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RESEARCH ARTICLE

Key variants via the Alzheimer's Disease Sequencing Project whole genome sequence data

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Abstract

INTRODUCTION: Genome-wide association studies (GWAS) have identified loci associated with Alzheimer's disease (AD) but did not identify specific causal genes or variants within those loci. Analysis of whole genome sequence (WGS) data, which interrogates the entire genome and captures rare variations, may identify causal variants within GWAS loci.

METHODS: We performed single common variant association analysis and rare variant aggregate analyses in the pooled population (*N* cases = 2184, *N* controls = 2383) and targeted analyses in subpopulations using WGS data from the Alzheimer's Disease Sequencing Project (ADSP). The analyses were restricted to variants within 100 kb of 83 previously identified GWAS lead variants.

Yanbing Wang and Chloé Sarnowski contributed equally to this work. Gina Peloso and Anita L. DeStefano contributed equally to the supervision of this work.

RESULTS: Seventeen variants were significantly associated with AD within five genomic regions implicating the genes *OARD1/NFYA/TREML1*, *JAZF1*, *FERMT2*, and *SLC24A4*. *KAT8* was implicated by both single variant and rare variant aggregate analyses.

DISCUSSION: This study demonstrates the utility of leveraging WGS to gain insights into AD loci identified via GWAS.

KEYWORDS
Alzheimer's disease, association analyses, diverse populations, genome-wide association study, single nucleotide variations, whole genome sequencing

1 | BACKGROUND

Alzheimer's disease (AD), the most common cause of dementia, has been ranked as the sixth leading cause of death in the United States and the fifth leading cause of death in older people (≥65 years old). Although the role of genetic factors in the development of AD has been widely recognized, genome-wide association studies (GWAS) typically identify regions or loci rather than specific genes and/or variants. Additionally, the loci identified by GWAS only explain a small portion of the total heritability of AD (h^2_{AD} = [0.58–0.79]).[1] Next-generation sequencing technology applied in diverse populations as part of the Alzheimer's Disease Sequencing Project (ADSP) may help to elucidate the genetic architecture of AD, and thus, aid in the development of effective strategies to diagnose, prevent, and treat AD.[2]

A recent large GWAS totaling 111,326 clinically diagnosed/"proxy" AD cases and 677,663 controls has identified over 70 loci associated with AD and related dementias.[3] However, the characterization of these loci remains incomplete. Leveraging whole genome sequence (WGS) data that encompass the full spectrum of genetic variation including common and rare variants might identify important AD genes within these GWAS loci and provide a better understanding of the biological mechanisms involved in the pathophysiology of AD.

Previous studies that used WGS to identify genetic loci associated with AD performed genome-wide association with limited sample sizes.[4–7] These prior WGS studies include a family-based study conducted in 2247 subjects from the National Institute of Mental Health (NIMH)/National Institute on Aging (NIA) with replication in 1669 independent participants from the Alzheimer's Disease Neuroimaging Initiative (ADNI)/ADSP.[4] More recently, the same team investigated the association of groups of rare variants in the same datasets using a sliding-window approach.[5] Additional studies conducted in Asian populations highlighted the importance of increasing the representation of understudied population groups and the potential of WGS to uncover population-specific genetic loci.[6,7] We posit that until WGS is available in much larger samples, this data type is better suited for interrogation of previously identified loci rather than identification of novel loci.

In this work, we performed a deep interrogation of known AD GWAS loci using the ADSP WGS data. We focused the scope of the current study by only considering the AD GWAS loci identified in the GWAS with the largest number of AD cases to date.[3] The ADSP aims to identify protective or risk genetic contributors for AD in populations with diverse ancestry. The ADSP has generated single nucleotide variant and insertion/deletion (indel) calls based on WGS data from 4789 participants, which are publicly available (R1 data release https://dss.niagads.org/datasets/ng00067-v1/). The goal of the current study is not the replication of prior GWAS findings as we are underpowered to do so. In addition, it is important to note that the ADSP sample in the current analyses is not independent of the sample used in Bellenguez et al.[3] Although independent samples are critical for replication, the goal of the current study is to provide a more comprehensive look at GWAS loci using more detailed data via WGS. Hence, it is appropriate to utilize a dataset that includes overlapping samples but novel genomic data.

We conducted single variant association analyses and rare variant aggregation association tests using the R1 WGS data of ADSP to identify specific genetic variants, genes, and non-coding regions associated with AD within previously identified AD loci. We also examined multi-ancestry evidence for AD associations through population-specific analyses in White/European-ancestry (EA), Black/African-American (AA), and Hispanic/Latino (HI) subgroups, and a multi-population meta-analysis. The insights gained from our analysis will contribute to a better understanding of AD pathogenesis and potentially identify new targets for AD drugs and treatment.

2 | METHODS

2.1 | Study participants

Data from the ADSP are available to qualified investigators via the NIA Genetics of Alzheimer's Disease Data Storage Site (NIAGADS) (https://dss.niagads.org/). This study was done under an approved NIAGADS research use statement and local Institutional Review Board approval. The current analyses focused on participants with WGS data in the NIAGADS file set named "R1 5K WGS Project Level VCF." WGS data have been generated in multiple cohorts as part of the ADSP. The ADSP data included in this study are comprised of distinct phases including the Discovery, Discovery Extension, and Augmentation phases. The

Discovery phase WGS was generated from individuals of multiplex AD families as previously described.[8–10] The Discovery Extension phase consisted of a family component and a case-control component. The Discovery Extension family component WGS was generated on additional members of selected families from the Discovery phase as well as members of 77 additional families. A set of 114 Hispanic control individuals was also sequenced with the family component.

A focus of the Discovery Extension case-control component was to increase the diversity of the ADSP samples. The ADSP Discovery Extension WGS was generated on 3082 individuals, with approximately one-third each from EA, AA, and HI populations. In the ADSP Discovery and Discovery Extension phases, sequencing was performed at three sequencing centers via the National Human Genome Research Institute (NHGRI). Sequence data for ADSP Augmentation Studies were supported by NIA and private funding and are shared with the research community via NIAGADS. The ADSP data coordinating center, the Genomic Center for AD (GCAD), produced a jointly called and quality controlled (QC'ed) dataset for WGS[10] that included the ADSP WGS Discovery, Discovery Extension, and from the Augmentation phase, the ADNI study. Details of studies included in the ADSP can be found at NIAGADS under the following dataset: NG00067 ADSP Umbrella Study (https://dss.niagads.org/datasets/ng00067/).

RESEARCH IN CONTEXT

1. **Systematic review**: Examination of peer-reviewed (PubMed) and preprint literature found limited studies of whole genome sequencing (WGS) data in relation to Alzheimer's disease (AD). The Alzheimer's Disease Sequencing Project WGS release of three datasets nearly doubles prior WGS sample sizes used in primary analyses related to AD. We performed association analyses using WGS to comprehensively interrogate variation, including rare variants, within previously identified loci from a recent genome-wide association study (GWAS).
2. **Interpretation**: We identified 17 genetic variants significantly associated with AD within five AD GWAS genomic regions implicating the genes *OARD1/NFYA/TREML1*, *JAZF1*, *FERMT2*, *SLC24A4*, and *KAT8*.
3. **Future directions**: Our study highlights the value of WGS data to implicate relevant variants within GWAS-associated AD loci and highlights the contribution of rare variants in AD risk. Future work includes association analyses in larger WGS datasets and biological studies to further characterize implicated variants.

2.2 | WGS quality control

Low-quality variants were filtered out based on the GCAD-provided flags, which were generated separately for the Family, Case-Control, and ADNI sub-studies.[10] In addition, GCAD provided the ABHet ratio computed as (the total reference reads over all heterozygous genotypes)/(total alternative and reference reads over all heterozygous genotypes). A variant was excluded if it failed the GATK Variant Quality Score Recalibration (VQSR) filter, if all genotypes were missing, if it was monomorphic, or if it had a low call rate across all studies. Additional filtering was implemented within each sub-study. If a variant had high read depth (>500 reads) within a sub-study or had ABHet < 0.25 or ABHet > 0.75 within a sub-study, all the genotypes within that sub-study were set to missing. After these filters were applied, a final call rate filter of 95% across all sub-studies was implemented.

2.3 | AD phenotype definition

The ADSP provides different AD status variable definitions for participants included via case-control versus family-based studies. AD case status in the current analyses was clinician-determined. The criteria varied by study and may have been based on cognitive testing, neuropathological examination, or physician diagnosis. In the current analysis, for individuals in the ADSP case-control study, we defined AD cases as individuals with either prevalent or incident AD. Case-control individuals with no prevalent or incident AD were defined as controls and those with missing status were defined as unknown. In the ADSP family phenotype file, possible values for the AD status variable include no dementia, definite AD, probable AD, possible AD, family-reported AD, other dementia, family reported no dementia, and unknown. For family-based individuals, we defined an AD case as either possible, probable, or definite AD. AD controls were defined as individuals coded as having no dementia. We redefined individuals with family-reported AD, other dementia, or unknown status as missing AD status. The ADNI phenotype data, which is part of the ADSP Augmentation study, provides information on mild cognitive impairment (MCI) in addition to AD status. Individuals with a current diagnosis of MCI ($N = 320$) were included as AD controls in the current study. After selecting genetically unique individuals with AD status available, a total of 4567 participants (2383 controls and 2184 cases) with WGS were included in the analyses.

2.4 | Analysis overview

Figure 1 provides an overview of our analysis workflow. Single variant association analysis was performed on common variants in both the pooled sample and population-specific samples. Two types of rare variant aggregate association analyses were performed in the pooled sample: gene-based testing and non-coding rare variant testing. To meet the goal of interrogating previously identified GWAS loci, we only considered analysis results for variants within 100 kb of the lead GWAS variants from Bellenguez et al.[3] Analysis details are provided below.

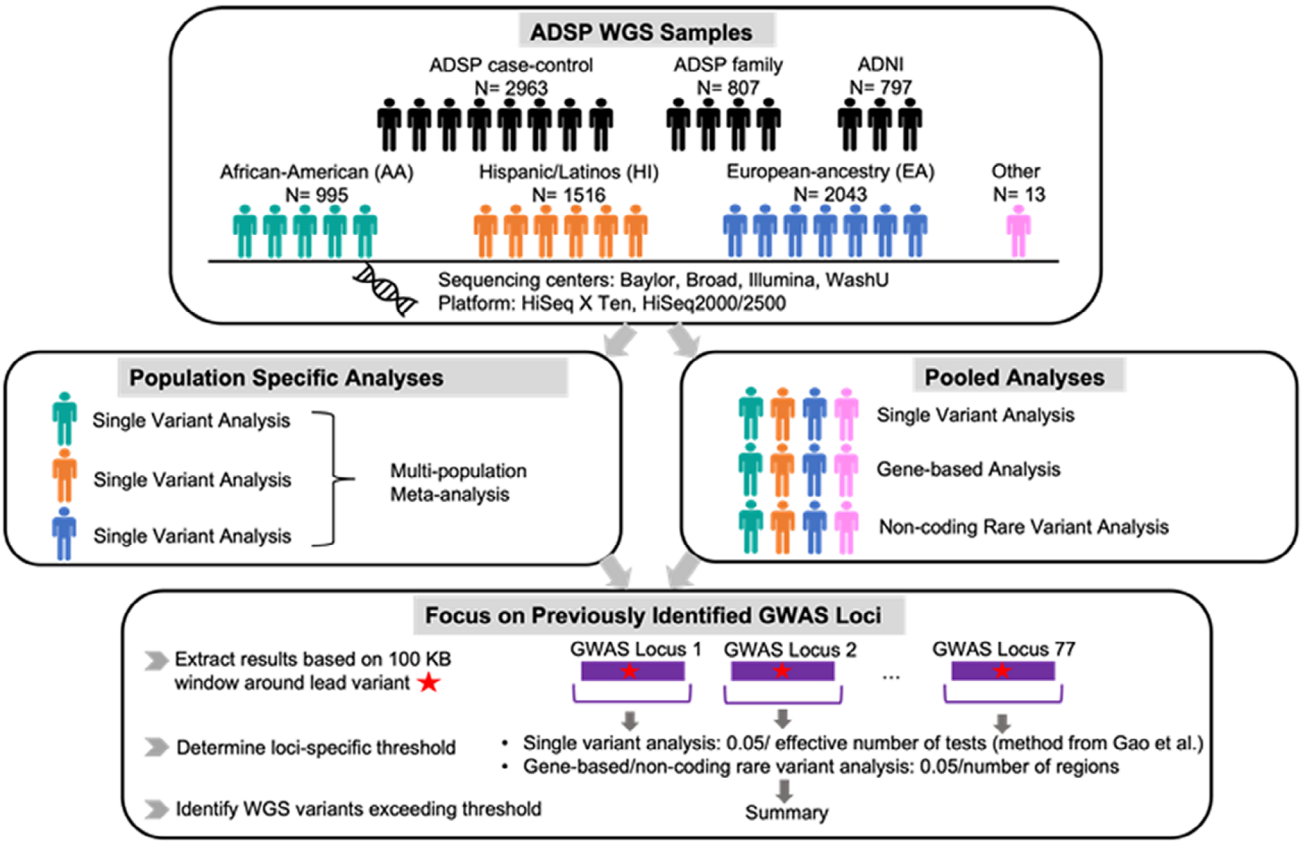

FIGURE 1 Schematic of the ADSP 5K analysis. ADNI, Alzheimer's Disease Neuroimaging Initiative; ADSP, Alzheimer's Disease Sequencing Project; GWAS, genome-wide association studies; WGS, whole genome sequence.

2.5 | Pooled sample single-variant association analysis

Single-variant association analysis of AD was performed on variants within GWAS loci for participants with both phenotype and genotype data available using GENESIS.[11] Principal component analysis (PCA) was performed as described in the supplemental methods to assess and adjust for the genetic ancestry of the study participants (Figure S1). The WGS samples included in the ADSP R1 WGS dataset were sequenced across four sequencing centers (Baylor College of Medicine Human Genome Sequencing Center, The Broad Institute, McDonnell Genome Institute at Washington University School of Medicine, and Illumina) and two sequencing platforms (Illumina HiSeq 2000/2500, and Illumina HiSeq X Ten). To control for the effects of study design and technical differences, we generated indicator variables (study × sequencing center × sequencing platform) with 10 categories based on Table 1. We considered these indicator variables as technical covariates and defined case-control × Broad × HiSeq X Ten, which had the largest number of observations, as the reference group. We used a generalized logistic mixed-effects model to account for relatedness through a genetic relationship matrix (GRM). The GRM was estimated based on the same variants used in the PCA. We included sex, the technical covariates, and PC2 (based on a Bonferroni corrected significant $p < 0.0016$ for testing 32 PCs) as covariates in the null model. We performed the analysis across autosomes and kept variants satisfying the following criteria: a call rate higher than 95%, and a minor allele count (MAC) higher than 20.

To determine if the significant variants identified were distinct from the lead GWAS variants,[3] we computed linkage disequilibrium (LD; r^2) between the significant variants and the lead GWAS variants within each population based on the ADSP genetic data.

2.6 | Population-specific association analysis

We conducted population-specific analyses (null model and association analyses) for AD using GENESIS, accounting for genetic relatedness using a GRM. We defined three population groups (EA, AA, and HI). We selected a total of 2144 EA participants based on PCA analysis performed using both the ADSP and the Human Genome Diversity Project (HGDP). Only participants who were not outliers based on six standard deviations (SD) from the mean for PCs 1 through 4 calculated in the European HGDP groups (Adygei, Basque, French, BergamoItalian, Orcadian, Russian, Sardinian, and Tuscan) were retained. We selected a total of 1028 AA and 1548 HI participants based on reported race and ethnicity. A total of 38 participants who identified as both African-American and Hispanic were placed in the Hispanic population. We included in the null model, in each population group, covariates

TABLE 1 Characteristics of the participants included in the ADSP R1 dataset.

	All (*N* = 4567)	AA (*N* = 995)	HI (*N* = 1516)	EA (*N* = 2043)	Other (*N* = 13)
Age (SD)	76.9 (8.3)	79.2 (7.6)	75.1 (8.5)	77.1 (8.4)	77.3 (6.6)
Alzheimer's disease (%)					
Case	2184 (47.8%)	463 (46.5%)	795 (52.4%)	921 (45.1%)	5 (46.2%)
Control	2383 (52.2%)	532 (53.5%)	721(47.6%)	1122 (54.9%)	8 (53.8%)
Sex (%)					
Female	2822 (61.8%)	710 (71.4%)	1020 (67.3%)	1086 (53.2%)	6 (38.5%)
Male	1745 (38.2%)	285 (28.6%)	496 (32.7%)	957 (46.8%)	7 (61.5%)
Study (%)					
ADNI	797 (17.5%)	26 (2.6%)	10 (0.7%)	750 (36.7%)	11 (84.6%)
ADSP- case-control	2963 (64.9%)	944 (94.9%)	1107 (73.0%)	911 (44.6%)	1 (7.7%)
ADSP- family	807 (17.7%)	25 (2.5%)	399 (26.3%)	382 (18.7%)	1 (7.7%)
Sequencing center (%)					
Baylor	1241 (27.2%)	0 (0)	1103 (72.8%)	138 (6.8%)	0 (0)
Broad	1263 (27.7%)	2 (0.2%)	286 (18.9%)	974 (47.7%)	1 (7.7%)
Illumina	797 (17.5%)	26 (2.6%)	10 (0.7%)	750 (36.7%)	11 (84.6%)
WashU	1266 (27.7%)	967 (97.2%)	117 (7.7%)	181 (8.9%)	1 (7.7%)
Platform (%)					
HiSeq X Ten	3227 (70.7%)	965 (97.0%)	1186 (78.2%)	1074 (52.6%)	2 (15.4%)
HiSeq2000/2500	1340 (29.3%)	30 (3.0%)	330 (21.8%)	969 (47.4%)	11 (84.6%)

Note: Populations defined are described in the Methods section.
Abbreviations: AA, Black/African-American; ADNI, Alzheimer's Disease Neuroimaging Initiative; ADSP, Alzheimer's Disease Sequencing Project; EA, White/European ancestry; HI, Hispanic/Latino.

associated with AD status at $p \leq 0.05$. The EA null model included sex, ADSP family study status, Illumina sequencing center, HiSeq X Ten platform, PC 2, PC 9, and PC 15. The HI null model included sex, all sequencing centers, HiSeq X Ten platform, PC 13, PC 16, and PC 17. The AA null model included sex, Illumina sequencing center, and PC 1. We performed association analyses, in each population group, and retained the results with a call rate higher than 95% and a MAC higher than 20. In addition, we performed a multi-population meta-analysis using three different models (fixed-effect, random-effect, and Han & Eskin's modified random-effect) implemented in Metasoft[12] by combining the population-specific results satisfying the criteria of a within-population MAC higher than 10. We then kept the meta-analysis results passing a total MAC across population groups higher than 20.

2.7 | Gene-based tests

We tested the association of aggregate groups of low frequency (minor allele frequency [MAF] < 5%) or rare (MAF < 1%) genetic variants with AD status. Annotation for all called variants was generated using Ensembl VEP91 by the ADSP annotation working group. We selected missense or loss of function (lof) genetic variants based on the most severe variant consequence according to the ADSP Annotation Working Group Ranking Process and listed in the annotation file (frameshift variant, inframe deletion, inframe insertion, missense variant, protein-altering variant, splice acceptor variant, splice donor variant, start lost, stop gained, and stop lost). We conducted the Sequence Kernel Association Test (SKAT, mmskat) and burden tests (combined multivariate and collapsing [CMC], emmaxCMC) with EPACTS (Efficient and Parallelizable Association Container Toolbox) using mixed-effect models adjusted for sex, technical covariates, and PCs significantly associated with AD status (PC2) while accounting for relatedness using a GRM.

2.8 | Non-coding rare variant analysis

For non-coding rare variant analysis, we used annotations from WGSA v0.8[13] including annotations from ANNOVAR, VEP, SnpEff, COSMIC, and SPIDEX. We conducted rare variant analysis using the variant-Set Test for Association using Annotation infoRmation (STAAR) method,[14] which was developed to boost the power of rare variant analyses by effectively incorporating both variant functional categories and multiple complementary functional annotations while accounting for relatedness and population structures. We used the same covariates (sex, technical covariates, and significant PCs) in the model as in the single-variant analysis. The GRM was incorporated to account for relatedness among samples.

We aggregated sites that overlap enhancers and promoters around gene transcription start sites (TSS). The promoters within 5 kb of a TSS that overlap DNase hypersensitivity sites (DHS) are defined as at least one WGSA H3K4me3 annotation for brain tissues (E067, E068,

E069, E070, E071, E072, E073, E074, E081, E082), and the enhancers within 20 kb of a TSS are defined by EnhancerFinder in Brain. We incorporated annotations from WGSA in the analysis, which include MAF, functional scores (GERP, GenoCanyon, RegulomeDB, FUNSEQ, CADD, Fathmm, EIGEN-PC), and the ENCODE score (DNASE). We then transformed the annotation scores to phred-scaled scores using $-10 \times \log10(\text{rank[score]}/M)$, where M is the total number of variants tested in the analysis.

2.9 | Focus on GWAS loci

Given the limited power to detect novel loci with the current sample size, we focused on exploiting WGS to provide insights on previously reported AD GWAS loci. We used the variants listed in Bellenguez et al. as the previously reported AD GWAS top variants.[3] For single variant association analyses, we looked up these lead variants in the ADSP WGS data. We then assessed ADSP WGS associations within 100 kb of each lead GWAS variant. For gene-based and non-coding rare variant analysis, we obtained the results for genes or regions in the 100 kb window around each lead variant. We included genes or non-coding regions for which any portion overlapped with the specified window. Using this paradigm, we identified 303 genes within 100 kb of the index single nucleotide polymorphisms (SNPs).

In general, we defined a threshold for statistical significance equal to 0.05/number of statistical tests and a suggestive threshold as 1/number of statistical tests. Within a 100 kb window, many single variant tests were highly correlated. Therefore, we computed the effective number of independent tests using the simpleM approach[15] and used the effective number of tests in the denominator when computing a window-specific threshold for single variant association testing. Effective numbers of tests were computed across the pooled sample and within each population subgroup (Table S1).

We leveraged publicly available multi-omic resources, from quantitative trait locus (xQTL) analyses applied to RNA sequence and DNA methylation from the dorsolateral prefrontal cortex of 411 older adults from the Religious Orders Study (ROS) and Memory and Aging Project (MAP) studies[16] to look up the main genetic variants from the pooled association analysis.

3 | RESULTS

3.1 | Description of the ADSP data

After the QC check of the ADSP data release NG00067.v2, there were over 95 million variants across 4733 participants. A total of 4567 individuals (2383 controls, 2184 cases) have available AD status and contributed to the analyses, among which 807 are from the ADSP family study, 2963 are from the ADSP case-control study, and 797 are from ADNI. The participants included in the analyses were more likely to be women (61.8%) than men. The distribution of study design membership, sequencing centers, and sequencing platforms is summarized in Table 1.

3.2 | Pooled sample single-variant association analysis

Genome-wide, there were about 20 million variants with a call rate higher than 95% and a MAC higher than 20 in the pooled sample analysis. Our model that included GRM and PC adjustments showed acceptable type-I error control ($\lambda = 1.05$, Figure S2). As expected, the strongest association was observed at the apolipoprotein E (*APOE*) locus, where the major *APOE* variant rs429358 ($p = 7.2 \times 10^{-77}$) was the top hit.

Among the specific lead GWAS variants from Bellenguez et al.,[3] none reached the strict significance threshold ($p < 6 \times 10^{-4}$, Bonferroni correction for the total number of variants tested) in the pooled sample association analysis. Full results for the 83 lead GWAS variants are provided in the supplement (Table S2).

Applying the significance thresholds based on the effective number of tests within 100 kb windows around the lead GWAS variants (Table S1), we identified 17 significant variants in the single variant association analysis in the pooled sample (Table 2). Sensitivity analysis performed removing the MCI individuals ($N = 320$) showed negligible change in *p*-values or effect size estimates (Table S3). These 17 variants occur in five genomic regions on chromosomes 6, 7, 14, and 16. Forest plots for the top variant in each of these five regions are presented in Figure 2. Examination of LD patterns shows near-perfect LD among the variants identified on chromosome 6, on chromosome 7, and for the one region on chromosome 14 with multiple variants. Only a single variant was identified on chromosome 16 and in one region on chromosome 14. Detailed LD information is provided in the supplement (Figure S3).

LD patterns were examined to assess if these associations represented the same signal as the lead GWAS variant from Bellenguez et al. or distinct signals. In the *SLC24A4* region, rs7155002 (14:92467728:C:T) was in high LD ($r^2 = 0.99$) with the lead GWAS variant rs7401792 (14:92472511:G:A) in the EA population. The LD was moderate in the other populations ($r^2 = 0.44$ and 0.74, for AA and HI, respectively) at the *SLC24A4* region. LD with the lead GWAS variant was not observed in any other region included in Table 2 ($r^2 < 0.02$) across all populations considered (Figure S3).

3.3 | Population-specific single-variant association analysis and multi-population meta-analysis

We conducted population-specific association analyses in the three main subgroups ($N = 2043$ EA; $N = 995$ AA, and $N = 1516$ HI participants). There was an acceptable type-I error in the population-specific analyses and the multi-population meta-analysis (Figures S4-S7). We confirmed the significant association of the *APOE* locus (rs429358) in both the population-specific analyses and the multi-population meta-analysis. However, as found in previous studies[17,18] the association was weaker in the HI population (beta = 1.17 in EA, 1.02 in AA, and 0.59 in HI).

Population-specific single-variant analyses identified 23 significant variants in 11 loci within 100 kb of the lead GWAS variants (Table 3).

TABLE 2 Significant variants from single-variant association analysis in the pooled ADSP sample within 100 kb of the 83 lead GWAS variants.

						Pooled single variant association analysis		
Chr:Pos:A2:A1[a]	rsid	Gene	Location	GWAS variants[b]	GWAS loci[b]	MAF	*p*-value	Beta
6:41067923:C:T	rs115774857	OARD1 (close gene APOBEC2)	intronic	rs143332484, rs75932628, rs10947943	TREM2, UNC5CL	0.0080	1.0E-04	1.016
6:41077355:A:G	rs145520578	OARD1, NFYA	intronic			0.0080	9.9E-05	1.018
6:41077511:A:C	rs115202236		intronic			0.0081	9.9E-05	1.018
6:41082030:G:A	rs12200736		intronic	rs143332484, rs75932628, rs60755019, rs10947943	TREM2, TREML2, UNC5CL	0.0080	1.0E-04	1.018
6:41083056:C:T	rs10947945		intronic			0.0080	1.0E-04	1.018
6:41088533:T:C	rs12210716		intronic			0.0080	1.0E-04	1.018
6:41147490:T:G	rs12199328	intergenic (close gene TREML1)				0.0080	1.0E-04	1.018
6:41173956:G:A[c]	rs10947950[c]	intergenic	intergenic	rs143332484, rs75932628, rs60755019	TREM2, TREML2	0.0128	1.4E-04	0.783
7:28034934:T:A	rs73683942	JAZF1	intronic	rs1160871	JAZF1	0.0188	7.5E-05	−0.627
7:28034935:C:G	rs78789160		intronic			0.0188	7.5E-05	−0.627
7:28035459:GAGAT:G	no rsids		intronic			0.0188	1.9E-05	−0.677
7:28037452:A:C	rs73683943		intronic			0.0191	3.8E-05	−0.644
7:28042506:C:G	rs60825597		intronic			0.0196	7.8E-05	−0.607
14:52885670:T:TA	rs1310103853	FERMT2	intronic	rs17125924	FERMT2	0.0174	4.5E-06	0.806
14:52932032:A:G	rs60609189		intronic			0.0189	7.4E-06	0.768
14:52992239:A:G	rs12431954	intergenic				0.0205	3.8E-06	0.763
14:92467728:C:T	rs7155002	SLC24A4	intronic	rs12590654, rs7401792	SLC24A4	0.4460	1.4E-05	−0.198
16:31117787:C:G	rs201871085	KAT8 (close gene BCKDK)	missense variant, non-coding transcript exon variant	rs889555	BCKDK	0.0108	2.4E-05	0.926

Abbreviations: ADSP, Alzheimer's Disease Sequencing Project; GWAS, genome-wide association studies; MAF, minor allele frequency.
[a]A1 corresponds to the alternate (effect) allele; the positions provided are on build 38.
[b]The GWAS variants and GWAS loci are based on the GWAS list from Bellenguez et al. (PMID: 35379992).
[c]Variant identified as significant in the multi-population meta-analysis (not in the pooled analysis).

Of these, 15 variants (eight loci) were identified in the EA population and eight variants (three loci) in the AA population. No significant variants were identified in the HI population. The only overlap in significant variants between the pooled sample and the population-specific single-variant analyses was a missense variant in *KAT8*, which was very rare in the AA and HI subsamples (Table S4).

3.4 | Gene-based tests

QQ plots for the SKAT and burden tests are provided in Figure S8. Using the multiple-testing correction threshold for 303 genes ($p < 1.7 \times 10^{-4}$), *KAT8* ($p = 2.2 \times 10^{-5}$, MAF < 5%) lying within 100 kb of a GWAS variant was detected to be significantly associated with AD status by SKAT, and it was also shown as a suggestive association ($p < 3.4 \times 10^{-3}$) using CMC ($p = 9.2 \times 10^{-4}$). Within 100 kb of GWAS variants, SKAT detected suggestive associations in *LAIR1* ($p = 0.0023$, MAF < 5%) and *ATF5* ($p = 5.7 \times 10^{-4}$, MAF < 5%), and CMC identified *TREM2* ($p = 3.3 \times 10^{-3}$ for MAF < 1% and 8.9×10^{-4} for MAF < 5%).

3.5 | Non-coding rare variant analysis

QQ plots showed deflated type-I error ($\lambda = 0.75$), most likely due to the small sample size, in the STAAR rare-variant analysis (Figure S9). No regions were identified as significant using the STAAR approach. The top STAAR results overlapping GWAS loci are shown in Table S2.

3.6 | xQTL analysis lookup

We did not identify significant mQTL or eQTL associations for the main genetic variants identified in the pooled analysis. We could not look up some of the less frequent variants on chromosomes 7, 14, and 16 in the QTL results as these analyses were restricted to common variants. Suggestive associations have been reported between

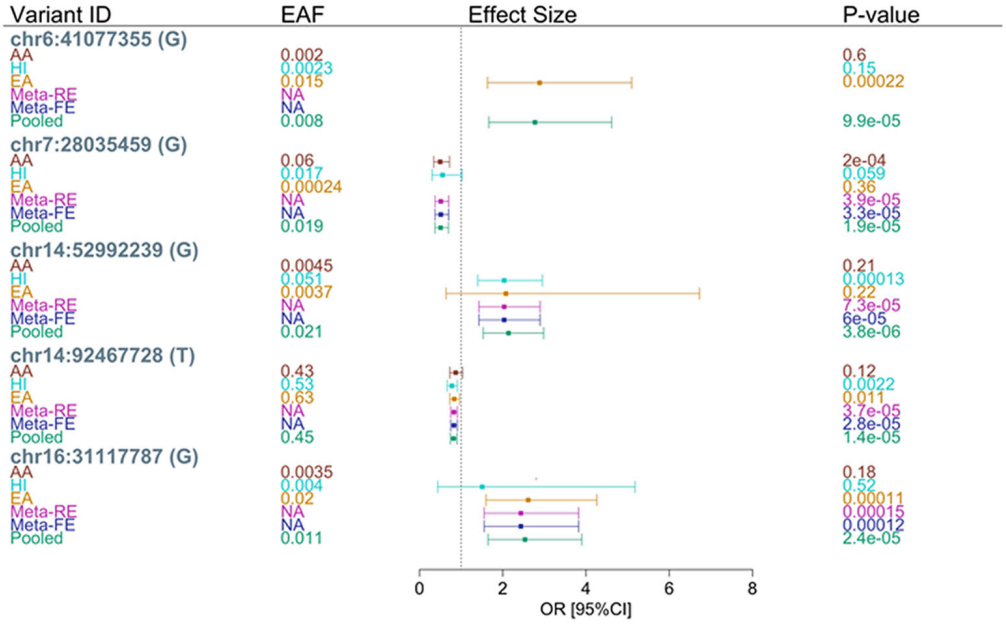

FIGURE 2 Top variants identified from single-variant association analysis in the pooled ADSP sample within 100 kb of the 83 lead genome-wide association studies (GWAS) variants. Variant ID is in the form of chromosome:position (effect allele). The positions provided are on build 38. EAF is the effect allele frequency, Meta-RE is the multi-population meta-analysis using a random effect model, Meta-FE is the multi-population meta-analysis using a fixed effect model. The *p*-value for Meta-RE is calculated using Han and Eskin's modified random effects model. The effect size and its 95% CI are not shown for variants with a minor allele count (MAC) < 10 in population-specific analysis. AA, Black/African-American; EA, White/European ancestry; HI, Hispanic/Latino.

rs10947950 (chromosome 6) and cg25473438 (beta = 0.24, $p = 1.4 \times 10^{-8}$) and between rs7155002 (chromosome 14) and cg12072028 (beta = 0.19, $p = 5.8 \times 10^{-6}$), Table S5. The CpG cg12072028 is located in the intron 1 of *RIN3* and modest associations have been described between rs7155002 and *RIN3* expression in the brain (beta = 0.04, $p = 0.01$), Table S5.

4 | DISCUSSION

GWAS have been essential in identifying genetic loci associated with AD. However, GWAS loci typically contain scores of genes and thousands of variants. Additional studies are needed to pinpoint specific genes or variants as the ones influencing the risk for AD. WGS provides complete genomic sequences and hence enumerates both common and rare variants. WGS therefore has the potential to provide information beyond common variants that are the cornerstone of GWAS. In the current study, we have examined WGS from the ADSP R1 dataset focusing on previously implicated regions to better understand important variants within AD GWAS loci in a diverse study sample. We identified 17 significant variants in five genomic regions using single-variant association analysis in the pooled sample. The majority of these variants were intronic, although two intergenic and one missense variant were also identified.

Bellenguez et al.[3] identified multiple lead GWAS variants on chromosome 6, which yielded overlapping 100 kb windows defined by our approach. We identified seven significant variants on chromosome 6 that are in nearly complete LD. Six of these variants are located within intronic regions of the *OARD1* and *NFYA* genes, and one variant is very close to *APOBEC2*. One variant was intergenic with the closest gene being *TREML1*. This region contains *TREM2*, for which several rare coding variants have been implicated as conferring risk for AD.[19–22] *TREM2* showed suggestive evidence of association in gene-based analyses indicating multiple variants in this region are likely to play an important role in AD. The missense variant rs75932628 was one of the lead GWAS variants from Bellenguez et al. and has been identified as a functional variant for AD.[22–24] The variant rs75932628 has an MAF = 0.0035 in the ADSP pooled sample and $p = 0.003$ for single-variant association with AD. This suggestive association is driven by the EA population (MAF = 0.007) as this variant is less frequently observed in the AA (MAF = 0.001) or HI (MAF = 0.0003) populations. Examination of LD suggests that the variants we identified implicating *OARD1/NFYA/TREML1* have an effect distinct from rs75932628. *OARD1* encodes a deacylase with a function to catalyze O-acetyl-ADP-ribose during multiple cellular processes. A homozygous mutation could lead to cell death and cause a form of childhood neurodegenerative disorder.[25] *NFYA* encodes a subunit of nuclear transcription factor Y, which is a ubiquitous transcription factor. The gene is involved in post-transcriptional regulation with tissue-specific preference, and it is suppressed in the brain of model mice with Huntington's disease[26] and spinal and bulbar muscular atrophy.[27] *TREML1* encodes a protein belonging to the family of triggering receptors expressed on myeloid cells-like (TREM). A deficiency of *TREML1* might result in hemorrhage due to localized inflammatory lesions.[28]

TABLE 3 Significant variants from single-variant association analyses in the ADSP population subsamples within 100 kb of the 83 lead GWAS variants.

	White/European Ancestry					Black/African American					Hispanic/Latino				
Chr:Pos:A2:A1[a]	*N*	Freq	MAC	*p* value	Beta	*N*	Freq	MAC	*p* value	Beta	*N*	Freq	MAC	*p* value	Beta
4:11052797:T:C	2040	0.0002	1	3.04E-01	2.069	984	0.137	270	8.37E-05	−0.534	1513	0.059	180	4.94E-01	0.113
4:11053332:C:T	2043	0.0002	1	3.04E-01	2.068	995	0.137	273	8.66E-05	−0.530	1516	0.059	179	4.83E-01	0.116
5:180211637:C:T	2042	0.143	584	7.14E-05	0.385	995	0.052	104	8.00E-02	−0.351	1514	0.110	333	9.48E-01	0.009
5:180214978:G:A	2042	0.143	586	5.37E-05	0.392	994	0.051	101	1.45E-01	−0.296	1514	0.109	330	9.39E-01	0.010
5:180216117:C:T	2041	0.143	582	3.69E-05	0.400	995	0.050	100	1.72E-01	−0.278	1512	0.096	289	6.05E-01	0.073
5:180222862:G:A	2042	0.144	590	3.70E-05	0.398	995	0.079	157	3.94E-01	−0.144	1516	0.124	377	9.75E-01	0.004
5:180224704:C:T	2041	0.145	591	2.85E-05	0.403	989	0.081	160	3.81E-01	−0.147	1511	0.124	375	9.48E-01	−0.008
8:11868930:C:G	2043	0.007	27	6.52E-05	1.627	995	0.003	6	5.52E-01	−0.494	1516	0.009	26	3.26E-01	−0.414
11:86068255:T:G	2042	0.810	774	6.19E-01	0.044	992	0.886	226	5.53E-05	0.576	1516	0.811	572	8.58E-01	−0.019
11:86068268:A:G	2042	0.810	774	6.19E-01	0.044	990	0.887	224	2.49E-05	0.607	1515	0.811	572	8.45E-01	−0.021
11:86072833:A:G	2042	0.815	755	6.67E-01	0.038	992	0.888	222	5.37E-05	0.577	1516	0.816	559	7.35E-01	−0.037
11:86186529:G:A	2038	0.142	577	8.10E-02	0.169	993	0.264	525	1.21E-04	−0.403	1516	0.245	742	1.52E-01	0.137
14:105740487:C:T	1863	0.524	1772	2.12E-05	−0.479	981	0.308	605	5.33E-01	0.074	1446	0.430	1244	7.48E-02	0.204
15:63375962:G:A	2042	0.0002	1	2.53E-01	2.318	994	0.101	200	1.18E-04	0.591	1514	0.035	105	9.71E-01	0.008
15:63376200:A:G	2042	0.0002	1	2.53E-01	2.317	994	0.106	210	1.24E-04	0.576	1515	0.040	122	7.96E-01	−0.052
16:31117787:C:G	1917	0.020	76	1.11E-04	0.961	991	0.004	7	1.77E-01	1.033	1489	0.004	12	5.16E-01	0.412
16:86357432:T:C	2043	0.088	359	3.53E-05	−0.497	995	0.132	262	7.55E-01	−0.043	1516	0.097	293	4.62E-01	0.100
17:46724128:T:C	2043	0.007	30	3.58E-05	1.607	995	0.002	3	5.80E-01	−0.643	1515	0.006	17	3.75E-01	0.514
17:46747538:C:T	2043	0.007	28	3.69E-05	1.649	994	0.002	3	5.79E-01	−0.645	1515	0.006	17	3.76E-01	0.513
17:58269710:G:A	2042	0.016	67	7.96E-05	1.069	995	0.004	8	7.23E-01	0.256	1515	0.005	14	7.84E-01	−0.169
20:56407698:G:A	2037	0.004	16	3.43E-05	2.328	991	0.001	2	8.15E-01	0.339	1516	0.002	6	8.86E-01	−0.172
20:56490678:G:T	2041	0.005	19	4.74E-05	2.021	995	0.002	4	4.93E-01	−0.703	1516	0.002	6	8.86E-01	−0.172
20:56505267:G:A	2041	0.005	20	1.57E-05	2.095	995	0.002	4	4.93E-01	−0.703	1513	0.002	6	8.83E-01	−0.177

Note: Variants with a MAC of <10 in a population subsample were not included in the multi-population meta-analysis.
Abbreviations: GWAS, genome-wide association studies; MAC, minor allele count.
[a]A1 corresponds to the alternate (effect) allele; positions provided are on build 38.

The five significant variants on chromosome 7 are in a strong LD block and all variants are intronic for *JAZF1*, which encodes a transcriptional repressor. The gene has been linked with diabetes mellitus and cancer, but also has a role in lipid metabolism supporting the connection between lipid levels and AD.[29] The *JAZF1* GWAS variant (rs1160871) is a strong eQTL in microglia and is considered a Tier 1 (highly plausible) AD gene.[3] The block of variants identified in the current study is not in LD with the lead GWAS variant rs1160871 (7:28129126:GTCTT:G) suggesting a distinct effect on AD.

We identified two regions on chromosome 14, with significant variants intronic to *FERMT2* and *SLC24A4*. The intronic variant rs7155002 for *SLC24A4* was in strong LD with the lead GWAS variant in the EA population, indicating a likely shared effect. Lookup in brain xQTL data shed light on potential biological regulatory mechanisms in *RIN3* that have also been implicated in AD.[30,31] *FERMT2* encodes plekstrin homology domain-containing family C member 1 and is known to be involved in amyloid-β precursor protein (APP) metabolism.[32] The under-expression of *FERMT2* was associated with mature APP level increment in the cell surface.[32] Previous studies reported that *FERMT2* is also involved in cardiac and skeletal muscle development[33] and cancer progression.[34,35] *SLC24A4* encodes a member of the potassium-dependent sodium/calcium exchanger protein family and is associated with neural development.[36] A homozygous mutation in *SLC24A4* may cause amelogenesis imperfecta,[37,38] but the function of *SLC24A4* in AD is not clearly understood.

A rare missense variant (rs201871085, MAF = 0.0108 in the pooled sample) within *KAT8* (lysine acetyltransferase 8) on chromosome 16 was significantly associated with AD. *KAT8* was also significant in the low-frequency variant gene-based analyses. *KAT8* encodes a member of the MYST histone acetylase protein family that has a characteristic MYST domain containing an acetyl-CoA-binding site, a chromodomain typical of proteins that bind histones, and a C2HC-type zinc finger. This gene has been recently identified by two large-scale GWAS of clinically diagnosed AD and family history of AD[39,40] and by a novel knockoff method when applied to the ADSP data.[41] Aberrant expression patterns of *KAT8* might be associated with AD progression.[42] *KAT8* appears to be a promising candidate gene that is involved in cerebral development[43] and may play a role in neurodegeneration in both AD and Parkinson's disease.[44,45] We were not able to look up the variant rs201871085 in the brain xQTL data. This variant might not have been analyzed due to a low frequency or a low quality of imputation, thus highlighting the importance of leveraging WGS data.

The ADSP represents a diverse population sample, although in this early release of ADSP WGS data, the sample size within a specific population is limited ($N_{EA} = 2043$, $N_{AA} = 995$, $N_{HI} = 1516$). Population-specific analyses provide information about patterns of allele frequency for AD-associated variants among populations. Among the five loci identified as significant in the pooled single-variant association analysis, two regions (chromosomes 6 and 16) displayed EA-specific associations and corresponded to low-frequency variants in EA that were rare in other population groups. One signal (chromosome 7) was driven by a variant common in AA with a low frequency in HI, and rare in EA. Finally, two regions (chromosome 14) were driven by HI signals with one variant common in all population groups, and one variant common in HI but rare in EA and AA. All these results are summarized in Table S4.

The signals identified only in AA in the population-specific analyses (chromosomes 4 and 14) corresponded to SNPs common in AA that were less common in HI and rare in EA. A few signals identified only in EA corresponded to variants that were rare in all population groups (chromosomes 8, 17, and 20). Two low-frequency signals identified only in EA (chromosomes 16 and 17) corresponded to SNPs that were rare in AA and HI. Finally, three signals identified only in EA (chromosomes 5, 14, and 16) corresponded to SNPs that were common in different population groups. All these results are summarized in Table 3.

A strength of this study is the analysis of WGS data jointly called and QC'ed by a single data coordinating center. The diversity in the genetic ancestry of the participants included is another strength. Despite this diversity, a limitation of the study is the moderate sample size, particularly within each population analyzed. To overcome this limitation, the main analyses were focused on the pooled sample. However, even within the pooled sample, we acknowledge that the power of the analyses was limited. For this reason, our goal was not to seek novel loci in a genome-wide search but to interrogate previously identified loci with the detailed data provided by WGS. With the limited sample size, single rare-variant associations that are close to the significance threshold should be interpreted with some caution. But we note that in all five genomic regions, there are significant low-frequency ($0.01 \leq$ MAF < 0.05) or common (MAF ≥ 0.05) variants rather than only rare (MAF < 0.01) variants.

The ADSP is ongoing with larger WGS datasets being publicly released and planned. Future analyses with larger sample sizes may yield additional insights, especially for population-specific effects. The current study demonstrates the importance of leveraging WGS data to gain insights into loci identified via GWAS and highlights the contribution of low-frequency variants to AD risk.

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CONFLICT OF INTEREST STATEMENT

The authors do not have declarations of interest to report. The funding sources of this study had no role in the study design, the collection, the analysis or the interpretation of data, in the writing of the report, or in the decision to submit the article for publication. Author disclosures are available in the supporting information.

CONSENT STATEMENT

All human subjects included in this study provided informed consent.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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APPENDIX 1: COLLABORATORS

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The full acknowledgement statement for the ADSP can be found at: https://dss.niagads.org/datasets/ng00067/

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The Cohort Contributors for the ADSP are provided in the Supplement.

The Alzheimer's Disease Neuroimaging Initiative (ADNI)

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