Evaluating the genetic effects of sex hormone on the development of mental traits: a polygenic score analysis and genome-wide genetic interaction analysis in the UK Biobank cohort

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Research

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Abstract

**Objective:** To evaluate the genetic effects of sex hormone on the development of mental traits.

**Methods:** The SNPs significantly associated with sex hormone traits were driven from a two-stage genome-wide association study (GWAS). Four sex hormone were selected in this study, including sex hormone-binding globulin (SHBG), testosterone, bioavailable testosterone and estradiol. The polygenic risk scores (PRS) of sex hormone traits were calculated from individual-level genotype data of the UK Biobank cohort. We then used logistic and linear regression models to assess the associations between individual PRS of sex hormone traits and the frequency of alcohol consumption, anxiety, intelligence and so on. Finally, genome-wide genetic interaction study (GWGIS) was performed to detect novel candidate genes interacting with the sex hormone on the development of fluid intelligence and the frequency of smoking and alcohol consumption by PLINK2.0.

**Results:** We observed positive associations between SHBG and the frequency of alcohol consumption \( (b=0.01, p=3.84\times10^{-11}) \) in males and females. In addition, estradiol was positively associated with the frequency of alcohol consumption \( (b=0.01, p=1.96\times10^{-8}) \), fluid intelligence \( (b=0.01, p=1.90\times10^{-2}) \) and the frequency of smoking \( (b=0.01, p=1.77\times10^{-2}) \) in males. Moreover, SHBG was associated with the frequency of alcohol consumption \( (b=0.01, p=2.60\times10^{-3}) \), fluid intelligence \( (b=0.01, p=4.25\times10^{-2}) \) and anxiety \( (b=-0.01, p=3.79\times10^{-2}) \) in females. Finally, GWGIS identified one significant loci, Tenascin R (TNR) \( \text{rs34633780,}\ p=3.45\times10^{-8} \) interacting with total testosterone for fluid intelligence.

**Conclusion:** Our study results support the genetic effects of sex hormone on the development of intelligence and the frequency of alcohol consumption.

1. Introduction

Mental disorders are highly prevalent and disabling globally, which lead to heavy burden on the health care system and society [1]. Based on the Global Burden of Disease, Injuries, and Risk Factors Study 2017 (GBD 2017), mental disorders consistently accounted for more than 14% of age-standardized years lived with disability for nearly 30 years [2]. It has been reported that 17.6% of adults suffered from a common mental disorder within the past 12 months and 29.2% across their lifetime [3]. Anxiety, alcohol use disorders and addiction are common mental disorders [3-5]. Interestingly, tobacco addiction is the most common co-occurring disorder among persons with serious mental illness [6]. The intelligence is linked to risk of the whole range of mental disorders [7].

Mental traits are multi-factorial, which are the result of multiple genetic and environmental factors that may interact in complicated ways to impact mental traits and disorders susceptibility. Addictions to alcohol and nicotine are heritable disorders [8]. The estimated heritability was 43% for tobacco usage and 19%-29% for alcohol dependence [8]. Addictive disorder has a strong heritable component with an estimated heritability around 30%-70% [9]. Sex differences in brain have known function to generate
differences in the control of gonadotropic hormones, reproductive behavior or cognitive functions [10]. The sex difference in the dopamine response in the nucleus accumbens may affect the different vulnerability to addictive disorders in males and females [11]. Sex hormone activity strongly affects the individual's behavior and the constitution of the brain [12].

Over past decade, there is robust evidence for the relationships between hormones and mental disorders [13-15]. For instance, Lenz et al. [13] indicated that exposure to sex hormone in utero and during early development would contribute to the risk of alcohol addiction later in life. Interestingly, they also observed bidirectional relationship between the sex hormone axis and alcohol drinking behavior [13]. The association of hormone with alcohol intake was also supported by experimental animal study [16], which have identified that estradiol can stimulate alcohol consumption and aggression in male mice. In addition, it has been found that the change in hormone levels overtime and the ratio of progesterone to estradiol were the strongest hormonal predictors of smoking behavior [15]. Sex differences in anxiety-like behavior partially were affected by aged-related testosterone decline in male rats [17]. Stanikov et al. [18] suggested that higher free testosterone imbalance may mediate depression in overweight premenopausal women. However, limited efforts have been paid to explore the interactions effects between genetic factors and sex hormone levels for mental traits from sex-specific genetic perspective.

Polygenic risk score (PRS) is a sum of risk alleles, weighted by their effect size estimated from previous published genome-wide association study (GWAS) . Utilizing identified susceptibility loci, PRS analysis can evaluate the effects of susceptible loci on disease risks and explore the genetic relationships between complex diseases and traits [9]. PRS has been applied in many studies of neuropsychiatric disorders [19, 20]. For instance, Jacqueline et al. [20] conducted PRS analysis to explore the possibility of overlapping genetic factors between smoking and the use of alcohol and cannabis. They found PRS of cigarettes per day were associated with the number of glasses alcohol per week and cannabis initiation [20]. In another study, researchers found PRS of nicotine metabolism can predict nicotine metabolism biomarkers [21]. Additionally, Belsky et al. [22] observed that individuals at higher PRS were more likely to persist longer in smoking heavily and develop nicotine dependence more frequently. Recently, Katherine et al. [23] conducted a two-stage GWAS in 425,097 United Kingdom (UK) Biobank study participants and identified 2,571 genetic variant-sex hormone associations. Using the PRS of sex hormone as instrumental variables, we can calculate the PRS of sex hormone and explore the correlations between PRS of sex hormone and mental traits.

GWAS have great power to identify susceptibility genetic loci associated with mental disorders [24, 25]. However, the significant loci identified by GWAS are usually limited and functionally independent. Generally, genetic effects are different between individuals due to gene-environmental (G×E) interactions which resulted from individuals responding differently to environmental stimuli depending on their genotype [26]. Identifying G×E interactions would improve risk-assessment for complex diseases and reveal underlying biological pathways [26]. The genome-wide genetic interaction study (GWGIS) can estimate the effect of G×E interactions [27]. GWGIS can investigate the genetic interaction effect in a
genome-wide scale, which can improve the ability of detecting genotype-phenotype associations missed in GWAS [27, 28].

In this study, we first calculated the PRS of sex hormone trait in UK Biobank cohort. Logistic and linear regression analyses were then performed to detect the associations between individual PRS value of sex hormone and the phenotypic data of mental traits in UK Biobank cohort. Finally, GWGIS was conducted to explore novel candidate genes interacting with sex hormone on the development of fluid intelligence and the frequency of smoking and alcohol consumption.

2. Materials And Methods

2.1 UK Biobank samples and mental phenotypes

The phenotypic and genotypic data of this study were driven from UK Biobank health resource (http://biobank.ndph.ox.ac.uk), which is a population-based prospective cohort study. The UK Biobank cohort collected 502,656 participants aged between 40 and 69, from 2006 to 2010 at recruitment. The study has collected a rich variety of phenotypic, health-related information on each participant, including physical and biological measurements, lifestyle indicators, imaging of the body and brain and genome-wide genotyping. Longitudinal follow-up for a wide range of health-related information are provided by linking health and medical records.

Several potential measures of smoking behavior was selected to define the phenotype of ever smoking. The UK Biobank data field of 20432 was described as ongoing behavioural or miscellaneous addiction. Anxiety and depression were defined according to the previous study [29], which was based on the general anxiety disorder (GAD-7) and Patient Health Questionnaire (PHQ-9) [30, 31]. Fluid intelligence score was described as a simple unweighted sum of the number of correct answers given to the 13 fluid intelligence questions. The maximum number of reported past or current cigarettes (or pipes/cigars) consumed per day was used to define the frequency of smoking (UK Biobank data fields: 20116, 2887 and 3456). In addition, the frequency of alcohol consumption (UK Biobank data field: 20117) was defined as the sum of all alcoholic beverages per week. Ethical approval of UK Biobank study was granted by the National Health Service National Research Ethics Service (reference 11/NW/0382). The detailed definition of phenotypes are shown in Additional file 1.

2.2 UK Biobank genotyping, imputation and quality control

A total of 488,377 participants have genome-wide genotype data, which were assayed using two similar genotyping array. DNA was extracted from stored blood samples when participants visited to a UK Biobank assessment Centre. Genotyping was carried out by Affymetrix UK BiLEVE Axiom Array or the Affymetrix UK Biobank Axiom arrays (Santa Clara, CA, USA), which shared 95% of marker content. Imputation was conducted by IMPUTE4 (https://jmarchini.org/software/) to carry out in chunks of approximately 50,000 imputed markers with a 250 kb buffer region. Routine quality checks was carried throughout the process, including sample retrieval, DNA extraction and genotype calling. Statistical tests
was performed to identify poor quality markers by checking for consistency of genotype calling across experimental factors, including batch effects, plate effects, departures from Hardy-Weinberg equilibrium, sex effects, array effects, and discordance across control replicates. Based on self-reported ethnicity (UK Biobank data field: 21000), the individuals were restricted to only “white British”. Finally, the participants who reported inconsistencies between self-reported gender and genetic gender, who were genotyped but not imputed, and who withdraw their consents were excluded. Detailed description of array design, genotyping and quality control procedures can be found in previous studies [32, 33].

2.3 GWAS data of sex hormone related traits

The sex hormone associated SNPs was driven from a published GWAS [23]. Briefly, the study analyzed four sex hormone traits, including sex hormone-binding globulin (SHBG), testosterone, bioavailable testosterone and estradiol. Association testing was conducted to account for cryptic population structure and relatedness by linear mixed models implemented in BOLT-LMM (v2.3.2). Genotypic data was driven from the ‘v3’ release of UKBB [32], which contained the full set of Haplotype Reference Consortium (HRC) and 1000 Genomes imputed variants. We selected sex hormone associated SNPs with significant threshold of $p<5\times10^{-8}$ to calculate PRS. Detailed description of sample characteristics, array design, quality control and statistical analysis can be found in the previous study.

2.4 PRS calculation of sex hormone related traits

Using the genotype data of UK Biobank cohort, PRS calculation was performed by using the PLINK’s "--score" command [34]. Briefly, PRS denotes the PRS of the sex hormone levels for the $i$th subjects, defined as,

$$P R S_i = \sum_{n=1}^{t} \beta_n S N P_{ni}$$

where $n$ ($n = 1, 2, 3, ..., t$) and $i$ ($i=1, 2, 3, ..., k$) denote the number of genetic markers and the sample size, respectively. $\beta_n$ is the effect parameter of risk allele of the $n$th significant SNP related to sex hormone levels, which obtained from the published study. $SNP_{ni}$ is the dosage (0 to 2) of the risk allele of the $n$th SNP for the $i$th subject. The PRS values were standardized to have mean 0 and variance 1 before further analyses.

2.4 Statistical analysis

Four serum level sex hormone traits, including SHBG, testosterone, bioavailable testosterone and estradiol, were analyzed both within and across sexes, with the exception of estradiol where analyses were performed only in men. Logistic regression model was performed to assess the associations between individual PRS of sex hormone traits and ever smoking and ongoing behavioural or miscellaneous addiction, respectively. Correspondingly, linear regression model was conducted to evaluate the correlations between individual PRS of sex hormone traits and anxiety score, depression score, fluid intelligence score, and the frequency of alcohol and smoking, respectively. The regression analyses were conducted by R software (version 3.5.3). Additionally, the sex, age, and 10 principle components of population structure were used as covariates in the regression model. Benjamin-Hochberg false discovery rate (FDR) was used to control the potential impact of multiple test problems in this study.
2.5 Genome-wide environmental interaction analysis

Based on the result of regression model, GWGIS was then performed to assess the interaction effects between genetic factors and sex hormone related PRS for fluid intelligence, and the frequency of smoking per day and alcohol consumption per week in UK Biobank cohort. The GWGIS was conducted by PLINK 2.0 [34, 35]. Letting D is the disease outcome variable, the penetrance models form is described as the following:

\[
\text{logit}[P(D = 1|G, E)] = \beta_0 + \beta_g G + \beta_e E + \beta_{ge} GE
\]

where G is genetic factors and E is the environmental factors [36]. In this study, the outcome variables were fluid intelligence score, and the frequency of smoking per day and alcohol consumption per week, and the instrumental variables were the PRS of serum sex hormone levels. The Hardy-Weinberg equilibrium (HWE) \( p \) values < 0.001 or minor allele frequencies (MAFs) < 0.01 or the SNPs with low call rates (< 0.90) were excluded in this study for quality control. Significant interactions were identified at \( p < 5.0 \times 10^{-8} \) in this study. Rectangular Manhattan plot was generated using the "CMplot" R script (https://github.com/YinLiLin/R-CMplot).

3.1 Result

A total of 18 significant associations were identified in this study, and the general characteristics of the subjects are presented in Table 1.

3.1 Associations between sex hormone related PRSs and mental traits in total samples

Three sex hormone traits were analyzed in males and females, including SHBG, total testosterone, and bioavailable testosterone. We observed positive associations between SHBG and the frequency of alcohol consumption (\( b=0.01, p=3.84\times10^{-11} \)), fluid intelligence (\( b=0.01, p=1.65\times10^{-2} \)) and ever smoking (\( b=-0.01, p=4.27\times10^{-3} \)). In addition, total testosterone was positively associated with the frequency of alcohol consumption (\( b=0.01, p=1.59\times10^{-5} \)) and addiction (\( b=0.10, p=2.75\times10^{-2} \)). No significant associations were found between bioavailable testosterone and mental traits. The basic characteristics of study subjects and detailed information are presented in Additional file 2.

3.2 Associations between sex hormone related PRSs and mental traits in males

Briefly, four sex hormone traits were analyzed in males, including SHBG, total testosterone, bioavailable testosterone and estradiol. Estradiol was positively associated with the frequency of alcohol consumption (\( b=0.01, p=1.96\times10^{-8} \)), fluid intelligence (\( b=0.01, p=1.90\times10^{-2} \)), the frequency of smoking (\( b=0.01, p=1.77\times10^{-2} \)) and ever smoking (\( b=0.01, p=4.18\times10^{-2} \)). In addition, total testosterone was associated with the frequency of alcohol consumption (\( b=0.01, p=2.69\times10^{-2} \)), the frequency of smoking (\( b=-0.01, p=2.07\times10^{-6} \)) and ever smoking (\( b=-0.01, p=2.13\times10^{-2} \)). SHBG was shown to be positively associated with the frequency of alcohol consumption (\( b=0.01, p=8.18\times10^{-5} \)). No significant
associations were found between bioavailable testosterone and mental traits. The basic characteristics of study subjects and detailed information are presented in Additional file 3.

### 3.3 Associations between sex hormone related PRSs and mental traits in females

Three sex hormone traits were analyzed in females, including SHBG, total testosterone, and bioavailable testosterone. SHBG was associated with the frequency of alcohol consumption \((b=0.01, p=2.60\times10^{-3})\), fluid intelligence \((b=0.01, p=4.25\times10^{-2})\) and anxiety \((b=-0.01, p=3.79\times10^{-2})\). In addition, total testosterone was associated with the frequency of alcohol consumption \((b=0.01, p=4.55\times10^{-6})\) and fluid intelligence \((b=-0.01, p=1.05\times10^{-2})\). We also observed negative association between bioavailable testosterone and fluid intelligence \((b=-0.01, p=5.74\times10^{-5})\). The basic characteristics of study subjects and detailed information are presented in Additional file 4.

### 3.4 Genome-wide genetic interaction analysis results

The Rectangular Manhattan plot is shown in Figure 1. GWGIS identified one significant loci, Tenascin R (TNR) \((rs34633780, p=3.45\times10^{-8})\) interacting with total testosterone for fluid intelligence. We also identified several loci for fluid intelligence, showing suggestive interaction signals \((p\leq5.00\times10^{-7})\), such as rs61808374 \((p=9.52\times10^{-8})\) and rs2301433 \((p=6.66\times10^{-8})\). Furthermore, we detected 10 suggestive associations \((p\leq5.00\times10^{-7})\) for the frequency of alcohol consumption, such as rs187545432 \((p=7.79\times10^{-8})\) and rs116420771 \((p=5.95\times10^{-8})\). Finally, we found several suggestive associations \((p\leq5.00\times10^{-7})\) for the frequency of smoking, such as rs61841834 \((p=2.79\times10^{-7})\) and rs79484573 \((p=3.54\times10^{-7})\). The detailed information is presented in table 2. The scatter diagrams of TNR was shown in Figure 2.

### 4. Discussion

Sex hormone supplementation has commonly effects on metabolic traits, sexual function and bone health [23]. Epidemiological study has indicated strong correlations between sex hormone supplements and health conditions [15]. However, the interactions effects between genetic factors and sex hormone levels for mental traits remain largely unknown now. Considering the effects of sex hormone on individual’s behavior and the constitution of the brain exhibiting fundamental differences between males and females, our study focuses on the potential impact of sex hormone on mental traits from sex-specific genetic perspective. We observed that the four sex hormone traits was associated with addiction, ever smoking, and the frequency of alcohol consumption. GWGIS further identified that the interaction of total testosterone with rs34633780 that mapped to the TNR gene can modulate the phenotype of fluid intelligence, possibly through influencing cognitive function.

TNR, a member of the tenascin family of neural extracellular matrix glycoproteins, primarily expressed in the central nervous system. This protein affects neural cell adhesion, neurite outgrowth and modulation of sodium channel function. It has been implicated that TNR was known to function in many neurological
diseases [37, 38], such as attention deficit hyperactivity disorder (ADHD) [38] and neurodegenerative disorders [37]. David et al. [39] reported that an individual with a homozygous deletion of the TNR gene was associated with intellectual disability, supporting the role of TNR in brain development and cognition in humans. Moreover, Anna et al. [40] reported a case with intellectual disability had a 6.14 Mb duplication at 1q25.1–q25.2 by utilizing array comparative genomic hybridization (array CGH). Interestingly, the TNR gene located within this region (1q25.1–q25.2). Additionally, genome-wide association analysis found a novel association of ADHD and with TNR gene [38]. In another study, researchers found TNR deficiency would cause an early onset and nonprogressive neurodevelopmental disorder [41]. To the best of our knowledge, the study involving biological processes of TNR in fluid intelligence is still less. Although indirect, our “TNR-Fluid intelligence” GWGIS finding, combined with findings reported for other psychiatric disorders [37, 38, 41], supporting the evidence of TNR in the aetiology of psychiatric conditions.

Another significant finding of this study is the disclosure of the association of SHBG with the frequency of alcohol consumption in males and females. SHBG, the major and specific binding protein for testosterone and estradiol, is known to regulate the bioavailability of sex steroids. Meanwhile, SHBG can assess the bioavailable testosterone level [42]. Lee et al. [43] have reported that serum SHBG level is an independent predictive factor for extraprostatic extension of tumor in prostate cancer patients. Higher SHBG concentrations were observed in the premenopausal women who consumed alcohol [44], which consistent with our result in females. Interestingly, Markus et al. [45] demonstrated that serum SHBG levels can be regulated by metabolic factors, including alcohol consumption and several drugs. Another study found high concentrations of SHBG were consistently related to type II alcoholism [46]. However, the association between SHBG concentrations and alcohol consumption has been inconsistent, with some evidence supporting decreased levels of SHBG with increased alcohol consumption in the United States men [47]. The difference in findings for alcohol and SHBG may be due to the samples size and different genetic background. The biological mechanism explanation for the correlation of SHBG with alcohol consumption is still unclear. In addition, we observed the negative association of SHBG with anxiety in women, which consistent with previous study [48]. Cameron, LD et al. [48] found high anxiety was correlated with lower levels of SHBG for women using tamoxifen. Interestingly, researchers also detected this relationship in subfertile males [48]. Lower secretion of SHBG was shown to be correlated with depression and anxiety [49]. Moreover, the positive association of SHBG with fluid intelligence was also observed in this study. Similarly, André Aleman et al. [50] found the significant correlation of SHBG with the fluid intelligence. Besides, significant difference in genotype distributions of SHBG (rs1799941) was found between control and intellectually gifted boys [51]. No association was observed between smoking status and SHBG in this study, which was consistent with previous study finding [47].

Total testosterone showed positive correlation with the frequency of alcohol consumption in this study. It has been identified that the frequency of alcohol consumption was positively associated with concentrations of total testosterone among adult men [47]. High concentrations of total testosterone were shown to be associated with type II alcoholism [46]. Martin et al. [52] observed that females with higher levels of testosterone were more likely to be using alcohol currently. In addition, total and
bioavailable testosterone showed negative associations with the fluid intelligence among women in this study. Recently, testosterone was recognized as an important contributor of intelligence during development [53]. There are increasing evidences of relationship between testosterone concentration and intelligence [53-55]. Tan et al. [54] reported that there was an inverse curvilinear association of total testosterone and fluid intelligence in women. In another study, researchers provided the causal evidence for the hypothesis that testosterone levels have negative influence on social intelligence [55]. Certainly, previous studies also detected this association in males [53, 56]. For instance, there is a significant negative correlation between the level of testosterone and intelligence in Chinese boys [53]. In contrast, Muller et al. [56] observed that higher total and bioavailable testosterone levels were associated with better cognitive performance in the oldest men. These studies [53-56] indicates that the relationship of testosterone and fluid intelligence varies from different genetic background and age.

Estradiol played an important role in the establishment of sex differences in brain structure and function, which may act primary target for the investigation of sex-related differences in alcohol effects [57]. Our findings also supported that estradiol was positively associated with the frequency of alcohol consumption among men. Population-based studies in adolescent males found higher salivary estradiol level was associated with earlier onset and higher quantity of alcohol use [58]. Experimental animal study [16] suggested that estradiol can influence voluntary alcohol consumption and alcohol related behaviors in male mice, including aggression and depression. Most interestingly, these effects are strongly gender dependence [16]. On the other hand, previous studies also reported that alcohol consumption can affect gonadal hormone. For instance, Sarkola et al. [59] found that estradiol levels were increased after intake of alcohol among subjects who used oral contraceptives. The positive association of estradiol with fluid intelligence was also observed among men in this study. In addition to be an ovarian hormone, estradiol is a neurosteroid synthesized by neural cells. Estrogens plays a fundamental role in a wide range of neuronal systems and complex cognitive processes, such as learning and memory [60].

It is important to emphasize that our study has two limitations. First, the samples all collected from UK Biobank. Our findings should be carefully interpreted when applied to different genetic background populations. Second, the sex hormone related SNPs sets were driven from previous GWAS. The accuracy of our regression analyses may be influenced by the power of previous GWAS of the sex hormone levels. Further replication studies with other genetic background individuals and experimental studies are required to verify the results of this study.

In conclusion, the standardized collection of genotype and sex hormone supplementation data in UK Biobank give us an opportunity to access the interaction effect between sex hormone trait and genetic factors for mental traits. We observed correlations between sex hormone and the frequency of alcohol consumption and fluid intelligence. The most significant interaction effect was observed between total testosterone and TNR for fluid intelligence. Our study findings could provide novel insights into the
impacts of sex hormone on mental traits and highlight the importance of sex specific effects of sex hormone on mental traits.

Table 1. The associations between sex hormone and mental disorders in males and females.
|                          | Number | Age±Sd   | b       | P value |
|--------------------------|--------|----------|---------|---------|
| **Total people**         |        |          |         |         |
| SHBG _ Ever smoking      | 484816 | 56.53±8.09 | 0.0084  | 4.27×10^{-3} |
| Total T _ Ongoing        | 2161   | 52.18±7.73 | 0.0972  | 2.75×10^{-2} |
| behavioural or           |        |          |         |         |
| miscellaneous addiction  |        |          |         |         |
| SHBG _ Fluid intelligence| 160121 | 56.70±8.15 | 0.0058  | 1.65×10^{-2} |
| SHBG _ Frequency of      | 388571 | 56.56±8.07 | 0.0101  | 3.84×10^{-11} |
| alcohol consumption      |        |          |         |         |
| Total T _ Frequency of   | 388571 | 56.56±8.07 | 0.0067  | 1.59×10^{-5} |
| alcohol consumption      |        |          |         |         |
| **Males**                |        |          |         |         |
| Total T _ Ever smoking   | 221669 | 56.74±8.19 | -0.01   | 2.13×10^{-2} |
| Estradiol _ Ever smoking | 221669 | 56.74±8.19 | 0.01    | 4.18×10^{-2} |
| Total T _ Frequency of   | 189153 | 56.84±8.15 | 0.0050  | 2.69×10^{-2} |
| alcohol consumption      |        |          |         |         |
| Total T _ Frequency of   | 185464 | 56.51±8.22 | -0.0108 | 2.07×10^{-6} |
| smoking                  |        |          |         |         |
| Estradiol _ Fluid        | 73236  | 56.99±8.25 | 0.0084  | 1.90×10^{-2} |
| intelligence             |        |          |         |         |
| Estradiol _ Frequency of | 189153 | 56.84±8.15 | 0.0128  | 1.96×10^{-8} |
| alcohol consumption      |        |          |         |         |
| Estradiol _ Frequency of | 185464 | 56.51±8.22 | 0.0054  | 1.77×10^{-2} |
| smoking                  |        |          |         |         |
| **Females**              |        |          |         |         |
| Bioavailable T _ Fluid   | 86777  | 56.46±8.06 | -0.0136 | 5.74×10^{-5} |
| intelligence             |        |          |         |         |
| SHBG _ Anxiety           | 85295  | 55.41±7.65 | -0.0071 | 3.79×10^{-2} |
| Variable                                      | N    | Mean±SD     | P-value | Odds Ratio |
|-----------------------------------------------|------|-------------|---------|------------|
| SHBG _ Fluid intelligence                      | 86777| 56.46±8.06  | 0.0067  | 4.25×10⁻²  |
| SHBG _ Frequency of alcohol consumption        | 199167| 56.29±7.97  | 0.0067  | 2.60×10⁻³  |
| Total T _ Fluid intelligence                    | 86777| 56.46±8.06  | -0.0084 | 1.05×10⁻²  |
| Total T _ Frequency of alcohol consumption      | 199167| 56.29±7.97  | 0.0102  | 4.55×10⁻⁶  |

Note: Bioavailable testosterone (Bioavailable T); sex hormone-binding globulin (SHBG); Total testosterone (Total T).

Table 2. The summary of the genetic variant interacting with total testosterone for fluid intelligence ($p<5.0×10⁻⁷$).
| Chr | SNP            | P value       | Gene |
|-----|----------------|---------------|------|
| 1   | rs34633780     | $3.45 \times 10^{-8}$ | TNR  |
| 1   | rs2301433      | $6.66 \times 10^{-8}$ | TNR  |
| 1   | rs12742766     | $9.29 \times 10^{-8}$ | TNR  |
| 1   | rs743903       | $9.35 \times 10^{-8}$ | TNR  |
| 1   | rs2901906      | $9.40 \times 10^{-8}$ | TNR  |
| 1   | rs61808374     | $9.52 \times 10^{-8}$ | TNR  |
| 1   | rs2239818      | $1.04 \times 10^{-7}$ | TNR  |
| 1   | rs3766679      | $1.11 \times 10^{-7}$ | TNR  |
| 1   | rs3766678      | $1.11 \times 10^{-7}$ | TNR  |
| 1   | rs12753536     | $1.15 \times 10^{-7}$ | TNR  |
| 1   | rs34789755     | $1.18 \times 10^{-7}$ | TNR  |
| 1   | rs34842046     | $1.22 \times 10^{-7}$ | TNR  |
| 1   | rs1981473      | $1.23 \times 10^{-7}$ | TNR  |
| 1   | rs35627767     | $1.31 \times 10^{-7}$ | TNR  |
| 1   | rs34347370     | $1.38 \times 10^{-7}$ | TNR  |
| 1   | rs3795402      | $1.57 \times 10^{-7}$ | TNR  |
| 1   | rs12729778     | $1.57 \times 10^{-7}$ | TNR  |
| 1   | rs743902       | $1.66 \times 10^{-7}$ | TNR  |
| 1   | rs71645245     | $1.66 \times 10^{-7}$ | TNR  |
| 1   | rs61806420     | $1.85 \times 10^{-7}$ | TNR  |
| 1   | rs74888939     | $1.86 \times 10^{-7}$ | TNR  |
| 1   | rs74399607     | $1.86 \times 10^{-7}$ | TNR  |
| 1   | rs61806381     | $1.90 \times 10^{-7}$ | TNR  |
| 1   | rs10489319     | $1.99 \times 10^{-7}$ | TNR  |
|   | rs2282731       | 2.27×10^{-7} | TNR |
|---|----------------|--------------|-----|
| 1 | rs34581198     | 2.28×10^{-7} | TNR |
| 1 | rs34442518     | 2.42×10^{-7} | TNR |
| 1 | rs61806384     | 2.47×10^{-7} | TNR |
| 1 | rs16848329     | 2.48×10^{-7} | TNR |
| 1 | rs10489320     | 2.55×10^{-7} | TNR |
| 1 | rs2301430      | 2.57×10^{-7} | TNR |
| 1 | rs12730963     | 2.62×10^{-7} | TNR |
| 1 | rs71645243     | 2.75×10^{-7} | TNR |
| 1 | rs34784860     | 2.75×10^{-7} | TNR |
| 1 | rs16848369     | 2.83×10^{-7} | TNR |
| 1 | rs61806423     | 2.89×10^{-7} | TNR |
| 1 | rs61806422     | 2.90×10^{-7} | TNR |
| 1 | rs34257437     | 3.08×10^{-7} | TNR |
| 1 | rs16848353     | 4.77×10^{-7} | TNR |
| 1 | rs35341067     | 4.84×10^{-7} | TNR |

**Note.** Chr, chromosome; SNP, single nucleotide polymorphism.

**Declarations**

**Ethics approval and consent to participate**

Ethical approval of UK Biobank study was granted by the National Health Service National Research Ethics Service (reference 11/NW/0382).

**Consent for publication**

Not applicable.

**Availability of data and material**
The UKB data are available through the UK Biobank Access Management System (https://www.ukbiobank.ac.uk/). We will return the derived data fields following UKB policy; in due course, they will be available through the UK Biobank Access Management System.

**Competing interests**

There are no competing interests to declare.

**Funding**

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**Authors' contributions**

Xiao Liang contributes to the design of the work, analysis of data and draft the paper; ShiQiang Cheng contributes to the part of data analysis and revises the paper; Jing Ye contributes to the part of data analysis; XiaoMeng Chu corrects the grammar issue and revises the paper; Yan Wen contributes to the part of data analysis; Li Liu revises the paper; Xin Qi drafts the table work; ChuJun Liang drafts the table work; YuMeng Jia approve of the version to be published; Feng Zhang contributes to the acquisition of UK biobank data and agree all aspects of the work in ensuring the work to be appropriately investigated and resolved.

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**References**

1. Antunes, A., et al., *Disability and common mental disorders: Results from the World Mental Health Survey Initiative Portugal*. European Psychiatry, 2018. 49: p. 56-61.

2. James, S.L., et al., *Global, regional, and national incidence, prevalence, and years lived with disability for 354 diseases and injuries for 195 countries and territories, 1990-2017: a systematic analysis for the Global Burden of Disease Study 2017*. Lancet, 2018. 392(10159): p. 1789-1858.

3. Steel, Z., et al., *The global prevalence of common mental disorders: a systematic review and meta-analysis 1980-2013*. International Journal of Epidemiology, 2014. 43(2): p. 476-493.

4. Els, C., *Addiction is a mental disorder, best managed in a (public) mental health setting - But our system is failing*. Canadian Journal of Psychiatry-Revue Canadienne De Psychiatrie, 2007. 52(3): p. 167-169.

5. Wittchen, H.U., et al., *The size and burden of mental disorders and other disorders of the brain in Europe 2010*. European Neuropsychopharmacology, 2011. 21(9): p. 655-679.

6. Ziedonis, D., J.M. Williams, and D. Smelson, *Serious mental illness and tobacco addiction: A model program to address this common but neglected issue*. American Journal of the Medical Sciences,
2003. 326(4): p. 223-230.

7. Gale, C.R., et al., Intelligence in Early Adulthood and Subsequent Hospitalization for Mental Disorders. Epidemiology, 2010. 21(1): p. 70-77.

8. Wilhelmsen, K.C. and C. Ehlers, Heritability of substance dependence in a native American population. Psychiatric Genetics, 2005. 15(2): p. 101-107.

9. Shen, W.W., et al., Biochemical Diagnosis in Substance and Non-substance Addiction, in Substance and Non-Substance Addiction, X. Zhang, J. Shi, and R. Tao, Editors. 2017, Springer-Verlag Singapore Pte Ltd: Singapore. p. 169-202.

10. De Vries, G.J., Minireview: Sex differences in adult and developing brains: Compensation, compensation, compensation. Endocrinology, 2004. 145(3): p. 1063-1068.

11. Thibaut, F., The role of sex and gender in neuropsychiatric disorders. Dialogues in clinical neuroscience, 2016. 18(4): p. 351-352.

12. Arnold, A.P. and S.M. Breedlove, Organizational and activational effects of sex steroids on brain and behavior: a reanalysis. Horm Behav, 1985. 19(4): p. 469-98.

13. Lenz, B., et al., Sex hormone activity in alcohol addiction: Integrating organizational and activational effects. Progress in Neurobiology, 2012. 96(1): p. 136-163.

14. Kranzler, H.R., et al., Genome-wide association study of alcohol consumption and use disorder in 274,424 individuals from multiple populations. Nature Communications, 2019. 10: p. 11.

15. Schiller, C.E., et al., Association Between Ovarian Hormones and Smoking Behavior in Women. Experimental and Clinical Psychopharmacology, 2012. 20(4): p. 251-257.

16. HilakiviClarke, L., Role of estradiol in alcohol intake and alcohol-related behaviors. Journal of Studies on Alcohol, 1996. 57(2): p. 162-170.

17. Domonkos, E., et al., Sex differences and sex hormones in anxiety-like behavior of aging rats. Hormones and Behavior, 2017. 93: p. 159-165.

18. Stanikova, D., et al., Testosterone imbalance may link depression and increased body weight in premenopausal women. Translational Psychiatry, 2019. 9: p. 12.

19. Chalmer, M.A., et al., Polygenic risk score: use in migraine research. Journal of Headache and Pain, 2018. 19: p. 10.

20. Vink, J.M., et al., Polygenic risk scores for smoking: predictors for alcohol and cannabis use? Addiction, 2014. 109(7): p. 1141-1151.

21. Chen, L.S., et al., Use of polygenic risk scores of nicotine metabolism in predicting smoking behaviors. Pharmacogenomics, 2018. 19(18): p. 1383-1394.

22. Belsky, D.W., et al., Polygenic Risk and the Developmental Progression to Heavy, Persistent Smoking and Nicotine Dependence Evidence From a 4-Decade Longitudinal Study. Jama Psychiatry, 2013. 70(5): p. 534-542.

23. Ruth, K.S., et al., Using human genetics to understand the disease impacts of testosterone in men and women. Nature Medicine, 2020. 26(2): p. 252+. 
24. Hou, L.P., et al., *Genome-wide association study of 40,000 individuals identifies two novel loci associated with bipolar disorder*. Human Molecular Genetics, 2016. **25**(15): p. 3383-3394.

25. Treutlein, J. and M. Rietschel, *Genome-Wide Association Studies of Alcohol Dependence and Substance Use Disorders*. Current Psychiatry Reports, 2011. **13**(2): p. 147-155.

26. Rask-Andersen, M., et al., *Gene-environment interaction study for BMI reveals interactions between genetic factors and physical activity, alcohol consumption and socioeconomic status*. Plos Genetics, 2017. **13**(9): p. 20.

27. Zhang, R., et al., *A genome-wide gene-environment interaction analysis for tobacco smoke and lung cancer susceptibility*. Carcinogenesis, 2014. **35**(7): p. 1528-35.

28. Arnau-Soler, A., et al., *Genome-wide by environment interaction studies of depressive symptoms and psychosocial stress in UK Biobank and Generation Scotland*. Transl Psychiatry, 2019. **9**(1): p. 14.

29. Davis, K.A.S., et al., *Indicators of mental disorders in UK Biobank—A comparison of approaches*. 2019. **28**(1).

30. Kessler, R.C., et al., *The World Health Organization Composite International Diagnostic Interview short-form (CIDI F)*. 1998.

31. Kroenke, K., et al., *The Patient Health Questionnaire Somatic, Anxiety, and Depressive Symptom Scales: a systematic review*. **32**(4): p. 345-359.

32. Bycroft, C., et al., *The UK Biobank resource with deep phenotyping and genomic data*. Nature, 2018. **562**(7726): p. 203-209.

33. Sudlow, C., et al., *UK biobank: an open access resource for identifying the causes of a wide range of complex diseases of middle and old age*. PLoS Med, 2015. **12**(3): p. e1001779.

34. Purcell, S., et al., *PLINK: a tool set for whole-genome association and population-based linkage analyses*. Am J Hum Genet, 2007. **81**(3): p. 559-75.

35. Kraft, P., et al., *Exploiting gene-environment interaction to detect genetic associations*. Hum Hered, 2007. **63**(2): p. 111-9.

36. Bulik-Sullivan, B., et al., *An atlas of genetic correlations across human diseases and traits*. Nat Genet, 2015. **47**(11): p. 1236-41.

37. Leprini, A., et al., *The human tenascin-R gene*. J Biol Chem, 1996. **271**(49): p. 31251-4.

38. Hawi, Z., et al., *A case-control genome-wide association study of ADHD discovers a novel association with the tenascin R (TNR) gene*. Transl Psychiatry, 2018. **8**(1): p. 284.

39. Dufresne, D., et al., *Homozgyous deletion of Tenascin-R in a patient with intellectual disability*. Journal of Medical Genetics, 2012. **49**(7): p. 451-454.

40. Kashevarova, A.A., et al., *Array CGH analysis of a cohort of Russian patients with intellectual disability*. Gene, 2014. **536**(1): p. 145-150.

41. Wagner, M., et al., *Loss of TNR causes a nonprogressive neurodevelopmental disorder with spasticity and transient opisthotonus*. Genetics in Medicine: p. 8.
42. Winters, S.J., et al., Testosterone, sex hormone-binding globulin, and body composition in young adult African American and Caucasian men. Metabolism, 2001. 50(10): p. 1242-7.

43. Lee, J.K., et al., Preoperative Serum Sex Hormone-Binding Globulin Level Is an Independent Predictor of Biochemical Outcome After Radical Prostatectomy. Medicine (Baltimore), 2015. 94(28): p. e1185.

44. Hirko, K.A., et al., Alcohol consumption in relation to plasma sex hormones, prolactin, and sex hormone-binding globulin in premenopausal women. Cancer Epidemiol Biomarkers Prev, 2014. 23(12): p. 2943-53.

45. Thaler, M.A., V. Seifert-Klauss, and P.B. Lupp, The biomarker sex hormone-binding globulin - from established applications to emerging trends in clinical medicine. Best Pract Res Clin Endocrinol Metab, 2015. 29(5): p. 749-60.

46. Stålenheim, E.G., et al., Testosterone as a biological marker in psychopathy and alcoholism. Psychiatry Res, 1998. 77(2): p. 79-88.

47. Shiels, M.S., et al., Association of cigarette smoking, alcohol consumption, and physical activity with sex steroid hormone levels in US men. Cancer Causes Control, 2009. 20(6): p. 877-86.

48. Cameron, L.D., et al., Trait anxiety and tamoxifen effects on bone mineral density and sex hormone-binding globulin. Psychosomatic Medicine, 2002. 64(4): p. 612-620.

49. Wdowiak, A., et al., Impact of emotional disorders on semen quality in men treated for infertility. Neuroendocrinology Letters, 2017. 38(1): p. 50-58.

50. Aleman, A., et al., Relationship between circulating levels of sex hormones and insulin-like growth factor-1 and fluid intelligence in older men. Exp Aging Res, 2001. 27(3): p. 283-91.

51. Celec, P., et al., Genetic Polymorphisms Related to Testosterone Metabolism in Intellectually Gifted Boys. Plos One, 2013. 8(1): p. 5.

52. Martin, C.A., et al., Alcohol use in adolescent females: Correlates with estradiol and testosterone. American Journal on Addictions, 1999. 8(1): p. 9-14.

53. Shangguan, F.F. and J.N. Shi, Puberty timing and fluid intelligence: A study of correlations between testosterone and intelligence in 8-to 12-year-old Chinese boys. Psychoneuroendocrinology, 2009. 34(7): p. 983-988.

54. Tan, U. and M. Tan, The curvilinear correlations between the total testosterone levels and fluid intelligence in men and women. International Journal of Neuroscience, 1998. 94(1-2): p. 55-61.

55. van Honka, J., et al., Testosterone administration impairs cognitive empathy in women depending on second-to-fourth digit ratio. Proceedings of the National Academy of Sciences of the United States of America, 2011. 108(8): p. 3448-3452.

56. Muller, M., et al., Endogenous sex hormone levels and cognitive function in aging men - Is there an optimal level? Neurology, 2005. 64(5): p. 866-871.

57. Erol, A., et al., Sex hormones in alcohol consumption: a systematic review of evidence. Addiction Biology, 2019. 24(2): p. 157-169.
58. de Water, E., et al., *Pubertal maturation and sex steroids are related to alcohol use in adolescents.* Horm Behav, 2013. **63**(2): p. 392-7.

59. Sarkola, T., et al., *Acute effect of alcohol on estradiol, estrone, progesterone, prolactin, cortisol, and luteinizing hormone in premenopausal women.* Alcoholism-Clinical and Experimental Research, 1999. **23**(6): p. 976-982.

60. Pompili, A., B. Arnone, and A. Gasbarri, *Estrogens and memory in physiological and neuropathological conditions.* Psychoneuroendocrinology, 2012. **37**(9): p. 1379-1396.

**Figures**

![Figure 1](https://github.com/YinLiLin/R-CMplot)

**Figure 1**

Genomic regions interacting with total testosterone for fluid intelligence. * Red plot represents the p<5×10−8. The plots were generated using the “CMplot” R script (https://github.com/YinLiLin/R-CMplot).
Figure 2

Scatter Diagram of TNR. *The X-axis represents SNP, and the Y-axis represents -log10 p-values of each variant. The plots were generated using R script.

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