

Online Research @ Cardiff

This is an Open Access document downloaded from ORCA, Cardiff University's institutional repository: <http://orca.cf.ac.uk/103406/>

This is the author's version of a work that was submitted to / accepted for publication.

Citation for final published version:

García-González, Judit, Tansey, Katherine E., Hauser, Joanna, Henigsberg, Neven, Maier, Wolfgang, Mors, Ole, Placentino, Anna, Rietschel, Marcella, Souery, Daniel, Zagar, Tina, Czernski, Piotr M., Jerman, Borut, Buttenschøn, Henriette N., Schulze, Thomas G., Zobel, Astrid, Farmer, Anne, Aitchison, Katherine J., Craig, Ian, McGuffin, Peter, Giupponi, Michel, Perroud, Nader, Bondolfi, Guido, Evans, David, O'Donovan, Michael Conlon, Peters, Tim J., Wendland, Jens R., Lewis, Glyn, Kapur, Shitij, Perlis, Roy, Arolt, Volker, Domschke, Katharina, Breen, Gerome, Curtis, Charles, Sang-Hyuk, Lee, Kan, Carol, Newhouse, Stephen, Patel, Hamel, Baune, Bernhard T., Uher, Rudolf, Lewis, Cathryn M. and Fabbri, Chiara 2017. Pharmacogenetics of antidepressant response: a polygenic approach. *Progress in Neuro-Psychopharmacology and Biological Psychiatry* 75 , pp. 128-134. 10.1016/j.pnpbp.2017.01.011 file

Publishers page: <http://dx.doi.org/10.1016/j.pnpbp.2017.01.011>
<<http://dx.doi.org/10.1016/j.pnpbp.2017.01.011>>

Please note:

Changes made as a result of publishing processes such as copy-editing, formatting and page numbers may not be reflected in this version. For the definitive version of this publication, please refer to the published source. You are advised to consult the publisher's version if you wish to cite this paper.

This version is being made available in accordance with publisher policies. See <http://orca.cf.ac.uk/policies.html> for usage policies. Copyright and moral rights for publications made available in ORCA are retained by the copyright holders.



Pharmacogenetics of antidepressant response: A polygenic approach

Judit García-González ^a, Katherine E. Tansey ^b, Joanna Hauser ^c, Neven Henigsberg ^d, Wolfgang Maier ^e, Ole Mors ^{f,g}, Anna Placentino ^h, Marcella Rietschel ⁱ, Daniel Souery ^j, Tina Žagar ^k, Piotr M. Czerski ^l, Borut Jerman ^{k,m}, Henriette N. Buttenschøn ⁿ, Thomas G. Schulze ^o, Astrid Zobebe ^o, Anne Farmer ^a, Katherine J. Aitchison ^p, Ian Craig ^a, Peter McGuffin ^a, Michel Giupponi ^q, Nader Perroud ^r, Guido Bondolfi ^s, David Evans ^t, Michael O'Donovan ^u, Tim J. Peters ^v, Jens R. Wendland ^w, Glyn Lewis ^x, Shitij Kapur ^a, Roy Perlis ^y, Volker Arolt ^z, Katharina Domschke ^{aa}, Major Depressive Disorder Working Group of the Psychiatric Genomic Consortium¹, Gerome Breen ^a, Charles Curtis ^a, Lee Sang-Hyuk ^a, Carol Kan ^a, Stephen Newhouse ^a, Hamel Patel ^a, Bernhard T. Baune ^{ab}, Rudolf Uher ^{ac}, Cathryn M. Lewis ^{a,2}, Chiara Fabbria ^{ad,2}

^a Institute of Psychiatry, Psychology and Neuroscience, King's College London, United Kingdom

^b College of Biomedical and Life Sciences, Cardiff University, Cardiff, United Kingdom

^c Laboratory of Psychiatric Genetics, Department of Psychiatry, Poznan University of Medical Sciences, Poznan, Poland

^d Croatian Institute for Brain Research, Medical School, University of Zagreb, Zagreb, Croatia

^e Department of Psychiatry, University of Bonn, Bonn, Germany

^f Psychosis Research Unit, Aarhus University Hospital, Risskov, Denmark

^g The Lundbeck Foundation Initiative for Integrative Psychiatric Research (iPSYCH), Aarhus, Denmark

^h Biological Psychiatry Unit and Dual Diagnosis Ward, Istituto Di Ricovero e Cura a Carattere Scientifico, Centro San Giovanni di Dio, Fatebenefratelli, Brescia, Italy

ⁱ Division of Genetic Epidemiology in Psychiatry, Central Institute of Mental Health, Mannheim, Germany

^j Laboratoire de Psychologie Médicale, Université Libre de Bruxelles and Psy Pluriel—Centre Européen de Psychologie Médicale, Brussels, Belgium

^k Institute of Public Health of the Republic of Slovenia, Ljubljana, Slovenia

^l Laboratory of Psychiatric Genetics, Poznan University of Medical Sciences, Poland

^m Department of Molecular and Biomedical Sciences, Jozef Stefan Institute, Ljubljana, Slovenia

ⁿ Translational Neuropsychiatry Unit, Department of Clinical Medicine, Aarhus University, Risskov, Denmark

^o Division of Genetic Epidemiology in Psychiatry, Central Institute of Mental Health, Mannheim, Germany

^p Department of Psychiatry, University of Alberta, Edmonton, AB, Canada

^q Department of Genetic Medicine and Laboratories, University Hospitals of Geneva, Geneva, Switzerland

^r Department of Psychiatry, University of Geneva, Geneva, Switzerland

s Center of Excellence for Drug Discovery in Psychiatry, GlaxoSmithKline Medicines Research Centre, Verona, Italy
t Medical Research Council CAiTE Centre, School of Social and Community Medicine, University of Bristol, Bristol, United Kingdom
u Medical Research Council Centre for Neuropsychiatric Genetics and Genomics, Department of Psychological Medicine and Neurology, School of Medicine, Cardiff University, Cardiff, United Kingdom
v School of Clinical Sciences, University of Bristol, Bristol, United Kingdom
w Pharma Research and Early Development, F. Hoffmann–La Roche, Basel, Switzerland
x Division of Psychiatry, University College London, London, UK
y Department of Psychiatry, Center for Experimental Drugs and Diagnostics, Massachusetts General Hospital, Boston, USA
z Department of Psychiatry, University of Münster, Münster, Germany
aa Department of Psychiatry Psychosomatics and Psychotherapy, University of Wuerzburg, Wuerzburg, Germany
ab Discipline of Psychiatry, School of Medicine, University of Adelaide, Adelaide, Australia
ac Department of Psychiatry, Dalhousie University, Halifax, Canada
ad Department of Biomedical and Neuromotor Sciences, University of Bologna, Bologna, Italy.

Abstract

Background: Major depressive disorder (MDD) has a high personal and socio-economic burden and N60% of patients fail to achieve remission with the first antidepressant. The biological mechanisms behind antidepressant response are only partially known but genetic factors play a relevant role. A combined predictor across genetic variants may be useful to investigate this complex trait.

Methods: Polygenic risk scores (PRS) were used to estimate multi-allelic contribution to: 1) antidepressant efficacy; 2) its overlap with MDD and schizophrenia. We constructed PRS and tested whether these predicted symptom improvement or remission from the GENDEP study (n = 736) to the STAR*D study (n = 1409) and vice-versa, including the whole sample or only patients treated with escitalopram or citalopram. Using summary statistics from Psychiatric Genomics Consortium for MDD and schizophrenia, we tested whether PRS from these disorders predicted symptom improvement in GENDEP, STAR*D, and five further studies (n = 3756).

Results: No significant prediction of antidepressant efficacy was obtained from PRS in GENDEP/STAR*D but this analysis might have been underpowered. There was no evidence of overlap in the genetics of antidepressant response with either MDD or schizophrenia, either in individual studies or a meta-analysis. Stratifying by antidepressant did not alter the results.

Discussion: We identified no significant predictive effect using PRS between pharmacogenetic studies. The genetic liability to MDD or schizophrenia did not predict response to antidepressants, suggesting differences between the genetic component of

depression and treatment response. Larger or more homogeneous studies will be necessary to obtain a polygenic predictor of antidepressant response.

1. Introduction

Major depressive disorder (MDD) is a common mental disorder characterized by sadness, anhedonia, guilt, feelings of low self-worth, poor concentration, disturbed appetite and sleep and suicidal thoughts (World Health Organization, 1993; American Psychiatric Association, 2013). Its heavy socio-economic and individual burden makes it a global concern: lifetime prevalence of MDD ranges from 10% to 15% and MDD is one of the top ten causes of years lived with disability (YLDs) world-wide (The WHO World Mental Health Survey Consortium, 2004; Global Burden of Disease Study 2013 Collaborators, 2015). Antidepressant drugs are the first-line treatment for MDD, with N30 antidepressant drugs available (Fabbri et al., 2016). Responses vary widely across individuals: one third of patients show complete remission after the first drug prescribed, one third improves after a change of treatment or augmentation, and one third fail to respond after two different antidepressants prescribed (Trivedi et al., 2006; Souery et al., 2011). For each patient, the most effective treatment can only be identified by trial and error - a lengthy process which delays recovery and leads to poorer clinical outcomes (Steimer et al., 2001). The ability to identify the most effective drugs for each patient or to predict treatment resistance would be a turning point in MDD treatment, enabling personalized prescribing. However, no predictor of antidepressant response is currently available; clinical characteristics are weak predictors of improvement in depressive symptoms, and no established biomarkers or genetic signatures exist for antidepressant response.

Genome-wide association studies (GWAS) to identify single nucleotide polymorphisms (SNPs) associated with antidepressant response have provided tentative hints, but most associations have been inconclusive and are unreplicated (Myung et al., 2015; Sasayama et al., 2013; Biernacka et al., 2015; GENDEP Investigators, MARS Investigators and STAR*D Investigators, 2013; Uher et al., 2010; Trivedi et al., 2006; Ising et al., 2009). These disappointing findings may be ascribed to several features of pharmacogenetic studies: limited sample size, heterogeneity between studies in design, drug, and assessment of outcome. Given the challenges of accruing sufficiently strong evidence to confirm association of a single SNP with antidepressant response, an alternative approach is to construct a single summary genetic variable representing genome-wide information which can be used for prediction.

Polygenic risk scores (PRS) capture in a single variable the additive effect of SNP alleles across the genome (Dudbridge, 2013). In contrast to GWAS analysis, where a single SNP must reach stringent significance levels, PRS are constructed from multiple SNPs with lower evidence of association, with the assumption that genetic markers that do not meet the genome-wide significance threshold might have good predictive power when they are considered collectively.

In this study we test whether polygenic risk scores can provide prediction of response to antidepressants, building PRS directly from clinical trials of antidepressant response (STAR*D, GENDEP) (Garriock et al., 2010; Uher et al., 2010), and secondly testing the hypothesis of whether genetic liability to the psychiatric disorders of MDD and schizophrenia

contributes to variation in antidepressant response. Indeed an overlap between the genetics of MDD and antidepressant response has been hypothesized, but MDD also shares susceptibility genetic factors with schizophrenia (Cross-Disorder Group of the Psychiatric Genomics Consortium, 2013), suggesting a possible overlap between the genetics of schizophrenia and antidepressant response. We analyse two large pharmacogenetic trials (GENDEP, STAR*D) and expand our study to other studies of antidepressant response, giving a substantial sample size in which to develop and test predictors of treatment response.

2. Materials and methods

2.1. Pharmacogenetic studies

Seven pharmacogenetic studies were included, all similar in their fundamental features: (1) participants were treatment-seeking individuals diagnosed with MDD based on DSM-IV/ICD-10 criteria (World Health Organization, 1993; American Psychiatric Association, 2013), with other psychiatric diagnoses excluded (schizophrenia spectrum disorders, bipolar disorders, current alcohol or drug dependence). For each study participant, prospective data on outcome of antidepressant treatment were recorded according to standard and comparable scales. Missing end-point measurements were imputed using the best unbiased estimate from a mixed-effect linear regression model, with fixed linear and quadratic effects of time and random effects of individual and centre of recruitment (for multi-centric studies) according to previous studies (Tansey et al., 2012; Uher et al., 2010). Patients were included in the analyses only if baseline assessment and at least one post-baseline assessment were available.

The GENDEP and STAR*D studies formed our primary studies for discovery and testing variants specific to antidepressant response. For testing the hypothesis that genetic liability for MDD and schizophrenia predicts antidepressant response, we included four further trials from the NEWMEDS consortium (GENPOD, GODS, GSK, Pfizer) (Tansey et al., 2012) and a newly genotyped naturalistic study from the University of Muenster (Baune et al., 2008, 2010). All studies were approved by local ethics boards of participating centres, and all participants provided written informed consent after the study procedures were explained and prior to sample collection. Detailed information for each sample are given in Table 1 and Supplementary Methods.

2.2. Outcome measures

Two phenotypes were investigated at the end-point of each study, a continuous measure of improvement, calculated as the percentage change in symptom score, and symptom remission (Table 1). Percent-age change was preferred to absolute change because it is less correlated with initial severity, relatively independent of the scale, and closely reflects clinician's impression of improvement (Uher et al., 2009; Lane, 2008; Mallinckrodt, Clark and David, 2001). Remission was defined as a score below a consensus cut-off that corresponds to absence of depression for each scale (Hamilton, 1967; Montgomery and Asberg, 1979; Beck et al., 1961). For GENDEP, remission was defined using HAMD-17, since there was stronger consensus about the threshold to identify remission on this scale compared to MADRS (Uher et al., 2008). Remission has lower power to detect an effect than a continuous measure (Streiner, 2002) but it may be associated with MDD prognosis (Gaynes et al., 2009).

Table 1
Pharmacogenetic study characteristics. MADRS; Montgomery-Åsberg Depression Rating Scale. QIDS-C16; Quick Inventory of Depressive Symptomatology-Clinician Rated. BDI; Beck Depression Inventory. HAMD-17; Hamilton Rating Scale for Depression (17 items). HAMD-21; Hamilton Rating Scale for Depression (21 items). SSRIs; selective serotonin reuptake inhibitors. SNRIs; serotonin and noradrenaline reuptake inhibitors.

	STAR*D	GENDEP	GENPOD	Pfizer	GSK	GODS	Muenster
Sample characteristics							
Study design	Trial	Trial	Trial	Trial	Trial	Trial	Naturalistic
N	1409	736	473	307	130	70	621
Scale for outcome assessment	QIDS-C16	MADRS	BDI	HAMD-17	HAMD-17	MADRS	HAMD-21
Time of end point assessment	12 weeks	12 weeks	12 weeks	6-8 weeks	12 weeks	12 weeks	6 weeks
Criteria for remission	QIDS-C16 ≤ 5	HAMD-17 ≤ 7	BDI < 10	HAMD-17 ≤ 7	HAMD-17 ≤ 7	MADRS ≤ 8	HAMD-21 ≤ 7
Treatment	citalopram	escitalopram nortriptyline	citalopram reboxetine	sertraline fluoxetine paroxetine	escitalopram	paroxetine	SSRIs, SNRIs, others
Genotyping platform	Affymetrix 500 K, Illumina Infinium Exome-24 v1.0	Illumina Human610, Infinium Exome-24 v1.0	Illumina 660 W	Illumina 660 W	Illumina 660 W	Illumina 660 W	Infinium PsychArray-24
Imputation panel	Haplotype Reference Consortium	Haplotype Reference Consortium	Haplotype Reference Consortium	Haplotype Reference Consortium	Haplotype Reference Consortium	Haplotype Reference Consortium	Haplotype Reference Consortium
Clinical characteristics							
% Female	59.9	62	69.2	67.2	54.5	53.4	43.1
Age at onset	27.3 (SD 14.2)	32.0 (SD 10.6)	39.4 (SD 12.5)	43.3 (SD 13.1)	36.4 (SD 11.9)	37.1 (SD 10.3)	39.0 (SD 15.0)
MDD severity	Moderate to Severe	Moderate to Severe	Moderate to Severe	Moderate to Severe	Moderate to Severe	Severe	Mild to Severe
Baseline measure	HAMD-17	HAMD-17	BDI	HAMD-17	HAMD-17	MADRS	HAMD-21
Score	22.4 (SD 4.9)	21.9 (SD 5.2)	33.4 (SD 9.7)	23.5 (SD 3.4)	23.0 (SD 3.1)	31.8 (SD 4.7)	22.3 (SD 7.3)
Achieved remission	602 (42.7%)	322 (44%)	171 (36%)	100 (32%)	56 (43%)	17 (24%)	279 (45%)

2.3. Psychiatric Genomics Consortium summary statistics

Genome-wide summary statistics for large meta-analysis from the Psychiatric Genomics Consortium (PGC) were used to construct PRS for MDD and schizophrenia for each participant in the pharmacogenomic studies. Summary statistics for schizophrenia were downloaded from pgc.unc.edu (36,989 schizophrenia cases, 113,075 controls) (Ripke et al., 2014). MDD summary statistics were from the latest PGC MDD meta-analysis comprising 51,865 MDD cases and 112,200 controls (unpublished data).

2.4. Statistical analysis

Individual-level genotypes were available for all pharmacogenetic studies. GENDEP and STAR*D were imputed using genotype data from genome-wide and exome arrays capturing both common and rare variation (Table 1; Supplementary Methods). The Muenster study was imputed from Infinium PsychArray-24, and phenotype and genotype data from studies in the NEWMEDS consortium (GENPOD, Pfizer, GSK, GODS) were used as previously reported (Tansey et al., 2012). All these studies were imputed using Minimac3 and the Haplotype Reference Consortium (HRC version 1) as reference panel. In STAR*D and GENDEP, tests of SNP association were performed using linear regression (for percentage change in symptom score) and logistic regression (remission) using PLINK (Purcell et al., 2007). Each model included co-variables of ancestry-informative principal components (PCs), age, base-line severity of depression and ascertainment centre (for multi-centre studies of STAR*D, GENDEP and Pfizer). The number of ancestry-informative PCs used for each sample is specified in Supplementary Methods and the first two PCs for each sample are plotted in Supplementary Fig. 1.

GWAS summary data from GENDEP, STAR*D, PGC-SCZ, and PGC-MDD were used as discovery studies. A schematic representation of study design is provided in Fig. 1. SNPs were clumped by linkage disequilibrium (LD) and p-value: SNP with the smallest p-value within a 250 Kb window were retained, and all SNPs in LD ($r^2 \geq 0.1$) with the retained SNP were excluded. When PGC-MDD was used as discovery study, markers with allele frequency

difference of over 0.15 between discovery and test data sets were excluded to ensure comparability given the different genotyping chips and imputation reference panels used. PRS were constructed using the software PRSice v.1.25 (Euesden, Lewis and O'Reilly, 2015). PRS were calculated as the sum of associated alleles, weighted by effect sizes, for SNPs with p-values less than pre-defined threshold PT . Nine p-value thresholds of PT (0.0001, 0.001, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 1) were used with all pruned SNPs included in the final threshold $PT = 1$. Symptom improvement and remission outcomes were regressed on polygenic scores, adjusting for the covariates as used in the GWAS analyses, and compared to a model including only covariates. The proportion of phenotypic variance explained by PRS was assessed by R^2 (for improvement) or Nagelkerke's R^2 (for remission). To decrease pharmacological heterogeneity across samples and to increase power, analyses were repeated stratifying by antidepressant, including only studies using escitalopram and citalopram (STAR*D, GSK, 417 GENDEP participants, 242 GENPOD participants and 121 Muenster participants).

Prediction of improvement from MDD and schizophrenia was implemented separately in each pharmacogenetic study, then a fixed effects meta-analysis was performed to combine results across studies at each PT . The use of a fixed effect approach was in line with previous meta-analyses in the field (e.g. GENDEP Investigators, MARS Investigators and STAR*D Investigators, 2013).

A Bonferroni correction was applied to account for multiple testing. We estimated $p = 0.01$ as an approximate correction for correlation between PRS at 9 PT values, and then corrected further for four independent hypotheses, giving a required significance level of $p = 0.0025$.

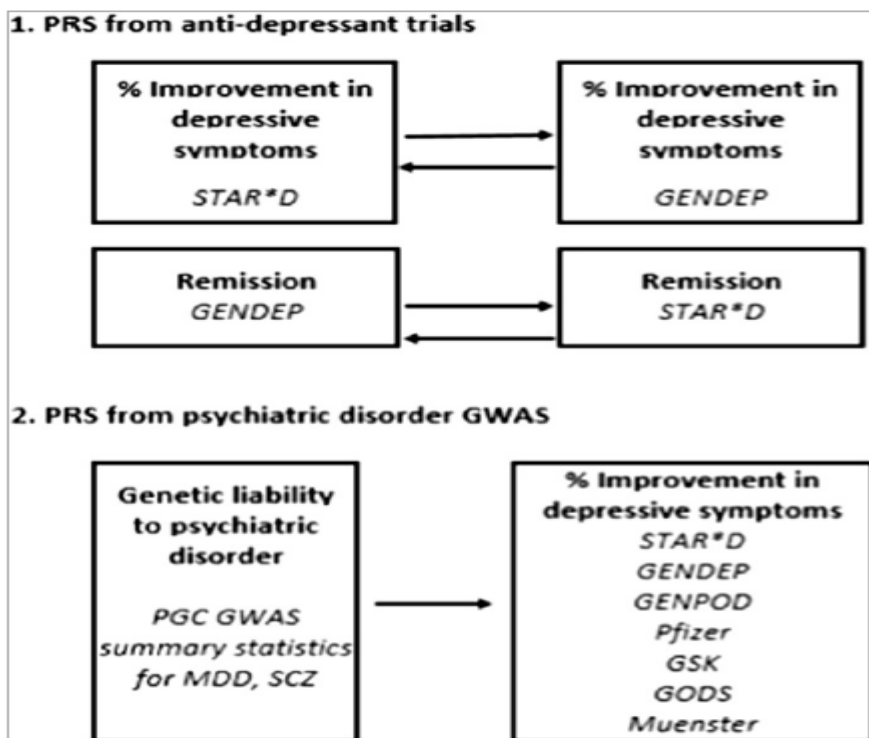


Fig. 1. Study design, capturing (1) prediction of improvement and remission using large antidepressant response trials as discovery studies, and (2) prediction from psychiatric disorder PRS, into all antidepressant studies. Arrows indicate PRS from discovery to test data sets. PGC = Psychiatric Genomics Consortium.

2.5. Power calculation

Power calculations for the polygenic analysis were performed using the R package AVENGEME (Palla and Dudbridge, 2015), at each PT. Models assumed SNP heritability of 0.21 for MDD (Cross-Disorder Group of the Psychiatric Genomics Consortium et al., 2013), 0.42 for response to antidepressants (Tansey et al., 2013) and 0.33 for schizophrenia (Ripke et al., 2013a). Lifetime prevalences used were 16.2% for MDD (Kessler et al., 2003), and 0.87% for schizophrenia (Perälä et al., 2007). The models used for power calculation assumed that the markers are independent and 5% of SNPs have an effect in the training phenotype. For cross-trait polygenic analysis (MDD, schizophrenia and antidepressant response), two hypothetical scenarios were tested, comparing change in prediction accuracy when covariance between genetic effects in the training and target samples were 25% or 50%.

With GENDEP or STAR*D as discovery sample, the power to detect the genetic contribution of response to antidepressants was limited (12% for improvement, 8% for remission). Using PGC MDD and PGC SCZ as discovery had higher power. Assuming a covariance of 25% between SCZ and improvement in depression symptoms gave 90% power in the combined pharmacogenetic samples. A covariance of 50% between MDD and improvement in depression symptoms had 90% power to detect an effect in the combined pharmacogenetic sample, but only power of 37% with 25% covariance.

3. Results

Firstly, we tested whether PRS predict improvement and remission in depression symptoms after twelve weeks of antidepressant treatment, using GENDEP and STAR*D. Each study was used as discovery and then as target study, testing the PRS constructed from STAR*D GWAS results in GENDEP, and vice-versa. No significant prediction of treatment response was attained for improvement or for remission in the whole sample (Supplementary Fig. 2) or restricting the analysis to citalopram/escitalopram (Supplementary Fig. 3) treated patients (Table 2). The lowest p-value of $p = 0.023$, using the GENDEP remission GWAS to predict remission in STAR*D, did not reach the required Bonferroni correction of 0.0025.

Secondly, we investigated whether genetic liability to MDD or schizophrenia predicted improvement in depressive symptoms, using meta-analyses from the Psychiatric Genomics Consortium (PGC) as discovery samples. Seven pharmacogenetic studies (including GENDEP and STAR*D) were used as independent target samples (3746 participants). Meta-analysis across studies (whole sample or citalopram/escitalopram treated patients) showed no predictive ability of genetic liability for MDD or for schizophrenia (Fig. 2), with the most significant result being for schizophrenia PRS at PT b 0.0001 ($p = 0.077$). Across all PT, PRS for MDD showed p-values ≥ 0.1 for the prediction of symptom improvement and regression coefficients explained 3% of the variance in symptom improvement. Results by-study at all PT values are given in Supplementary Tables 1–2.

4. Discussion

In this study, we assessed whether the outcomes of antidepressant treatment may be predicted by PRS for (a) improvement and remission from an independent sample, (b) genetic liability to MDD, and (c) genetic liability to schizophrenia. Using each of the two largest available pharmacogenetic samples on antidepressant response (GENDEP and STAR*D) as baseline studies failed to predict antidepressant response in the other study. A previous study (GENDEP Investigators, MARS Investigators and STAR*D Investigators, 2013) found a small predicting ability of a PRS calculated in a meta-analysis of GENDEP-MARS studies in STAR*D, accounting for about 1.2% of the variance in outcomes in STAR*D. The present study was performed using individual datasets as discovery samples but increasing the number of genetic variants from ~1.2 million to ~7 million. PRS built from well-powered PGC studies for MDD and schizophrenia did not predict symptom improvement, either in individual pharmacogenetic studies, or in a meta-analysis. The strongest (non-significant) polygenic overlap with PGC MDD and schizophrenia data was found for the Pfizer pharmacogenetic sample (Supplementary Tables 1 and 2). This sample included a higher proportion of females and patients with later MDD onset compared to other samples, with a shorter trial duration, but we did not have the power to determine how these differences may have played a role in the results. A previous analysis of PRS for bipolar disorder did not predict antidepressant response in STAR*D and the NEWMEDS studies, so this analysis was not repeated here (Tansey et al., 2014).

Table 2

Prediction of improvement in depression symptoms and remission after 12 weeks of antidepressant treatment. Results are shown for the PT threshold attaining the lowest p-value. R²; Proportion of variance explained.

Discovery sample	Target sample	Phenotype	P _T	No. of SNPs	R ²	p-Value
Whole sample						
GENDEP	STAR*D	Improvement	0.001	1422	0.00079	0.280
		Remission	0.0001	934	0.00044	0.024
STAR*D	GENDEP	Improvement	0.05	39,471	0.00173	0.237
		Remission	0.5	214,280	0.00212	0.234
Analyses including only citalopram/escitalopram treated subjects						
GENDEP	STAR*D	Improvement	0.001	1429	0.00056	0.361
		Remission	0.001	827	0.00199	0.130
STAR*D	GENDEP	Improvement	0.05	39,471	0.00214	0.313
		Remission	0.5	214,280	0.00335	0.255

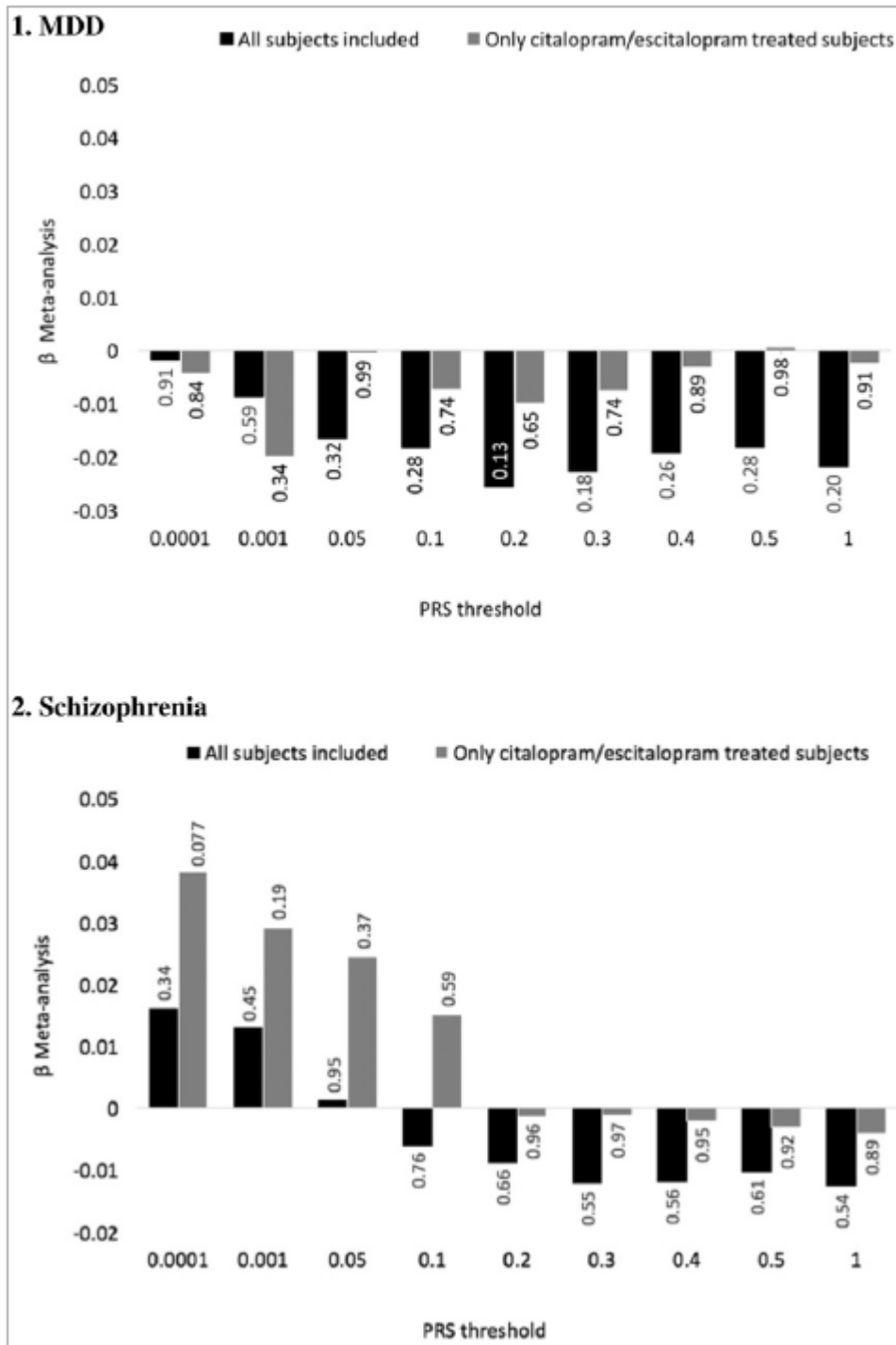


Fig. 2. Meta-analysis of PRS effect sizes (β) in seven pharmacogenetic studies for (1) MDD and (2) schizophrenia PRS. Labels show p-values for meta-analyses at each p threshold.

This study represents the largest investigation of the PRS for antidepressant response to date, including the majority of currently available pharmacogenetic data on antidepressant response in MDD (3746 participants from 7 studies). Both PGC discovery studies were well powered. The PGC schizophrenia study identified a genetic component accounting for approximately 7% of the liability to schizophrenia. MDD shares susceptibility genetic factors with schizophrenia (Cross-Disorder Group of the Psychiatric Genomics Consortium, 2013),

suggesting a possible overlap between the genetics of schizophrenia and antidepressant response. The unpublished PGC MDD meta-analysis has a substantially increased sample size from the previous study (Ripke et al., 2013b) as well as from the recent MDD GWAS from 23andMe (Hyde et al., 2016). MDD PRS comparable to the ones we calculated could not be constructed from the 23andme study since only SNPs with $p < 10^{-5}$ are publicly available.

Despite the extensive resources analysed, the power to detect predictions across study using PRS remained low for antidepressant response, although the power was adequate when we investigated common genetic liability with MDD and schizophrenia. The modest pharmacogenetic study sample sizes also precluded other whole-genome-approaches to estimate genetic correlation using GCTA or LD score regression (Yang et al., 2011; Bulik-Sullivan et al., 2015). A sample size ten-times larger would be required to achieve 80% for polygenic prediction between studies of antidepressant response. National registers and electronic medical records of large health care organisations could be used to achieve a study of this magnitude, but requires substantial resources for selection of appropriate subjects, phenotyping DNA collection, genotyping and analysis. The power to detect common liability with psychiatric disorders was higher, but required the assumption of high genetic correlation.

Other limitations of the study arise from the differences in pharmacogenetic studies in characteristics of ascertainment, baseline severity, treatment, assessment of outcome and length of follow-up. We chose to focus on two largest studies (GENDEP, STAR*D) to test PRS for antidepressant response, to avoid adding multiple smaller studies where noise would outweigh signal. In the higher powered analysis assessing genetic component of MDD and schizophrenia, we included all available pharmacogenetic studies. Although there were substantial differences in the design of the studies, inclusion criteria were relatively similar and it was possible to establish comparable outcome measures. Ethnicity is also a possible cause of stratification in GWAS despite correction using ancestry-informative principal components. Heterogeneity across samples due to ethnicity or other factors may be a limitation of the fixed-effects meta-analysis that we carried out.

We performed a single sub-analysis restricting to participants treated by citalopram or escitalopram, since escitalopram is the active isomer of citalopram ($N = 2308$ participants) (Svensson and Mansfield, 2004). These analyses also failed to predict improvement of antidepressant symptoms or remission. Many further sub-hypotheses could be tested, for example, stratifying by sex, symptom dimensions, age, or severity. Recognising the need to balance a larger effect size in one subgroup against the smaller sample size and increased correction for multiple testing, we focused on the key hypotheses (Traylor, Markus and Lewis, 2015).

The identification of individual genetic associations with antidepressant treatment response has been challenging, with no genome-wide studies identifying replicated signals for association (Uher et al., 2010; Garriock et al., 2010; Ising et al., 2009). Since no major, single locus variants play a major role in treatment response, building polygenic predictors, which capture modest effects at multiple SNPs, may be a feasible alternative. STAR*D, GENDEP and other NEWMEDS studies show a strong polygenic component to the genetic architecture of response to antidepressants, with common genetic variation estimated to

explain 42% of individual differences (SE = 0.180, $p = 0.009$) (Tansey et al., 2013). With the decreasing costs of genotyping, and increasing access to such data, a PRS could form a powerful predictor response, and be of clinical value, as already seen in predicting disease risk (Chhibber et al., 2014; Chatterjee, Shi and García-Closas, 2016). Other strategies, such as machine learning application to clinical and genetic variables in STAR*D and NEWMEDs studies showed some prediction based on both genetic and clinical characteristics, which was antidepressant specific (Iniesta et al., 2016).

We selected here two reasonable polygenic hypotheses that (1) the European Federation of Pharmaceutical Industries and Associations (EFPIA) in-kind contribution and financial contribution from the European Union Seventh Framework Programme (FP7/2007-2013).

This article represents independent research part funded by the National Institute for Health Research (NIHR) Biomedical Research Centre at South London and Maudsley NHS Foundation Trust and King's College London. The views expressed are those of the authors and not necessarily those of the NHS, the NIHR or the Department of Health.

The funding source had no role in study design, collection, analysis or interpretation of data, in the writing of the report or in the decision to submit the article for publication.

Acknowledgements

We thank the NIMH for access to data on the STAR*D study. We also thank the authors of previous publications in this dataset, and foremost, we thank the patients and their families who accepted to be enrolled in the study. Data and biomaterials were obtained from the limited access datasets distributed from the NIH-supported “Sequenced Treatment Alternatives to Relieve Depression” (STAR*D). The study was supported by NIMH Contract No. N01MH90003 to the University of Texas Southwestern Medical Center. The ClinicalTrials.gov identifier is NCT00021528.

We thank the University of Muenster, Germany, for having given the possibility of analysing their data on the MDD cohort that they collected between 2004 and 2006.

We also thank the authors of previous publications in these datasets, and foremost, we thank the patients who enrolled in these studies.

References

- American Psychiatric Association, 2013. Diagnostic and Statistical Manual of Mental Disorders. fifth ed. DSM-5. American Psychiatric Publishing (5 edition).
- Baune, B.T., Dannlowski, U., Domschke, K., Janssen, D.G.A., Jordan, M.A., Ohrmann, P., Bauer, J., Biros, E., Arolt, V., Kugel, H., Baxter, A.G., Suslow, T., 2010. The interleukin 1 beta (IL1B) gene is associated with failure to achieve remission and impaired emotion processing in major depression. *Biol. Psychiatry* 67 (6):543–549.
<http://dx.doi.org/10.1016/j.biopsych.2009.11.004>.
- Baune, B.T., Hohoff, C., Berger, K., Neumann, A., Mortensen, S., Roehrs, T., Deckert, J., Arolt, V., Domschke, K., 2008. Association of the COMT val158met variant with antidepressant treatment response in major depression. *Neuropsychopharmacology* 33 (4): 924–932.
<http://dx.doi.org/10.1038/sj.npp.1301462>.
- Beck, A.T., Ward, C.H., Mendelson, M., Mock, J., Erbaugh, J., 1961. An inventory for measuring depression. *Arch. Gen. Psychiatry* 561–571 (4 pp).

Biernacka, J.M., Sangkuhl, K., Jenkins, G., Whaley, R.M., Barman, P., Batzler, A., Altman, R.B., Arolt, V., Brockmüller, J., Chen, C.H., Domschke, K., Hall-Flavin, D.K., Hong, C.J., Illi, A., et al., 2015. The International SSRI Pharmacogenomics Consortium (ISPC): a genome-wide association study of antidepressant treatment response. *Transl. Psychiatry*:e553 (5 pp). 10.1038/tp.2015.47.

Bulik-Sullivan, B.K., Loh, P.-R., Finucane, H.K., Ripke, S., Yang, J., Patterson, N., Daly, M.J., Price, A.L., Neale, B.M., 2015. LD score regression distinguishes confounding from polygenicity in genome-wide association studies. *Nat. Genet.* 47 (3):291–295. <http://dx.doi.org/10.1038/ng.3211>.

Chatterjee, N., Shi, J., García-Closas, M., 2016. Developing and evaluating polygenic risk prediction models for stratified disease prevention. *Nat. Rev. Genet.* 17 (7): 392–406. <http://dx.doi.org/10.1038/nrg.2016.27>.

Chhibber, A., Kroetz, D.L., Tantisira, K.G., McGeachie, M., Cheng, C., Plenge, R., Stahl, E., Sadee, W., Ritchie, M.D., Pendergrass, S.A., 2014. Genomic architecture of pharmacological efficacy and adverse events. *Pharmacogenomics* 15 (16):2025–2048. <http://dx.doi.org/10.2217/pgs.14.144>.

Cross-Disorder Group of the Psychiatric Genomics Consortium, 2013m. Identification of risk loci with shared effects on five major psychiatric disorders: a genome-wide analysis. *Lancet* 381 (9875):1371–1379. [http://dx.doi.org/10.1016/S0140-6736\(12\)62129-1](http://dx.doi.org/10.1016/S0140-6736(12)62129-1) (London, England).

Cross-Disorder Group of the Psychiatric Genomics Consortium, Lee, S.H., Ripke, S., Ross B.M., Faraone, S.V., Purcell, S.M., Perlis, R.H., Mowry, B.J., Thapar, A., Goddard, M.E., Witte, J.S., Absher, D., Agartz, I., Akil, H., et al., 2013m. Genetic relationship between five psychiatric disorders estimated from genome-wide SNPs. *Nat. Genet.* 45 (9): 984–994. <http://dx.doi.org/10.1038/ng.2711>.

Dudbridge, F., 2013. Power and predictive accuracy of polygenic risk scores Naomi R. Wray (ed.). *PLoS Genet.* 9 (3):e1003348. <http://dx.doi.org/10.1371/journal.pgen.1003348>.

Euesden, J., Lewis, C.M., O'Reilly, P.F., 2015. PRSice: Polygenic risk score software. *Bioinformatics* 31 (9):1466–1468. <http://dx.doi.org/10.1093/bioinformatics/btu848>.

Fabbri, C., Crisafulli, C., Calabrò, M., Spina, E., Serretti, A., 2016. Progress and prospects in pharmacogenetics of antidepressant drugs. *Expert Opinion on Drug Metabolism & Toxicology*:pp. 1–12. <http://dx.doi.org/10.1080/17425255.2016.1202237>.

Garriock, H.A., Kraft, J.B., Shyn, S.I., Peters, E.J., Yokoyama, J.S., Jenkins, G.D., Reinalda, M.S., Slager, S.L., McGrath, P.J., Hamilton, S.P., 2010. A genomewide association study of citalopram response in major depressive disorder. *Biol. Psychiatry* 67 (2):133–138. <http://dx.doi.org/10.1016/j.biopsych.2009.08.029>.

Gaynes, B.N., Warden, D., Trivedi, M.H., Wisniewski, S.R., Fava, M., Rush, A.J., 2009. What did STAR*D teach us? Results from a large-scale, practical, clinical trial for patients with depression. *Psychiatr. Serv.* 60 (11):1439–1445 (Washington, D.C.). 10.1176/ps.2009.60.11.1439.

GENDEP Investigators, MARS Investigators and STAR*D Investigators, 2013i. Common genetic variation and antidepressant efficacy in major depressive disorder: a meta-analysis of three genome-wide pharmacogenetic studies. *Am. J. Psychiatry* 170 (2): 207–217. <http://dx.doi.org/10.1176/appi.ajp.2012.12020237>.

Global Burden of Disease Study 2013 Collaborators, 2015. Global, regional, and national incidence, prevalence, and years lived with disability for 301 acute and chronic diseases and injuries in 188 countries, 1990–2013: a systematic analysis for the global burden of disease study 2013. *Lancet* 386 (9995):743–800 (London, England). 10.1016/S0140-6736(15)60692-4.

Hamilton, M., 1967. Development of a rating scale for primary depressive illness. *Br. J. Soc. Clin. Psychol.* 6 (4), 278–296.

Hyde, C.L., Nagle, M.W., Tian, C., Chen, X., Paciga, S.A., Wendland, J.R., Tung, J.Y., Hinds, D.A., Perlis, R.H., Winslow, A.R., 2016. Identification of 15 genetic loci associated with risk of major depression in individuals of European descent. *Nat. Genet.* 48 (9):1031–1036. <http://dx.doi.org/10.1038/ng.3623>.

Iniesta, R., Malki, K., Maier, W., Rietschel, M., Mors, O., Hauser, J., Henigsberg, N., Dernovsek, M.Z., Souery, D., Stahl, D., Dobson, R., Aitchison, K.J., Farmer, A., Lewis, C.M., et al., 2016. Combining clinical variables to optimize prediction of antidepressant treatment outcomes. *J. Psychiatr. Res.*:94–102 (78 pp). 10.1016/j.jpsychires.2016.03.016.

Ising, M., Lucae, S., Binder, E.B., Bettecken, T., Uhr, M., Ripke, S., Kohli, M.A., Hennings, J.M., Horstmann, S., Kloiber, S., Menke, A., Bondy, B., Rupperecht, R., Domschke, K., et al., 2009. A genomewide association study points to multiple loci that predict antidepressant drug treatment outcome in depression. *Arch. Gen. Psychiatry* 66 (9): 966–975. <http://dx.doi.org/10.1001/archgenpsychiatry.2009.95>.

Kessler, R.C., Berglund, P., Demler, O., Jin, R., Koretz, D., Merikangas, K.R., Rush, A.J., Walters, E.E., Wang, P.S., National Comorbidity Survey Replication, 2003. The epidemiology of major depressive disorder: results from the National Comorbidity Survey Replication (NCS-R). *JAMA* 289 (23):3095–3105. <http://dx.doi.org/10.1001/jama.289.23.3095>.

Lane, P., 2008. Handling drop-out in longitudinal clinical trials: a comparison of the LOCF and MMRM approaches. *Pharm. Stat.* 7 (2):93–106. <http://dx.doi.org/10.1002/pst.267>.

Mallinckrodt, C.H., Clark, W.S., David, S.R., 2001. Accounting for dropout bias using mixed effects models. *J. Biopharm. Stat.* 11 (1–2):9–21. <http://dx.doi.org/10.1081/BIP-100104194>.

Montgomery, S.A., Asberg, M., 1979. A new depression scale designed to be sensitive to change. *Br. J. Psychiatry J. Ment. Sci.* 382–389 (134 pp).

Myung, W., Kim, J., Lim, S.-W., Shim, S., Won, H.-H., Kim, S., Kim, S., Lee, M.-S., Chang, H.S., Kim, J.-W., Carroll, B.J., Kim, D.K., 2015. A genome-wide association study of antidepressant response in Koreans. *Transl. Psychiatry*:e633 (5 pp). 10.1038/tp.2015.127.

Kim, J.-W., Carroll, B.J., Kim, D.K., 2015. A genome-wide association study of antidepressant response in Koreans. *Transl. Psychiatry*:e633 (5 pp). 10.1038/tp.2015.127.

Palla, L., Dudbridge, F., 2015. A fast method that uses polygenic scores to estimate the variance explained by genome-wide marker panels and the proportion of variants affecting a trait. *Am. J. Hum. Genet.* 97 (2):250–259. <http://dx.doi.org/10.1016/j.ajhg.2015.06.005>.

Perälä, J., Suvisaari, J., Saarni, S.I., Kuoppasalmi, K., Isometsä, E., Pirkola, S., Partonen, T., Tuulio-Henriksson, A., Hintikka, J., Kieseppä, T., Härkänen, T., Koskinen, S., Lönnqvist, J., 2007. Lifetime prevalence of psychotic and bipolar I disorders in a general population. *Arch. Gen. Psychiatry* 64 (1):19–28. <http://dx.doi.org/10.1001/archpsyc.64.1.19>.

Purcell, S., Neale, B., Todd-Brown, K., Thomas, L., Ferreira, M.A.R., Bender, D., Maller, J., Sklar, P., de Bakker, P.I.W., Daly, M.J., Sham, P.C., 2007. PLINK: a tool set for whole-genome

association and population-based linkage analyses. *Am. J. Hum. Genet.* 81 (3): 559–575. <http://dx.doi.org/10.1086/519795>.

Ripke, S., Neale, B.M., Corvin, A., Walters, J.T.R., Farh, K.-H., Holmans, P.A., Lee, P., Bulik-Sullivan, B., Collier, D.A., Huang, H., Pers, T.H., Agartz, I., Agerbo, E., Albus, M., et al., 2014. Biological insights from 108 schizophrenia-associated genetic loci. *Nature* 511 (7510):421–427. <http://dx.doi.org/10.1038/nature13595>.

Ripke, S., O'Dushlaine, C., Chambert, K., Moran, J.L., Kähler, A.K., Akterin, S., Bergen, S.E., Collins, A.L., Crowley, J.J., Fromer, M., Kim, Y., Lee, S.H., Magnusson, P.K.E., Sanchez, N., et al., 2013a. Genome-wide association analysis identifies 13 new risk loci for schizophrenia. *Nat. Genet.* 45 (10):1150–1159. <http://dx.doi.org/10.1038/ng.2742>.

Ripke, S., Wray, N.R., Lewis, C.M., Hamilton, S.P., Weissman, M.M., Breen, G., Byrne, E.M., Blackwood, D.H.R., Boomsma, D.I., Cichon, S., Heath, A.C., Holsboer, F., Lucae, S., Madden, P.A.F., et al., 2013b. A mega-analysis of genome-wide association studies for major depressive disorder. *Mol. Psychiatry* 18 (4):497–511. <http://dx.doi.org/10.1038/mp.2012.21>.

Sasayama, D., Hiraishi, A., Tatsumi, M., Kamijima, K., Ikeda, M., UmeneNakano, W., Yoshimura, R., Nakamura, J., Iwata, N., Kunugi, H., 2013. Possible association of CUX1 gene polymorphisms with antidepressant response in major depressive disorder. *Pharmacogenomics J.* 13 (4):354–358. <http://dx.doi.org/10.1038/tpj.2012.18>.

J., Demyttenaere, K., Kasper, S., Lecrubier, Y., Montgomery, S., Zohar, J., Mendlewicz, J., 2011. Switching antidepressant class does not improve response or remission in treatment-resistant depression. *J. Clin. Psychopharmacol.* 31 (4):512–516. <http://dx.doi.org/10.1097/JCP.0b013e3182228619>.

Steimer, W., Müller, B., Leucht, S., Kissling, W., 2001. Pharmacogenetics: A new diagnostic tool in the management of antidepressive drug therapy. *Clin. Chim. Acta* 308 (1–2): 33–41. [http://dx.doi.org/10.1016/S0009-8981\(01\)00423-5](http://dx.doi.org/10.1016/S0009-8981(01)00423-5).

Streiner, D.L., 2002. Breaking up is hard to do: the heartbreak of dichotomizing continuous data. *Can. J. Psychiatry* 47 (3), 262–266.

Svensson, S., Mansfield, P.R., 2004. Escitalopram: superior to citalopram or a chiral chimera? *Psychother. Psychosom.* 73 (1):10–16. <http://dx.doi.org/10.1159/000074435>.

Tansey, K.E., Guipponi, M., Domenici, E., Lewis, G., Malafosse, A., O'Donovan, M., Wendland, J.R., Lewis, C.M., McGuffin, P., Uher, R., 2014. Genetic susceptibility for bipolar disorder and response to antidepressants in major depressive disorder. *Am. J. Med. Genet. B Neuropsychiatr. Genet.* 165 (1):77–83. <http://dx.doi.org/10.1002/ajmg.b.32210>.

Tansey, K.E., Guipponi, M., Hu, X., Domenici, E., Lewis, G., Malafosse, A., Wendland, J.R., [ajmg.b.32210](http://dx.doi.org/10.1002/ajmg.b.32210).

Tansey, K.E., Guipponi, M., Hu, X., Domenici, E., Lewis, G., Malafosse, A., Wendland, J.R., Hauser, J., Henigsberg, N., Hu, X., Jerman, B., Maier, W., Mors, O., O'Donovan, M., et al., 2012. Genetic predictors of response to serotonergic and noradrenergic antidepressants in major depressive disorder: a genome-wide analysis of individual-level data and a meta-analysis. *PLoS Med.* 9 (10):e1001326. <http://dx.doi.org/10.1371/journal.pmed.1001326>.

The WHO World Mental Health Survey Consortium, 2004. Prevalence, severity, and unmet need for treatment of mental disorders in the world health organization world mental health surveys. *JAMA* 291 (21):2581–2590. <http://dx.doi.org/10.1001/jama.291.21.2581>.

Traylor, M., Markus, H., Lewis, C.M., 2015. Homogeneous case subgroups increase power in genetic association studies. *Eur. J. Hum. Genet.* 23 (6):863–869.

<http://dx.doi.org/10.1038/ejhg.2014.194>.

Trivedi, M.H., Rush, A.J., Wisniewski, S.R., Nierenberg, A.A., Warden, D., Ritz, L., Norquist, G., Howland, R.H., Lebowitz, B., McGrath, P.J., et al., 2006. Evaluation of outcomes with citalopram for depression using measurement-based care in STAR*D: implications for clinical practice. *Am. J. Psychiatr.* (online Available from:

<http://ajp.psychiatryonline.org/doi/abs/10.1176/appi.ajp.163.1.28> Accessed 10 May 2016).

Uher, R., Farmer, A., Maier, W., Rietschel, M., Hauser, J., Marusic, A., Mors, O., Elkin, A., Williamson, R.J., Schmael, C., Henigsberg, N., Perez, J., Mendlewicz, J., Janzing, J.G.E., et al., 2008. Measuring depression: comparison and integration of three scales in the GENDEP study. *Psychol. Med.* 38 (2) (Available from: http://www.journals.cambridge.org/abstract_S0033291707001730doi:10.1017/S0033291707001730 Accessed 7 July 2016).

Uher, R., Maier, W., Hauser, J., Marusic, A., Schmael, C., Mors, O., Henigsberg, N., Souery, D., Placentino, A., Rietschel, M., Zobel, A., Dmitrzak-Weglarz, M., Petrovic, A., Jorgensen, L., et al., 2009. Differential efficacy of escitalopram and nortriptyline on dimensional measures of depression. *Br. J. Psychiatry J. Ment. Sci.* 194 (3):252–259. <http://dx.doi.org/10.1192/bjp.bp.108.057554>.

Uher, R., Perroud, N., Ng, M.Y., Hauser, J., Henigsberg, N., Maier, W., Mors, O., Placentino, A., Rietschel, M., Souery, D., et al., 2010. Genome-wide pharmacogenetics of antidepressant response in the GENDEP project. *Am. J. Psychiatr.* ([online] Available from: <http://ajp.psychiatryonline.org/doi/pdf/10.1176/appi.ajp.2009.09070932> Accessed 12 February 2016).

World Health Organization, 1993. The ICD-10 Classification of Mental and Behavioural Disorders: Diagnostic Criteria for Research. (No Place). World Health Organisation (1 Jan. 1993).

World Health Organization, 1993. The ICD-10 Classification of Mental and Behavioural Disorders: Diagnostic Criteria for Research. (No Place). World Health Organisation (1 Jan. 1993).

Yang, J., Lee, S.H., Goddard, M.E., Visscher, P.M., 2011. GCTA: a tool for genome-wide complex trait analysis. *Am. J. Hum. Genet.* 88 (1):76–82. <http://dx.doi.org/10.1016/j.ajhg.2010.11.011>.