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Genome-wide meta-analyses identify multiple loci associated with smoking behavior

The Tobacco and Genetics Consortium*

Note: Supplementary information is available on the Nature Genetics website.

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Abstract

Consistent but indirect evidence has implicated genetic factors in smoking behavior[1,2]. We report meta-analyses of several smoking phenotypes within cohorts of the Tobacco and Genetics Consortium (n = 74,053). We also partnered with the European Network of Genetic and Genomic Epidemiology (ENGAGE) and Oxford-GlaxoSmithKline (Ox-GSK) consortia to follow up the 15 most significant regions (n > 140,000). We identified three loci associated with number of cigarettes smoked per day. The strongest association was a synonymous 15q25 SNP in the nicotinic receptor gene *CHRNA3* (rs1051730[A], β = 1.03, standard error (s.e.) = 0.053, $P = 2.8 \times 10^{-73}$). Two 10q25 SNPs (rs1329650[G], β = 0.367, s.e. = 0.059, $P = 5.7 \times 10^{-10}$; and rs1028936[A], β = 0.446, s.e. = 0.074, $P = 1.3 \times 10^{-9}$) and one 9q13 SNP in *EGLN2* (rs3733829[G], β = 0.333, s.e. = 0.058, $P = 1.0 \times 10^{-8}$) also exceeded genome-wide significance for cigarettes per day. For smoking initiation, eight SNPs exceeded genome-wide significance, with the strongest association at a nonsynonymous SNP in *BDNF* on chromosome 11 (rs6265[C], odds ratio (OR) = 1.06, 95% confidence interval (Cl) 1.04–1.08, $P = 1.8 \times 10^{-8}$). One SNP located near *DBH* on chromosome 9 (rs3025343[G], OR = 1.12, 95% Cl 1.08–1.18, $P = 3.6 \times 10^{-8}$) was significantly associated with smoking cessation.

Previous genome-wide association studies (GWAS) for smoking behavior (Supplementary Table 1) have identified a chromosome-15 nicotinic acetylcholine receptor gene cluster as being associated with smoking quantity[3]. The Tobacco and Genetics (TAG) Consortium conducted GWAS meta-analyses across 16 studies originally designed to evaluate other phenotypes (for example, cardiovascular disease and type 2 diabetes). We examined four carefully harmonized smoking phenotypes (see Online Methods)—smoking initiation (ever versus never been a regular smoker), age of smoking initiation, smoking quantity (number of cigarettes smoked per day, CPD) and smoking cessation (former versus current smokers)—among people of European ancestry (Table 1). Smoking cessation contrasted former versus current smokers, where current smokers reported at interview that they presently smoked and former smokers had quit smoking at least 1 year before interview. Smokers who had quit smoking for less than 1 year at interview were excluded from the analysis to minimize misclassification, as relapse after initial smoking cessation occurs in 70% to 80% of former smokers within the first year[4].

The 16 TAG studies performed their own genotyping, quality control and imputation (see Supplementary Tables 2 and 3 and Online Methods). Studies ranged in size from n = 585 to n = 22,037 and were genotyped on six different platforms. Genotype imputation[5] resulted in a common set of ~2.5 million SNPs (Supplementary Table 3). Imputed allele dosages for each SNP (that is, the number of copies of the minor allele) were tested for association with each smoking phenotype, using an additive model.

We performed a fixed-effect meta-analysis for each smoking phenotype by computing pooled inverse variance–weighted β coefficients, s.e. values and z-scores for each SNP[6]. Fixed-effects analyses are regarded as the most efficient method for discovery in the GWAS setting[7,8]. Heterogeneity across studies was investigated using the I^2 statistic[9]. Random-effects analyses are presented in Supplementary Table 4. We used a significance threshold of $P < 5 \times 10^{-8}$ (refs. 10,11).

In the initial TAG meta-analysis, only one locus contained SNPs that exceeded genome-wide significance for one of the four phenotypes (Fig. 1 and Supplementary Table 4). A total of 130 SNPs in the 15q25.1 nicotinic receptor gene cluster were significantly associated with CPD (n = 38,181, minimum $P = 4.2 \times 10^{-35}$ at rs12914385 in *CHRNA3*). One SNP approached significance for smoking cessation (n = 41,278, minimum $P = 5.5 \times 10^{-8}$ for rs7872903, located ~17 kb 5′ of *DBH* on chromosome 9). No SNPs were significantly associated with ever versus never regular smokers (n = 74,035, minimum $P = 2.2 \times 10^{-7}$ at rs16941640 in *CDC27*) or age

of smoking initiation (n = 24,114, minimum $P = 1.6 \times 10^{-6}$ at rs2806464, located 3′ of *DISC1*) in the initial TAG meta-analysis.

To follow up associations identified in the TAG Consortium analyses, we partnered with the ENGAGE and Oxford-GlaxoSmithKline (Ox-GSK) consortia and conducted a reciprocal exchange of summary results for the 15 most significant genetic regions for three smoking phenotypes[12,13]. Our regions were defined by clusters of P values < 10^{-4} (that is, where the correlations (r^2) were >0.5 and/or the SNPs were located <50 kb apart; Supplementary Table 5). Sample sizes across the three consortia were n = 143,023 for smoking initiation, n = 73,853 for CPD and n = 64,924 for smoking cessation (data on age of smoking initiation were not available in ENGAGE or Ox-GSK).

Results of the most significant SNPs for each smoking phenotype across the three consortia are summarized in Table 2. We identified three loci associated with CPD. The synonymous SNP rs1051730 in *CHRNA3* showed the strongest association: each copy of the A allele corresponded to an increase in smoking quantity of 1 CPD (β = 1.03, s.e. = 0.056, $P = 2.8 \times 10^{-73}$, $I^2 = 0.66$; Fig. 2) and accounted for 0.5% of the variance in CPD. The SNP rs16969968 [G], which has been proposed as a causal variant in this region[14], was the second most significant SNP associated with CPD ($P = 5.57 \times 10^{-72}$; Supplementary Fig. 1). In tests of association for SNPs within the 15q25.1 region conditional on rs1051730, we observed residual associations, with the most significant signals at rs684513[G] ($P = 6.3 \times 10^{-9}$), in *CHRNA5*, and rs9788682[G] ($P = 1.06 \times 10^{-8}$) and rs7163730[G] ($P = 1.22 \times 10^{-8}$), in *LOC123688* (Supplementary Fig. 2 and Supplementary Table 6). Our results suggest that several markers within this region may influence CPD independently. Fine mapping and the use of the 1000 Genomes Project data should help refine these signals. We investigated whether the 15q25.1 region was associated with smoking initiation and smoking cessation as well, but no SNP in that region exceeded genome-wide significance (smoking initiation minimum P = 0.98; smoking cessation minimum $P = 1.75 \times 10^{-5}$).

In addition, markers within regions on chromosomes 10q23 and 19q13 were significantly associated with CPD. The SNPs rs1329650[G] (β = 0.367, s.e. = 0.059, $P = 5.7 \times 10^{-10}$; Fig. 2) and rs1028936[A] (β = 0.446, s.e. = 0.074, $P = 1.3 \times 10^{-9}$; Supplementary Fig. 1) are located in a noncoding RNA (*LOC100188947*), where each additional copy of a risk allele corresponded to an increase in smoking quantity of ~0.5 CPD. Linkage disequilibrium (LD) between these SNPs is moderate ($r^2 = 0.46$), suggesting that they may represent one signal. To our knowledge, this region has not been previously investigated in relation to smoking behavior or other addiction phenotypes.

The third locus identified for CPD lies in the first intron of *EGLN2* on chromosome 19q13, 40 kb from the 3′ end of *CYP2A6*. One SNP, rs3733829, exceeded genome-wide significance, and each copy of the G allele corresponded to an increase in smoking quantity of <0.5 CPD (β = 0.333, s.e. = 0.058, $P = 1.0 \times 10^{-8}$; Fig. 2). *CYP2A6* is an established candidate gene for smoking, as it encodes for an enzyme involved in the metabolic inactivation of nicotine to cotinine[15]. Many allelic variants of CYP2A6 result in slower metabolism of nicotine[16] and are associated with lower prevalence of smoking and lower amounts of cigarette use[16,17]. We interpret this finding with caution, as only one SNP upstream of *CYP2A6* was observed and the strength of its association was moderate. However, the 19q13 region merits continued investigation given its biological plausibility as involved in nicotine metabolism and because several markers within this region were identified in the ENGAGE Consortium[12]. The SNP identified in our study (rs3733829) lies directly between, and shows moderate LD with, the two most significant markers identified in ENGAGE.

Eight SNPs around *BDNF* exceeded genome-wide significance for smoking initiation analyses across the three consortia (Fig. 3). The minimum *P* value was at the missense variant rs6265 ($P = 1.8 \times 10^{-8}$) located in the first exon of *BDNF* on chromosome 11. Each copy of rs6265 [C] conferred a 6% increase in the relative risk of regular smoking (OR = 1.06, 95% c.i. 1.04–1.08); rs6265 accounted for 0.03% of the variance. BDNF belongs to a family of neurotrophins that regulate synaptic plasticity and survival of cholinergic and dopaminergic neurons[18]. The eight SNPs overlap an antisense transcript (*BDNFos*). *BDNF* is expressed at high levels in the prefrontal cortex and hippocampus, which are brain regions implicated in the cognitive-enhancing effects of nicotine[19]. Although the molecular mechanisms underlying this association have yet to be elucidated, it is plausible that genetic variation at *BDNF* could alter the rewarding effects of nicotine through modulation of dopamine reward circuits and could contribute to the salience of nicotine's effects by altering formation of drug-related memories that promote continued use after initial exposure. The SNP rs6265 has been found to be associated with substance-related disorders, eating disorders and schizophrenia[20]. Most recently, it was identified in a GWAS for body mass index[21]; the allele associated with a greater body mass index was the same allele associated with regular smoking in our study.

For smoking cessation, one SNP, located 23 kb 5′ of *DBH* on chromosome 9, achieved genome-wide significance: rs3025343[G] was associated with former smoking status (OR = 1.12, 95% c.i. 1.08–1.18, $P = 3.6 \times 10^{-8}$; Fig. 3) and accounted for 0.19% of the variance in smoking cessation. Because DBH catalyzes conversion of dopamine to norepinephrine, there has been interest in *DBH* as a candidate gene for various psychiatric phenotypes, including smoking behavior[22]. Although the SNP identified in this study does not cause amino acid residue changes in DBH, gene expression may be modified either directly or through other variant(s) in strong LD. This view is supported by evidence that a genetic variant (C1021T or rs1611115), located upstream of the *DBH* translational start site, accounts for 51% of the variation in plasma-DBH activity in European-Americans[22]. Alternatively, the SNP identified in our study or a variant in LD may influence expression of other genes nearby (*ADAMTSL2*, *FAM163B* or *SARDH*), which would introduce new pathways to our current understanding of addiction biology.

To our knowledge, the sample sizes for the TAG Consortium alone and combined with the ENGAGE and Ox-GSK consortia are among the largest genetic meta-analyses yet conducted23. Notably, most of the loci identified in this study reside in or near known candidate genes involved in the neurobiology of smoking, which differs from the results of previous GWAS, in which variants identified have generally not been in regions previously suspected. The lack of findings for smoking initiation and cessation is noteworthy in light of considerable genetic epidemiological data suggesting a role for genetic factors in different aspects of smoking behavior (for example, heritability estimates are often >0.50)1, and we note that the loci identified do not of themselves account for more than small fractions of the phenotypic heritability. Additional smoking behavior loci may be identified with improved genomic coverage and analysis of gene-gene and gene-environment interaction, copy number variation or epigenetic effects. We acknowledge that imprecision in phenotypic assessment and differences across studies could have added noise sufficient to blur all but the most prominent genetic signals. Smoking behavior obtained by questionnaires may be subject to phenotypic misclassification. Recent work24 has shown that genetic variation at 15q25.1 influences cotinine (the main and long-lived metabolite of nicotine) measurements more strongly than it influences CPD values obtained by means of a questionnaire. Future smoking GWAS that use biomarkers or longitudinal assessments that refine phenotypic assessments by incorporating time to quitting or relapsing to smoking may be required. In addition, inclusion of multiple ethnic groups will enhance the investigation of the genetics of smoking.

Notably, the five significant loci identified in these meta-analyses were each associated with only one specific smoking phenotype. Our findings suggests that separate genetic loci contribute modestly to phenotypic variability in each aspect of smoking behavior, which, in turn, may have implications for the way in which smoking cessation therapies and tobacco control efforts are designed and targeted.

Methods

Methods and any associated references are available in the online version of the paper at http://www.nature.com/naturegenetics/.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Appendix

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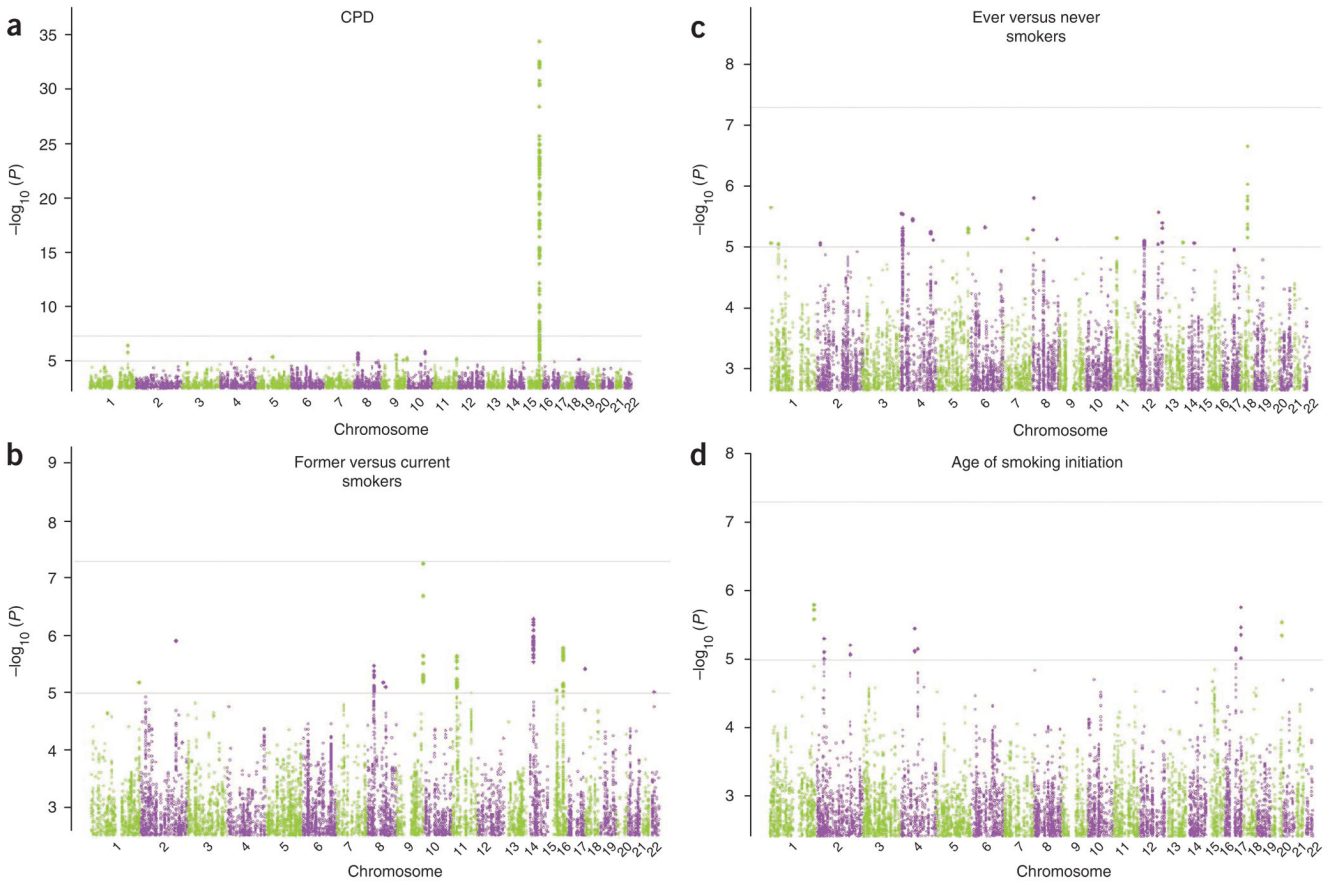

Figure 1.

Genome-wide association results for the TAG Consortium. Manhattan plots showing significance of association of all SNPs in the TAG Consortium meta-analyses for four smoking phenotypes. (**a**–**d**) Manhattan plots show SNPs plotted on the *x* axis according to their position on each chromosome against, on the *y* axis (shown as $-\log_{10} P$ value), the association with CPD (**a**), former versus current smoking (**b**), ever versus never smoking (**c**) and age of smoking initiation (**d**).

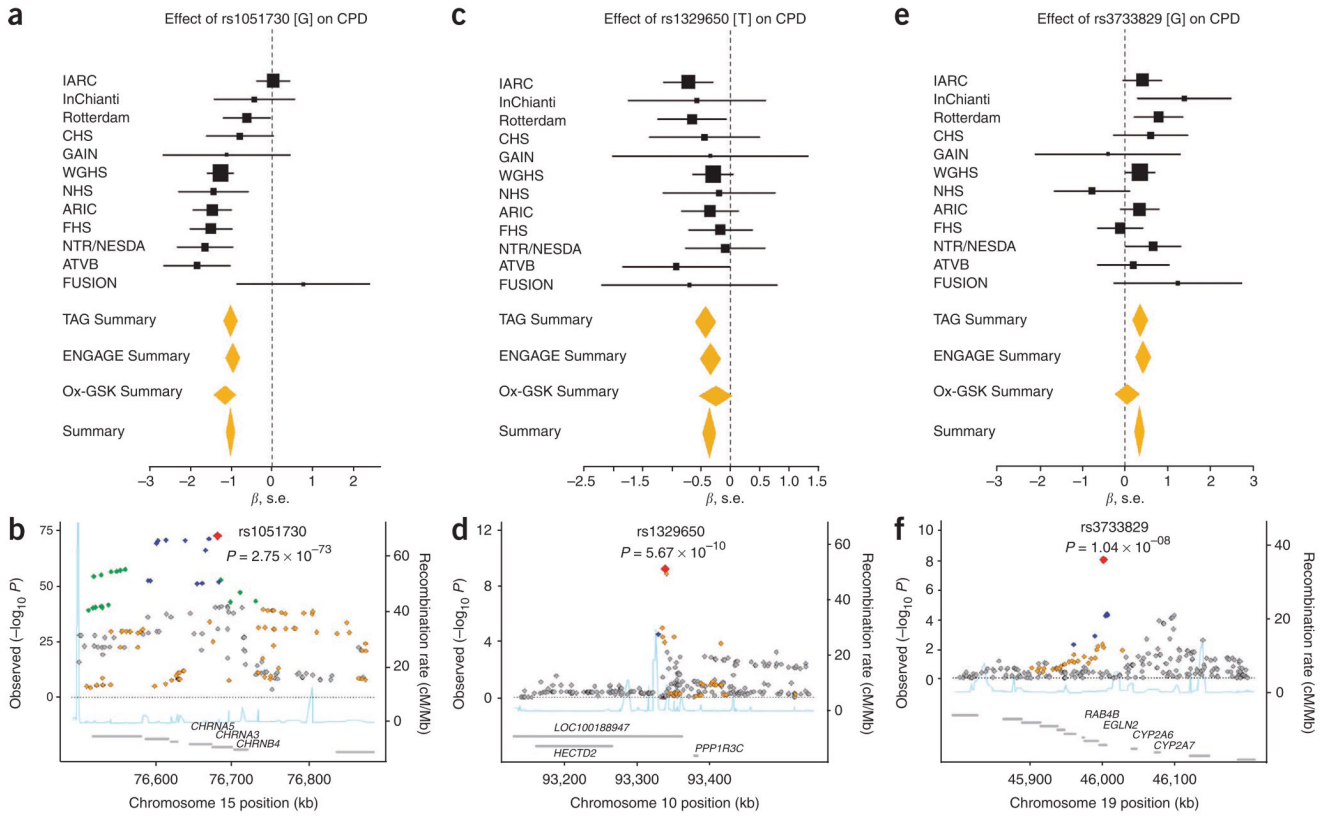

Figure 2.

Forest and regional plots of significant associations for CPD from meta-analyses of the TAG, Ox-GSK and ENGAGE consortia. (**a**–**f**) Regional association plots show SNPs plotted by position on chromosome against $-\log_{10} P$ value with each smoking phenotype. Estimated recombination rates (from HapMap-CEU) are plotted in light blue to reflect the local LD structure on a secondary *y* axis. The SNPs surrounding the most significant SNP (red diamond) are color coded to reflect their LD with this SNP (using pairwise r^2 values from HapMap-CEU): blue, $r^2 \geq 0.8$–1.0; green, 0.5–0.8, orange, 0.2–0.5; gray, <0.2. The gray bars at the bottom of the plot represent the relative size and location of genes in the region.

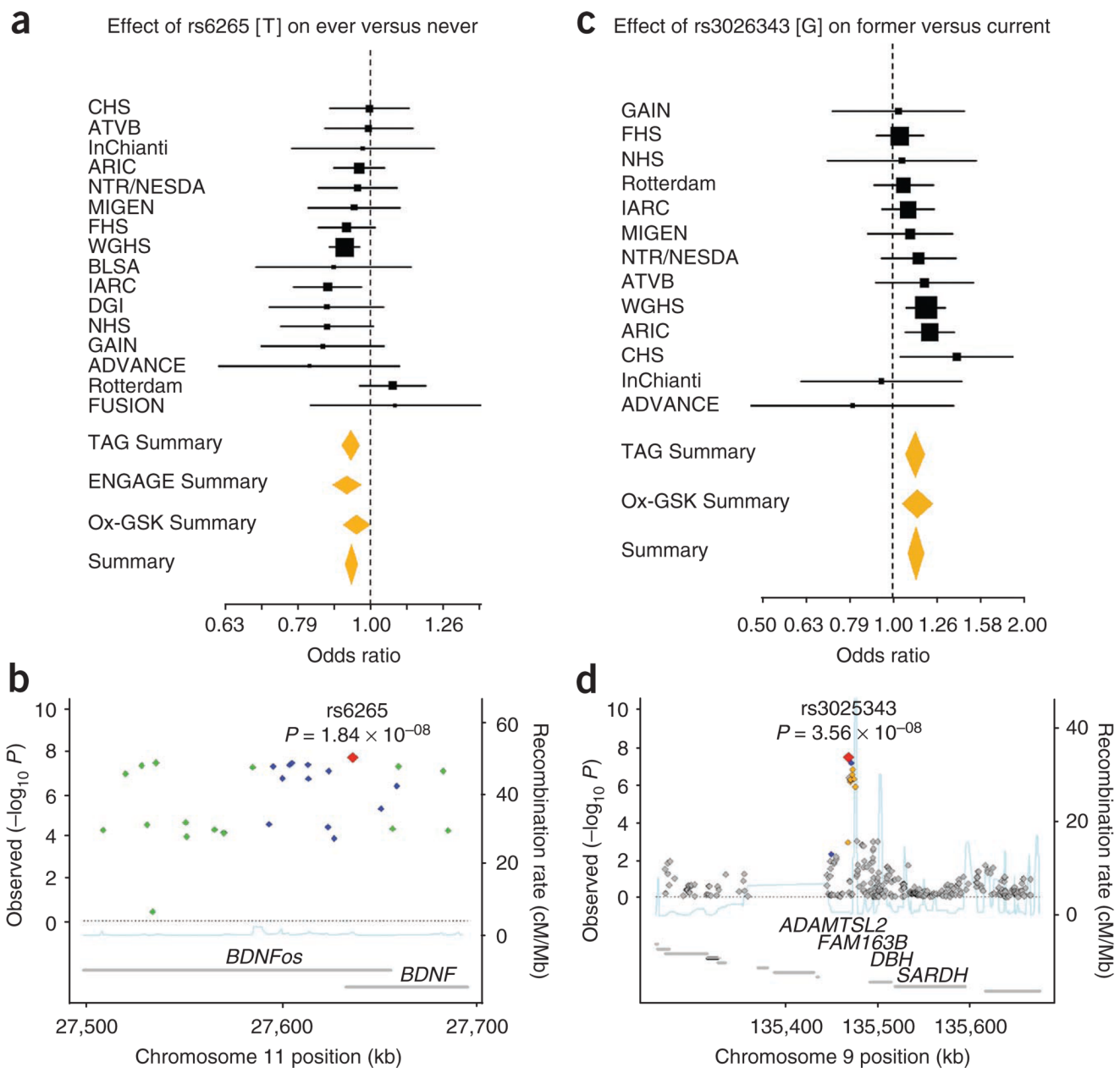

Figure 3.

Forest and regional plots of significant associations for smoking behavior. (**a**–**d**) Shown are plots for smoking initiation (**a**,**b**) and smoking cessation (**c**,**d**) from meta-analyses of the TAG, Ox-GSK and ENGAGE consortia. Regional association plots show SNPs plotted by position on the chromosome against $-\log_{10} P$ value with each smoking phenotype. Estimated recombination rates (from HapMap-CEU) are plotted in light blue to reflect the local LD structure on a secondary *y* axis. The SNPs surrounding the most significant SNP (red diamond) are color coded to reflect their LD with this SNP (using pairwise r^2 values from HapMap CEU): blue, $r^2 \geq 0.8$–1.0; green, 0.5–0.8; orange, 0.2–0.5; gray, <0.2. The gray bars at the bottom of the plot represent the relative size and location of genes in the region.

Table 1

Descriptive characteristics of the 16 studies participating in the TAG Consortium

Study	*n* (% female)	Age[a], mean (s.d.)	Ever smokers (%)	CPD, mean (s.d.)[b]	Age of initiation of smoking[a], mean (s.d.)[b]	Former smokers (%)[b]
Population-based cohort studies						
Atherosclerosis Risk in Communities (ARIC)	8,330 (52.9)	54.3 (5.7)	60.4	21.0 (11.7)	18.6 (5.1)	57.4
Baltimore Longitudinal Study of Aging (BLSA)	856 (46.0)	48.1 (17.8)	54.0	NA	19.3 (5.9)	NA
Cardiovascular Health Study (CHS)	3,236 (60.8)	72.3 (5.4)	52.3	17.8 (11.8)	19.6 (6.6)	77.8
Invecchiare in Chianti (InCHIANTI)	1,200 (55.2)	68.4 (15.5)	43.9	14.8 (9.4)	32.2 (16.7)	57.0
Rotterdam Study	5,610 (60.3)	69.1 (8.9)	59.2	15.8 (11.7)	20.4 (8.2)	62.6
Framingham Heart Study (FHS)	7,257 (53.7)	45.4 (10.9)	54.2	15.5 (10.8)	17.9 (4.2)	61.7
Women's Genome Health Study (WGHS)	22,037 (100)	54.7 (7.1)	49.2	16.0 (11.0)	NA	75.2
Case-control studies						
Atherosclerotic Disease Vascular Function and Genetic Epidemiology (ADVANCE)	585 (58.8)	45.8 (5.9)	47.7	13.1 (14.2)	17.0 (4.6)	65.2
Atherosclerosis, Thrombosis and Vascular Biology Italian Study Group (ATVB)	3,260 (11.6)	39.6 (4.9)	68.1	23.4 (14.7)	17.4 (4.0)	21.3
Diabetes Genetic Initiative (DGI)	2,504 (50.0)	61.6 (10.6)	37.7	NA	19.0 (5.5)	NA
Finland-United States Investigation of NIDDM Genetics (FUSION)	1,055 (52.8)	64.0 (7.5)	46.8	16.3 (12.4)	21.0 (7.0)	65.0
International Agency for Research on Cancer (IARC)	8,381 (24.7)	59.6 (10.1)	75.2	19.3 (12.9)	18.7 (5.6)	31.4
Myocardial Infarction Genetics Consortium (MIGen)	2,647 (38.5)	48.8 (8.2)	64.3	NA	NA	41.1
Nurses' Health Study (NHS)	2,249 (100)	70.5 (6.4)	53.8	18.5 (10.5)	19.6 (3.6)	88.7
Netherlands Twin Registry-Netherlands Study of Depression and Anxiety (NTR/NESDA)	3,438 (66.9)	43.8 (13.4)	64.9	14.5 (9.8)	16.4 (4.2)	52.6
MGS (GAIN):controls	1,390 (54.1)	51.1 (17)	55.9	19.3 (16.4)	NA	62.9

[a] Age in years.

[b] Calculated among ever regular smokers.

NA, not available.

Table 2

Meta-analytic results from three GWAS smoking consortia

		TAG meta-analysis					Ox-GSK meta analysis				ENGAGE meta analysis				Combined results			
SNP	**Alleles**	**Coded AF**	***n***	**β**	**s.e.**	***P* value**	***n***	**β**	**s.e.**	***P* value**	***n***	**β**	**s.e.**	***P* value**	***n***	**β**	**s.e.**	***P* value**
CPD[a]: *CHRNA3*																		
rs1051730	G/A	0.65	38,181	−1.0207	0.086	8.00×10^{-33}	14,952	−1.1593	0.139	8.88×10^{-17}	20,720	−0.9648	0.089	2.15×10^{-27}	73,853	−1.0209	0.056	2.75×10^{-73}
rs16969968	G/A	0.65	38,181	−1.0150	0.085	4.48×10^{-33}	14,952	−1.1153	0.137	3.72×10^{-16}	20,720	−0.9426	0.089	2.07×10^{-26}	73,853	−1.0029	0.056	5.57×10^{-72}
CPD: in *LOC100188947*																		
rs13279650	T/G	0.28	38,181	−0.4317	0.091	2.33×10^{-6}	14,952	−0.2568	0.145	7.61×10^{-2}	20,720	−0.3464	0.092	1.73×10^{-4}	73,853	−0.3673	0.059	5.67×10^{-10}
rs10128936	C/A	0.18	37,284	−0.5545	0.116	1.57×10^{-6}	14,952	−0.2451	0.176	1.65×10^{-1}	20,720	−0.4252	0.113	1.77×10^{-4}	72,956	−0.4464	0.074	1.29×10^{-9}
CPD: *EGLN2*, near *CYP2A6*																		
rs3733829	G/A	0.36	38,181	0.3538	0.090	$7.67 \times 10^{-}$	14,952	0.0477	0.145	7.43×10^{-1}	20,720	0.4204	0.089	2.90×10^{-6}	73,853	0.3328	0.058	1.04×10^{-8}
Smoking initiation (ever versus never smokers): *BDNF*																		
rs6265	T/C	0.21	74,035	−0.0630	0.015	1.72×10^{-5}	34,226	−0.0448	0.022	4.48×10^{-2}	34,762	−0.0762	0.024	1.39×10^{-3}	143,023	−0.0614	0.011	1.84×10^{-8}
rs10835442	T/A	0.26	74,035	−0.0568	0.014	3.39×10^{-5}	34,226	−0.0386	0.021	6.36×10^{-2}	34,762	−0.0674	0.020	9.60×10^{-4}	143,023	−0.0551	0.010	3.31×10^{-8}
rs4923457	T/A	0.23	74,035	−0.0600	0.014	2.08×10^{-5}	34,226	−0.0421	0.022	5.05×10^{-2}	34,762	−0.0752	0.024	1.91×10^{-3}	143,023	−0.0586	0.011	3.33×10^{-8}
rs4923460	T/G	0.23	74,035	−0.0598	0.014	2.22×10^{-5}	34,226	−0.0427	0.022	4.81×10^{-2}	34,762	−0.0734	0.024	2.51×10^{-3}	143,023	−0.0583	0.011	4.08×10^{-8}
rs4923134	T/C	0.23	74,035	−0.0603	0.014	1.90×10^{-5}	34,226	−0.0421	0.022	5.08×10^{-2}	34,762	−0.0725	0.024	2.81×10^{-3}	143,023	−0.0582	0.011	4.11×10^{-8}
rs13024100	G/A	0.26	74,035	−0.0557	0.014	4.86×10^{-5}	34,226	−0.0460	0.021	2.62×10^{-2}	34,762	−0.0651	0.022	2.88×10^{-3}	143,023	−0.0554	0.010	4.44×10^{-8}
rs6489320	T/A	0.24	74,035	−0.0597	0.014	2.04×10^{-5}	34,226	−0.0387	0.021	6.78×10^{-2}	34,762	−0.0723	0.024	2.13×10^{-3}	143,023	−0.0571	0.010	4.91×10^{-8}
rs879048	C/A	0.23	74,035	−0.0598	0.014	2.28×10^{-5}	34,226	−0.0409	0.022	5.86×10^{-2}	34,762	−0.0728	0.024	2.41×10^{-3}	143,023	−0.0578	0.011	4.94×10^{-8}
Smoking cessation (former versus current smokers): near *DBH*																		
rs3025343	G/A	0.84	41,278	0.1177	0.026	5.68×10^{-6}	23,646	0.1295	0.041	1.76×10^{-3}	NA	NA	NA	NA	64,924	0.1210	0.022	3.56×10^{-8}

All SNPs coded to NCBI Build 36/UCSC hg18 forward strand. Coded allele frequency refers to the allele analyzed as the predictor allele; it is not necessarily the minor allele. For CPD, 174 SNPs followed up across three consortia; 130 exceeded genome-wide significance and the two top SNPs are presented. NA, not available.

[a] CPD was analyzed as a continuous variable representing the number of cigarettes smoked per day. Smoking initiation and smoking cessation were analyzed as dichotomous variables, contrasting ever versus never and former versus current smokers, respectively.