

Impact of Early-Life Inflammation and APOE Genotype on the Microglial Omic Profile During Alzheimer's Disease Pathology

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1 **Abstract**

2 Alzheimer's disease (AD) is characterized by amyloid- β (A β) plaque deposition, tau pathology, and neuroinflammation, with genetic variation in the apolipoprotein E (APOE) gene representing the strongest risk factor for late-onset AD. Microglia, the brain's resident immune cells, are increasingly recognized as central to disease progression through their roles in neuroinflammation and A β clearance. In this study, we investigated how APOE genotype (E3 vs E4) and early-life inflammation interact to shape microglial states in a mouse model of A β pathology. Using single-cell RNA sequencing of microglia isolated from EFAD mice treated with lipopolysaccharide (LPS) or vehicle at postnatal day 9, we identified distinct microglial transcriptional states and assessed their proportions and gene expression profiles. E4FAD mice exhibited a higher proportion of disease-associated microglia (DAM) compared to E3FAD mice. Moreover, early-life inflammation induced long-lasting, genotype-specific alterations: LPS reduced the abundance of an NF- κ B-enriched Cytokine Response microglial population and downregulated pro-inflammatory genes in E4FAD, but not E3FAD, mice. These findings suggest that early-life immune events interact with APOE genotype to shape microglial responses to amyloid pathology and may offer targets for modulating disease-associated inflammation.

15 **Introduction/Background**

16 *Alzheimer's Disease and Neuroinflammation*

17 Alzheimer's disease (AD) is a progressive neurodegenerative disorder and the leading cause of dementia worldwide, affecting more than 55 million people as of 2019 (1). It is defined by the accumulation of extracellular amyloid- β (A β) plaques and intracellular tau neurofibrillary tangles, which are now considered central pathological hallmarks of the disease (2).

21 In addition to these proteinopathies, AD is characterized by widespread synaptic loss, neuronal degeneration, and a robust neuroinflammatory response. Microglia, the resident immune cells of the central nervous system (CNS), are key contributors to this inflammatory milieu. They participate in A β clearance, phagocytosis, synaptic pruning, and cytokine production, and have been implicated in both protective and pathogenic roles.

25 The increasing recognition of neuroinflammation as a core feature of AD has led to renewed interest in
26 microglial biology, particularly in the context of genetic and environmental risk factors that may shape microglial
27 responses during disease progression.

28 ***Microglia in Alzheimer's Disease***

29 Microglia are highly dynamic cells that continually survey the brain parenchyma. Their functions are diverse and
30 include responding to injury, clearing debris, and remodeling synapses. Early frameworks categorized microglia
31 as either "resting" or "activated," or applied the simplified 'M1/M2' designation. These binary models are now
32 considered oversimplified and inadequate for describing the true range of microglial phenotypes observed in
33 health and disease.

34 Advances in single-cell RNA sequencing (scRNA-seq) have transformed our understanding of microglial
35 heterogeneity. In particular, studies in mouse models of AD have identified a transcriptional program termed Dis-
36 ease-Associated Microglia (DAM), characterized by downregulation of homeostatic markers such as Tmem119
37 and P2ry12, and upregulation of genes involved in lipid metabolism, phagocytosis, and inflammation, including
38 Trem2, Apoe, Cst7, and Tyrobp (3), (4).

39 Subsequent work has revealed additional microglial subsets, including interferon-responsive, antigen-pre-
40 senting, and proliferative populations. However, there is limited consensus regarding nomenclature or functional
41 distinctions between these clusters. Moreover, it remains unclear how these states arise, how stable they are
42 across contexts, and how they relate to disease mechanisms *in vivo*.

43 ***Sex Differences in Alzheimer's Disease***

44 One important but often underappreciated aspect of AD is its differential impact on biological sex. Women
45 represent nearly two-thirds of AD patients, and several studies have reported that female individuals exhibit
46 more severe A β plaque burden, increased tau pathology, and faster cognitive decline compared to males (5). These
47 differences may be influenced by sex hormones, immune system regulation, and differential gene expression,
48 although the underlying mechanisms remain incompletely understood.

49 Sex also interacts with genetic risk factors. The APOE4 allele has been associated with a greater increase in
50 AD risk in women compared to men (6). In light of these findings, and because immune responses are known to
51 differ by sex, this study focuses exclusively on female mice. This choice enhances the interpretability of microglial
52 responses in a biologically relevant context and avoids the confounding influence of sex-dependent variability.

53 *APOE Genotype Modulates Microglial Function*

54 The apolipoprotein E (APOE) gene is the strongest known genetic risk factor for late-onset Alzheimer's disease
55 (AD). The three most common alleles, APOE2, APOE3, and APOE4, differ by two amino acid substitutions. These
56 differences give rise to distinct protein isoforms that vary in their effects on lipid metabolism and amyloid- β
57 ($\text{A}\beta$) clearance (7). Among them, APOE4 is linked to increased $\text{A}\beta$ aggregation, reduced clearance, disrupted
58 microglial lipid processing, and altered inflammatory signaling, while APOE2 is considered protective (8), (9).

59 Under normal physiological conditions, APOE is primarily produced by astrocytes. However, in the presence
60 of $\text{A}\beta$ pathology, APOE expression in microglia increases substantially. Experimental models using APOE
61 knockouts or humanized APOE alleles have shown that APOE regulates key microglial functions, including
62 transcriptional responses to $\text{A}\beta$, phagocytic activity, and the production of inflammatory mediators (4), (10).

63 These observations support the hypothesis that APOE isoforms play a critical role in directing microglial
64 behavior and may influence their progression into DAM or other disease-associated phenotypes.

65 *5xFAD and EFAD*

66 Studying the interplay between APOE genotype and microglial activation in humans is difficult due to limited
67 access to living brain tissue and the confounding effects of postmortem delay. As a result, transgenic mouse
68 models have become essential tools for investigating AD mechanisms.

69 The 5xFAD mouse model expresses five familial AD mutations in APP and PSEN1, leading to accelerated
70 $\text{A}\beta$ deposition, gliosis, and synaptic degeneration by six months of age (11). However, this model expresses the
71 murine Apoe gene, which differs from the human gene in structure and function.

72 To address this limitation, the EFAD model was created by crossing 5xFAD mice with human APOE knock-
73 in lines. EFAD mice express human APOE2, APOE3, or APOE4 alleles and recapitulate many of the genotype-

74 specific effects observed in humans. E4FAD mice, in particular, exhibit higher plaque load and more pronounced
75 neuroinflammatory signatures compared to E3FAD or E2FAD mice (12).

76 This model provides a powerful system for dissecting how human APOE isoforms influence microglial
77 responses to A β in vivo.

78 *Microglial Priming*

79 In addition to genetic risk, microglial states may be shaped by early-life environmental exposures. One mecha-
80 nism through which this occurs is innate immune memory, a process by which transient inflammatory stimuli
81 produce long-lasting changes in microglial function (13).

82 Previous studies have shown that systemic administration of lipopolysaccharide (LPS) during early devel-
83 opment can lead to persistent alterations in microglial gene expression, inflammatory responses, and behavior
84 later in life (14). However, these effects are context-dependent and may differ by genetic background, sex, and
85 timing of exposure.

86 Work from our laboratory has demonstrated that LPS injection at postnatal day 9 (P9) improves long-term
87 memory performance and enhances microglial internalization of A β in 5xFAD mice (15). These findings suggest
88 that early immune activation may modulate the trajectory of microglial aging and response to pathology, possibly
89 in a beneficial manner.

90 *Study Rationale and Objectives*

91 The current study was designed to test the hypothesis that early-life inflammation interacts with APOE genotype
92 to shape microglial transcriptional states in the context of A β pathology. To investigate this, we used EFAD mice
93 expressing human APOE3 or APOE4 alleles. At postnatal day 9, animals were treated with LPS or vehicle, and
94 at six months of age, microglia were isolated for single-cell RNA sequencing.

95 This approach allowed us to examine both cell-type proportions and transcriptional profiles across multiple
96 experimental conditions. Our aim was to determine whether APOE isoform modifies the microglial response to
97 early-life priming, with a particular focus on disease-associated and pro-inflammatory transcriptional states.

98 This study is part of a broader investigation integrating transcriptomics, proteomics, histology, and
99 behavioral analysis to understand how genetic and environmental risk factors converge to influence neuroin-
100flammation in AD.

101 **Materials and methods**

102 **Animals**

103 Humanized APOE3 and APOE4 knock-in mice were crossed with the 5xFAD mouse model to generate E3FAD and
104 E4FAD mice, as previously described (Youmans et al., 2012). Wild-type (WT) littermates were used as controls.
105 Mice were housed in a controlled environment (12-hour light/dark cycle, constant temperature and humidity)
106 with free access to food and water. All procedures were conducted in compliance with the European Union
107 laboratory regulations for animal experiments and were approved by the Animal Research Committee of Lund
108 University.

109 **Table 1: Summary of Number of Animals by Genotype and Treatment**

110	Genotype	Treatment	# of Animals
111	E3WT	Vehicle	4
112		LPS	3
114	E3FAD	Vehicle	4
115		LPS	3
117	E4WT	Vehicle	4
118		LPS	3
120	E4FAD	Vehicle	4
121		LPS	5
123	Total Animals		30

124 **Experimental procedure and sample processing**

125 Only female mice were used in this study, as described in the Introduction. At postnatal day 9 (P9), E3FAD, E4FAD,
126 and their wild-type (WT) littermates received a single intraperitoneal (i.p.) injection of either lipopolysaccharide
127 (LPS, 1 mg/kg) or vehicle (0.9% saline) (see Table 1 for group assignments). At six months of age, mice were
128 euthanized by transcardial perfusion. Brains were rapidly dissected, and the right hemisphere was used for
129 microglial cell isolation

130 Microglial enrichment was performed using magnetic-activated cell sorting (MACS) with CD11b Mi-
131 croBeads and LS columns. Enriched microglia were further purified by fluorescence-activated cell sorting (FACS)
132 using an ARIA III flow cytometer. Cells positive for CD45, CX3CR1, and CD11b were collected for downstream
133 analyses.

134 **Cell Sequencing**

135 From each experimental sample, approximately 2,500 sorted microglial cells were loaded for single-cell capture
136 and cDNA library preparation using the 10x Genomics Chromium Single Cell 3' v3 reagent kit and workflow.
137 Individual samples were barcoded using cell-hashing antibodies and pooled into groups of four samples per
138 sequencing run. Libraries were sequenced on an Illumina platform.

139 Raw sequencing data were processed with CellRanger (10x Genomics, v6.1.2) using the mouse reference
140 genome GRCm39 (mm39). This pipeline included alignment, filtering, barcode counting, and UMI (unique
141 molecular identifier) counting to generate feature-barcode matrices for each library.

142 **Quality Control, Normalization, and Data Correction**

143 Individual libraries were first filtered to remove cells identified as empty droplets or doublets using the HashSolo
144 algorithm (16). Additional quality control (QC) filters were applied to each library: cells with fewer than 2,000
145 total counts, fewer than 300 expressed genes, greater than 5% mitochondrial gene expression, or fewer than 5%
146 ribosomal gene expression were removed. The 5% mitochondrial threshold was selected based on recommenda-
147 tions by Osorio and Cai, who showed that this cutoff effectively excludes apoptotic cells in mouse scRNA-seq data
148 and improves downstream interpretability (17). Genes expressed in fewer than three cells were also excluded. QC
149 metrics and visualizations for each sample, both pre- and post-filtering, are included in Supplementary Figure 1
150 and Supplementary Table 1.

151 After filtering, individual libraries were merged into a single dataset using Anndata's concat function with
152 an outer join along the cell axis and a unique merge for the gene axis. Raw counts were saved as a separate layer
153 before normalization. Normalization was performed using Scanpy's normalize_total function followed by log-
154 transformation with log1p.

155 Following initial normalization, the merged dataset was examined for the presence of contaminating
156 non-microglial cells. Based on clustering, expression of canonical marker genes, and manual annotation, cells
157 identified as non-microglia were removed. The dataset was re-normalized after removal of non-microglial cells
158 using the same normalization strategy.

159 Highly variable genes (HVGs) were then identified using Scanpy's highly_variable_genes function with
160 sample ID as the batch key. These HVGs were used for subsequent dimensionality reduction steps, including
161 principal component analysis (PCA).

162 The merged dataset was assessed for batch effects using PCA. Several batch correction methods were tested,
163 including Harmony (integration via latent space correction), BBKNN (graph-based nearest neighbor correction),
164 and ComBat (empirical Bayes adjustment). Ultimately, batch effects were not observed to be significant, and no
165 batch correction was applied.

166 A high contribution of mitochondrial genes to variance across cells was observed during HVG and PCA
167 analysis. To reduce this effect, mitochondrial gene expression was regressed out using Scanpy's regress_out
168 function prior to downstream analyses.

169 **Table 2: Summary of Datasets Before and After Quality Control**

Library	Before		After	
	# of Cells	# of Genes	# of Cells	# of Genes
D1	3403	33989	2903	14987
D2	5041	33989	4698	15514
D3	5029	33989	4081	15463
D4	3892	33989	3558	15052
D5	3825	33989	3606	15260
D6	4408	33989	3603	15788
D7	3643	33989	3103	14935
D8	3903	33989	3601	15926
Merged	-	-	29153	17341

181 **Clustering and Annotation**

182 Principal component analysis (PCA) was computed on normalized, log-transformed data. Neighborhood graphs
183 were constructed using the top 25 principal components as input after analyzing the scree plot, and uniform

184 manifold approximation and projection (UMAP) embeddings were calculated with a min_dist parameter of 0.5
185 to preserve both local and global structures.

186 Leiden clustering (18) was performed iteratively across a range of resolutions (0.1–1.9 in steps of 0.1). UMAPs
187 colored by cluster identities were visually inspected at each resolution to identify regions of high heterogeneity
188 and monitor for under- and overclustering. Annotation started with the highest resolution clustering to capture
189 fine-grained heterogeneity and then merged clusters that showed high similarity in their gene expression
190 profiles. Overclustering was identified when newly created clusters did not significantly differ from neighboring
191 clusters in their top differentially expressed genes (DEGs).

192 DEGs were identified using the Wilcoxon rank-sum test (rank_genes_groups function). DEGs were calcu-
193 lated for each cluster against the total dataset and neighbouring clusters to merge clusters with insufficiently
194 distinct expression profiles. Expression profile annotations were assigned based on the combination of differen-
195 tial expression profiles, cluster relationships, and comparison to canonical gene signatures described in previous
196 studies, including Keren-Shaul et al. (3) , Olah et al. (19) , Prater et al. (20) , Mancuso et al. (21) , Sala-Frigerio et
197 al. (22) , Mathys et al. (23) , Millet et al. (24) , (25) , (26) .

198 Clusters were annotated into 9 expression profiles; Homeostatic, DAM, MHC-II/Antigen Presentation DAM,
199 Cytokine Response, Cycling(G2M/Cdk1+), BAM-like, Neuronal surveillance/Ribosomal biogenesis, DAM with
200 Ribosomal upregulation, and Immediate Early Gene (IEG) Enriched Homeostatic. Naming of profiles was based
201 on similarity to previously described profiles in the literature, though should not be considered a formal defin-
202 ition.

203 Cluster Proportions

204 The proportion of each cluster was calculated as the number of cells in the cluster divided by the total number
205 of cells in the sample. A three-way ANOVA was performed to assess the effect of genotype (E3 vs E4), treatment
206 (LPS vs Vehicle), and disease status (FAD vs WT) on the proportion of each cluster. An ordinary least squares
207 (OLS) linear regression model was fit to the data with the proportion of each cluster as the dependent variable
208 and the variable main effects and interactions as predictors. Tukey's Honest Significant Difference (HSD) test

209 was used for post-hoc pairwise comparisons between conditions. All statistical analyses were performed using
210 the statsmodels package in Python.

211 **Pseudobulk Analysis**

212 Pseudobulk analysis was performed to more robustly identify DEGs between condition groups as it has been
213 shown to significantly reduce the number of false positives and increase the accuracy of subsequent enrichment
214 analyses as compared to the Wilcoxon rank-sum test (27). The Python package ‘Decoupler’ was used to generate
215 pseudobulk profiles for each individual mouse using the ‘sum’ method. The pseudobulk profiles were then used to
216 identify DEGs between groups using ‘PyDeseq2’, a python implementation of the DESeq2 algorithm (28,29). The
217 Wald test was used to generate p-values with cook’s filtering and correction for multiple testing using Benjamini-
218 Hochberg method. The model was fit with disease status (FAD vs WT), APOE genotype (E3 vs E4), and treatment
219 (LPS vs Vehicle) as factors with their interactions, and specific comparisons were extracted using the ‘results’
220 function. Genes were considered differentially expressed if they had an adjusted p-value < 0.05 and a log2 fold
221 change > |0.25|. The pseudobulk DEGs were then used for downstream analysis including Gene Ontology (GO)
222 enrichment analysis.

223 **Gene Set Enrichment Analysis (GSEA)**

224 Gene Set Enrichment Analysis (GSEA) is a statistical method used to determine whether selected sets of genes
225 show statistically significant differences between two biological states (30). Rather than focusing only on statis-
226 tically significant DEGs, as other methods do, GSEA evaluates the entire set of genes ranked by a metric which
227 reflects their different expression between conditions, thereby better capturing the pathway-level enrichment
228 differences.

229 For each contrast of interest, genes were ranked by their Wald test statistic derived from the pseudobulk
230 differential expression analysis. GSEA was then performed using the implementation provided in the Decoupler
231 package (28), with the MSigDB Hallmark gene sets (31) as the reference collection. This approach enabled the
232 identification of pathways significantly enriched in up- or down-regulated genes across our conditional contrasts
233 of interest.

234 **Proteomic Analysis**

235 ***Sample Preparation***

236 50 µg of protein was digested on S-Trap micro spin columns (ProtiFi) with sequencing-grade trypsin (1:25)
237 overnight at 37 °C following the manufacturer's protocol.

238 ***LC–MS/MS Acquisition***

239 Peptides (500 ng) were analyzed on an Evosep One–timsTOF HT system in diaPASEF mode (16 windows, 400–
240 1 200 m/z, 0.60–1.60 1/K₀; 1.8 s cycle), using 0.1 % formic acid mobile phases.

241 ***Data Quantification***

242 Raw files were processed in Spectronaut v19 (directDIA) using default MS2 quantification and MaxLFQ. The
243 UniProt mouse reference proteome (17 184 entries), supplemented with human APOE3, APOE4, and 5×FAD APP/
244 PSEN1 sequences, served as the search database. Carbamidomethylation of cysteine and oxidation of methionine
245 were set as fixed and variable modifications, respectively; up to two missed cleavages were allowed. False
246 discovery rate was controlled at 1 % for both peptide and protein levels.

247 (Full protocol provided in Supplementary Methods)

248 ***Data Analysis***

249 Log₂-transformed normalized label-free quantification (LFQ) values from Spectronaut v19 were imported into
250 R (v4.x), reshaped and annotated with sample metadata using tidyverse and dplyr [(32)]. Metadata fields included
251 sample ID, genotype, treatment, age, sex and batch. A SummarizedExperiment object was generated with DEP
252 (v2.0.0) [(33)] for downstream analyses.

253 Comprehensive quality control was conducted within DEP. Density and box plots of log₂ intensities were
254 inspected to confirm consistent normalization across samples. Protein detection frequency was assessed by
255 counting proteins detected in n samples, and the distribution was visualized to evaluate assay coverage. Missing
256 data patterns were explored by generating heatmaps of missingness and plotting the fraction of missing values
257 against intensity. On the basis of these diagnostics, missing values were classified as Missing Not At Random
258 (MNAR) and found to be enriched at low intensities. Imputation was performed using the MinProb algorithm (q

259 = 0.5) as implemented in DEP. Additional exploratory analyses included Principal Component Analysis (PCA),
260 hierarchical clustering, heatmaps of Pearson correlation coefficients between samples.

261 Differential abundance analysis was conducted with limma [(34)]. Linear models were fitted to \log_2 inten-
262 sities with genotype, treatment and their interaction specified as factors. An empirical Bayes procedure with
263 mean-variance trend fitting and robust hyperparameter shrinkage was applied. Contrasts were defined to test
264 the effect of LPS within APOE3, the effect of LPS within APOE4, and the interaction between genotype and
265 treatment. Proteins with nominal $P < 0.05$ were selected for visualization. Volcano plots were generated using
266 ggplot2, displaying $-\log_{10}(P)$ versus \log_2 fold change with top hits annotated. Concordance with transcriptomic
267 data was assessed by plotting proteomic \log_2 fold changes against matching RNA-seq contrasts and calculating
268 Spearman correlation coefficients.

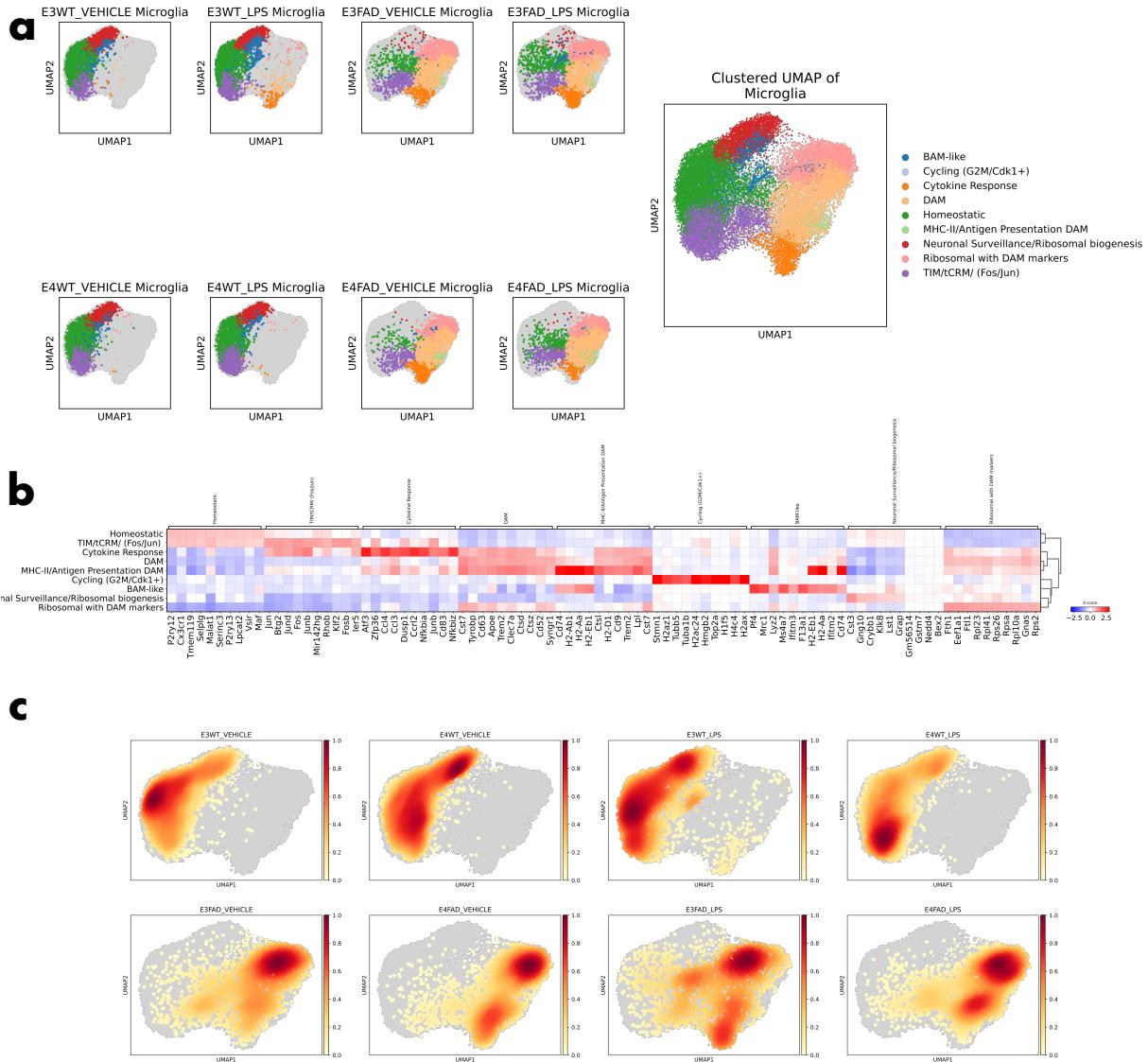
269 Pathway enrichment analysis was performed using Camera [(35)] in limma against KEGG pathways from
270 the Molecular Signatures Database (MSigDB) C2:CP (curated canonical pathways) [(31)]. Camera's competitive
271 gene set test, which estimates inter-gene correlation from the dataset to control type I error, was executed with
272 default settings using the full vector of \log_2 fold changes as input. Pathways were ranked by false discovery rate
273 for interpretation.

274 Results

275 Cluster Expression Profiles

276 Following dimensionality reduction and Leiden clustering, we identified nine distinct microglial expression
277 profiles based on differentially expressed genes (DEGs) between clusters and reference to canonical expression
278 signatures described in previous studies. Cluster annotation was guided by comparisons to known microglial
279 states in both mouse and human brain studies, including those by Keren-Shaul et al. (3), Sala-Frigerio et al.
280 (22), Olah et al. (19), Mathys et al. (23), and others. The final annotated expression profiles were: Homeostatic,
281 DAM, MHC-II/Antigen Presentation DAM, Cytokine Response, Cycling (G2M/Cdk1+), BAM-like, Neuronal
282 Surveillance/Ribosomal Biogenesis, Ribosomal DAM, and Immediate Early Gene (IEG) Enriched Homeostatic.

283 These expression profiles are visualized in Figure 1. The UMAP plots (Figure 1a) show cluster organization
 284 across the entire dataset and by condition. Figure 1b displays the top 10 DEGs for each cluster when compared
 285 to the rest, and Figure 1c shows density plots of cluster distributions per condition.



286 **Figure 1: Distinct Expression Clusters and Their Proportions by Condition**
 287 **a.** UMAP visualizations of the dataset colored by manually annotated expression profiles, entire
 288 dataset, and by condition. **b.** Heatmap of the top 10 differentially expressed genes for each cluster
 289 expression profile showing scaled log-normalized expression values (z-scores). **c.** UMAP density plots
 290 for each condition.

291 The Homeostatic cluster was characterized by high expression of canonical microglial maintenance genes,
 292 including P2ry12, Tmem119, and Cx3cr1, and served as a reference for identifying more activated or altered
 293 states. The IEG cluster shared elevated expression of homeostatic markers but also showed upregulation of

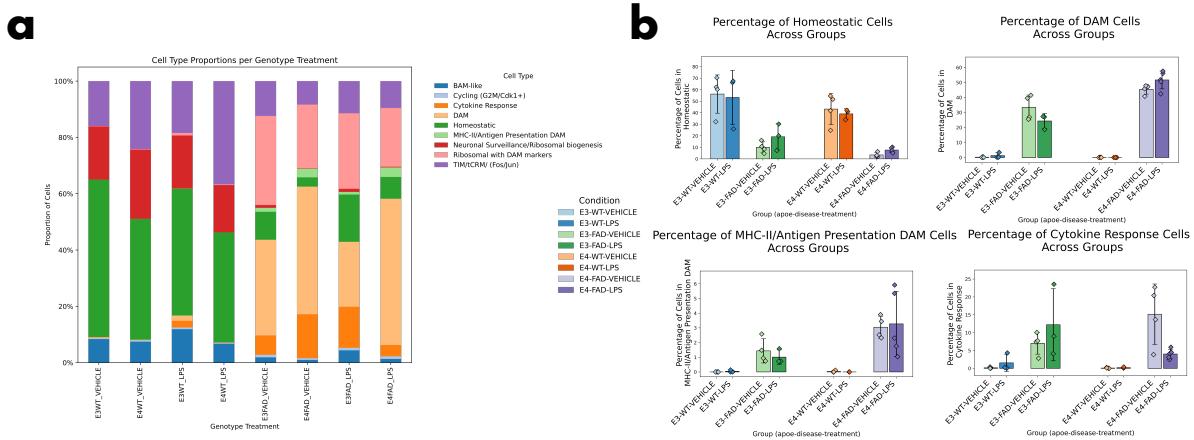
294 immediate early genes such as Fos, Jun, and Egr1, a pattern that has been interpreted as both a stimulus-
295 responsive microglial state and, alternatively, as a dissociation-induced artifact (24,36).

296 Two small clusters were also identified. The Cycling cluster was defined by elevated expression of cell
297 cycle and proliferation-associated genes such as Stmn1, Top2a, and H2az1, consistent with previously reported
298 populations of proliferative microglia in AD models and aged brain tissue (22,26,37). The BAM-like (Border-
299 Associated Macrophage-like) cluster was characterized by high expression of perivascular macrophage markers
300 including Pf4, Mrc1, and Ms4a7. Although microglial enrichment was performed during FACS, this population
301 likely reflects a small number of CNS-associated macrophages retained during sorting.

302 The DAM (Disease-Associated Microglia) cluster showed a transcriptional profile closely matching that
303 originally described by Keren-Shaul et al. (3), including high expression of Trem2, Apoe, Cst7, Tyrobp, and Clec7a,
304 accompanied by suppression of homeostatic genes. Three additional clusters were identified with overlapping
305 DAM features but distinct gene expression signatures. The Cytokine Response cluster exhibited elevated expres-
306 sion of inflammatory chemokines and NF- κ B target genes such as Ccl3, Ccl4, and Il1b. The MHC-II/Antigen
307 Presentation DAM cluster was enriched for antigen presentation genes including Cd74, H2-Ab1, H2-Aa, and H2-
308 Eb1. The Ribosomal DAM cluster retained DAM-like features with additional upregulation of ribosomal genes.

309 *Expression Profile Proportions Across Conditions*

310 After identifying different expression profiles in the dataset, the relative abundance of each cell type was
311 assessed across experimental conditions. The proportions observed in the eight experimental groups are shown
312 in Figure 2a, with absolute cell counts presented in Supplementary Figure 2 and corresponding values listed in
313 Supplementary Table 2. Disease versus wild-type is the main cause of variation in cell type composition, with
314 the most pronounced differences observed in the homeostatic and DAM clusters. Homeostatic cells accounted
315 for 39–56% of the population in WT mice, compared to only 3–17% in FAD mice, representing a statistically
316 significant reduction (ANOVA $p < 1e-8$; linear model coefficient = +46.2%, $p < 0.001$). The APOE genotype was
317 not associated with a statistically significant change in homeostatic cell proportions, nor was there a significant
318 difference with LPS treatment.



319 **Figure 2: Changes in Cluster Proportions by Condition**

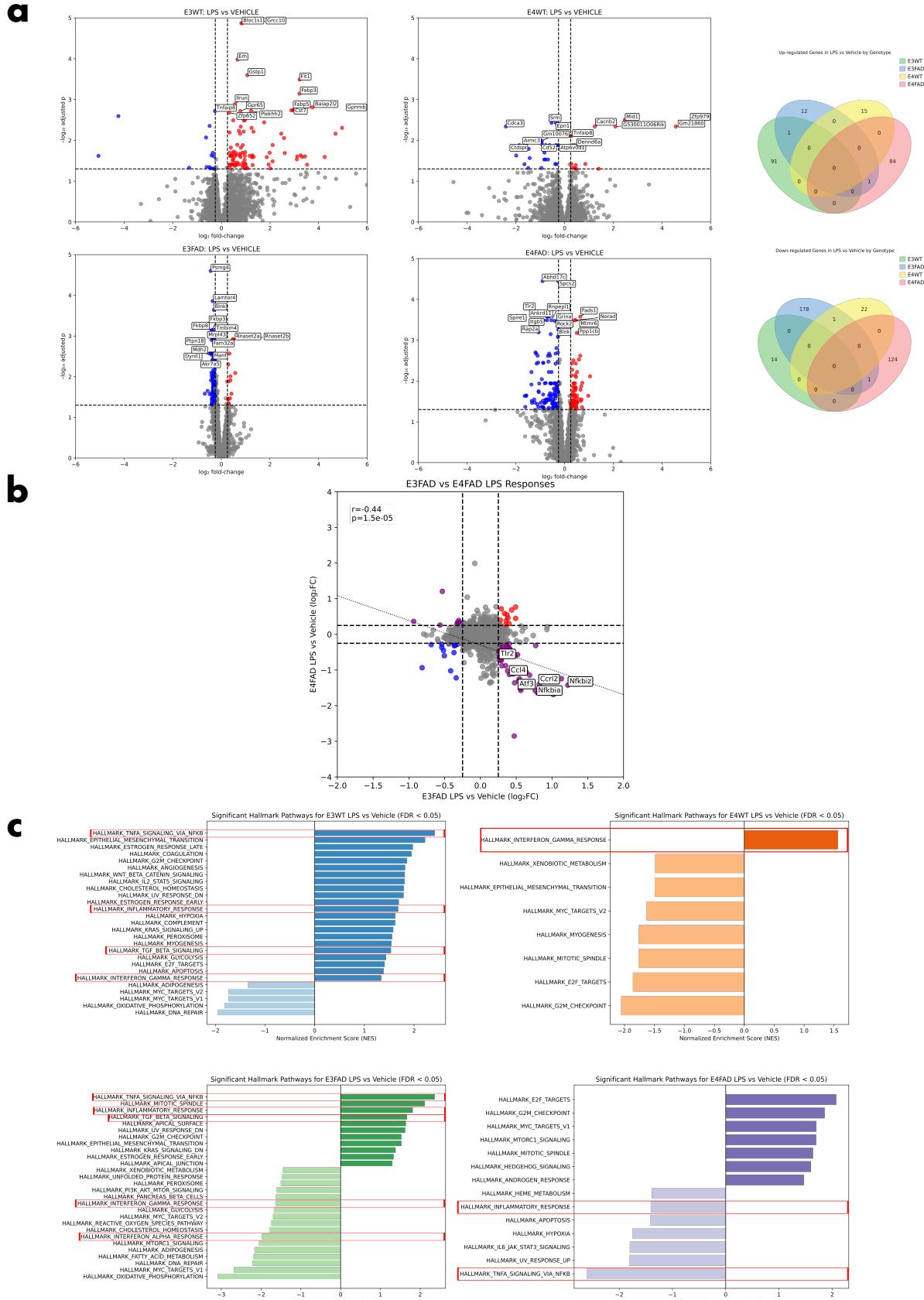
320 **a.** Stacked Bar plot of the proportion of each cluster in each condition. **b.** Bar plots of the proportion of
321 specific clusters in each condition, significant differences determine by three way anova and Tukey's
322 post-hoc test and indicated by asterisks.

323 The DAM cluster was absent in all WT groups except for a small proportion (1.9%) in the E3WT LPS group
324 and ranged from 23-52% in FAD mice. Additionally, E4FAD mice have a larger proportion of DAM microglia
325 than E3FAD mice (interaction coefficient = +12.3%, p = 0.012), which is consistent with previous single cell
326 studies. The three clusters representing more "activated" states similar to DAM (Cytokine Response, MHC-II/
327 Antigen Presentation DAM, and Ribosomal DAM), also show zero or very low proportions in WT mice, and are
328 significantly increased in FAD mice.

329 The Cytokine Response cluster shows an interesting pattern in which the E4FAD LPS group has a signifi-
330 cantly lower proportion of cells compared to the E4FAD vehicle group (Tukey p-adj = 0.028), while the E3FAD
331 LPS group is not significantly different from the E3FAD vehicle group (Tukey p-adj = 0.807). This suggests an
332 APOE isoform-specific effect of LPS priming on this microglial population. This interpretation is supported by
333 a statistically significant three-way interaction term in the ANOVA (p = 0.038) and a notable effect size in the
334 linear model (coefficient = -15.1%, p = 0.038), indicating that LPS treatment reduces the proportion of Cytokine
335 Response cells specifically in E4FAD mice.

336 ***E4FAD but Not E3FAD or WT Mice Exhibit Reduced NfkB-related Expression after LPS Priming***

338 To more robustly identify differentially expressed genes (DEGs) between conditions, pseudobulk analysis was
339 performed on the dataset. This involves summing the expression each gene in all cells from an individual mouse
340 to create a single expression profile, aiding in overcoming the sampling variability in single cell RNA sequencing.
341 The pseudobulk profiles can then be used to identify DEGs with methods typically used for bulk RNA sequencing
342 data, such as DESeq2 which produces fewer false positives than the more common Wilcoxon rank-sum test
343 used in single cell analysis. DEGs were identified between the LPS and vehicle treatment groups in the four
344 genetic backgrounds, the results of which are visible in the volcano plots in Figure 3a. There are no more than 1
345 significant DEG which is shared between any of the comparisons. However, as a general pattern it can be seen
346 that the FAD mice have a much larger number of downregulated genes in the LPS treatment group compared to
347 the vehicle group, while the WT mice show a much smaller number of downregulated genes.



348 **Figure 3: Differentially expressed Genes and Pathways in LPS versus Vehicle Treated Mice**

349 **a.** Volcano plots of pseudobulk DEGs in LPS versus vehicle comparisons in the four genotypes with
350 top genes labelled. **b.** Correlation plot of LogFC values of genes in LPS versus vehicle treatment in
351 E3FAD compared to E4FAD. Pearson's correlation computed on genes above the logFC threshold of
352 0.25 **c.** GSEA of significant pathways in the LPS versus vehicle comparisons computed on Wald test_{16/31}
353 statistics.

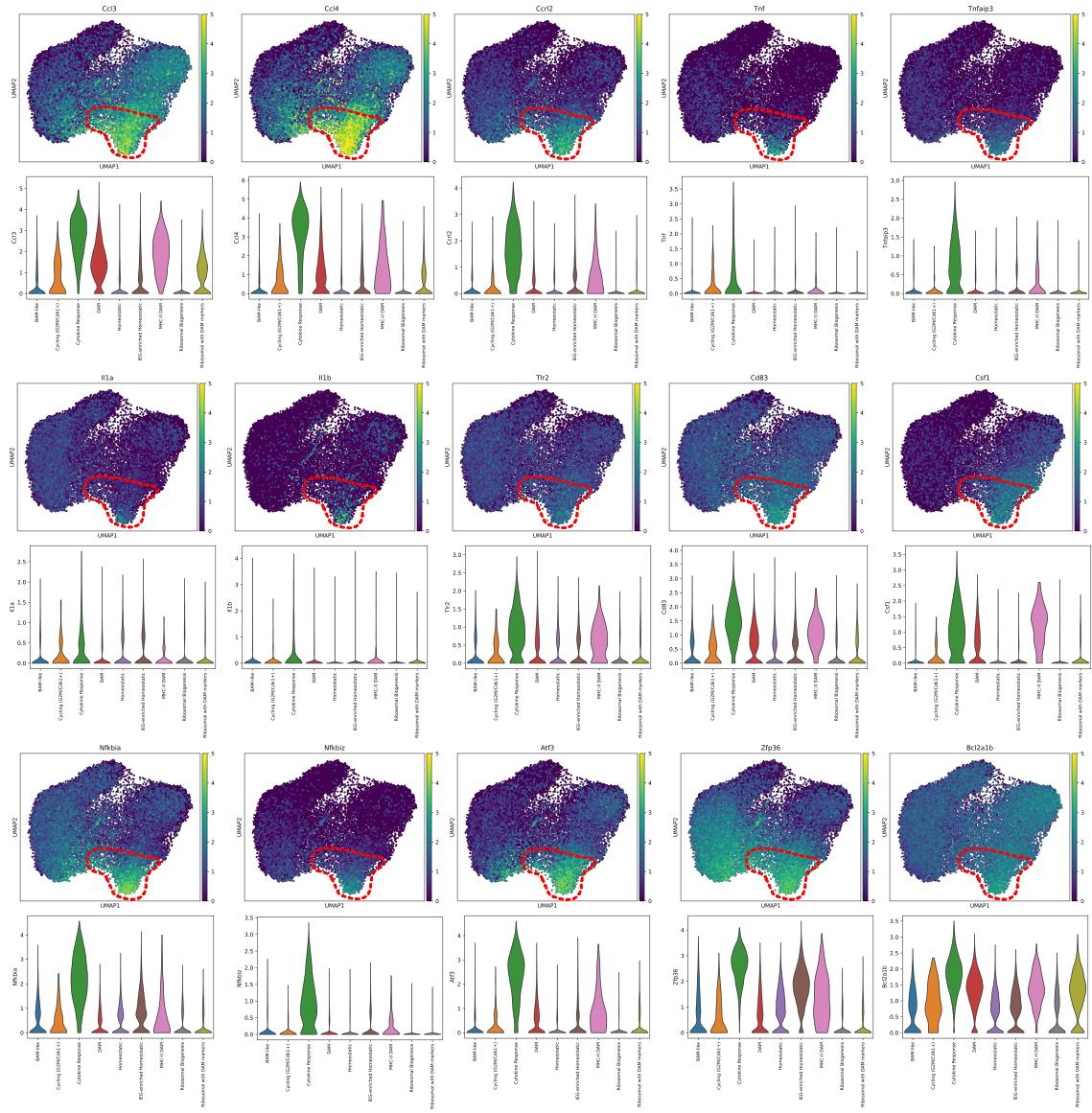
354 When the E3FAD and E4FAD LPS treatment group DEGs are compared, a statistically significant correlation is
355 observed (Pearson's $r = -0.44$, $p = 1.5\text{e-}5$), indicating that genes that are upregulated in E3FAD mice are likely
356 to be downregulated in E4FAD mice. A number of these genes are those associated with the NfkB pathway,
357 including Ccl4, Tlr2, and Nfkbia. Based on the pseudobulk DEGs, Gene Set Enrichment Analysis (GSEA) was
358 performed to identify pathways that were significantly enriched in the LPS treatment groups. The results (Fig 3c)
359 show that the top upregulated pathways in both E3WT and E3FAD groups are TNF-a signaling via NfkB, while
360 it is the top downregulated pathway in the E4FAD group. It does not appear in the significant pathways in the
361 E4WT group, however the top upregulated pathway in this group is Interferon gamma response. Additionally,
362 the E3WT and E3FAD groups show significant upregulation of the Inflammatory response pathway and TGF
363 beta signaling, while the E4FAD group shows downregulation of the Inflammatory response pathway and no
364 upregulation of inflammatory pathways.

365 ***Cytokine Response Microglia***

366 Given that the dampening of NF- κ B-related pathways in the E4FAD LPS group coincided with a reduced
367 proportion of Cytokine Response microglia, the transcriptional profile of this cluster was examined to assess its
368 potential contribution to the observed pseudobulk differences.

369 The Cytokine Response cluster was marked by elevated expression of genes associated with pro-inflam-
370 matory signaling and canonical NF- κ B pathway activation. These included the chemokines Ccl3 and Ccl4, the
371 interleukins Il1a and Il1b, and the TNF family member Tnf. Several key regulators and targets of NF- κ B signaling,
372 including Nfkbia, Nfkbiz, and Tnfaip3, were also upregulated. Additional genes enriched in this cluster were
373 involved in stress response (Atf3, Gadd45b), immune regulation (Cd83, Zfp36, Bcl2a1b), pattern recognition
374 (Tlr2), cytokine signaling (Csf1), and chemokine receptor activity (Ccrl2).

375 These expression patterns are shown in Figure 4. UMAP projections reveal that these transcripts are highly
376 expressed within the Cytokine Response cluster, with limited expression in other microglial states. Violin plots
377 further illustrate the cluster-specific enrichment of these genes.



378 **Figure 4: Genes in the Cytokine Response Cluster**

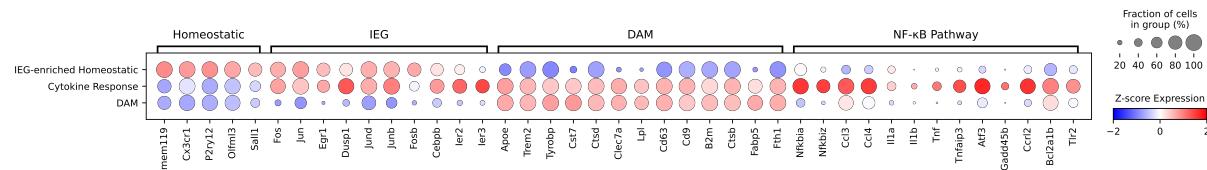
379 UMAP plots of the dataset colored by the expression of specific genes which are differentially upreg-
 380 ulated in the Cytokine Response cluster and which are part of the NF- κ B pathway paired with the
 381 violin plots in all clusters.

382 The selective expression of inflammatory genes within this cluster, combined with its reduced abundance in
 383 E4FAD mice following LPS treatment, suggests that changes in this microglial state contribute to the largest
 384 observed pathway-level differences in the more conservative pseudobulk analysis.

385 In addition to the upregulation of pro-inflammatory signaling genes, the Cytokine Response cluster was
 386 found to show elevated expression of several immediate early genes (IEGs), including Fos, Jun, Egr1, and

387 Dusp1. This overlap prompted further comparison with the IEG-enriched cluster, which also showed increased
388 expression of these same IEGs relative to the rest of the dataset. Despite this similarity, clear differences were
389 observed between the two clusters. The IEG-enriched cluster retained high expression of canonical homeostatic
390 markers such as Tmem119, Cx3cr1, and P2ry12, which were largely absent in the Cytokine Response cluster. In
391 contrast, the Cytokine Response cluster was enriched for DAM-associated genes including Apoe, Clec7a, Trem2,
392 and Ctsd, both in comparison to the total population and when directly compared to the IEG-enriched cluster.

393 When compared to the DAM cluster, the Cytokine Response cluster remained distinct. The DAM cluster did
394 not show enrichment for IEGs or NF- κ B pathway-associated transcripts, suggesting that the Cytokine Response
395 cluster represents a distinct activation state with overlapping features of both DAM and IEG-enriched microglia.
396 These relationships are visualized in the dot plot in figure 5.



397 **Figure 5: Comparison of Overlapping and Distinct Features Between Microglial States**

398 Dot plot showing the expression of immediate early genes (IEGs), homeostatic markers, DAM-
399 associated genes, and NF- κ B pathway-related transcripts across the Cytokine Response, IEG-enriched,
400 and DAM clusters. Dot size represents the fraction of cells expressing each gene, calculated using a
401 threshold of log-normalized expression > 0 (equivalent to raw counts ≥ 1). Color indicates average
402 expression level scaled across clusters (Z-score normalized).

403 *Proteomic Analysis*

404 The relationship between mRNA from transcriptomic analysis and protein levels in vivo is complex and affected
405 by many factors including translation, post-translational modifications, and degradation. It is well known to not
406 be a one-to-one relationship, and the correlation between mRNA and protein levels varies by tissue type and
407 cell type and is often low (Liu 2016). In order to further support the findings from the transcriptomic analysis,
408 proteomic analysis was performed on the same samples. to be continued

409 **Discussion**

410 *Microglial Heterogeneity in Alzheimer's Disease*

411 Neuroinflammation has become recognized as a central phenomenon in the pathogenesis of Alzheimer's disease
412 (AD), both regulating and responding to amyloid- β production, plaque formation, tau hyperphosphorylation, and
413 synaptic and neuronal loss, within a complex and dynamic system that remains incompletely understood (38).
414 While all central nervous system (CNS) cell types have been implicated, accumulating evidence has positioned
415 microglia—the resident innate immune cells of the brain—as central players in these processes. As research into
416 microglial involvement in AD has expanded, so too has the understanding of their diverse functional states.
417 However, the molecular mechanisms governing transitions between these states remain poorly defined.

418 Advances in laboratory techniques and in particular single-cell transcriptomics have given us an entirely
419 new view of microglial heterogeneity. The outdated binary classification of microglia into “resting” or “activated”
420 states has been replaced by an understanding of multiple distinct transcriptional states influenced by disease
421 progression, brain region, age, microenvironment, and genetic background. This shift has been driven by
422 studies describing specific microglial activation profiles, among which the Disease-Associated Microglia (DAM)
423 program, described by Keren-Shaul et al. (3), remains the most influential. This transcriptional program was
424 proposed to occur in two stages, dependent on TREM2 signaling, and in response to amyloid deposition.
425 Subsequent studies have identified a broader array of microglial states, including cycling, antigen-presenting,
426 phagocytic, and various pro-inflammatory states. The current challenge in this area of research is integrating
427 a rapidly expanding body of evidence produced with varied model systems, methodologies, nomenclatures and
428 sometimes conflicting interpretations.

429 APOE genotype remains the strongest genetic risk factor for late-onset Alzheimer's disease, and in the
430 context of microglial heterogeneity, its importance has become increasingly apparent. APOE is highly expressed
431 by microglia in response to amyloid pathology and has been shown to modulate a number of microglial func-
432 tions including phagocytosis, lipid metabolism, and inflammatory signaling. The data presented here provide
433 additional evidence for APOE-dependent modulation of microglial state. As expected, homeostatic microglia

434 represented the majority population in wild-type mice and were nearly absent in the presence of amyloid
435 pathology. FAD mice showed a marked shift toward DAM and related activated states, with a significantly higher
436 proportion of DAM microglia observed in E4FAD compared to E3FAD mice. This finding is consistent with
437 previous studies using humanized APOE models.

438 ***Early-Life Immune Priming Alters Microglia Trajectory***

439 LPS priming of microglia has been shown to influence their function both acutely and over extended periods
440 following the initial insult (39). Unpublished data from members of our lab have demonstrated that LPS adminis-
441 tration at postnatal day 9 alters the microglial response to amyloid pathology later in life. Changes were observed
442 in the transcriptional levels of specific cytokines, and a microglial population not present in vehicle-treated mice
443 was identified ((15), preprint). These findings, combined with the well-established role of APOE in modulating
444 microglial state and inflammatory signaling, motivated the present analysis to investigate how human APOE
445 isoforms may interact with early-life immune priming to shape microglial phenotypes in the context of AD-
446 related pathology.(should I add a sentence here saying why post-natal day 9?)

447 The data presented here provide additional evidence for the impact of APOE genotype on microglial pheno-
448 types and the modulatory effect of LPS priming. As expected, a majority of microglia in non-disease (WT) mice
449 were assigned to the homeostatic cluster, with near-zero representation in the disease-associated transcriptomic
450 profiles. In contrast, FAD mice exhibited a substantial shift, with large proportions of their microglial populations
451 classified into disease-associated clusters and a corresponding reduction in homeostatic cells. An increased
452 proportion of microglia in the DAM cluster was observed in E4FAD mice compared to their E3FAD counterparts,
453 consistent with previous studies using mice expressing human APOE alleles.

454 ***Genotype-Specific Modulation of Inflammatory Signal***

455 The analysis shows a genotype-specific priming effect on the expression of particular cytokines and inflamma-
456 tory genes, primarily those in the canonical NF-κB signaling pathway. In mice treated with LPS, a downregulation
457 of these genes was observed specifically in E4FAD animals, while an upregulation was seen in the LPS-treated
458 E3FAD group (Fig. 3). The genes associated with these pathways were not expressed uniformly across the
459 microglial population, indicating that the observed transcriptional changes were not global but instead reflect the

460 behavior of a specific microglial subset. This subset, identified as the Cytokine Response cluster, was not present
461 in non-disease mice, indicating that its emergence is dependent on amyloid pathology. Cluster-level analysis
462 suggests that the observed pathway-level effect in E4FAD mice treated with LPS is driven by a reduction in the
463 proportion of microglia occupying this state.

464 ***Contextualizing the Cytokine Response Cluster***

465 A Cytokine Response cluster, defined by increased expression of cytokines, chemokines, and NF- κ B-related
466 genes, has been observed in other studies. Lee et al. (10) used E3FAD and E4FAD mice challenged with LPS and
467 performed single-cell sequencing 24 hours later; a cluster enriched for NF- κ B-related transcripts was identified,
468 with higher abundance in E3 compared to E4. Mancuso et al. (21) identified a transcriptionally similar population
469 in their xenograft model, significantly enriched in the presence of amyloid pathology, although no APOE
470 genotype-specific differences were reported. Hammond et al. (25) analyzed healthy mice across a range of ages
471 and identified microglial clusters with similar chemokine and cytokine expression profiles, which increased in
472 abundance with age. This microglial phenotype has now been identified across multiple models and conditions;
473 however, its functional role in Alzheimer's disease remains unclear.

474 Beyond the identification of this cluster, cytokine signaling more broadly remains poorly characterized
475 in the context of AD. Cytokines have been proposed to contribute to increased amyloid- β production and
476 accumulation (40), and microglial phagocytosis of amyloid- β has been shown to induce cytokine release (41).
477 Other studies have reported that interleukin-1 β reduces microglial clearance of amyloid- β (42) and that cytokine
478 production is associated with neuronal loss. However, there is also evidence that LPS-induced inflammation can
479 promote amyloid- β clearance (43). These findings highlight the complexity of cytokine signaling in AD, which
480 is governed by context-specific feedback loops that depend critically on the specific cytokines, chemokines, and
481 signaling pathways involved, as well as their timing and intensity

482 Continued investigation of these microglial populations will be important for understanding their function,
483 how they develop and progress, and how they transition across brain regions and in response to disease states.
484 The analysis presented here suggests that this population can be modulated by pre-symptomatic intervention,
485 which may represent a viable therapeutic strategy. This transcriptomic analysis forms part of a larger study

486 examining the interaction between early-life LPS priming and APOE genotype. Unpublished data from this study
487 indicate improved short-term memory performance in LPS-treated E4FAD mice, an effect not observed in their E3
488 counterparts. Taken together, these findings suggest that modulating microglial phenotype at an early timepoint
489 may yield beneficial effects on Alzheimer's disease-related outcomes.

490 ***Biological vs. Artifactual: Evaluating Immediate Early Gene Expression***

491 One of the subclusters identified in our dataset shows upregulation of immediate early genes (IEGs), most
492 prominently from the Fos and Jun families, while also retaining expression of canonical homeostatic microglial
493 markers. This pattern, referred to here as IEG-enriched, has been previously reported by Marsh et al. (36) who
494 showed that it can be induced by enzymatic dissociation during single-cell processing. They found that the use
495 of mechanical dissociation or the addition of transcriptional inhibitors, such as actinomycin D, during enzymatic
496 dissociation could prevent the emergence of this expression pattern. Based on these findings, they concluded that
497 this IEG-rich profile represents an ex vivo stress response, and advocated for the use of transcriptional inhibitors
498 as a standard practice for microglial single-cell experiments.

500 However, more recent studies suggest that this signature may not be purely artifactual. Mancuso et al.
501 (21) generated a single-cell microglial transcriptomic dataset using the App^{NL-G-F} amyloid mouse model with
502 transplanted human microglia expressing APOE2, APOE3, or APOE4, and included transcriptional inhibitors
503 specifically to address the ex vivo activation signature reported by Marsh. Despite this, they still identified a
504 cluster they termed "Transitioning Cytokine Response Microglia" (tCRM), which they describe as "...show high
505 levels of homeostatic genes but also express CRM markers." The top 15 DEGs for this cluster (FOS, JUN, DUSP1,
506 KLF2, HSPA1A1A, IER2, IER3, RHOB, JUNB, Ch25H, HSPA1AB, JUND, FOSB, CEBPD, RGS1) are primarily
507 immediate early genes and closely resemble the ex vivo stress signature identified by Marsh. While Mancuso et
508 al. did not report any APOE isoform-specific differences in this population, they found that it was significantly
509 reduced in APOE knockout mice, suggesting that despite the use of inhibitors, this expression profile may reflect
a real APOE-dependent microglial state.

510 Further evidence for the biological relevance of this type of expression pattern comes from Millet et al.
511 (24), who performed scRNA-seq on microglia from E3 and E4 × 5xFAD mice aged to 96 weeks. They identified

512 a population they termed “Terminally Inflammatory Microglia” (TIM), which was enriched in aged animals and
513 which they describe as “marked by concomitant expression of inflammatory genes such as S100a8 and S100a9
514 and immediate early response genes such as Fos, Jun, and Egr1.” Although their protocol did not include
515 transcriptional inhibitors and they acknowledge resemblance to the ex vivo stress profile reported by Marsh, they
516 argue that TIMs represent a bona fide microglial state. They support this by showing that similar populations
517 are seen in human snRNAseq datasets prepared using both mechanical and enzymatic dissociation, and that the
518 TIM cluster is more prevalent in aged brains and modulated by APOE genotype.

519 A more recent study by Mulenge et al. (44) extended the work of Marsh by evaluating the effects of both
520 dissociation and sorting. They confirmed that transcriptional inhibitors can suppress IEG expression but also
521 showed that FACS sorting itself induces an ex vivo activation signature. Specifically, they found that Zfp36,
522 Dusp1, Jun, Ccl4, Ccl3, Tnf, Socs3, and Hspa1a were consistently upregulated across sorted datasets. However,
523 they noted that this expression was generally elevated across the entire dataset and not confined to specific
524 clusters.

525 In our data, by contrast, these IEG and cytokine-related genes are not uniformly upregulated across the
526 full microglial population but are instead restricted to the Cytokine Response and IEG-enriched clusters. This
527 spatial restriction, along with parallels to expression profiles seen in Mancuso and Millet even in the presence
528 of transcriptional inhibitors, supports the interpretation that these clusters represent true biological microglial
529 states, not merely artifacts of tissue processing.

530 ***Conclusions and Future Directions***

531 Continued investigation of these microglial populations will be important for understanding their function,
532 how they develop and progress, and how they transition across brain regions and in response to disease states.
533 The analysis presented here suggests that this population can be modulated by pre-symptomatic intervention,
534 which may represent a viable therapeutic strategy. This transcriptomic analysis forms part of a larger study
535 examining the interaction between early-life LPS priming and APOE genotype. As part of this effort, additional
536 data are being generated to validate these transcriptional findings through complementary proteomic analysis
537 using mass spectrometry from the same experimental model. Immunohistochemical staining of brain sections

538 will be used to validate microglial responses and assess amyloid plaque burden, providing a spatial context for
539 the observed molecular changes. These datasets will be integrated with behavioral testing results, which have
540 already indicated improved short-term memory performance in LPS-treated E4FAD mice, an effect not observed
541 in their E3 counterparts. Together, these analyses aim to establish a more comprehensive understanding of how
542 early-life immune events intersect with genetic risk to influence microglial function and disease progression in
543 Alzheimer's disease.

544 **Supplemental Information**

545 TO PUT IN SUPPLEMENTARY DATA:

546 • QA plots before & after filtering

547 • mito %

548 • ribo %

549 • # genes / cell

550 • PCA coloured by library, condition

551 • PCA scree plot

552 • Wilcoxon DEG top genes for each cluster against rest and against closest clusters? probably as a table or attached .xlsx? with logfc/
553 pvals_adj

554 • Pseudobulk plots

555 • PCA plots

556 • metadata pca heatmap

557 •

558 **Supporting Table 3: Detailed Summary of Quality Control Filtering for Each Dataset**

559

Unique												
560	Initial				(Low)	(Low)	Cells	Re-	Initial	Genes	Re-	Final
561	Dataset	Cells	(Mito)	(Ribo)	Counts)	Genes)	moved	Genes	moved	Final Cells	Genes	
562	D1	5500	97	197	465	2	500	33989	19002	5000	14987	
563	D2	3683	85	150	400	3	450	33989	18200	3233	15789	
564	D3	4717	110	180	420	1	480	33989	17800	4237	16189	
565	D4	3968	90	160	380	2	420	33989	18700	3548	15289	
566	D5	4220	95	170	390	1	440	33989	18000	3780	15989	
567	D6	3890	88	155	370	2	410	33989	18900	3480	15089	
568	D7	4405	102	165	450	1	500	33989	17600	3905	16389	
569	D8	3600	80	145	360	2	400	33989	19100	3200	14889	
570	Merged	-	-	-	-	-	-	-	-	28643	17429	

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