

Genetic Risk Variants for Social Anxiety

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Social anxiety is a neurobehavioral trait characterized by fear and reticence in social situations. Twin studies have shown that social anxiety has a heritable basis, shared with neuroticism and extraversion, but genetic studies have yet to demonstrate robust risk variants. We conducted genomewide association analysis (GWAS) of subjects within the Army Study To Assess Risk and Resilience in Servicemembers (Army STARRS) to (i) determine SNP-based heritability of social anxiety; (ii) discern genetic risk loci for social anxiety; and (iii) determine shared genetic risk with neuroticism and extraversion. GWAS were conducted within ancestral groups (EUR, AFR, LAT) using linear regression models for each of the three component studies in Army STARRS, and then meta-analyzed across studies. SNP-based heritability for social anxiety was significant ($h^2_g = 0.12$, $P = 2.17 \times 10^{-4}$ in EUR). One meta-analytically genomewide significant locus was seen in each of EUR (rs708012, Chr 6: BP 36965970, $P = 1.55 \times 10^{-8}$; beta = 0.073) and AFR (rs78924501, Chr 1: BP 88406905, $P = 3.58 \times 10^{-8}$; beta = 0.265) samples. Social anxiety in Army STARRS was significantly genetically correlated (negatively) with extraversion ($r_g = -0.52$, se = 0.22, $P = 0.02$) but not with neuroticism ($r_g = 0.05$, se = 0.22, $P = 0.81$) or with an anxiety disorder factor score ($r_g = 0.02$, se = 0.32, $P = 0.94$) from external GWAS meta-analyses. This first GWAS of social anxiety confirms a genetic basis for social anxiety, shared with extraversion but possibly less so with neuroticism. © 2017 Wiley Periodicals, Inc.

Key words: anxiety; extraversion; neuroticism; social anxiety; social phobia

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INTRODUCTION

Social anxiety is a dispositional trait that involves emotional discomfort and reticence in situations where an individual is subject to the scrutiny of others [Craske and Stein, 2016]. Social anxiety disorder (SAD) is characterized by severe anxiety in social situations, which are therefore often avoided, resulting in distress and/or functional impairment [Heimberg et al., 2014]. SAD is among the most common of the anxiety disorders, with a 12-month prevalence in the range of 5–8% and lifetime prevalence 8–12% [Ruscio et al., 2008]. It also has an early age of onset, and is associated with the frequent subsequent accrual of comorbid mental health problems such as, major depression and substance use disorders [Stein and Stein, 2008].

Relatively little is known about the genetics of either social anxiety or SAD [Stein and Gelernter, 2014]. We have shown in prior studies that there is a heritable basis to social anxiety [Stein et al., 2002] and SAD [Stein et al., 2001], and completed a genetic linkage study consistent with the expected polygenicity [Gelernter et al., 2004]. A recent meta-analysis of 13 cohorts (42,585 subjects) showed that genetic and non-shared environmental factors explain most of the individual differences for both social anxiety as a trait and social anxiety as a disorder [Scaini et al., 2014]. Although several candidate gene studies have reported associations with SAD and related traits (e.g., shyness) [Arbelle et al., 2003; Smoller et al., 2008], none has been satisfactorily replicated [Stein and Gelernter, 2014].

The purpose of the present study is to use genomewide association methods to elucidate the genetic architecture of social anxiety. To the best of our knowledge, this is the first GWAS specifically focused on social anxiety. SAD is considered by some to be a temperamental extreme of social anxiety, though factors other than severity may play a role in distinguishing a normal-range trait from disorder [Campbell-Sills et al., 2015]. There is no doubt, however, that social anxiety is a core feature of SAD and, as such, a better understanding of the biological basis of the former will contribute to deeper knowledge about the pathophysiology of the latter [Fox and Kalin, 2014].

Patients with SAD are also known to score very low on the personality trait *extraversion* (i.e., they are extremely “*introverted*”) [Bienvenu et al., 2004; Jylha et al., 2009; Watson and Naragon-Gainey, 2014]. Accordingly, there may be value in

exploring the genetic relationship between extraversion—a trait that has been the subject of a recent, large, genetic meta-analysis [van den Berg et al., 2016]—and social anxiety. This approach is compatible with the notion of studying an “endophenotype” for SAD, as well as with the Research Domain Criteria (RDoC) tactic of studying mental disorders by focusing on their basic underlying dimensions [Cuthbert, 2015].

Another personality trait, neuroticism—the recent subject of two large genetic meta-analyses [Genetics of Personality Consortium et al., 2015; Smith et al., 2016]—is thought to underlie many anxiety and depressive disorders, and the evaluation of its genetic relationship to social anxiety would also be informative. We also explored the genetic relationship of social anxiety to an anxiety disorder factor score derived in a large anxiety disorder GWAS meta-analysis [Otowa et al., 2016]. As a “negative control” we also determined the genetic relationship of social anxiety with Alzheimer’s disease [Lambert et al., 2013].

Lastly, given the well-characterized phenotype of hyper-sociality and low social anxiety in Williams Syndrome (WS) [Morris, 2010; Barak and Feng, 2016], we reasoned that scrutiny of this region might reveal associations with social anxiety. We therefore, paid particular attention to the WS Region (7q11.23 [70–76 Mb]) in our analyses.

METHODS

Subjects

Detailed information about the design and conduct of Army STARRS is available in a separate report [Ursano et al., 2014]. The recruitment, consent, human subject, and data protection procedures were approved by all collaborating organizations.

New soldier study (NSS). The NSS was carried out among new soldiers at the start of their basic training at one of three Army Installations between April 2011 and November 2012. Of 39,784 NSS participants who completed the computerized self-administered questionnaire (SAQ), 33,088 (83.2%) provided blood samples. Genotyping was conducted on samples from the first half of the cohort, from which samples were selected based on phenotype (enriched for probable cases of PTSD, Major Depressive Disorder, Generalized Anxiety Disorder, and suicidality, and then including controls with none of these disorders) (NSS1; N = 7,999). When the

TABLE I. Social Anxiety Factor Scores (by Ancestry) and Sex and Age Distributions in the Samples

	NSS1 (N = 7519)			NSS2 (N = 2700)			PPDS (N = 7109)		
	N	Mean	SD	N	Mean	SD	N	Mean	SD
Population									
European American	4728	0.179	0.893	1807	0.240	0.912	4733	−0.157	0.889
African American	1350	0.107	0.936	399	0.154	0.939	873	−0.180	0.848
Latino American	1441	0.157	0.890	494	0.259	0.901	1503	−0.180	0.882
Sex (% male)		82.5			78.7			94.0	
Age (years)		21.0	3.3		20.3	3.2		26.0	5.9

remaining half of the cohort collection was completed, we selected a subset (focused on post-traumatic stress disorder and suicidal behaviors as principal targets for Army STARRS) for genotyping (NSS2; N = 2,835).

Pre/post-deployment survey (PPDS). The PPDS is a multi-wave panel survey that collected baseline data (T0) from US Army soldiers in three Brigade Combat Teams (BCTs) during the first quarter of 2012, within approximately 6 weeks of their deployment to Afghanistan. 7,927 PPDS soldiers with eligible SAQ responses were genotyped for GWAS.

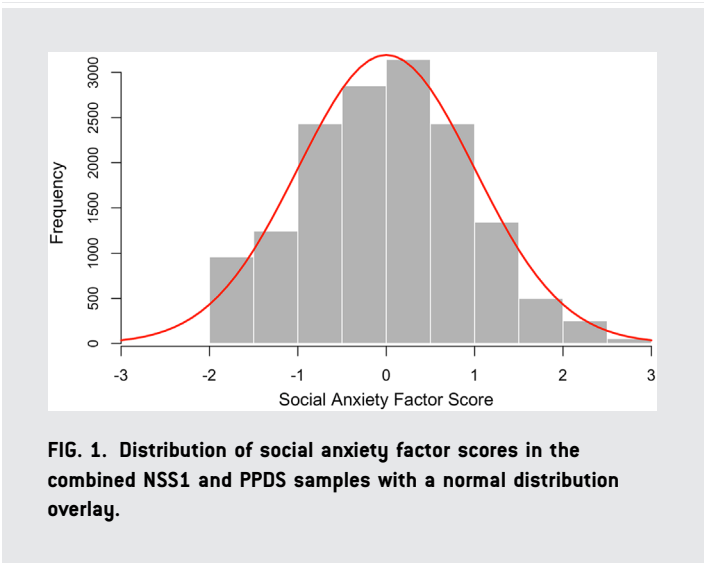
Demographics

The population, sex, and age composition of our analyzed sample is shown in Table I. As expected, the PPDS subjects were older than the new recruits in the NSS. Social anxiety factor scores and standard deviations (SD) are as shown.

Measures

The SAQ included a computerized version of the Composite International Diagnostic Interview screening scales (CIDI-SC) [Kessler and Ustun, 2004]. Four survey items were identified as having content validity consistent with social anxiety. These items, each scored from one (exactly like me) through five (not at all like me) were: “I am much more shy than most people;” “I am pretty quiet around people I don’t know well;” “I get embarrassed easily,” and “I am an outgoing social person” (this item was reverse scored). Also included was a fifth survey item consisting of a single yes/no question (coded 5/1) with face validity for SAD: “Were you ever in your life so painfully shy or scared of social situations, (e.g., attending a party, speaking to strangers, eating in public), that you avoided social situations whenever you could?”).

Factor analysis was used to determine the dimensionality of the five social anxiety items using a random sample of individuals from the NSS1 and PPDS (including all ethnic groups, therefore yielding



a larger sample than analyzed here in the GWAS). The full sample (n = 14,592) was split in half to create training and testing datasets (n = 7,296 each). Exploratory factor analyses conducted using the training dataset, followed by confirmatory factor analyses conducted using the testing dataset both supported a unidimensional measurement model. Measurement invariance was assessed between the NSS1 and PPDS. The analyses indicated non-invariant item thresholds between the NSS1 and PPDS samples that was remedied by adding age as a covariate. Final parameter estimates and factor scores were computed for the combined NSS and PPDS sample (NSS1 and PPDS shown in Fig. 1).

DNA Genotyping, Imputation, and Population Stratification Adjustment

Detailed information on genotyping, genotype imputation, population assignment, and principal component analysis for

TABLE II. SNP-Based Heritability of Social Anxiety (Meta-Analysis Across NSS1, NSS2, PPDS)

	h ² _g	SE (h ² _g)	P-value	95%CI	
All samples					
EUR	0.12	0.033	2.17 × 10 ^{−4}	0.05	0.18
AFR	0.12	0.134	0.176	−0.14	0.38
LAT	0.21	0.102	0.020	0.01	0.41
Male					
EUR	0.14	0.037	8.77 × 10 ^{−5}	0.07	0.21
AFR	0.17	0.174	0.148	−0.17	0.52
LAT	0.19	0.117	0.047	−0.04	0.42
Female					
EUR	0.15	0.316	0.323	−0.47	0.77
AFR	0.28	0.490	0.291	−0.68	1.24
LAT	0.67	0.627	0.158	−0.55	1.90

h²_g, SNP-based heritability; SE, standard error; CI, confidence interval; EUR, European American; AFR, African American; LAT, Latino American. All models adjusted for 10 PCs and study components. The all samples model additionally adjusted for gender.

TABLE III. NSS1, NSS2, and PPDS GWAS Meta-Analysis Results at $P < 10^{-6}$

CHR	BP	SNP	A1 (MAF)	A2	BETA	P
AFR						
1	88406905	rs78924501	T [0.09]	C	0.265	$3.58 \times 10^{-8*}$
EUR						
6	36949527	rs2293390		C	0.0613	4.80×10^{-07}
6	36965970	rs708012	T [0.32]	C	0.0732	$1.55 \times 10^{-8*}$
LAT						
7	49136131	rs35200331	T [0.148]	C	0.1482	2.25×10^{-7}
7	70464765	rs74820377	T [0.186]	C	0.1859	7.71×10^{-7}
11	89078387	rs60391512	T [0.390]	C	0.3900	7.48×10^{-7}
12	108618081	rs117328207	T [0.641]	C	0.6412	4.94×10^{-7}
ALL						
1	88406905	rs78924501	T [0.241]	C	0.2414	1.97×10^{-7}
6	97374850	rs13203153	A [0.061]	G	0.0606	3.08×10^{-7}
6	97391272	rs2223614	A [0.062]	C	0.0619	2.40×10^{-7}
6	97404417	rs34663994	A [0.058]	C	0.0583	8.32×10^{-7}

MAF, minor allele frequency.

* $P < 5 \times 10^{-8}$

population stratification adjustment are included in our previous report [Stein et al., 2016] and in Supplementary Materials. Whole blood samples were shipped to Rutgers University Cell and DNA Repository (RUCDR), where they were frozen for later DNA extraction using standard methods. NSS1 and PPDS samples were genotyped using the Illumina OmniExpress + Exome array with additional custom content. NSS2 samples were genotyped on the Illumina PsychChip.

Relatedness testing was carried out with PLINK v1.90 [Purcell et al., 2007; Chang et al., 2015] and pairs of subjects with π of >0.2 were identified; one member of each relative pair was removed at random. Genotype imputation was performed with a 2-step pre-phasing/imputation approach with a reference multi-ethnic panel from 1,000 Genomes Project (August 2012 phase 1 integrated release; 2,186 phased haplotypes with 40,318,245 variants). We removed SNPs that were not present in the 1,000 Genomes Project reference panel, had non-matching alleles to 1,000 Genome Project reference, or had ambiguous, unresolvable alleles (AT/GC SNPs with minor allele frequency [MAF] >0.1). A total of 664,457 SNPs for the Illumina OmniExpress array and 360,704 for the Illumina PsychChip entered the imputation procedure.

Since the Army STARRS subjects are from various ancestral backgrounds, we first assigned our samples into major population groups (European [EUR], African [AFR], or Latino [LAT]) (see Supplementary Materials for details of population assignment procedure; also see [Stein et al., 2016]). We excluded an Asian [ASI] group that was too small for separate analysis based on principal components (PCs). We then obtained PCs within each population group for population stratification adjustment (see also Supplementary Materials). We performed the following quality control (QC) procedure to obtain the genotype data for population assignment and principal component analysis (PCA). We kept autosomal SNPs with missing rate <0.05 ; kept samples with individual-wise missing rate <0.02 ; kept SNPs with missing rate

<0.02 ; and kept SNPs with missing rate difference between PTSD cases and controls <0.02 (to minimize the bias due to differences in genotyping across PTSD cases and controls according to our sampling scheme). After QC, we merged our study samples with HapMap3 samples. We kept SNPs with minor allele frequency (MAF) >0.01 and performed LD pruning at $R^2 > 0.02$. Finally, we excluded SNPs in the MHC region (Chr 6:25-35Mb) and Chr 8 inversion (Chr 8:7-13Mb).

Statistical Analysis

GCTA [Yang et al., 2011] with imputed data (modified from [Chen et al., 2015; Yang et al., 2015]) was used to estimate the proportion of variance in social anxiety scores explained by common SNPs (i.e., SNP-heritability, h^2_g). We calculated the genetic relationship matrix with PLINK v1.90 on combined samples across three studies within each of the three populations (EUR, LAT, and AFR). We estimated h^2_g of social anxiety with linear mixed models implemented in GCTA software, adjusted for 10 PCs, study, and gender. We further stratified the sample by gender and estimated gender-specific h^2_g . P -value and 95% confidence intervals (CI) were calculated for each h^2_g estimate. Given the small proportion of women in our sample, the calculation of female-specific h^2_g estimate is likely to be underpowered and should be interpreted in that light. Finally, we performed stratified LDSC to detect enrichment of h^2_g in functional annotation domains. We used 24 predefined annotation domains as described in [Finucane et al., 2015]. We estimated the enrichment of h^2_g for each functional annotation domain with block jackknife standard error.

PLINK v1.90 [Purcell et al., 2007; Chang et al., 2015] was used to perform genomewide association tests for social anxiety factor scores (SOCANX) on imputed SNP dosage with linear regression adjusted for the top 10 within-population principal components

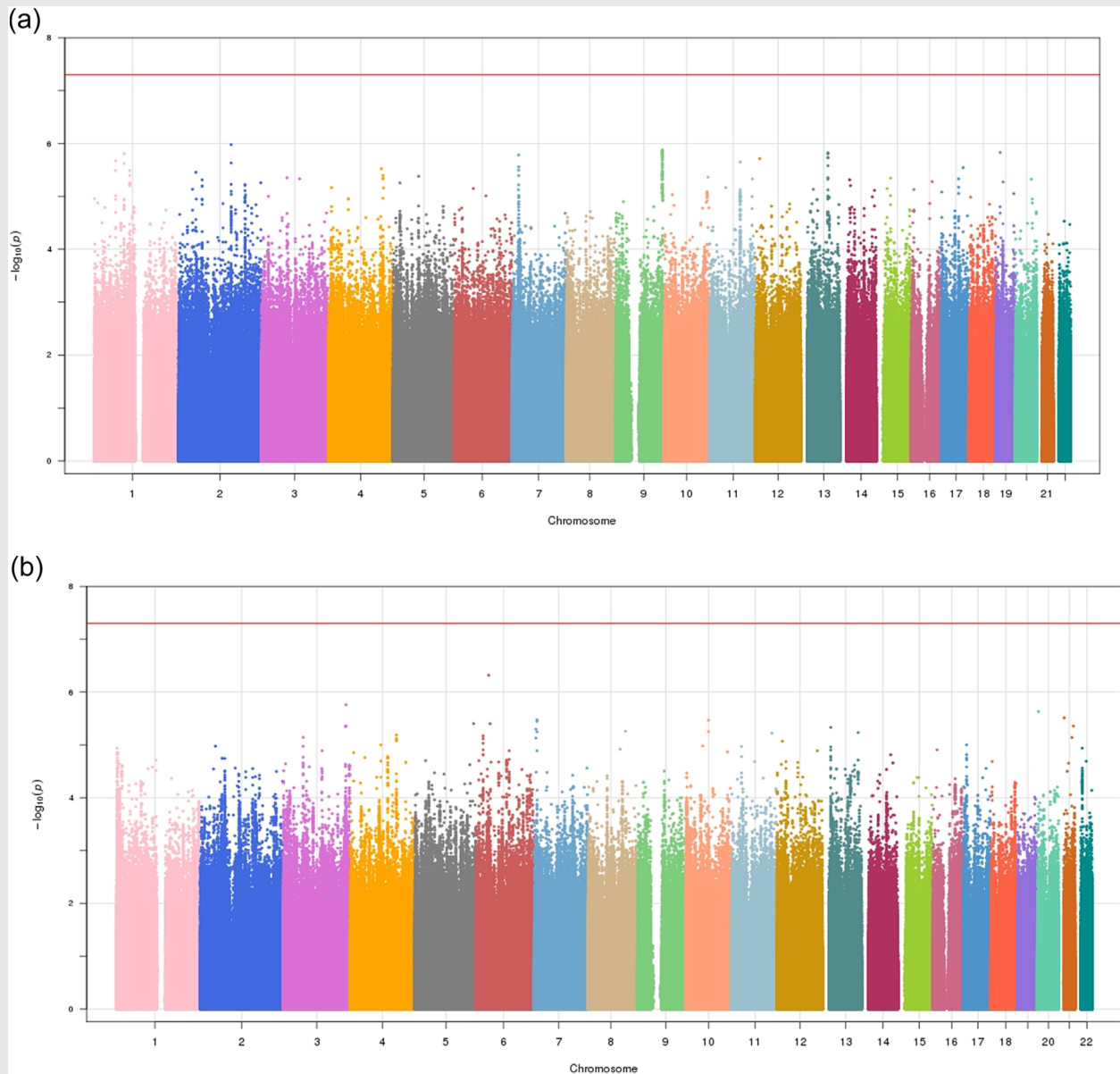


FIG. 2. Manhattan plots of NSS1, NSS2, and PPDS meta-analysis in [a] African American samples, identifying genome-wide significant association for social anxiety with rs78924501 on Chr 1 ($\lambda_{GC} = 1.013$). [b] European American samples, identifying a genome-wide significant association for social anxiety with rs708012 on Chr 6 ($\lambda_{GC} = 1.020$).

(PCs). We considered adjusting these analyses for other traits that influenced the sampling in NSS1 and NSS2, but the complexity of those sampling schemes (e.g., enriched for multiple disorders) did not lend itself to the derivation of a suitable set of covariates; this may be considered a limitation of the current analyses. We filtered out SNPs with $MAF < 0.01$ or imputation quality score (INFO) < 0.8 . GWAS was conducted in the three studies (NSS1, NSS2, and PPDS) separately within each of the three ancestral groups (EUR, AFR, LAT) and then meta-analyzed within ancestry group, but across studies. We report fixed-effects models as our primary analysis in the Results, but random-effects models yielded

virtually identical results and I^2 values and P -values for heterogeneity across studies supported the use of fixed-effects models (see Supplementary Materials).

Meta-analysis was conducted using an inverse variance-weighted fixed effects model in PLINK. A P -value of 5×10^{-8} was used as the threshold for genomewide significance. The meta-analysis of all three studies within ancestral groups is the primary analysis.

We used LD score regression (LDSC) [Bulik-Sullivan et al., 2015] to test the genetic correlation between social anxiety and other traits in European samples using recently published

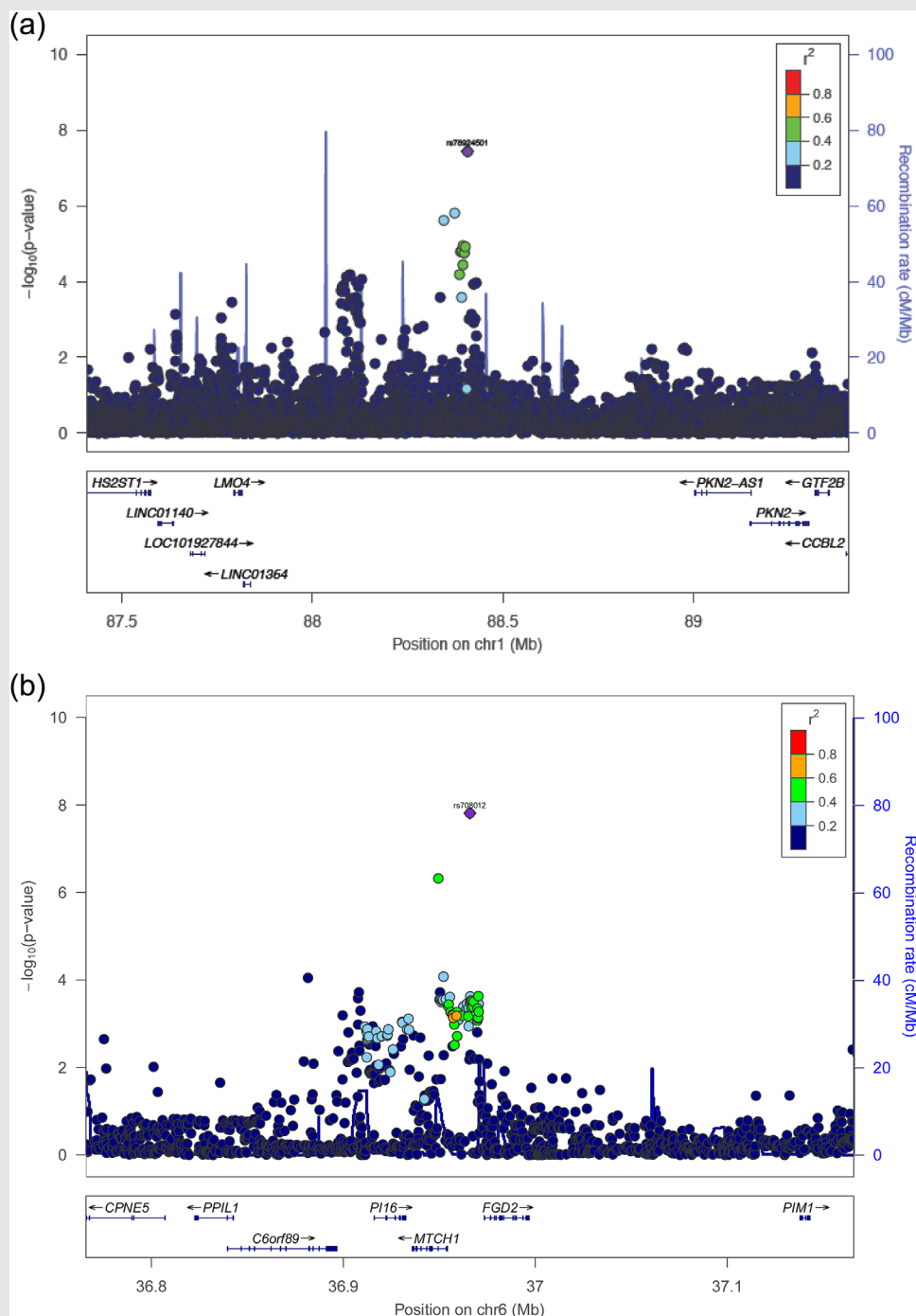


FIG. 3. Regional plots of (a, top panel) rs78924501 on Chr 1 in African American subjects and (b, bottom panel) rs708012 on Chr 6 in European American subjects.

meta-analytic GWAS for anxiety disorders [Otowa et al., 2016], neuroticism [Genetics of Personality Consortium et al., 2015], and extraversion [van den Berg et al., 2016], respectively. As a negative control, we also tested the genetic correlation between social anxiety and Alzheimer's disease [Lambert et al., 2013].

We performed gene-set analysis (GSA), or pathway analysis, using software INRICH [Lee et al., 2012] to identify enriched association signals of social anxiety in gene sets aggregated in biological pathways. We used the clumping functionality (R^2 threshold was 0.5) in PLINK1.9 to identify LD-independent

regions based on index SNPs with $P < 0.0001$ in the final meta-analysis in European American samples.

RESULTS

SNP-Based Heritability of Social Anxiety Phenotype

We estimated SNP-based heritability (h^2_g) using GCTA [Yang et al., 2011]. We found significant h^2_g estimates of 12% for social anxiety (SOCANX), seen in the meta-analysis across studies in the European American sample ($P = 2.17 \times 10^{-4}$; 95% CI: 0.05–0.18). The h^2_g estimate is 12% ($P = 0.176$, 95% CI: 0.14–0.38) in the African American sample and 21% ($P = 0.020$, 95% CI: 0.01–0.41) in the Latino American sample, but neither was statistically significant after multiple comparison correction. The male-specific h^2_g estimate of social anxiety for European Americans is 14% with a significant P -value of 8.77×10^{-5} (95% CI: 0.07–0.21), while the female-specific h^2_g estimate is 15% with P -value of 0.323. Details of these analyses, by ancestral group and sex, are included in Table II.

Enrichment of SNP-Based Heritability by Functional Annotation

We estimated the enrichment of h^2_g by 24 main annotation domains for social anxiety. The h^2_g for each of the 24 annotation domains were simultaneously estimated using the association analysis summary results from the meta-analysis of European American samples in PPDS, NSS1, and NSS2. We did two functional enrichment analyses, one based on the “full baseline model” that is not cell type specific and the other that is central nervous system (CNS) specific. Both models showed very similar results and we did not observe any significant enrichment of h^2_g by functional annotation (See Supplementary Materials).

Genomewide Association Analyses

One SNP on chromosome 1 (rs78924501, BP 88406905, $P = 3.58 \times 10^{-8}$; beta = 0.265) was genomewide significantly associated with SOCANX in the meta-analysis across the three studies in the AFR subsample (Figs. 2a and 3a). One SNP on chromosome 6 (rs708012, BP 36965970, $P = 1.55 \times 10^{-8}$; beta = 0.073) was genomewide significantly associated with SOCANX in the meta-analysis across the three studies in the European American sample (Figs. 2b and 3b). Whereas, these results were obtained using fixed effects analysis, random effects analyses identified the same two SNPs, respectively, as genomewide significant (see Supplementary Materials). We did not find similar results for either SNP in the other ancestry groups or in any of the trans-ethnic meta-analyses (Table III; results at $P < 10^{-6}$ shown).

Examination of the WS Region (Fig. 4) revealed several SNPs that were nominally significantly associated with SOCANX, the strongest association being found for rs56081032 (MAF = 0.17, $P = 3.55 \times 10^{-3}$). However, a set-based permutation test of association of SNPs in the WS region (defined as 72.5–74.5 MB), conducted using PLINK [Purcell et al., 2007], showed no

TABLE IV. LDSC Determination of Genetic Correlation in EUR Subjects of Social Anxiety Score with Other Traits (From External Study Meta-analyses With Pubmed ID [PMID] Shown)

Phenotype	PMID	r_g	SE (r_g)	P
Anxiety disorder [factor score]	26754954	0.02	0.32	0.94
Neuroticism	25993607	0.05	0.22	0.81
Extraversion	26362575	−0.52	0.22	0.02
Alzheimer’s disease	24162737	0.06	0.23	0.79

statistically significant association between the WS region and social anxiety (data available from authors upon request).

Genetic Correlations

LDSC. Social anxiety was significantly—and negatively—genetically correlated with extraversion [van den Berg et al., 2016] ($r_g = -0.52$, $se = 0.22$, $P = 0.02$) in European samples. Genetic correlations with neuroticism [Genetics of Personality Consortium et al., 2015] and with an anxiety disorders quantitative factor score (derived from a multivariate analysis combining information across various anxiety disorder clinical phenotypes) [Otowa et al., 2016] were of smaller magnitude ($r_g = 0.05$ –0.22) and not statistically significant (Table IV). Genetic correlation with Alzheimer’s disease [Lambert et al., 2013], intended as a “negative control,” was as anticipated, small, and not statistically significant ($r_g = 0.06$, $se = 0.23$, $P = 0.79$).

Gene Set Analysis (GSA)

We identified 103 genomic regions showed association signals with social anxiety through PLINK clumping function. We tested for enrichment of genes from a certain gene-set (pathway) in these 103 genomic regions. We performed the enrichment test based on 3,425 pathways from the Gene Ontology (GO) database, each with 5–200 genes. Pathways showed suggestive enrichment P -value (nominal $P < 0.05$) are shown (Table V); no pathway had a statistically significant P -value after multiple testing correction.

DISCUSSION

This study is to the best of our knowledge, the first GWAS of social anxiety conducted to date. Consistent with prior twin studies, but using GWAS methods to calculate SNP-based heritability, we confirmed that social anxiety has a heritable basis. The magnitude of heritability we found is in the range of that found using the same methods for other traits such as neuroticism (15%) [Smith et al., 2016]. According to twin studies, genetic factors that influence individual variation in extraversion and neuroticism appear to account entirely for the genetic risk for SAD [Bienvenu et al., 2007], highlighting the value of examining the molecular genetic determinants of both these traits as a means to identifying risk

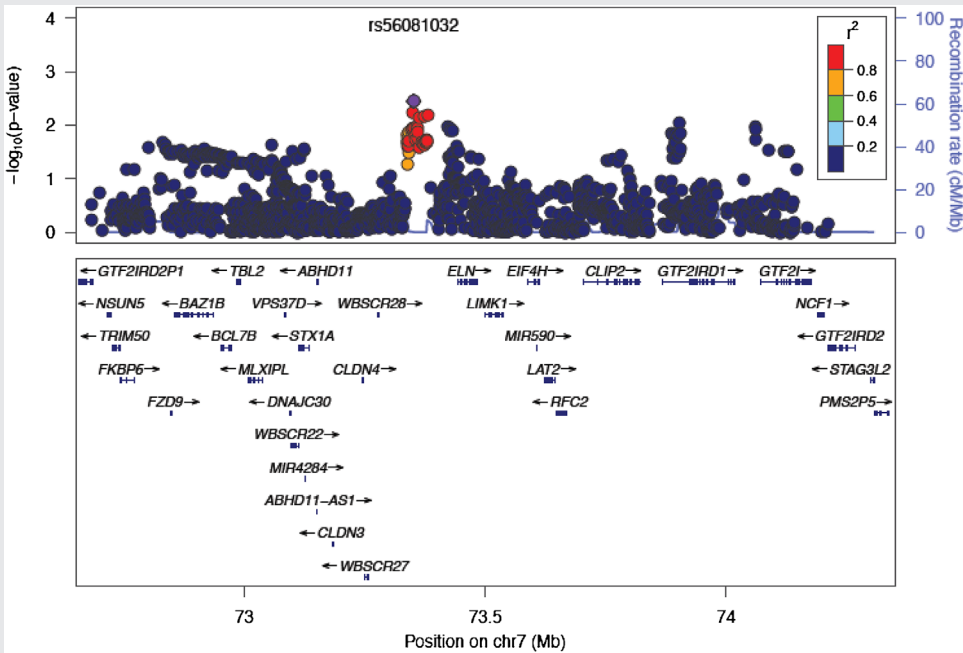


FIG. 4. Regional plot of rs56081032 (within the Williams syndrome region) in European Americans.

loci for SAD. A large meta-analysis of GWAS datasets for extraversion identified no genomewide significant loci, nor did a significant SNP-based heritability estimate emerge [van den Berg et al., 2016]. Recent meta-analyses of genomewide association studies (GWAS) have revealed genomewide significant loci for neuroticism [Genetics of Personality Consortium et al., 2015; Smith et al., 2016] and it might be expected that risk loci for these traits might overlap with those for SAD.

Interestingly, consistent with the high negative phenotypic correlation between social anxiety and extraversion seen in the literature [Bienvenu et al., 2004; Jylha et al., 2009; Watson and

Naragon-Gainey, 2014], using LDSC we found evidence in our European samples of a strong and statistically significant negative genetic correlation between social anxiety in our study and extraversion in a published GWAS meta-analysis dataset [van den Berg et al., 2016]. In contrast, we failed to find evidence of a significant genetic correlation between social anxiety in our study and neuroticism in a published neuroticism GWAS meta-analysis dataset [Genetics of Personality Consortium et al., 2015]. It is conceivable that failure to find genetic correlations between social anxiety and neuroticism is a result of inadequate power, although the external GWAS for neuroticism and extraversion were both

TABLE V. Gene-Set Analysis Using INRICH to Enrich Association Signals for Social Anxiety

Pathway	Go ID	Size	Overlap	P-value	Corrected P-value
Estrogen_metabolic_process	GO:0008210	10	4	0.0002	0.127
Luteinization	GO:0001553	7	3	0.0017	0.617
S-adenosylhomocysteine_metabolic_process	GO:0046498	6	3	0.0046	0.876
BRCA1-A_complex	GO:0070531	6	3	0.018	0.994
Lung_alveolus_development	GO:0048286	23	3	0.023	0.997
Anterior/posterior_pattern_formation	GO:0009952	96	7	0.024	0.997
Phosphoinositide_3-kinase_cascade	GO:0014065	10	3	0.033	0.999
Insulin-like_growth_factor_binding	GO:0005520	19	3	0.035	0.999
Respiratory_gaseous_exchange	GO:0007585	27	4	0.037	0.999
Chromatin_remodeling	GO:0006338	45	5	0.041	0.999
Positive_regulation_of_actin_filament_polymerization	GO:0030838	14	3	0.043	1.000
Multicellular_organism_growth	GO:0035264	25	3	0.046	1.000

Size, number of genomic regions defining the pathway; Overlap, number of LD-independent social anxiety associated regions that overlap with the genomic regions defining the pathway; P-value, nominal P-value for enrichment with 1,000,000 permutations; Corrected P-value, P-value after multiple testing correction.

large ($N > 60,000$ subjects) and, in fact, included the same subjects. But it is also possible that despite considerable shared phenotypic variance, the shared genetic variance between social anxiety and extraversion is larger than that shared between social anxiety and neuroticism. Larger social anxiety samples will be needed to resolve this issue.

There have also been GWAS studies of internalizing disorders (which would include SAD) [Hettema et al., 2015] and GWAS [Otowa et al., 2014] and meta-analytic reports of GWAS [Otowa et al., 2016] of anxiety disorders (which would also include SAD). As such, risk loci detected in those studies could be relevant to social anxiety and SAD, but this possibility cannot be determined from those studies because they did not specifically examine social anxiety phenotypes. We failed, in fact, to find a significant genetic correlation between an anxiety disorder factor from the aforementioned anxiety disorder GWAS [Otowa et al., 2016] and social anxiety. It is uncertain to what extent genetic risk for the dimensional trait studied here maps onto the disorder (i.e., SAD). It will be important for future research to examine the risk loci identified in our study (rs78924501 on Chr1 in the AFR sample, and rs708012 on Chr6 in the EUR sample) for their possible association with SAD and other anxiety-related disorders. Of particular note, the Chr1 risk SNP is downstream from *CCBL2*, also known as *KYAT3* (Kynurenine Aminotransferase 3), which encodes an aminotransferase involved in the metabolism of tryptophan. *KYAT3* variation has previously been described in relation to risk for major depression [Claes et al., 2011]. Abnormal brain tryptophan metabolism and its possible relationship to altered serotonin synthesis and signaling have been at the forefront of recent hypotheses about the pathophysiology of SAD [Frick et al., 2015; Stein and Andrews, 2015], with another tryptophan metabolic pathway gene, *TPH2* (tryptophan hydroxylase 2) recently implicated as a risk locus [Furmark et al., 2016]. Taken together, these observations call for additional studies of a role for genetic variation in serotonin signaling pathways in social anxiety and SAD.

Individuals with WS, caused by hemizygous microdeletion of a portion of 7q11.23, have a behavioral phenotype that includes extreme gregariousness and hypersociability [Morris, 2010; Barak and Feng, 2016]. As such, WS presents a remarkable mirror image of the behavioral phenotype of SAD. Accordingly, we decided to pay particular attention to the Williams region as part of our analysis. A region-based test of SNPs in this region failed to find evidence of significant association. Nevertheless, we found nominally significant association with several SNPs in the Williams region (the most significant of which was rs56081032 (MAF = 0.17, $P = 3.55 \times 10^{-3}$). This SNP is approximately 600 Kb upstream from another gene in the Williams Region, *GTF2I*, variants in which have been suggested to influence extraversion and anxiety proneness in healthy adults [Jabbi et al., 2015; Swartz et al., 2015]. These observations suggest that it may be fruitful to scrutinize the Williams region more carefully, in order to fully test the hypothesis that copy-number variants in this region might influence risk for disorders associated with elevated social anxiety (e.g., SAD).

Our results should be interpreted in light of several additional limitations. First, samples sizes—especially within ancestral groups—are likely to be insufficiently powered to detect loci of modest effect. Much larger samples will be needed to discern genes of

smaller effect. Second, the publicly available external GWAS datasets to which we had access consisted solely of individuals of European descent, and it is therefore possible that the conclusions we have drawn regarding genetic correlations may apply only to that tested ancestral group. Third, it is important to remember that our focus here has been on social anxiety as a continuous trait. Although we believe that understanding the genetic architecture of social anxiety and its relationship to other traits will be informative toward the understanding of a disorder marked by heightened levels of social anxiety, namely SAD, this is an empirical question that can only be answered by direct application of our findings to samples of patients with SAD and other anxiety disorders. Fourth, our sample is mostly male, but SAD has a strong female predominance. It may be that the genetic factors influencing SAD vary by sex, although our failure to obtain a statistically significant heritability estimate in women is almost certainly due to low power for this sex-specific analysis. Fifth, our sample is entirely military, and it is possible that generalizability to the general population is limited.

In summary, this first GWAS of social anxiety confirms a genetic basis for social anxiety, shared with extraversion but possibly less so with neuroticism. Scrutiny of the Williams Region for copy-number variants relevant to social anxiety should be attempted. Such studies hold the promise of leading to a better understanding of risk for early-onset disorders such as SAD and related conditions.

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Access To Data And Data Analysis

Murray B. Stein MD, MPH had full access to all the data in the study, takes responsibility for the integrity of the data, the accuracy of the data analysis. Drs. Stein, Chen, Gelernter, Jain, Jensen, Maihofer, Ripke, Smoller, as well as Ms. Sun, conducted, are jointly responsible for the data analysis.

Conflict of Interest Disclosure

Dr. Stein has in the last 3 years been a consultant for Healthcare Management Technologies, and Actelion, Dart Neuroscience, Janssen, Oxeia Biopharmaceuticals, Pfizer, Resilience Therapeutics, and Tonix Pharmaceuticals. Dr. Kessler has in the last 3 years been a consultant for Hoffman–La Roche, Inc., Johnson & Johnson Wellness and Prevention, and Sanofi–Aventis Groupe. Dr. Kessler has served on advisory boards for Mensante Corporation, Plus One Health Management, Lake Nona Institute, and US Preventive Medicine. Dr. Kessler owns 25% share in DataStat, Inc. Dr. Smoller

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article.