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Polygenic scores for intelligence, educational attainment and schizophrenia are differentially associated with core autism features, IQ, and adaptive behaviour in autistic individuals

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Abstract

Importance

Schizophrenia, educational attainment, and intelligence are all genetically correlated with autism. However, autism is a complex condition, with several different core (such as social communication difficulties and repetitive and restricted behaviour) and associated features (such as IQ and adaptive behaviour) contributing to the underlying heterogeneity. It is unknown to what extent polygenic scores (PGS) for these three phenotypes are associated with the core and associated autism features.

Objective

To investigate the association of PGS for intelligence, educational attainment and schizophrenia on core autism features, IQ and adaptive behaviour in autistic individuals. To further investigate the effects of stratifying by sex and IQ on these associations.

Design

PGS association for the three phenotypes with 12 different autism core and associated features in three cohorts followed by meta-analysis. We additionally conducted sensitivity analyses by stratifying for sex and IQ.

Settings:

Three cross-sectional, multi-centre cohorts comprising autistic with genotype data, and phenotypic information.

Participants

Autistic individuals (total N: 2,512 – 3,681) from three different cohorts: Simons Simplex Collection ($N_{\max} = 2,233$), Autism Genetic Research Exchange ($N_{\max} = 1,200$), and AIMS-2-TRIALS LEAP ($N_{\max} = 262$)

Main outcome measures

Association of PGS for intelligence, educational attainment, and schizophrenia with core autism features, measures of intelligence, and adaptive behaviour in autistic individuals

Results

We identified a similar pattern of correlation among core and associated autism features across all three cohorts. Cluster analyses of these features identified two broad clusters – one consisting of the core features, and another consisting of IQ and adaptive behaviour. PGS for intelligence were only associated with measures of intelligence and adaptive behaviour (e.g. for full-scale IQ, Beta = 0.08, 95%CI = 0.11 – 0.04) for PGS for educational attainment were associated for measures of intelligence, adaptive behaviour, and additionally, non-verbal communication as measured by ADI – a core-autism feature (e.g. for full-scale IQ, Beta = 0.05, 95%CI = 0.08 – 0.02; for ADI non-verbal communication, Beta = 0.05, 95%CI = 0.09 – 0.01). Finally, PGS for schizophrenia were associated with two core autism features: restricted and repetitive behaviour and verbal communication difficulties as measured by the

ADI-R (e.g. for ADI restricted and repetitive behaviour: Beta = 0.06, 95%CI = 0.09 – 0.02). Most of these associations were also significant when restricting it to males only or to individuals with IQ > 70. We find limited evidence for heterogeneity between cohorts.

Conclusion and relevance

We identify specific and different patterns of association between PGS for the three phenotypes and core and associated autism features. This provides greater resolution into the shared genetics between autism and the three phenotypes, and suggests one method to investigate heterogeneity in autism and co-occurring conditions.

Key Questions

Question: Are polygenic scores (PGS) for intelligence, educational attainment, and schizophrenia differentially associated with core autism features, IQ, and adaptive behaviour in autistic individuals?

Findings: Across three cohorts, we identify that PGS for intelligence, educational attainment and schizophrenia are associated with different features in autistic individuals. PGS for intelligence were primarily associated with adaptive behaviour and IQ, PGS for schizophrenia were associated with some core autism features, whilst PGS for educational attainment were associated with IQ, adaptive behaviour, and some core autism features.

Meaning: Our findings suggest that the shared genetics between autism and intelligence, educational attainment, and schizophrenia emerge primarily from specific of core and associated features which are different for the three sets of PGS tested.

1 Introduction

2 Autism is a set of complex and heterogeneous neurodevelopmental conditions
3 characterised by difficulties in social communication, unusually repetitive and restricted
4 behaviour and interests, difficulties adjusting to unexpected change, and altered sensory
5 processing (1,2). Autism also frequently co-occurs with other medical, neurodevelopmental,
6 or mental health conditions (3,4). Autism is substantially heritable, with twin and familial
7 heritabilities between 50–90% (5–8). Significant progress has been made in identifying
8 common genetic variants (9) and genes enriched for rare and protein truncating variants
9 associated with autism (10–12). Additionally, genome-wide association studies (GWAS)
10 have identified shared genetics between autism and a number of other phenotypes, including
11 schizophrenia ($r_g = 0.24 \pm 0.04$), educational attainment ($r_g = 0.20 \pm 0.02$), and intelligence (r_g
12 $= 0.22 \pm 0.03$) (9,13).

13
14 Autism is unlikely to be a single condition but a composite of multiple, partly
15 dissociable core features (e.g. social interaction and communication difficulties, and
16 restricted interested and repetitive behaviour) and associated features like difficulties in
17 adaptive behaviour and a wide IQ range (14–19). These core and associated features
18 contribute to heterogeneity in autism and are associated with differential outcomes in autistic
19 individuals (20,21). Therefore, investigating the genetics of autism as a single phenotype may
20 provide incomplete information about prognosis and outcomes in autistic individuals.

21
22 While schizophrenia, educational attainment, and intelligence are all genetically
23 correlated with autism, we still do not know which core and associated features of autism
24 these phenotypes are genetically correlated with. In other words, are polygenic scores (PGS)
25 for these phenotypes associated with all core and associated autism features, or are they
26 associated with only some of the core and associated features? Finally, how do other sources
27 of heterogeneity such as participants' IQ or sex affect these associations? This can provide
28 better resolution of the shared genetics between various core and associated features and
29 other co-occurring conditions, and identify axes to potentially stratify autistic individuals
30 along to provide better care and support.

31
32 To address these questions, we investigated the association of PGS for three well-
33 powered GWAS (intelligence, educational attainment and schizophrenia) with 12 different
34 core and associated autism features in 2,512 – 3,681 autistic individuals from three cohorts.
35 These 12 features represent the core aspects of autism such as restricted and repetitive
36 behaviour and interests, and social interaction and communication difficulties, and associated
37 features such as measures of IQ and adaptive behaviour. We additionally conduct sensitivity
38 analyses by stratifying for males and individuals with $IQ > 70$, and investigate differences in
39 PGS associations between cohorts.

40
41
42
43

44 **Methods**

45 **Overview of the cohorts**

46 We conducted PGS analyses in three cohorts of autistic individuals: The Simons
47 Simplex Collection (SSC) (22), the Autism Genetic Resource Exchange (AGRE, CHOP
48 sample) ($N_{\max} = 1,200$) (23), and the AIMS-2-TRIALS LEAP sample ($N_{\max} = 262$) (24).
49 Participants in all three cohorts were recruited across multiple sites. For each cohort, we
50 restricted our analyses to autistic individuals who passed the genetic quality control and who
51 had the relevant phenotype, resulting in a total sample size ranging from 2,512 - 3,681. We
52 compare the demographic characteristics of these cohorts in **Table 1**. Further details of these
53 cohorts are provided in the **eMethods 1**.

54

55

Insert Table 1 here

56

57 **Genetic quality control, imputation, and polygenic score generation**

58 Full details of the genetic quality control are provided in **eMethods2**. Briefly, quality
59 control was conducted for each cohort separately, by array. We excluded participants with
60 genotyping rate $< 95\%$, excessive heterozygosity (± 3 standard deviations from the mean),
61 who were not of European ancestry as identified using multidimensional scaling, had
62 mismatched genetic and reported sex, and families with Mendelian errors $> 10\%$. SNPs were
63 excluded with genotyping rate $< 10\%$, or deviated from Hardy-Weinberg equilibrium (p -
64 value $< 1 \times 10^{-6}$). Imputation was conducted using Michigan Imputation Server (25) using the
65 1000 genomes Phase 3 v5 as the reference panel (26) (for AGRE and SSC) or using HRC
66 r1.1 2016 reference panel (for AIMS-2-TRIALS). SNPs with minor allele frequency $< 1\%$ or
67 an imputation $r^2 < 0.6$ were excluded.

68

69 GWAS used to generate PGS were identified *a priori* using statistical power analyses
70 (27) using https://eagenetics.shinyapps.io/power_website/. Details of parameters used are
71 provided in **eTable 1**. We assumed a SNP heritability of 0.15 for the core and associated
72 autism features and a sample size of 3,000. We conducted power analyses for seven relatively
73 well-powered GWAS that are genetically correlated with autism. The GWAS for autism (9)
74 was excluded as this overlaps with the SSC and AGRE datasets. We subsequently restricted
75 our analyses to only GWAS that had around 80% statistical power at a genetic correlation of
76 0.25 or greater than 60% power at a genetic correlation of 0.2, which is similar to the genetic
77 correlation between autism and educational attainment, intelligence and schizophrenia. Three
78 phenotypes met our criteria: 1. Educational attainment (28) ($N = 766,345$, excluding the
79 23andMe dataset), 2. Intelligence (29) ($N = 269,867$), and 3. Schizophrenia (30) (56,418
80 cases and 78,818 controls). All three GWAS are genetically correlated with autism, and PGS
81 for these GWAS are over-transmitted from parents to autistic children (13), suggesting that
82 the observed genetic correlations with autism are not due to other confounding factors such as
83 ascertainment bias.

84

85 PGS were generated for three phenotypes using PRSice2 (31), using independent
86 SNPs (clumping r^2 of 0.1 and 250 kb) present in both the GWAS and the testing datasets.

87 Given the limited testing sample size and the number of tests conducted, we chose *a priori* p-
88 value thresholds that explained maximum variance in the three phenotypes: $p \leq 1$ for the
89 educational attainment and intelligence GWASs (28,29), and $p \leq 0.1$ (30) for the
90 schizophrenia GWAS. The total number of SNPs included are provided in **eTable 2**.

91

92 **Autism core and associated features**

93 We identified 12 autism core and associated features that are: 1. Widely used in studies
94 related to autism; 2. Are a combination of parent-, self-, other-report and performance-based
95 measures to investigate if reporter status affects the PGS association, 3. Collected in all three
96 cohorts; and 4. Cover a range of core and associated features in autism. Details of each
97 feature is provided in the **eMethods 3**. The core features are:

98

- 99 1. ADOS: Social Affect (ADOS SA)
- 100 2. ADOS: Restricted and Repetitive Behaviour domain total score (ADOS RRB)
- 101 3. ADI: Communication (verbal) domain total score* (ADI VC)
- 102 4. ADI: Communication (nonverbal) domain total score* (ADI NVC)
- 103 5. ADI: Restricted and repetitive behaviour domain total score (ADI RRB)
- 104 6. ADI: Social domain total score (ADI SOC)
- 105 7. Repetitive Behaviour Scale – Revised (RBS)
- 106 8. Parent-reported Social Responsiveness Scale: Total raw scores (SRS)

107

108 The associated features are :

- 109 1. Vineland Adaptive Behaviour Composite Standard scores (VABS)
- 110 2. Full-scale IQ (FSIQ)
- 111 3. Verbal IQ (VIQ)
- 112 4. Non-verbal IQ (NVIQ)

113

114 * Verbal and non-verbal communication scores were not separately calculated in the AIMS2-
115 TRIALS-LEAP dataset. We thus used a total communication score and meta-analysed it with
116 the verbal and non-verbal communication scores in the other two cohorts.

117

118 **Statistical analyses**

119 For each cohort, PGS were regressed against the autism features with sex and the first
120 15 genetic principal components as covariates in all analyses, with all variables standardised
121 (mean = 0, standard deviation = 1). Additionally, age of participants in the AIMS-2-TRIALS
122 LEAP cohort, and genotype array in the SSC cohort were included as covariates. Age at
123 completion of each measure was only available in the AIMS-2- TRIALS LEAP dataset. IQ
124 type and ADOS module were included as additional covariates. For SSC and AIMS-2-
125 TRIALS LEAP as only unrelated individuals were included, a linear model was used. AGRE
126 includes a large number of multiplex families with multiple autistic individuals per family.
127 Thus, to retain all participants, we used linear mixed effects regression with family ID
128 included as a random intercept to account for relatedness between individuals.

129 Effect sizes were meta-analysed across the three cohorts using inverse variance
130 weighted meta-analyses with the following formula:

$$w_i = 1/SE_i^2$$
$$SE_{meta} = \sqrt{1/\sum_i w_i}$$
$$Beta_{meta} = \sum_i \beta_i w_i / \sum_i w_i$$

131
132 Where β_i is the standardized regression coefficient of the PGS, SE_i is the associated standard
133 error, and w_i is the weight. p-values were calculated from Z scores ($Beta_{meta}/SE_{meta}$).

134
135 Variance explained was estimated (R^2) by squaring the $Beta_{meta}$. Given the high
136 correlation between the autism features and phenotypes, we used Benjamini-Hochberg False
137 Discovery Rates to correct for multiple testing (q-value < 0.05).

138
139 Core and associated autism features are quantitatively and qualitatively different
140 between sexes (32). Further, autistic individuals with co-occurring ID are enriched for rare
141 and *de novo* protein-truncating variants (PTV) (33,34), suggesting that some of the variation
142 in these phenotypes may be attributed to this class of genetic variants in these individuals
143 (35,37). So, we conducted sensitivity analyses by restricting the samples to only males (N =
144 3,040 – 2,125) or individuals with IQ > 70 (N = 2,319 – 1,801). We did not test for
145 association between FSIQ and VIQ and the three PGS in the AGRE in the two sensitivity
146 analyses, as fewer than 20 individuals had scores on these measures. We followed the same
147 statistical analysis pipeline for the two sensitivity analyses, and identified significant
148 associations using Benjamini-Hochberg FDR correction (q-value < 0.05).

149
150 To understand how the features correlated with each other, we conducted Pearson's
151 correlation analyses followed by hierarchical clustering for each cohort (**eMethods 4**).

152
153 All analyses were conducted in R. Data and software availability is provided in
154 **eMethods 5**.

155 156 **Ethics**

157 We received ethical approval to access and analyse de-identified genetic and
158 phenotypic data from the three cohorts from the University of Cambridge Human Biology
159 Research Ethics Committee.

160 161 162 **Results**

163 164 **Phenotypic correlation in the three cohorts**

165 Pearson's correlation produced a similar correlation profile across all three cohorts
166 with two clusters – a core autism cluster with all core autism features, and an associated
167 feature cluster with all three IQ measures and VABS (**Figure 1, eFigures 1 – 3, eTables 3 -**

168 5). The two clusters were largely negatively correlated with each other. Within the autism
169 cluster, hierarchical clustering suggested that instrument type had primacy over domain. For
170 instance, the ADOS subscales clustered closely together, and as did the two parent-report
171 measures (SRS and RBS).

172

173

Insert Figure 1 here

174

175 Correlation analyses of the correlation coefficients across pairs of features identified
176 high correlations for all three pairs (SSC-AGRE: $r = 0.89$, $p\text{-value} < 2 \times 10^{-16}$; SSC-AIMS-2-
177 TRIALS LEAP: $r = 0.92$, $p\text{-value} < 2 \times 10^{-16}$; and AGRE – AIMS-2-TRIALS LEAP: $r = 0.92$,
178 $p\text{-value} < 2 \times 10^{-16}$) (**Figure 2**).

179

180

Insert Figure 2 here

181

182 **Polygenic score analyses**

183

184 PGS for intelligence were positively associated with all measures of IQ and VABS
185 with concordant effect direction in all cohorts: FSIQ (Beta = 0.08 ± 0.02 , $q\text{-value} = 6.69 \times 10^{-4}$,
186 $R^2 = 0.63\%$), VIQ (Beta = 0.06 ± 0.02 , $q\text{-value} = 5.21 \times 10^{-3}$, $R^2 = 0.37\%$), NVIQ (Beta =
187 0.09 ± 0.02 , $q\text{-value} = 3.82 \times 10^{-5}$, $R^2 = 0.77\%$), and VABS (Beta = 0.06 ± 0.02 , $q\text{-value} =$
188 1.91×10^{-2}) (**Figure 3 and eTable 6**).

188

189 Similarly, PGS for educational attainment were positively associated with all
190 measures of IQ and VABS with concordant effect direction in all cohorts: FSIQ (Beta =
191 0.06 ± 0.02 , $q\text{-value} = 2.36 \times 10^{-3}$, $R^2 = 0.30\%$), VIQ (Beta = 0.06 ± 0.01 , $q\text{-value} = 6.69 \times 10^{-4}$, R^2
192 $= 0.32\%$), NVIQ (Beta = 0.05 ± 0.01 , $p\text{-value} = 7.57 \times 10^{-3}$, $R^2 = 0.21\%$), and VABS (Beta =
193 0.04 ± 0.02 , $q\text{-value} = 4.53 \times 10^{-2}$, $R^2 = 0.20\%$) (**Figure 3 and eTable 6**). There were no
194 statistically significant differences in effect sizes between the PGS for education and
195 intelligence for all measures of IQ.

196

197 Interestingly, PGS for educational attainment were also positively associated with
198 scores on the verbal and non-verbal communication subscales of the ADI, though the effect
199 directions were not concordant in the three cohorts (ADI NVC: Beta = 0.05 ± 0.02 , $q\text{-value} =$
200 3.23×10^{-2} , $R^2 = 0.26\%$ ADI VC: Beta = 0.05 ± 0.02 , $q\text{-value} = 2.69 \times 10^{-2}$, $R^2 = 0.27\%$) (**Figure**
201 **3 and eTable 6**). Higher scores on the ADI are associated with more difficulties with
202 communication.

203

204 PGS for schizophrenia were positively associated with two ADI subscales (ADI RRB:
205 Beta = 0.06 ± 0.02 , $q\text{-value} = 5.21 \times 10^{-3}$, $R^2 = 0.39\%$, ADI NVC: Beta = 0.05 ± 0.02 , $q\text{-value} =$
206 3.23×10^{-2} , $R^2 = 0.32\%$) (**Figure 3 and eTable 6**). The effect direction was concordant in all
207 three cohorts for ADI RRB but not for ADI NVC (**eTable 6**).

208

209

Insert Figure 3 here

210

211 **Assessing heterogeneity across cohorts and polygenic scores**

212 We next conducted binomial sign test to investigate effect direction concordance
213 between the three cohorts. Formal tests of heterogeneity are likely to be biased given the
214 small number of studies included (36), so we assessed heterogeneity using sign tests
215 assessing effect directions. 32 out of 36 tests had concordant effect direction between the
216 SSC and the AGRE cohorts (p-value = 1.94×10^{-6} , binomial sign test), 21 out of 30 between
217 the SSC and AIMS-2-TRIALS (p-value = 0.04), and 22 out of 30 between the AGRE and the
218 AIMS-2-TRIALS dataset (p-value = 0.01), suggesting largely similar effect directions across
219 cohorts.

220

221 We also investigated the concordance of effect direction between the three sets of
222 PGS for the 12 features tested using the meta-analysed effect direction. All 12 tests had
223 concordant effect direction between the PGS for educational attainment and intelligence (p-
224 value = 4.8×10^{-4} , binomial sign test), but only 6 of 12 has concordant effect direction between
225 PGS for schizophrenia and both educational attainment and intelligence (p-value = 1). This is
226 expected given the high genetic correlation between intelligence and educational attainment
227 ($r_g = 0.72 \pm 0.011$), but the low genetic correlation between schizophrenia and intelligence (r_g
228 = -0.21 ± 0.025) and educational attainment ($r_g = 0.01 \pm 0.017$).

229

230 **Sensitivity analyses**

231 As the AIMS-2-TRIAL LEAP dataset significantly differed from the AGRE and the
232 SSC datasets in terms of fraction of female autistic or autistic individuals with $IQ < 70$, we
233 conducted two sensitivity analyses (**Methods**). In the males-only analyses, PGS for
234 intelligence were associated with FSIQ and NVIQ (**eFigure 4** and **eTable 7**). PGS for
235 educational attainment were associated with the two ADI communication subscales, RBS,
236 FSIQ, and VIQ. Finally, PGS for SCZ were associated with ADI: RRB.

237

238 In the $IQ > 70$ analyses, PGS for intelligence and educational attainment were
239 associated with FSIQ, VIQ, and NVIQ. Notably, the variance explained in this subset of
240 individuals for these three phenotypes were 2 – 3 times higher than the variance explained in
241 the primary analyse. Additionally, PGS for educational attainment were associated with
242 scores on the VABS, RBS, and ADI: NVC. Finally, PGS for schizophrenia were
243 significantly associated with ADI: RRB and NVIQ (**eFigure 5** and **eTable 8**). In both
244 sensitivity analyses, the effect directions were concordant for all significant associations.

245

246

247 **Discussion**

248 Given demographic differences between the three cohorts, we first compared the
249 patterns of phenotypic correlations for the core and associated autism features in the three
250 cohorts, and identified a similar pattern in all three datasets. The core features clustered
251 together, and the measures of intelligence and adaptive behaviour clustered together. This
252 was confirmed by high Pearson's correlation between pairs of features across the three
253 cohorts.

254

255 PGS for the three phenotypes were differentially associated with the features tested.
256 Specifically, PGS for educational attainment and intelligence were positively associated with
257 all three measures of IQ and VABS. The shared genetics between VABS and educational
258 attainment and intelligence is unsurprising, given the modest to substantial phenotypic
259 positive correlations between VABS and measures of IQ in the three cohorts ($r = 0.36$ to
260 0.68). Sensitivity analyses in autistic individuals with $IQ > 70$ confirmed the association
261 between the measures of IQ and PGS for educational attainment and intelligence. Previous
262 research has suggested that protein truncating rare and *de novo* variants are negatively
263 associated with measures of IQ and scores on the VABS in autistic individuals (10,33,39),
264 though these sets of variants are enriched in individuals with $IQ < 70$. In contrast, in our
265 analyses, PGS for educational attainment and intelligence explained a greater proportion of
266 variance in measures of IQ in autistic individuals with $IQ > 70$ compared to all autistic
267 individuals, suggesting a more prominent role for PGS in measures of IQ in autistic
268 individuals without intellectual disability. Taken together, our analyses suggest that in autistic
269 individuals, similar to the general population (28,29,38), genetic variants across the allelic
270 frequency spectrum contribute to differences in IQ and related measures, but the relative
271 contribution of different sets of genetic variants may differ based on intellectual disability.

272
273 PGS for educational attainment were also associated with higher scores on the two
274 ADI communication subdomains (verbal and non-verbal communication), which is in the
275 opposite direction to what's been observed between social and communication difficulties
276 and educational attainment in the general population ($r_g = -0.30 \pm 0.11$, $P = 0.007$) (18).
277 Sensitivity analyses restricting to either males or individuals with $IQ > 70$ also identified
278 significant associations between PGS for educational attainment and ADI communication
279 subdomains with concordant effect direction across all three datasets. This inversion in effect
280 direction between social and communication difficulties and educational attainment in the
281 typical population and autistic individuals must be further investigated. In the two sensitivity
282 analyses PGS for educational attainment were negatively associated with scores on the RBS,
283 though this was only nominally significant in the non-stratified analyses. The variance
284 explained by the PGS for educational attainment for RBS-R in the subgroups was 2 – 2.5x
285 the variance explained in the primary analyses, highlighting, yet again, heterogeneity within
286 the autism spectrum based on IQ and sex.

287
288 PGS for schizophrenia, on the other hand, were positively associated with scores on
289 ADI: RRB and ADI: NVC. However, only the association with ADI: RRB was significant in
290 the two sensitivity analyses. In the general population, there is some evidence to suggest that
291 PGS for schizophrenia are associated with social and communication difficulties (40,42).
292 However, to our knowledge, this is the first report linking PGS for schizophrenia with
293 restricted and repetitive behaviour, though RRBs are elevated in individuals with
294 schizophrenia (41).

295
296 The sample size for each individual cohort was limited, and the number of cohorts
297 were small excluding the possibility of conducting formal tests of heterogeneity between
298 cohorts. However, analyses of effect direction of the three sets of PGS revealed broad

299 similarities between cohorts, with notably high concordance in effect direction between the
300 AGRE and the SSC cohorts. This is notable given the substantial differences in demographic
301 characteristics between the cohorts, and potential differences in the SNPs used to generate the
302 polygenic scores for the three cohorts.

303

304 Comparing the physical correlations to the effect direction of the PGS further helps to
305 elucidate the differences between the three sets of PGS. Whilst PGS for SCZ is positively
306 associated with the autism core features, and negatively with the associated features, the PGS
307 for educational attainment and IQ were positively associated with most features tested.
308 Notably, PGS for schizophrenia were *significantly associated* with some autism core features,
309 PGS for intelligence were *significantly associated* with all associated features, whereas PGS
310 for educational attainment were *significantly associated* with all associated features and some
311 autism core features suggesting differential association. However, we note that the statistical
312 significance of these associations will be influenced by sample size. In other words, larger
313 sample sizes may identify other associations between the PGS and the features.

314

315 Our study also provides a cautionary note about instrument bias which is reflected in
316 the PGS associations. For example, restricted and repetitive behaviours are primarily
317 measured here using RBS, ADI-RRB and ADOS-RRB. The phenotypic correlations between
318 these are low to modest ($r : 0.11 - 0.48$). Further, SCZ PGS are only associated with ADI-
319 RRB, and PGS for educational attainment are only associated with RBS (in the sensitivity
320 analyses). Together this suggests that idiosyncratic and systematic differences (e.g. reporter
321 bias, number of questions) makes it challenging to compare different core and associated
322 features even if they are meant to capture the same underlying latent trait. Phenotypically,
323 this manifests as modest correlations, and genetically this suggests different underlying
324 genetic architectures for these features, both of which have been demonstrated before (43–
325 45).

326

327 **Limitations**

328

329 Whilst the largest study to date, we were statistically well powered to investigate the
330 shared genetics only with three phenotypes, and were not well-powered to explore the co-
331 variance explained at multiple different p-value thresholds in the training datasets. Larger
332 datasets may identify additional significant associations between the current PGS and
333 features tested. Further, whilst well powered, PGS still do not account for all the SNP
334 heritability. We also do not examine the role of rare and low-frequency variants in this study,
335 which are also associated with autism and the three phenotypes (33,38,46). Finally, each
336 many phenotypes included in the study (e.g. SRS and RBS-R) can be further divided into
337 additional subdomains based on factor analyses or evaluating the items included. A
338 comprehensive investigation across all subdomains is warranted, yet is only possible with
339 additional datasets that provide sufficient statistical power.

340

341 **Conclusions**

342 Core and associated autism features are differentially associated with PGS for
343 intelligence, educational attainment, and schizophrenia. We find limited evidence for
344 heterogeneity between cohorts despite differences in demographic characteristic, though
345 stratifying for males and IQ > 70 identified additional associations with PGS. Our study
346 provides insights into the underlying heterogeneity in autism, and provides greater resolution
347 to the shared genetics between autism and intelligence, educational attainment, and
348 schizophrenia.

349

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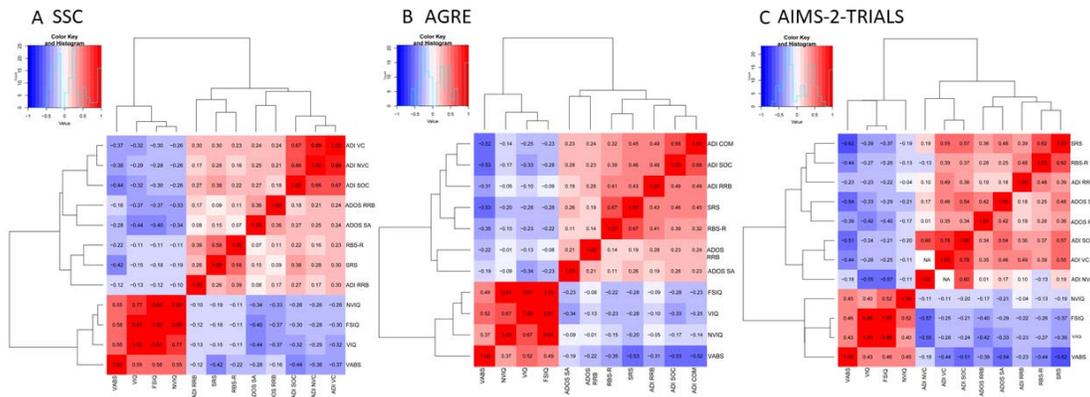
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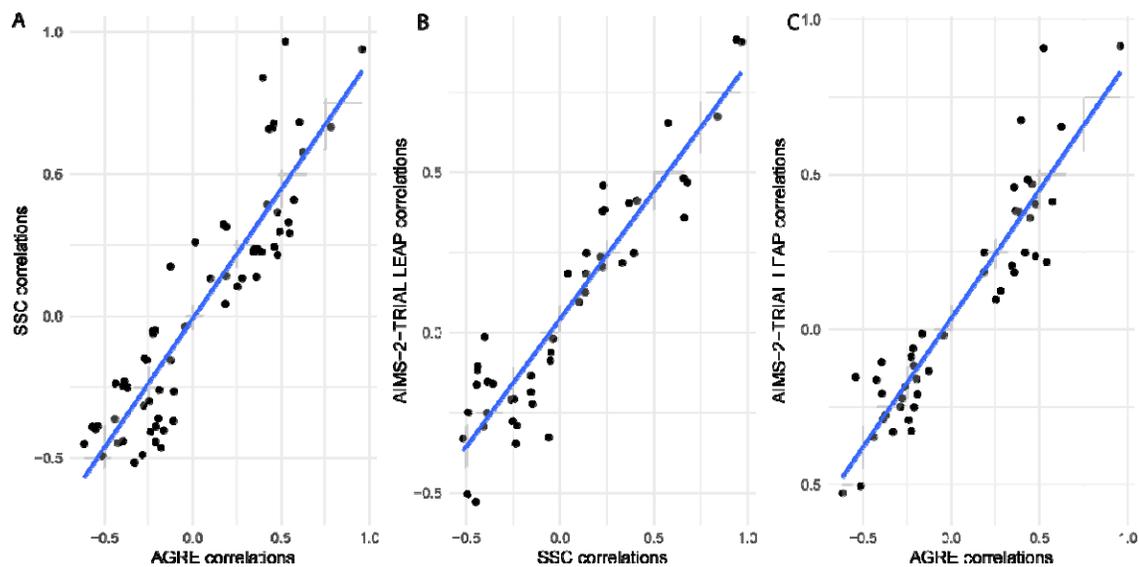
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506 **Figure 1: Heatmap of the phenotypic correlations in the three cohorts**



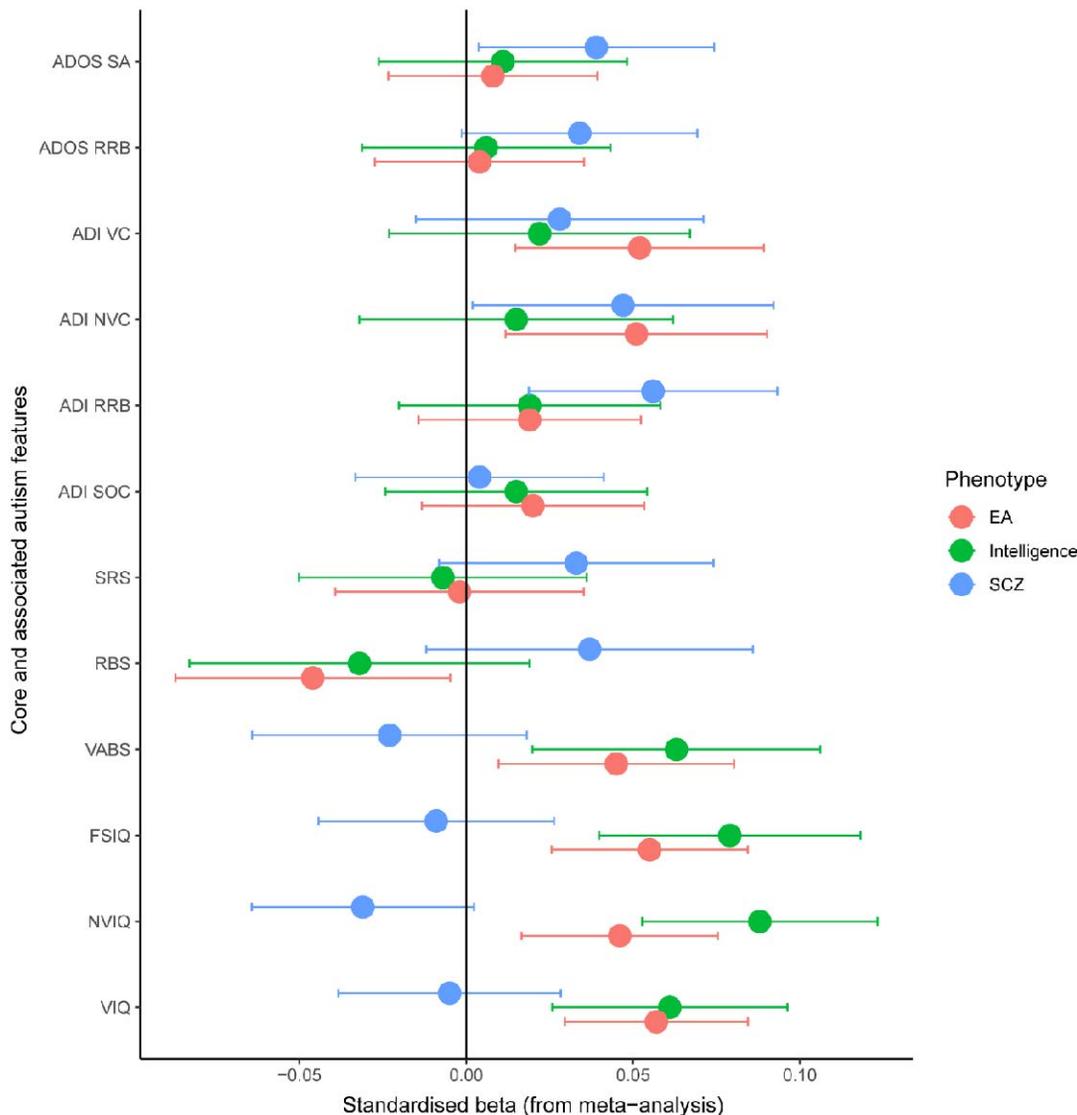
507
 508 *This figure provides the correlation heatmap for the correlations for autism core features,*
 509 *IQ, and adaptive behaviour in the: A. SSC; B. AGRE; and C: AIMS-2-TRIALS LEAP cohorts.*
 510 *Hierarchical clustering tree is also provided for each of the plots. Red colour indicates a*
 511 *positive correlation, while blue indicates a negative correlation. Individual plots for each*
 512 *cohort with greater resolution is provided in eFigures 1 – 3. Separate verbal communication*
 513 *and non-verbal communication ADI scores (ADI VC and ADI NVC) were not available for*
 514 *the AIMS-2-TRIALS LEAP, so we used a composite ADI communication score (ADI COM).*
 515 *Additionally, we did not identify individuals who had both ADI VC and ADI NVC scores in*
 516 *the AGRE cohort, and hence could not calculate the correlations between these two subscales*
 517 *in the AGRE cohort. The features are: ADOS - Social Affect (ADOS SA); ADOS - Restricted*
 518 *and Repetitive Behaviour domain total score (ADOS RRB); ADI - Communication (verbal)*
 519 *domain total score (ADI VC); ADI - Communication (nonverbal) domain total score (ADI*
 520 *NVC); ADI - Restricted and repetitive behaviour domain total score (ADI RRB); ADI -*
 521 *Social domain total score (ADI SOC); Repetitive Behaviour Scale – Revised (RBS-R);*
 522 *Vineland Adaptive Behaviour Composite Standard scores (VABS); Parent-reported Social*
 523 *Responsiveness Scale - Total raw scores (SRS); Full-scale IQ (FSIQ); Verbal IQ (VIQ); and*
 524 *Non-verbal IQ (NVIQ).*

525 **Figure 2: Correlations of correlations among pairs of autism core and associated**
526 **features across the three cohorts**



527
528 *This figure provides the correlation between the correlation coefficients of pairs of core and*
529 *associated autism features in two datasets. A: Between the SSC and AGRE ($r = 0.89$, p -value*
530 *$< 2 \times 10^{-16}$); B: Between AIMS-2-TRIALS LEAP and SSC ($r = 0.92$, p -value $< 2 \times 10^{-16}$); and C:*
531 *Between AIMS-2-TRIALS and AGRE ($r = 0.92$, p -value $< 2 \times 10^{-16}$). Pearson's correlation*
532 *coefficient was calculated. The shaded portion of the line indicates the 95% confidence*
533 *interval for the correlation.*

534 **Figure 3: Polygenic score association of the three phenotypes with the autism core**
 535 **features, measures of IQ, and adaptive behaviour**



536
 537 *This figure provides the meta-analysed regression Beta and the associated 95% confidence*
 538 *intervals for the three phenotypes (EA = educational attainment in red, SCZ = schizophrenia*
 539 *in blue, and intelligence in green) against the core autism features, measures of IQ, and*
 540 *adaptive behaviour. These are: ADOS - Social Affect (ADOS SA); ADOS - Restricted and*
 541 *Repetitive Behaviour domain total score (ADOS RRB); ADI - Communication (verbal)*
 542 *domain total score (ADI VC); ADI - Communication (nonverbal) domain total score (ADI*
 543 *NVC); ADI - Restricted and repetitive behaviour domain total score (ADI RRB); ADI -*
 544 *Social domain total score (ADI SOC); Repetitive Behaviour Scale – Revised (RBS); Vineland*
 545 *Adaptive Behaviour Composite Standard scores (VABS); Parent-reported Social*
 546 *Responsiveness Scale - Total raw scores (SRS); Full-scale IQ (FSIQ); Verbal IQ (VIQ); and*
 547 *Non-verbal IQ (NVIQ).*

548
 549