been followed up to age 32 years, enabling us to test whether genotype accounted for heterogeneity in criminal offending through that age. We obtained conviction data by searching the computerized New Zealand Police database, with the informed consent of the study participants. Computerized records covered all courts in Australia, New Zealand, and the surrounding islands. Twenty percent of study participants had been convicted of a criminal offense, including nonviolent (eg, drug trafficking, theft, burglary) and violent (eg, assault, rape, robbery, manslaughter) offenses; traffic offenses were excluded.

DNA EXTRACTION AND GENOTYPING
In the Cardiff ADHD Genetic Study, DNA was obtained from venous blood or mouthwash samples from all participants. In the E-Risk Study, DNA was obtained via buccal swabs from 96% of participants. In the Dunedin Longitudinal Study, DNA was obtained from 97% of participants (93% via blood and 7% via buccal swabs). To avoid potential problems of population stratification, DNA from Dunedin cohort members of Maori origin was not included. Genotyping protocols are summarized in “Supplementary Methods” (available at http://archpsyc.ama-assn.org). Allele frequencies in all samples were consistent with reported allele frequencies in white individuals. Participants in each sample were split into 3 groups on the basis of genotype: individuals homozygous for the low COMT–activity allele (Met/Met, 25% of the Cardiff, 26% of the E-Risk, and 25% of the Dunedin cohorts), individuals homozygous for the high COMT–activity allele (Val/Val, 21% of the Cardiff, 25% of the E-Risk, and 25% of the Dunedin cohorts), and heterozygotes (Val/Met, 54% of the Cardiff, 49% of the E-Risk, and 50% of the Dunedin cohorts). We have previously demonstrated that there is no evidence for significant association between the COMT Val158Met variant and ADHD in the Cardiff sample, using family-based association analysis (χ² = 0.02, P = .88). Similarly, the COMT Val158Met variant was also not associated with ADHD in the E-Risk cohort (χ² = 0.18, P = .91; the percentage of children meeting diagnostic criteria for ADHD in each genotype group was 8% in the Met/Met, 8% in the Val/Met, and 7% in the Val/Val genotypes) nor in the Dunedin cohort (χ² = 0.50, P = .78; the percentage of children meeting diagnostic criteria for ADHD in each genotype group was 5% in the Met/Met, 6% in the Met/Val, and 5% in the Val/Val genotypes).

STATISTICAL ANALYSIS
Association with antisocial behavior was tested using multiple regression analysis. Possession of at least 1 Met allele (vs the Val/Val genotype) was the independent (predictor) variable. To test whether the association of the Val158Met variant with antisocial behavior was stronger among children with diagnosed ADHD than among children without ADHD, an interaction term (ADHD × COMT Val158Met) was also included. We used ordinary least squares regression to analyze continuous outcome measures and binomial regression to analyze categorical outcome measures. For all samples, genotyping was performed blind to phenotype and the hypothesis of this study. Study protocols were approved by the institutional review boards of the participating universities, and informed consent was obtained from study participants.

Among ADHD cases in the Cardiff sample, we observed a significant association between COMT Val158Met and the total number of conduct disorder symptoms (Figure 1). Individuals homozygous for the Val allele had significantly more conduct disorder symptoms than Met allele carriers (b = 0.43, SE = 0.21, t = 2.02, P = .05). Haplotypes at COMT have been reported to be associated with alteration in COMT expression and thus may modify the functional effects at the Val/Met locus. We therefore examined the 2 other markers in COMT (rs737865 near exon 1 and rs165599 near the 3'-untranslated region), which, together with the Val158Met variant (rs4680), define those haplotypes. Neither marker alone was found to be associated with ADHD in a previous analysis of this sample, nor were haplotypes constructed from any combination of the 3 markers. Similarly, neither marker showed a trend for association with childhood conduct disorder symptoms (rs737865, b = −0.23, SE = 0.17, t = 1.36, P = .17; rs165599, b = −0.12, SE = 0.18, t = 0.68, P = .50). These findings indicated that the COMT Val158Met variant was associated with antisocial behavior in this sample.

We turned to the E-Risk Study to test replication of findings in the Cardiff clinical sample. The E-Risk cohort faithfully represents population heterogeneity within ADHD cases and within children without ADHD. The cases were not subject to factors that could bias recruit-
The association between the Val158Met variant and antisocial behavior showed some specificity to the molecular genetic basis for dividing children with diagnosed ADHD into those with and without risk for antisocial behavior. The association between the Val158Met variant and criminal behavior was significantly stronger among children with ADHD than among children without (b = −0.18, z = 0.06, P = .95). The association between the Val158Met variant and criminal behavior was significantly stronger among children with ADHD than among children without (b = 1.85, SE = 0.35, z = 2.41, P = .02), confirming that the COMT Val158Met variant is a risk factor for antisocial behavior in ADHD cases but is not a susceptibility gene for antisocial behavior in the general population.

Five points are relevant for interpreting the findings across the 3 samples. First, the COMT Val/Val genotype was not associated with ADHD symptom severity (Table 1) and the association between this genotype and antisocial behavior remained after controlling for ADHD symptom severity (Cardiff cohort, b = 0.40, SE = 0.21, t = 1.91, P = .06; E-Risk cohort, b = 0.26, SE = 2.83, t = 2.21, P = .03; Dunedin cohort, b = 0.83, SE = 0.42, t = 2.00, P = .05). Second, the COMT Val/Val genotype was not associated with lower IQ scores (Table 1), and the association between this genotype and antisocial behavior remained after controlling for IQ (Cardiff cohort, b = 0.51, SE = 0.20, t = 2.55, P = .01; E-Risk cohort, b = 5.66, SE = 3.03, t = 1.87, P = .06; Dunedin cohort, b = 0.97, SE = 0.44, z = 2.19, P = .03). (Post hoc analysis also revealed no association between the COMT genotype and maternal smoking during pregnancy, a putative risk factor for conduct disorder.)

Third, the association between the COMT Val/Val genotype and antisocial behavior among children with ADHD was not an artifact of ethnic stratification: The Cardiff ADHD Genetic Study enrolled only white children; our analyses of the New Zealand birth cohort (Dunedin Longitudinal Study) excluded individuals of Maori origin; and in the E-Risk Study, the relationship between genotype risk and antisocial behavior was reestimated excluding non-white children with ADHD (n = 15), yielding nearly identical results (b = 1.61, SE = 3.15, t = 1.96, P = .05). Fourth, the association between the COMT Val/Val genotype and antisocial behavior among children with diagnosed ADHD is unlikely to be because of selective receipt of or in response to medication. In the Cardiff clinical sample, children with the Val/Val genotype were no less likely to have ever received medication than Met carriers (χ² = 0.09, P = .81), and among medicated children, there was no association between the Val158Met variant and positive medication response assessed by the Clinical Global Impressions scale (b = −0.07, SE = 0.11, t = −0.67, P = .51). Fifth, the molecular genetic basis for dividing children with diagnosed ADHD into those with and without risk for antisocial behavior showed some specificity to the COMT Val158Met single nucleotide polymorphism, as the association was not found with polymorphisms in 2 dopamine-system candidate genes widely hypothesized to be relevant in the pathogenesis of ADHD and its clinical
features: the 10-repeat allele of a variable number of tandem repeats in the 3’-untranslated region of the dopamine transporter gene (DAT1) and the 7-repeat allele of a variable number of tandem repeats polymorphism in the dopamine D4 receptor gene (DRD4). In contrast to COMT Val158Met, these were not consistent, significant predictors of antisocial behavior in children with ADHD across our 3 samples (Table 2).

We found evidence in 3 independent studies that heterogeneity, in terms of antisocial behavior, among children with diagnosed ADHD is associated with variation in the COMT gene. Pooling results across these 3 samples, along with results from a Canadian clinical study (the Douglas Hospital Study39), the mean effect size for the difference in antisocial behavior between COMT Val/Val homozygotes and Met carriers was 0.32 (95% confidence interval, 0.05-0.59; $z = 2.30$; $P = .02$) (Figure 4). The replicability is notable for 3 reasons: Val/Val homozygotes were observed to be more antisocial than Met carriers in both clinic-referred and community samples; were assessed using different, albeit age-appropriate, measures of the same putative antisocial phenotype; and were assessed in different stages of life. The replicability is not perfect, and a false-positive association cannot be ruled out with certainty. Future studies can build on the meta-analysis reported here to refine the estimate of the association between COMT and antisocial behavior among children with ADHD.

Table 1. Antisocial Outcomes, ADHD Symptom Severity, and Intelligence Among Children With Diagnosed ADHD as a Function of the COMT Val158Met Genotype

<table>
<thead>
<tr>
<th>Measure</th>
<th>COMT Val158Met Genotype</th>
<th>Association Between COMT Val158Met and Study Measuresa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Met/Met</td>
<td>Val/Met</td>
</tr>
<tr>
<td>No. of participants</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cardiff ADHD Genetic Study</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conduct disorder symptom score</td>
<td>59</td>
<td>130</td>
</tr>
<tr>
<td>ADHD symptom scale score</td>
<td>0.76 (1.28)</td>
<td>0.82 (1.29)</td>
</tr>
<tr>
<td>IQC</td>
<td>14.03 (2.65)</td>
<td>15.02 (2.26)</td>
</tr>
<tr>
<td>Social classd</td>
<td>90.0 (11.06)</td>
<td>90.13 (11.76)</td>
</tr>
<tr>
<td>Environmental Risk Study</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aggressive behavior scale score</td>
<td>63.41 (15.89)</td>
<td>63.18 (13.19)</td>
</tr>
<tr>
<td>ADHD symptom scale score</td>
<td>12.39 (2.98)</td>
<td>12.05 (2.84)</td>
</tr>
<tr>
<td>IQe</td>
<td>88.8 (12.90)</td>
<td>90.34 (15.85)</td>
</tr>
<tr>
<td>Social classd</td>
<td>1.65 (0.84)</td>
<td>1.75 (0.81)</td>
</tr>
<tr>
<td>Dunedin Longitudinal Study</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antisocial composite index</td>
<td>1.27 (1.42)</td>
<td>1.56 (1.25)</td>
</tr>
<tr>
<td>Adult court convictions, %</td>
<td>27</td>
<td>33</td>
</tr>
<tr>
<td>ADHD symptom scale score</td>
<td>13.00 (7.6)</td>
<td>8.48 (6.3)</td>
</tr>
<tr>
<td>IQf</td>
<td>97.52 (14.92)</td>
<td>88.60 (13.43)</td>
</tr>
<tr>
<td>Social classd</td>
<td>1.55 (0.69)</td>
<td>1.85 (0.60)</td>
</tr>
</tbody>
</table>

Abbreviations: ADHD, attention-deficit/hyperactivity disorder; COMT, catechol O-methyltransferase gene; Met, methionine; Val, valine.

a Values are mean (SD) unless otherwise specified.

b In each sample, multiple regression analysis was used to compare COMT Val/Val homozygotes with Met carriers.

c Assessed using the Wechsler Intelligence Scale for Children.34

d Reported on a 3-point scale (1 = low, 3 = high).

e Assessed using a short form of the Wechsler Preschool and Primary Scale of Intelligence, Revised.35 Scores were standardized (mean, 100 [SD, 15]).

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The neurobiological route by which the observed COMT effect is achieved remains speculative. One possibility is that COMT is related to impaired executive functions. The COMT gene is relevant for dopamine metabolism in the PFC, and is a candidate gene for modulating PFC executive functions. Emerging imaging data are consistent regarding the importance of the COMT variant in PFC function, which is impaired in those with antisocial behavior and ADHD. Executive dysfunctions interfere with children's ability to control their own behavior, impairing them to consider the future implications of their acts. Such children may have difficulty understanding the negative effect their behavior has on others, fail to hold abstract ideas of ethical values and future rewards in their minds, and fail to inhibit inappropriate behavior or adapt behavior to changing social circumstances. For this reason, Sapolsky has noted that the PFC is the closest thing we possess to a superego. This hypothesis merits further scrutiny, using developmentally appropriate measures of prefrontally guided behaviors, though initial reports, including data from the Cardiff ADHD Genetic Study, did not find an association between the COMT genotype and several tests of executive functioning. Another possibility is that the COMT variant escapes to emotional dysregulation. Imaging findings suggest that COMT Val alleles are related to reduced responsiveness to unpleasant stimuli, which may be a marker of aggressive, sometimes violent, behavior in a subset of individuals.

Importantly, COMT does not appear to be a susceptibility gene for aggression or antisocial behavior; there was no evidence of an association between the COMT ValMet variant and antisocial behavior (nor with ADHD) in the general population. Rather, the COMT ValMet variant influenced phenotypic variation within children with ADHD and predicted which of these chil-
Children would engage in antisocial behavior. That the asso-
ciation between genotype and antisocial behavior was
conditional on ADHD diagnosis suggests that the in-
volvement of COMT in antisocial behavior relies on the
interaction(s) with other genes or other etiological fac-
tors involved in ADHD (hence, the association between
genotype and antisocial behavior was not observed among
children without ADHD). Such a situation is antici-
pated by animal research showing that genetic variants
are associated with highly variable phenotypes depend-
ing on genetic background (eg, knockouts lead to dif-
ferent phenotypic effects in different strains); COMT may
thus operate as a modifier gene, acting against a back-
ground of other etiological factors to affect clinical fea-
tures and ADHD course rather than as a direct suscepti-
bility gene. For example, in the Cardiff sample, the
association between COMT and antisocial behavior is most
pronounced among children with low birth weight, but
given the relatively small number of ADHD cases, we could
not explore this possibility in the 2 birth cohort studies.

The clinical implications of these findings are prema-
ture. However, the results illustrate how genetic infor-
ma...

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