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## Neonatal Brain Injury Triggers Niche-Specific Changes to Cellular Biogeography

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9      **ABSTRACT**

10     Preterm infants are at risk for brain injury and neurodevelopmental impairment due, in part, to white  
11    matter injury following chronic hypoxia exposure. However, the precise molecular mechanisms by which  
12    neonatal hypoxia disrupts early neurodevelopment are poorly understood. Here, we constructed a brain-  
13    wide map of the regenerative response to newborn brain injury using high-resolution imaging-based  
14    spatial transcriptomics to analyze over 800,000 cells in a mouse model of chronic neonatal hypoxia.  
15    Additionally, we developed a new method for inferring condition-associated differences in cell type spatial  
16    proximity, enabling the identification of niche-specific changes in cellular architecture. We observed  
17    hypoxia-associated changes in region-specific cell states, cell type composition, and spatial organization.  
18    Importantly, our analysis revealed mechanisms underlying reparative neurogenesis and gliogenesis,  
19    while also nominating pathways that may impede circuit rewiring following neonatal hypoxia. Altogether,  
20    our work provides a comprehensive description of the molecular response to newborn brain injury.

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35 **SIGNIFICANCE STATEMENT**

36 Children born prematurely are at risk for white matter injury and cerebral dysmaturation, which  
37 predispose to life-long neurological impairments. Here, we used a mouse model of chronic neonatal  
38 hypoxia that mimics some of the features of preterm brain injury and performed high resolution spatial  
39 transcriptomics using multiplexed error-robust fluorescence *in situ* hybridization (MERFISH). We  
40 developed a new approach to map cell-cell relationships, which revealed profound changes to cellular  
41 organization in response to newborn brain injury. We defined cellular communication networks and  
42 signaling pathways that likely contribute to hypoxia-responsive neurogenesis and gliogenesis, as well as  
43 cell- and region-specific factors that may disrupt neurologic recovery and repair.

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59 **INTRODUCTION**

60 Preterm birth is the leading cause of neonatal morbidity and mortality in developed countries and  
61 affects approximately 15 million infants annually (Blencowe et al., 2013a). While significant strides have  
62 been made in neonatal health care leading to increased survival rates, the long-term impact of premature  
63 birth on the trajectory of neurodevelopment remains a major unsolved challenge. Survivors of preterm  
64 birth are at high risk for neurodevelopmental impairment, including cognitive and motor disability, as well  
65 as autism spectrum disorder, epilepsy, and attention-deficit/hyperactivity disorder (Blencowe et al.,  
66 2013b; Crump et al., 2021; Hirvonen et al., 2017; Rommel et al., 2017). The causes of brain injury in  
67 preterm infants are complex and multifactorial, but chronic exposure to hypoxia (HX) due to lung  
68 immaturity is an important driver of brain injury and maldevelopment. Importantly, white matter injury  
69 (WMI) is most prevalent in infants born at early gestational ages preceding the onset of myelination. This  
70 suggests a developmental susceptibility of immature oligodendrocyte (OL)-lineage cells to HX-ischemia,  
71 oxidative stress, and impaired cerebral perfusion, leading to maturational failure (Salmaso et al., 2014).  
72 Despite this understanding, we lack therapies to protect the preterm brain or to promote recovery during  
73 this critical developmental window.

74 A mouse model of chronic sublethal HX, in which neonatal mice are exposed to one week of 10%  
75 oxygen, replicates many structural and pathophysiological aspects of human preterm injury and has been  
76 widely used to study preterm WMI (Fagel et al., 2006; Forbes et al., 2020; Jablonska et al., 2022;  
77 Salmaso et al., 2014). However, most studies have focused on injury and repair within the OL-lineage,  
78 rather than brain-wide changes in the response to neonatal HX and the role of cell-cell communication  
79 networks. Importantly, there is growing recognition that the local microenvironment in specific brain  
80 regions dictates many aspects of cell fate and state (Herrero-Navarro et al., 2021; Joglekar et al., 2021;  
81 Tan et al., 2020), which highlights the necessity of characterizing brain region-specific cellular programs  
82 that govern recovery and repair. Glial identity varies based on cortical location (Hilscher et al., 2022;  
83 Spitzer et al., 2019; Stogsdill et al., 2022) and the local spatial niche may inform injury response (Brandi  
84 et al., 2022; Hammond et al., 2019). It is therefore likely, but incompletely understood, that a similar  
85 region-specific injury response occurs in the context of chronic neonatal HX.

To address this gap in knowledge, we applied spatially resolved single-cell transcriptomics (multiplexed error-robust fluorescence *in situ* hybridization, MERFISH) to explore how neonatal HX affects the brain's spatial organization and signaling landscape. Unlike traditional droplet-based single-cell genomics, MERFISH captures sub-cellular localization of gene expression within the native tissue context, offering insight into cellular organization and architecture (Allen et al., 2023; Zhang et al., 2023, 2021). We performed MERFISH on the mouse brain following chronic sublethal neonatal HX and on age-matched normal oxygen (normoxic, NX) controls. At baseline (under NX conditions), we identified brain region-specific cell states and signaling-associated gene expression profiles in non-neuronal cells. Following neonatal HX, we identified increased oligodendrocyte precursor cell (OPC) proliferation but arrested differentiation of these cells into mature OL in the subventricular zone (SVZ) and corpus callosum. We characterized region- and cell type-specific gene expression changes that may inhibit functional myelination and repair, including upregulation of extracellular matrix components and other mediators known to inhibit oligodendrogenesis. Further, to quantify compositional changes to the cellular microenvironment after HX, we developed a novel approach to infer changes in the spatial proximity of neighboring cell types. Using this method, we found extensive reorganization of local cellular architecture in the cortex, SVZ, and corpus callosum following HX. Overall, these results provide novel insights into the mechanisms underlying white matter regeneration in the neonatal brain and underscore the complex multicellular processes in the regenerative response to HX-induced preterm WMI.

## **MATERIALS AND METHODS**

### **Mouse Model of Chronic Sublethal Hypoxia**

All animal experiments were performed in accordance with the SickKids Research Institute policies. CD-1 mice (Strain: 022) were purchased from Charles River Laboratories. The animals were kept in 12/12 hour light/dark cycles with free access to food and chow, and bred at the [AUTHOR'S UNIVERSITY]. Offspring CD-1 mice were exposed to an oxygen concentration of either 10% (HX) or 21% (NX) in a HX chamber from postnatal day 3 (P3) to P11, lasting eight consecutive days (Fagel et al.,

112 2006; Jablonska et al., 2022; Sathyanesan et al., 2018). Mouse dams were rotated daily. At P11, mice  
113 were removed from the chamber and transferred to a room with normoxic conditions (21% oxygen) until  
114 euthanasia by CO<sub>2</sub> at P21. Fresh brain tissue was harvested and immediately placed in optimal cutting  
115 temperature (OCT) solution and frozen at -80°C until MERFISH processing. Male offspring were used for  
116 MERFISH experiments.

117 **MERFISH Gene Panel Design**

118 We created a panel of 497 genes (Extended Data Table 1-1) to study the cellular architecture and  
119 signaling landscape of the murine forebrain using MERFISH. To guide the identification of diverse cell  
120 types in the brain, the panel included 181 genes that are known cell-type specific markers or have been  
121 previously shown to have enriched expression in a specific population of cells. This list targeted known  
122 cell types within major forebrain structures including the cortex, white matter tracts, striatum, and SVZ.  
123 The remaining 316 genes were components of biological pathways shown previously or hypothesized to  
124 play a role in the pathophysiology of chronic neonatal HX. This included components of signaling  
125 pathways known to regulate oligodendrogenesis, myelination, or that have previously been implicated in  
126 the pathophysiology of WMI such as WNT signaling (Chavali et al., 2020; Varela-Nallar et al., 2014),  
127 BMP signaling (Dizon et al., 2011; Wu et al., 2012), SHH signaling (Bergles and Richardson, 2015; Wu et  
128 al., 2012), FGF signaling (Furusho et al., 2015, 2012), EGF signaling (Aguirre et al., 2007), Ephrin  
129 signaling (Harboe et al., 2018; Li et al., 2022), cytokine signaling (Kirby et al., 2019), senescence  
130 (Nicaise et al., 2019; Safaiyan et al., 2016), and oncogenes (Courtois-Cox et al., 2008). Each gene was  
131 assigned a 20-bit binary barcode which was used to decode sequential imaging data to assign detected  
132 transcripts to the appropriate gene.

133 **MERFISH Tissue Processing and Sample Preparation**

134 All MERFISH sample preparation was performed under RNase-free conditions. Frozen embedded  
135 brains were cryo-sectioned at 10 µm thickness at -21°C and mounted onto room temperature (RT)  
136 MERSCOPE beaded coverslips (Vizgen, Cat: 10500001). After adhering, sections were allowed to  
137 refreeze for 5-15 min, then fixed in 4% paraformaldehyde (PFA) diluted in 1X PBS for 15 min. Sections

138 were washed three times with 1X PBS for 5 min each, then stored in 70% ethanol (EtOH) overnight at  
139 4°C to permeabilize the tissue. Sections were stored in 70% EtOH for a maximum of 3 weeks.

140           Sample preparation was performed using the sample preparation kit (Vizgen, Cat: 10400012) and  
141 Vizgen manufacturer instructions for unfixed tissue. First, sections were washed with 1X PBS followed by  
142 Sample Prep Wash Buffer (Vizgen, PN 20300001). Sections were incubated in Formamide Wash Buffer  
143 (Vizgen, PN 20300002) for 30 min at 37°C, then incubated in the gene panel mix for 42-46 hour (hr) at  
144 37°C. Sections were then incubated two times in Formamide Wash Buffer for 30 min each at 47°C, and  
145 washed with sample prep wash buffer for at least 2 min. Sections were coated in gel embedding solution  
146 (0.05% w/v ammonium persulfate, 0.05% v/v N,N,N',N'-tetramethylethylenediamine in Gel Embedding  
147 Premix (Vizgen, PN 20300004)) and incubated at room temperature (RT) for 1.5 hr, cleared in 1:100  
148 proteinase K in Clearing Premix (Vizgen, PN 20300003) at 37°C overnight or for a maximum of 7 days to  
149 clear lipids and proteins that may contribute to auto-fluorescence background noise. Prior to imaging,  
150 sections were washed two times with Sample Prep Wash Buffer, incubated in DAPI and PolyT Staining  
151 Reagent (Vizgen, PN 20300021) for 15 min on a rocking platform, incubated in Formamide Wash Buffer  
152 for 10 min and washed again with Sample Prep Wash Buffer.

153 **MERFISH Imaging**

154           Imaging was performed on the MERSCOPE platform (Vizgen, Cat: 10000001) according to  
155 manufacturer instructions. Briefly, samples were loaded into the flow chamber of the instrument and the  
156 desired region for imaging was selected using a low-resolution mosaic of DAPI and PolyT stains.  
157 Samples were imaged at high-resolution with a 7-plane z-stack and 1.5 µm spacing between adjacent z-  
158 planes to capture the entire 10 µm thickness of the tissue sections. Samples were then automatically  
159 imaged according to MERSCOPE imaging presets.

160 **MERFISH Bioinformatics Workflow**

161           After imaging, transcript barcodes were decoded and assigned to the appropriate gene.  
162 MERFISH images were segmented using Vizgen's post-processing tool (VPT) and Cellpose 2.0  
163 (Pachitariu and Stringer, 2022), a machine learning algorithm (RRID:[SCR\\_021716](#)). DAPI and PolyT

164 signals were used to delineate cell boundaries for each field-of-view. Individual RNA molecules were  
165 assigned to a cell based on whether they were positioned within the marked boundary. Anatomical  
166 segmentation was performed based on tissue morphology and region-specific gene expression patterns.  
167 This revealed 8 gross anatomical regions: cortex (marked by high expression of *Slc7a6* and *Slc17a7*);  
168 corpus callosum, anterior commissure, septal white matter tracts (all marked by high expression of *Cnp*  
169 and *Pip1*), SVZ (marked by high expression of *Foxj1*, *Sox2*, and *Ascl1*), caudoputamen (marked by high  
170 expression of *Foxo1*, *Crym*, and *Gad1/2*), lateral septal nucleus (marked by expression of *Sp8* and *Sp9*),  
171 anterior commissure (marked by high expression of *Cnp*, and *Pip1*), bed nucleus of the stria terminalis  
172 (marked by *Cartpt*), and the regions ventral to the caudoputamen and anterior commissure, which were  
173 collectively labeled lower gray matter (high expression of *Gad1*, and *Dlx1/2*). Meninges (high expression  
174 of *Col1a1* and *Gfap*) were grouped with the cortex. The cortex was further segmented into upper,  
175 superficial cortex layers (marked by high expression of *Cux2*, *Cartpt*, *Kitl*, and *Rgs8*), and deeper cortex  
176 layers (marked by high expression of *Bcl11b*, *Fezf2*, *Otx1*, and *Tle4*).

177 To obtain a cell-by-gene matrix of each biological sample tissue replicate, we adapted an existing  
178 bioinformatic pipeline (Allen et al., 2023) as follows. (1) To remove segmentation artifacts of extremely  
179 small or large cells, we removed cells with a volume less than  $50\mu\text{m}^3$  or larger than three times the  
180 median volume of all cells. (2) Cells with zero RNA molecules were removed. (3) In a  $10\mu\text{m}^2$  thick tissue  
181 slice, the spatial orientation of cells within the section resulted in partial imaging of their soma. To  
182 account for potential RNA discrepancies, gene expression for each cell was normalized by their volume  
183 and multiplied by 1000. (4) Cells with total RNA counts falling below 2% quantile or exceeding the 98%  
184 quantile were excluded. (5) Potential doublets were removed using Scrublet (RRID:[SCR\\_018098](#)), a  
185 program that generates artificial doublets by comparing gene expression profiles of randomly selecting  
186 cells with segmented cells in the dataset and using a k-nearest neighbor (kNN) to output a predicted  
187 doublet score. Cells with a Scrublet-based doublet score of greater than 0.20 were excluded for further  
188 analysis, accounting for 2.5-3.5% of cells across samples.

189 Data was then processed using the Seurat V5 package in R (RRID:[SCR\\_016341](#)). First, each  
190 dataset was normalized using Seurat's SCTransform function and cells from each gross anatomical

region were grouped into separate Seurat objects. We focused subsequent analyses on cells contained in 3 brain regions: cortex, corpus callosum, and SVZ. We integrated and scaled gene expression from cells from each of six samples ( $n = 3$  HX and  $n = 3$  NX). Only genes with sufficient expression across cells in that region (ranging from 475-495 genes) were integrated and used to compute principal components and uniform manifold approximation and projection (UMAP). Cell clustering was performed using shared nearest neighbors-cliq (SNN-cliq). Cell typing and subtyping was performed using canonical markers. To improve our cell type identification, we removed (1) clusters that did not express cell type-specific marker genes, and thus could not be assigned to a cell type, and (2) clusters of cells that expressed two or more mutually exclusive cell-type-specific marker genes. The former excluded potential non-cell artifacts or cells which could not be identified with the implemented gene panel, and the latter excluded potential doublets.

## 202 **Cell Proportion Analysis**

203 To determine differences in Cell Type abundance in response to HX, we calculated cell type proportions for each Cell Subtype class within each region. For each biological replicate and each region, the total number of cells in each Cell Subtype was divided by either the total number of cells in the region or the total number of cells in the region corresponding to a broad cell class (e.g., neurons, glia, OL-lineage). Statistical differences in cell proportions were calculated using an unpaired, two-tailed, Student's t-test comparing HX and NX ( $n = 3$  each) for each Cell Subtype of each region.

## 209 **Cell-Level Proximity Analysis**

210 To understand how the composition of cellular neighborhoods are affected by neonatal HX, we developed a novel method to quantify condition-related differences in local cell type proximity. For each cell  $i$ , a k-dimensional tree was used to count the number of neighboring type B cells,  $N_B$ , and the total number of neighboring cells (irrespective of type),  $N_{total}$ , within a specified radius  $r$ . For each sample and brain region, we defined a minimum distance unit,  $d$ , as the median of the smallest distances between all cell pairs for each sample. A restricted radius ( $r = 5 * d$ ) was selected to focus on the immediate proximity interactions between Cell Types. The proportion of type B cells within this radius is given by:

$$B_{ratio_i} = \frac{N_B}{N_{total}}$$

217

218       The  $B_{ratio}$  provides a normalized measure of the local proportion or density of cell type B in the  
 219 proximity to a reference cell  $i$ . We note that  $B_{ratio}$  is asymmetric (e.g., the proportion of astrocytes in the  
 220 proximity of neurons is different from the proportion of neurons in the proximity of astrocytes), which  
 221 allows for discriminating when the neighborhood of one cell type is enriched or depleted for another cell  
 222 type, but not vice versa. We further note that this analysis of local cell proximity or density is conceptually  
 223 similar to the analysis of global cell proportion differences defined above.

224       To identify differences in local cell type proximity under NX and HX conditions, we used a  
 225 Generalized Linear Mixed-Effects Model (GLMM) implemented via the glmmTMB R package and  
 226 goodness-of-fit calculations evaluated by the DHARMA package (RRID:[SCR\\_022136](#)). This statistical  
 227 model addresses the non-independence of within-tissue sample observations and is applied to the log-  
 228 transformed  $B_{ratio}$ , with a small offset to accommodate zeroes. This approach quantifies the impact of  
 229 condition on cell type distributions, while accounting for inter-sample variability:

$$\log(B_{ratio} + 0.001) \sim Condition + (1| Sample)$$

230       The effect size and FDR for the condition coefficient were assessed. Significant coefficients (FDR  
 231 < 0.05) indicated a change in cell proximity under HX conditions relative to NX, suggesting a disruption in  
 232 cellular neighborhoods. A positive effect size indicated that cell type B is more densely clustered near cell  
 233 type A (center cell) in HX compared to NX, suggesting increased proximity. In contrast, a negative effect  
 234 size indicated that cell type B is closer to cell type A in NX compared to HX, indicating a relative decrease  
 235 in proximity under hypoxic conditions.

### 237 **Differential Gene Expression Analysis**

238       To identify the differentially expressed genes between conditions and regions, we employed  
 239 MAST (Finak et al., 2015) using Seurat's FindMarkers function on the raw counts matrix. Only genes  
 240 expressed in a minimum of 5% of cells in either comparison group were tested. P-values were adjusted  
 241 with the Benjamini-Hochberg (BH) correction method to obtain FDR values. Specific  $\log_2(FC)$  values are

242 reported in Extended Data Table 5-1. Genes with a  $|\log_2(\text{FC})| > 0.25$  and FDR < 0.05 were considered  
243 significantly differentially expressed.

244 **Cell State Scoring**

245 To calculate cell state scores, we selected genes whose expression has been previously shown  
246 to be enriched in cells primed for OL differentiation (OL genesis score) or enriched in mature OLs (OL  
247 maturation score (Floriddia et al., 2020; Marques et al., 2016; Takeuchi et al., 2020); enriched in reactive  
248 astrocytes over homeostatic astrocytes (reactive astrocyte score(Liddelow et al., 2017; Matusova et al.,  
249 2023; Zamanian et al., 2012)); and enriched in reactive microglia compared to homeostatic microglia  
250 (reactive microglia score) (Paolicelli et al., 2022). Cell state scores were calculated for each cell from the  
251 normalized, integrated datasets by taking the average z-score for the genes in the cell state gene list in  
252 each cell. Then, cell state scores for specific cell groups (i.e., specific Cell Types or Cell Subtypes for  
253 each replicate for each anatomical region) were calculated by taking the average cell state score across  
254 all cells within that group of cells. To compare changes from NX to HX, statistical analysis was performed  
255 using the two-tailed, unpaired, Student's t-test comparing the cell state scores from the 3 NX replicates to  
256 3 HX replicates within each cell type and anatomical region analyzed. Genes used for the OL genesis  
257 score were *Ptprz1*, *Qk*, *Itpr2*, *Gpr17*, *Fyn*, and *Tcf7l2*. Genes used for the OL maturation score were *Mog*,  
258 *Mag*, *Cnp*, *Plp1*, *Myrf*, *Egr2*, *Fos*, *Fosb*, *Klk6*, *Ptgds*, *Car2*, *Grm3*, *Npsr1*, *Jph4*, *Aspa*, *Msmo1*, *Sqle*,  
259 *Hmgcs1*, *Idi1*, *Opalin*, and *Trf*. Genes used for the reactive astrocyte score were *Serpina3n*, *C3*, *Emp1*,  
260 *Gfap*, *Ggta1*, *H2-T23*, *Cd109*, *Hspb1*, and *Icn2*. Genes used for the reactive microglia score were *Lpl*,  
261 *Cst7*, *Ptprc*, *Trem2*, *Lgals3*, *Axl*, *Lyz2*, *Clec7a*, *Spp1*, *Cst7*, and *Apoe*.

262 **Ligand-Receptor (LR) Analysis**

263 We performed ligand-receptor (LR) interaction analysis on the raw gene expression datasets  
264 using CellChat v2 (RRID:SCR\_021946) (Jin et al., 2023). For each experimental condition, spatial  
265 coordinates were aggregated, and an average spot size was computed to normalize the interaction  
266 distances. Coordinates from individual replicates were appropriately translated to prevent overlap and  
267 maintain the spatial integrity of the samples. The preprocessed data was then converted to a CellChat  
268 object, which encapsulated the gene expression matrix, cellular metadata, and spatial coordinates. In our

269 analysis, we grouped cells based on both Cell Type and Cell Subtype classes and incorporated spatial  
270 data to contextualize cell interactions within the tissue architecture. We then aligned our gene expression  
271 data with established molecular communication networks to predict potential LR and in turn cell-cell  
272 interactions. The likelihood and extent of intercellular signaling interactions was estimated by assessing  
273 the expression of LR pairs. Truncated mean calculation for average gene expression per cell group and  
274 bootstrapping for statistical inference were performed to ensure estimation robustness. The  
275 communication probabilities were calculated, accounting for the effect of spatial distance on signaling  
276 potential by adjusting for the scaled interaction range and considering contact-based nearest neighbor  
277 interactions. Subsequently, pathways were aggregated, and centrality analysis was performed to identify  
278 key nodes within the communication network. To explore the differential intercellular communication  
279 networks between HX and NX, data from both conditions were integrated. Differential expression  
280 analysis was then carried out to identify genes that displayed significant changes in expression levels,  
281 with a threshold of p-value < 0.01. Changes in ligand and receptor expression level, with a  
282  $|\log_2(\text{FC})| > 0.25$  were considered significant.

283 **Code Accessibility**

284 The custom code for cell proximity analysis has been uploaded to GitHub: <https://github.com/keon->  
285 [arbabi/spatial\\_hypoxia/blob/main/keon\\_spatial\\_analyses.R](https://github.com/keon-arbabi/spatial_hypoxia/blob/main/keon_spatial_analyses.R)

286 **Tissue preparation and immunofluorescence staining**

287 Brains were harvested from P20 HX and NX exposed mice, fixed in 4% paraformaldehyde (PFA) for 24  
288 hours at 4°C, washed 3 times with PBS, stored in 30% sucrose in PBS for at least 48 hours at 4°C,  
289 embedded in optimum cutting temperature (O.C.T.) mounting medium (Tissue-Tek), and stored at -80°C.  
290 Frozen embedded brains were sectioned coronally at 20um and stored at -80°C. For  
291 immunofluorescence staining, brain sections were first dried for 20 minutes at 37°C, washed 3 times with  
292 PBS, incubated in blocking solution containing (10% BSA, 6% normal donkey serum, 0.1% Triton X-100  
293 for 1 hour at RT, then incubated in primary antibody solution containing 1:500 anti-NCAN (Cedarlane,  
294 Cat: AF5800-SP) diluted in blocking buffer overnight at 4°C. Sections were then washed 3 times with  
295 PBS-T (0.1% Triton X-100 in PBS) and incubated in Alexa Fluor 555 labelled secondary antibody solution

296 (1:500 diluted in PBS-T, ThermoFisher, Cat: A-21436) for 1 hour at RT. Sections were then washed 3  
297 times with 0.1% Triton X-100 and mounted with Fluoromount mounting medium with DAPI  
298 (ThermoFisher, Cat: #00-4959-52).

299 **Immunofluorescence Imaging**

300 Immunofluorescence stained slides were scanned on a 3DHistech Pannoramic 250 Flash III Slide  
301 Scanner using a Zeiss 40 × 0.95 NA objective. The instrument was operated in extended focus mode  
302 (seven focal planes spanning a 5-μm axial distance) to capture the entire cell volume across each tissue  
303 section. The microscope is housed in the Imaging Facility at The Hospital for Sick Children in Toronto  
304 (ON, Canada).

305 **NCAN fluorescence Intensity Analysis**

306 Immunofluorescence images were imported to the HALO Image Analysis Platform (Indica Labs,  
307 v.3.5.3577.173) for analysis. To quantify differences in NCAN distribution across the depth of the cortex,  
308 the cortex of each coronal section (from pia to corpus callosum) was manually segmented into three  
309 approximately equidistant regions encompassing the superficial cortical layers, middle cortical layers, and  
310 deep cortical layers. Average fluorescence intensity was quantified using the HALO Area Quantification  
311 FL module for each region.

312

313 **RESULTS**

314 We employed a widely used mouse model of chronic sublethal HX to investigate the brain's  
315 regenerative response to neonatal injury (Figure 1A, experimental schema). Mouse litters were exposed  
316 to 10% oxygen (HX) or 21% oxygen (normoxia, NX) between P3-11 (see *Methods*), a developmental  
317 period in mice that resembles the third gestational trimester in humans (Semple et al., 2013). Mouse  
318 dams were rotated daily between NX and HX conditions to avoid any confounding based on maternal  
319 care or nutrition. All mice were then moved to an environment with normal levels of oxygen until they  
320 were sacrificed at P21 (see *Methods*). We focused specifically on P21 as it represents a peak time during

321 the post-injury repair period (Fagel et al., 2006; Forbes et al., 2020; Jablonska et al., 2022; Salmaso et  
322 al., 2014).

323 We performed multiplexed error-robust fluorescence *in situ* hybridization (MERFISH) on coronal  
324 brain sections from three HX and three NX mice (see *Methods*). An RNA probe panel of 497 genes  
325 (Extended Data Table 1-1) was selected to enable the identification of major forebrain cell types as well  
326 as components of biologically relevant pathways including growth factors, Wingless-related integration  
327 site (WNT)/ $\beta$ -catenin, bone morphogenic protein (BMP), immune recognition and regulation, perineuronal  
328 net components, and senescence-associated genes (see *Methods*). Cells were segmented using an  
329 established deep-learning algorithm, CellPose 2.0 (Pachitariu and Stringer, 2022), to predict cell  
330 boundaries based on DAPI, a nuclear stain, and PolyT, an mRNA stain (see *Methods*). After  
331 segmentation, transcript counts were normalized by volume and quality control filtering was performed to  
332 remove segmented cells with abnormal physical size, low total number of transcripts, and potential  
333 doublets (Figure 1A, see *Methods*). The resulting dataset, encompassing all replicates and all regions,  
334 had a median volume of 179.5  $\mu\text{m}^3$  per cell and a median expression of 285.6 transcripts per cell.

335 Each coronal MERFISH image of the mouse brain was labeled based on region-specific marker  
336 genes and anatomic landmarks to define regions for downstream analysis (Figures 1B-C). After  
337 normalizing each sample, we independently integrated and analyzed cells from select regions including  
338 the cortex, corpus callosum, SVZ, caudate putamen (CP), lateral septal nucleus (LS), anterior  
339 commissure (Aco), and septal white matter tracts (SWM), respectively, across all datasets. Highly  
340 variable genes were used to compute principal components for uniform manifold approximation and  
341 projection (UMAP) and shared nearest neighbor clustering. After filtering, the final datasets included  
342 668,947 cortex, 8,708 corpus callosum, 10,754 SVZ, 83,235 CP, 19,088 LS, 4,311 Aco, and 12,837  
343 SWM cells across all samples, for a total of 807,880 transcriptionally profiled cells in these regions  
344 (Figures 2B-C, 3A, 3D, and Extended Data Figure 2-1A-D). Our analyses focused on the cortex, corpus  
345 callosum, and SVZ, given their relevance to HX injury and ample cell numbers, contributing statistical  
346 power to our findings. The number of unique genes and transcripts per cell for these three regions are  
347 displayed in Extended Data Figure 2-2A-F.

348

349 **Cell type identification by MERFISH**

350 A major benefit of high-resolution spatial transcriptomics is the potential to characterize cell type  
351 diversity within defined anatomical borders. As such, we analyzed each major anatomic region  
352 independently to ascertain region-specific cell type composition and spatially restricted cell types. In the  
353 cortex and corpus callosum, we classified cells at two levels of cell-type resolution. First, we identified  
354 broad cell type categories (referred to as “Cell Types”), then each Cell Type group was further sub-  
355 clustered to identify more specific subtypes or region-specific cell states (the “Cell Subtypes”). SVZ cells  
356 were classified at one level of resolution which included mostly broad cell type categorizations with the  
357 exception of NSC subtypes. Other regions such as the CP, LS, ACo and SWM, that were not analyzed in  
358 depth in this paper, were classified at one level of resolution with broad categories using the same criteria  
359 described below for Cell Types in the cortex and corpus callosum. Unless otherwise specified, genes  
360 used for characterizing cell types were selected from well-known and widely used brain cell-type  
361 markers.

362 For cortex and corpus callosum, Cell Types included non-neuronal cells corresponding to OL-  
363 lineage cells, vascular and perivascular cells (from here on collectively termed vascular cells), astrocytes,  
364 and microglia; and neuronal cells present only in the cortex, corresponding to excitatory neurons and  
365 interneurons. These included clusters of OL-lineage cells identified with markers such as *Olig1*, *Olig2*,  
366 *Sox8*, and *Sox10*; clusters of astrocytes identified with *Aqp4* and *S100b*; clusters of vascular cells  
367 identified with at least one of *Pecam1*, *Col1a1*, or *Pdgfrb*; and microglia identified with *Cx3cr1* (Figure 2A-  
368 B for cortex and 3A-B for corpus callosum). In the cortex only, clusters of excitatory neurons were  
369 identified with high expression of *S/c17a7* along with some other excitatory neuron genes like *Neurod2*  
370 and the layer-specific markers described later while interneurons were identified with *Gad1* and *Gad2*  
371 (Figure 2C-D).

372 Next, each Cell Type group in the cortex and corpus callosum was subsetted and independently  
373 clustered to identify distinct clusters for subclassification into Cell Subtypes. In the cortex, interneurons  
374 formed three subtype clusters (Extended Data Figure 2-3A), each enriched for known markers of

375 interneuron subpopulations: *Pvalb* (Int 1), *Sst* (Int 2), and *Prox1* (Int 3) (Figure 2D). Int1 and Int2 were  
376 spatially concentrated in middle to deeper cortical layers whereas Int3 was concentrated in upper cortical  
377 layers (Figure 2I). Excitatory neurons formed 10 clusters (Extended Data Figure 2-3B) which were  
378 annotated based on their spatial distribution in the cortex (Figure 2J) and expression of known cortical  
379 layer markers (Figure 2D). These included a cluster of cells that were spatially concentrated in cortical  
380 layers I-III and expressed *Cux2* and *Mef2c* (Exc-1,2,3); a cluster of cells spatially concentrated in cortical  
381 layers II and III which expressed high *Cux2*, *Mef2c*, *Satb2*, and *Lmo4* (Exc-2,3); a cluster of cells spatially  
382 concentrated in cortical layers II-IV and expressed *Mef2c* and *Lmo4* (Exc-2,3,4); a cluster of cells  
383 spatially concentrated in cortical layers II-IV and all three layers of the piriform cortex and expressed low  
384 levels of *Mef2c* and *Lmo4* (Exc-2,3,4,P); a cluster of cells spatially concentrated in piriform layer 1 and  
385 expressing *Mef2c*, *Lmo4*, *Bcl11b*, *Foxo1*, and *Cntn6* (Piri1); a cluster of cells spatially concentrated in  
386 cortical layers V and expressing *Dkk3*, *Foxp1*, *Lmo4*, *Satb2*, and *Mef2c* (Exc5); a cluster of cells spatially  
387 concentrated in cortical layers V and VI and expressing *Tle4*, *Dkk3*, and *Fezf2* (Exc-5,6); a cluster of cells  
388 spatially concentrated in cortical layer VIb and piriform layers 2 and 3, and expressing *Nr4a2* (Exc-  
389 6b,P2,3); a cluster of cells spatially concentrated in cortical layers 6b and the subplate, and expressing  
390 *Ccn2*, *Tle4*, *Nr4a2*, *Satb2*, and *Rgs8* (Exc-6b,SP); and a cluster of cells spatially concentrated in the  
391 subplate and expressing *Nr4a2*, *Dkk3*, *Lmo4*, *Satb2*, *Mef2c*, and *Cux2* (SP) (Extended Data Figure 2-3B  
392 and Figures 2D, and 2J).

393 OL-lineage cell clusters in the cortex (Figure 2A) and corpus callosum (Figure 3B) were classified  
394 as OPCs if they expressed *Pdgfra*, and OLs if they expressed *Mag* and no *Pdgfra*. OPCs formed one  
395 distinct cluster in the corpus callosum (Extended Data Figure 3-1A), but two clusters in the cortex  
396 (Extended Data Figure 2-3C). In both regions, OLs formed multiple clusters corresponding to different  
397 stages of lineage progression with graded expression patterns of the canonical OL marker *Mag* and other  
398 genes described in previous studies as necessary for and upregulated at different stages of OL  
399 development. OL clusters with the lowest expression of *Mag* and moderate to high enrichment of OL  
400 differentiation and early marker genes *Fyn* (Osterhout et al., 1999) and *Gpr17* (Fumagalli et al., 2011)  
401 were classified as newly formed OLs (OL-new); clusters with high enrichment for *Fyn*, *Gpr17*, and other

402 OL differentiation genes such as *Tcf7l2* (Guo and Wang, 2023) and *Myrf* (Bujalka et al., 2013) were  
403 classified as immature OLs (OL-immat); and clusters with the highest expression of *Mag* and enriched for  
404 mature, myelinating OL genes *Trf* (Bujalka et al., 2013), *Car2* (Floriddia et al., 2020), and *Opalin*  
405 (Marques et al., 2016) were classified as mature OLs (Figure 2A and Extended Data Figure 2-3C for  
406 cortex and Figure 3B and Extended Data Figure 3-1A for corpus callosum). OLs in the cortex, particularly  
407 OL-immat and OL-mat, were enriched in the deeper layers (Figure 2E). In the corpus callosum, OL-new  
408 was enriched ventrally (Figure 3C', 3C''), in regions adjacent to the SVZ. This suggests that these newly  
409 formed OLs appear to migrate from the SVZ towards the corpus callosum.

410 Astrocyte clusters were subclassified as reactive astrocytes if they expressed high *Gfap* and were  
411 differentially enriched for at least two of the reactive astrocyte markers *Serpina3n*, *Ggta1* (Liddelow et al.,  
412 2017), and *C3* (Clarke et al., 2018), and classified as homeostatic astrocytes otherwise in both the cortex  
413 (Figure 2A and, for better visualization, Extended Data Figure 2-3E) and corpus callosum (Figure 3B and  
414 Extended Data Figure 3-1C). In the cortex, reactive astrocytes formed two clusters (Extended Data  
415 Figure 2-3D), with one population (Astro-react1) distributed throughout the cortex and meninges, and the  
416 second population (Astro-react2) concentrated in the meninges (Figure 2F). Analysis of differentially  
417 expressed genes (DEGs) between these two clusters revealed that Astro-react1 was enriched for *Gria2*  
418 *Vcam1*, *Sox9*, and *Notch1/2*, and Astro-react2 was enriched for *Gfap*, *S100b*, and *Sparc* (Figure 2A). In  
419 the corpus callosum, we identified one cluster of reactive astrocytes (Astro-react) which, like Astro-react1  
420 of the cortex, differed from the meninge-enriched astrocytes with their high expression of *Vcam1* and  
421 *Sox9* (Figure 3B and Extended Data Figure 3-1B). In both the cortex (Figure 2A and Extended Data  
422 Figure 2-3D) and corpus callosum (Figure 3B and Extended Data Figure 3-1B) we identified three  
423 clusters of homeostatic astrocytes (Astro-hom1, Astro-hom2, Astro-hom3). Similar naming of these  
424 clusters in the two regions does not imply transcriptomic similarity.

425 Microglia clusters in the cortex (Figure 2A) and corpus callosum (Figure 3B) were subclassified as  
426 reactive microglia if they expressed high levels of the reactive microglia marker *Trem2* or subclassified as  
427 homeostatic microglia otherwise. Cortical microglia formed one homeostatic cluster (Micro-hom) and two  
428 reactive clusters (Extended Data Figure 2-3F) whereas corpus callosum microglia formed one

429 homeostatic (Micro-hom) and one reactive cluster (Micro-react) (Extended Data Figure 3-1D). Microglia  
430 subtypes were distributed throughout the cortical layers (Figure 2G) and corpus callosum (Figure 3C',  
431 3C'').

432       Vascular cell clusters in the cortex (Figure 2A) and corpus callosum (Figure 3B) were  
433 subclassified as pericytes (Peri) if they expressed high levels of pericyte markers *Pdgfrb* and *Atp13a5*,  
434 fibroblasts (Fibro) if they expressed high levels of fibroblast markers *Col1a1* and *Col1a2*, and endothelial  
435 cells if they expressed high levels of endothelial cell markers *Pecam1*, *Esam*, and *Cdh5*; low levels of  
436 pericyte and fibroblast markers. Pericytes formed only one cluster in both cortex (Extended Data Figure  
437 2-3G) and corpus callosum (Extended Data Figure 3-1E). In the cortex, fibroblasts formed four clusters  
438 (Extended Data Figure 2-3G). In general, there was a higher density of fibroblasts in the meninges  
439 compared to the cortex, but one cluster in particular. Fibro-1 was highly concentrated in the meninges  
440 (Figure 2H). Compared to the other fibroblast clusters, Fibro-1 was differentially enriched for genes like  
441 *Cxcl12*, *Gfap*, and *Pdgfra* (Figure 2A). In the corpus callosum, fibroblasts formed one distinct cluster  
442 (Extended Data Figure 3-1E). Endothelial cells formed three clusters in the cortex (Extended Data Figure  
443 2-3G) and formed two clusters in the corpus callosum (Extended Data Figure 3-1E).

444       In the SVZ, we identified vascular cells, microglia, ependymal cells, slowly-proliferating neural  
445 stem cells (NSCs), transit amplifying progenitors (TAPs), OPCs, and neuroblasts (Figure 3D). Slowly-  
446 proliferating NSCs were identified by their expression of known and recently established SVZ NSC  
447 markers *Vcam1*, *Thbs4*, *Tspan18*, and *Slc1a3* (Borrett et al., 2020) and absence of *Mki67*, TAPs by their  
448 expression of *Mki67*, *Egfr*, *Ascl1* and *Dlx2*, neuroblasts by their expression of *Dlx2* and *Dcx* and absence  
449 of *Ascl1*, and ependymal cells were identified by their expression of *Foxj1* (Figure 3E). Iterative clustering  
450 of NSCs revealed 3 clusters (Extended Data Figure 3-1F): one cluster was enriched for *Crym*, a ventral  
451 SVZ (ganglionic eminence) marker (Borrett et al., 2020), and spatially enriched along the ventrolateral  
452 wall of the SVZ (NSC-vent); one cluster was enriched for the known NSC gene *Tnc* and spatially  
453 enriched along the dorsal wall of the ventricle (NSC-dors); and the third cluster was enriched for *Ednrb*, a  
454 recently characterized SVZ NSC gene (Yuzwa et al., 2017), and spatially enriched along the septal wall  
455 of the ventricle (NSC-sept) (Figure 3E and 3I). Of the two neuroblast clusters, one was classified as

456 olfactory bulb neuroblasts (NB-OB) for its expression of *Sp8*, a marker that is prominent in most  
457 neuroblasts destined for the olfactory bulb (Gaborieau et al., 2018) (Figure 3E). The other neuroblast  
458 cluster (NB) may represent those that will migrate either to the olfactory bulb or to the caudoputamen  
459 (Bordiuk et al., 2014; De Marchis et al., 2004).

460

#### 461 **Region-specific patterns of signaling-related gene expression in the NX brain**

462 Recent studies have suggested that cellular phenotypes are at least partly informed by spatial  
463 location in the brain (Allen et al., 2023; Stogsdill et al., 2022; Zhang et al., 2021). Before investigating  
464 how HX alters region-specific cellular signaling profiles, we first compared transcriptional profiles of non-  
465 neuronal cells between distinct brain regions (SVZ, corpus callosum, superficial layers of the cortex, and  
466 deep layers of the cortex) in the P21 NX brain to identify baseline regional heterogeneity. This was done  
467 by differential gene expression analysis where a false discovery rate (FDR) < 0.05 and  $\log_2$  fold-change  
468 ( $\log_2(\text{FC})$ ) > 0.25 were used to identify statistically significant differences in each comparison (see  
469 *Methods*). We observed extensive differences in signaling-related gene expression levels across all  
470 regions and cell types.

471 Notably, vascular cells were remarkably different between the upper and deep cortical layers with  
472 respect to expression of genes involved in WNT, Insulin-like growth factor (IGF), BMP, and fibroblast  
473 growth factor (FGF) signaling. Upper cortex vascular cells were enriched for expression of *Fzd1/2/7*,  
474 *Wnt4/5a*, *Sfrp1*, *Igf2*, *Igfbp2*, *Bmp4/5/7*, *Fgf1*, *Fgfr1*, and *Fgfr2*, while deep cortex vascular cells were  
475 enriched for expression of *Igf1r* and *Apc* (Extended Data Figure 4F and Extended Data Table 5-1).  
476 Compared to the corpus callosum and SVZ, vascular cells of the upper cortex but not the deep cortex  
477 were enriched for WNT ligand (*Wnt5a*), BMP ligand (*Bmp4/5/7*), and IGF ligand (*Igf2*, *Igfbp2*) genes  
478 (Extended Data Figure 4B-F and Extended Data Table 5-1). These results suggest activation of the  
479 canonical WNT pathway within vascular cells in the upper cortex, and robust WNT inhibition mediated by  
480 the negative regulator *Apc* within vascular cells in the deep cortex of the NX brain.

481 OPCs in different regions exhibited unique patterns of signaling-related gene expression. For  
482 example, SVZ and corpus callosum OPCs expressed higher levels of *Bmp4* and *Notch1*, while cortical

483     OPCs expressed higher levels of *Cx3cl1* (Extended Data Table 5-1). Microglia also showed notable  
484     differences between regions in the NX brain. SVZ microglia exhibited higher expression of genes  
485     involved in WNT signaling, such as *Fzd1/2/5/8*, *Lrp4/6/8*, *Sfrp1*; genes involved in sonic hedgehog (SHH)  
486     signaling such as *Ptch1*, *Gli1/3*; and Ephrin signaling genes such as *Efna2*, *Efnb2/3*, *Epha4*, and *Ephb1*  
487     compared to the corpus callosum, deep cortex, and upper cortex (Extended Data Figure 4A-C and  
488     Extended Data Table 5-1). This may suggest that in the postnatal mouse brain, microglia in the SVZ are  
489     uniquely suited for sensing and regulating the SVZ niche to modulate neurogenesis (Ribeiro Xavier et al.,  
490     2015)

491

492     **HX-associated changes in cellular composition**

493         We next assessed differences in global cell type proportions between HX and NX by leveraging  
494         the multiple biological replicates for each condition (see *Methods*). In the corpus callosum, we found that  
495         the proportion of newly formed OLs was markedly reduced following HX (42% reduction,  $p = 0.016$ ),  
496         while the proportion of OPCs was significantly increased (72% increase,  $p = 0.025$ ; Figure 3F-G). These  
497         findings corroborate the idea that chronic sublethal neonatal HX induces WMI followed by a robust period  
498         of oligodendrogenesis (Fagel et al., 2006; Jablonska et al., 2022). However, we did not detect a  
499         significant change in the proportion of any OL-lineage Cell Subtypes in the cortex (Figure 2L). This could  
500         imply that OL lineage cells in the cortex are less severely affected by HX.

501         We also observed a significant increase in the proportion of reactive astrocytes in the corpus  
502         callosum in HX (32% increase,  $p = 0.037$ , Figure 3F). This is consistent with previous work showing that  
503         there is an increase in the number of C3-expressing reactive astrocytes in the corpus callosum following  
504         acute perinatal WMI (Back and Rosenberg, 2014; Renz et al., 2022). In the cortex, we did not observe a  
505         significant change in the proportion of reactive astrocytes, but the proportion of Astro-hom3 was  
506         significantly reduced (21% reduction,  $p = 0.044$ ).

507         In the cortex of HX mice, we identified a significant increase in the abundance of Endo-1 cells, the  
508         most abundant subpopulation of endothelial cells (45% increase,  $p = 0.015$ , Figure 2M), suggestive of  
509         vascular remodeling.

510        Lastly, we observed a significant increase in the proportion of a large population of excitatory  
511 neurons in layer II-III (14% increase,  $p = 0.019$ ), and a significant decrease in a small population of  
512 excitatory neurons in layers I-III (51% reduction,  $p = 0.049$ , Figure 2K), indicating a change in the cell  
513 type composition of upper layer excitatory neurons. We also observed an increase in the proportion of  
514 Int1, a population of cortical interneurons (12% increase,  $p = 0.038$ , Figure 2K). An increase in cortical  
515 neurons could suggest a disruption or delay in programmed neuron death and clearing in the middle-  
516 upper cortical layers (the last layers to form and mature), a process that largely takes place in the first  
517 week after birth, coinciding with the timing of HX exposure (Castillo-Ruiz et al., 2020; Pfisterer and  
518 Khodosevich, 2017). No significant change was observed in the proportion of SVZ cell types (Figure 3H).

519

## 520 **Proximity analysis reveals widespread HX-associated changes in local cellular architecture**

521        We next evaluated changes in local cellular neighborhood composition associated with neonatal  
522 HX. Unlike spot-based spatial transcriptomics methods, MERFISH enables us to accurately map both  
523 spatial locations and transcriptional identities of individual brain cells. We leveraged this information using  
524 a novel computational approach for quantifying condition-associated differences in local cell type  
525 proximities (see *Methods*), which addresses some limitations of existing methods (Dries et al., 2021;  
526 Palla et al., 2022). Briefly, we calculated the condition-related differences in the proportion of cells of one  
527 type in the vicinity of a second type, thus capturing asymmetrical differences in local proportions between  
528 cell types. For example, our approach can detect the depletion of astrocytes surrounding neurons when  
529 the reverse is not true. Second, we directly compare cell type proximities between conditions using a  
530 general linear mixed effects model, accounting for the statistical non-independence of measures from the  
531 same tissue sample when there are multiple biological replicates (see *Methods*). We applied this  
532 approach at the microscale, capturing local changes in proximity that matter for cellular interaction,  
533 however, we note that such differences may also reflect global cellular abundance differences between  
534 conditions (e.g., those shown in Figure 2K-M and 3F-H).

535        In the cortex, neonatal HX was associated with decreased proximity of homeostatic astrocytes to  
536 several cell types (Figure 4A), including OPC2 ( $\beta = -0.46$ ,  $FDR = 8.45 \times 10^{-5}$ ; Figure 4D), newly formed

537 OLs ( $\beta = -0.48$ ; FDR = 0.012), and immature OLs ( $\beta = -0.43$ , FDR =  $4.21 \times 10^{-3}$ ). This may indicate a  
538 disruption in the supportive interactions provided by astrocytes, such as the secretion of local factors  
539 (e.g. BDNF, CNTF) that promote OL maturation and myelination during healthy conditions and following  
540 injury.(Miyamoto et al., 2015) HX induced dramatic changes in the proximity of different populations of  
541 cortical excitatory neurons to other neurons and non-neuronal cells. For example, after HX, a population  
542 of upper layer excitatory neurons, Exc-1,2,3, had decreased proximity to interneurons (Int-3,  $\beta = -0.15$ ,  
543 FDR =  $6.65 \times 10^{-6}$ ), reactive ( $\beta = -0.06$ , FDR = 0.046) and homeostatic astrocytes ( $\beta = -0.13$ , FDR =  $1.07$   
544  $\times 10^{-3}$ ), and OPC2 ( $\beta = -0.05$ , FDR =  $1.93 \times 10^{-3}$ ; Figure 4A).

545 In the corpus callosum following HX (Figure 4B), we observed significantly reduced proximity of  
546 newly formed OLs in the neighborhoods of several cell types, including OPCs ( $\beta = -0.37$ , FDR =  $6.82 \times$   
547  $10^{-3}$ ; Figure 4E) and endothelial cells ( $\beta = -0.65$ , FDR = 0.011). Additionally, we observed reduced  
548 proximity of surrounding reactive astrocytes ( $\beta = -0.57$ , FDR =  $2.62 \times 10^{-13}$ ) and microglia ( $\beta = -0.45$ ,  
549 FDR = 0.016) near homeostatic astrocytes. Such local interactions are likely essential for OL maturation  
550 and efficient myelination.(Miyamoto et al., 2015) The altered spatial organization of these cells potentially  
551 contributes to the impaired myelination characteristic of diffuse WMI.

552 In the post-HX SVZ, NSCs showed significantly increased proximity to differentiating neuroblasts  
553 ( $\beta = 0.28$ , FDR =  $7.12 \times 10^{-3}$ ), with a trending increase in proximity to OPCs, microglia, and vasculature  
554 (Figure 4C and 4F). These changes align with the roles of activated microglia in promoting  
555 oligodendrogenesis and neurogenesis. The closer association with vascular components may indicate an  
556 adaptive response to HX, possibly involving angiogenesis or enhanced metabolic support. Neuroblasts  
557 saw increased proximity to NSCs ( $\beta = 0.36$ , FDR =  $1.61 \times 10^{-4}$ ), microglia ( $\beta = 0.81$ , FDR =  $6.90 \times 10^{-4}$ ),  
558 and OPCs ( $\beta = 0.54$ , FDR = 0.026). These changes could reflect neural repair through enhanced  
559 interactions of neuroblasts with NSCs for proliferation, with microglia for inflammation resolution, and with  
560 OPCs for myelination, altogether accelerating recovery processes. Overall, these observations suggest a  
561 reorganization or adaptation of the SVZ niche in response to neonatal HX, highlighting the region's  
562 plasticity under developmental stress.

563 In total, our proximity analysis emphasizes a crucial spatial component to the effects of neonatal  
564 HX beyond gene expression. Changes were extensive and heterogeneous across cell types and regions,  
565 ranging from disrupted myelination in the corpus callosum to adaptive cellular reorganization in the SVZ.

566

567 **Neonatal HX alters regional patterns of signaling-related gene expression**

568 We next analyzed cell type- and region-specific transcriptional changes between HX and NX  
569 conditions using differential gene expression analysis (see *Methods*). This comparative analysis aimed to  
570 identify molecular processes perturbed during HX exposure in the context of early brain development. In  
571 all cell type populations assayed in the SVZ, corpus callosum, and cortex, we found that the vast majority  
572 of significant DEGs were upregulated following HX (Figure 5A-C and Extended Data Table 5-1). While  
573 many genes exhibited widespread cell-type specific changes, many cells also shared DGEs within the  
574 forebrain regions (Figure 5D-F).

575 We expanded our findings from the differential gene expression analysis by focusing on  
576 understanding cell-cell signaling after neonatal HX. Neighboring cells communicate via secreted  
577 molecules (ligands) that can act on receptors in nearby cells. These ligand-receptor (LR) networks are  
578 fundamental signaling nodes that regulate circuit function and injury response. To understand how local  
579 cell-cell communication networks change in the context of neonatal brain injury, we performed a spatially-  
580 informed LR analysis using CellChat v2 (see *Methods*). We grouped predicted LR pairs based on  
581 whether signaling occurred within the same cell type (e.g., OPC to OPC; intra-lineage) or between  
582 different cell types (e.g., microglia to OPC; inter-lineage). After exposure to neonatal HX, we identified  
583 region-specific cellular programs governing regenerative oligodendrogenesis and neurogenesis.

584 In the SVZ, we found that HX induced an upregulation of *Egfr*, *Lmnb1*, and the proliferation  
585 marker *Mki67* within most SVZ cell types, including the neural progenitors NSCs, OPCs, and TAPs,  
586 suggestive of NSC activation (Figure 5G and Extended Data Table 5-1) (Koufi et al., 2023). In response  
587 to HX, neural progenitors also upregulated genes involved in OL differentiation such as *Qk* and *Ptprz1*,  
588 and neurogenic genes including *Dcx*, *Gria2*, and *Stmn1*, suggestive of increased neurogenic and  
589 gliogenic priming (Extended Data Table 5-1). We observed dramatic changes in BMP, WNT, and Notch

590 signaling in the SVZ, consistent with their role in regulating stem and progenitor cell maintenance,  
591 proliferation, differentiation, and fate decisions (Figures 5G and 6A-B, Extended Data Tables 5-1 and 6-  
592 1). Specifically, there was a significant increase in *Bmp7* expression in OPCs (Figures 5G) and an  
593 increase in BMP7 and BMP4 signaling from OPCs to OPCs, NSCs, TAPs, microglia, and vascular cells  
594 (Figure 6A-B). In addition, the WNT ligand *Wnt7a*, the receptor *Lrp6*, the effector *Ctnnb1*, and target gene  
595 *Ccnd1* all demonstrated increased expression in most SVZ cells, including NSCs, after HX (Figure 5G  
596 and Extended Data Table 5-1) which translated to a widespread increase in WNT signaling (Figure 6B  
597 and Extended Data Table 6-1). In the HX SVZ, *Notch1* and *Notch2* receptors were upregulated in most  
598 cell types, while the ligand genes *Dll1* or *Dll4* were upregulated in vascular cells, TAPs, and immune cells  
599 (Figure 5G and Extended Data Table 5-1) which translated to an increase in Notch signaling between  
600 these cell types (Extended Data Table 6-1). Interestingly, we found increased transforming growth factor  
601  $\beta$ -2 and 3 (TGF $\beta$ -2/3) signaling between the vasculature and microglia in the SVZ after HX (Figure 6B  
602 and Extended Data Table 6-1). TGF $\beta$  is a critical component of the microglial pro-neurogenic response  
603 (Battista et al., 2006; De Lucia et al., 2016; Makwana et al., 2007).

604 In the corpus callosum, we identified several signaling nodes that promote white matter recovery  
605 after neonatal HX, including upregulation of MAG to MAG and TGF- $\alpha$  to epidermal growth factor receptor  
606 (EGFR) signaling between Cell Subtypes of OL-lineage cells (Extended Data Table 6-1). We observed  
607 increased WNT signaling from astrocytes and OLs, increased IGF2/IGF1R signaling from vascular cells  
608 to astrocytes and OLs, and increased CNTN1-Notch signaling between OLs, astrocytes, and vascular  
609 cells (Extended Data Table 6-1). Changes in Notch signaling was a commonly identified theme in the  
610 corpus callosum: *Notch1* and *Notch2* were upregulated in astrocytes and OL-lineage cells and the ligand  
611 *Dll1* was upregulated in OL lineage cells (Figure 5G and Extended Data Table 5-1). Moreover, we found  
612 increased GAS6 signaling through its receptors (TAM receptors, encoded by *Tyro3*, *Axl*, *Mer*) between  
613 microglia and astrocytes, vascular cells, and OL-lineage cells (Extended Data Table 6-1). Following  
614 demyelinating injury, GAS6-TAM signaling promotes remyelination and glial cell development, including  
615 suppression of a deleterious (anti-regenerative) microglia response (Binder et al., 2011, 2008). Notably,  
616 we found evidence of neurovascular adaptation after HX, including upregulation of genes involved in cell

migration and vascular permeability (*Fstl1* and *Itgb1*) (Fujioka et al., 2017) in vascular cells in the corpus callosum, which may promote immune cell infiltration and/or guide the migration of new neurons and glial cells (Figure 5G and Extended Data Table 5-1). We observed an increase in inflammatory and migratory signaling from corpus callosum fibroblasts, including upregulation of Interleukin 34 (IL-34) to colony stimulating factor 1 receptor (CSF1R) and ephrin A1 (EFNA1) to Ephrin type-A receptor 7 (EphA7) ligand-receptor pairs, both of which may support glial scar formation (Figure 6C-D and Extended Data Table 6-1) (Bellver-Landete et al., 2019; Gerber et al., 2018; Zhou et al., 2023).

In the cortex, LR analysis was notable for a broad, multicellular increase in several signaling pathways previously implicated in brain circuit wiring and the response to injury. Endothelin-1 (EDN1)/Endothelin Receptor Type B (EDNRB) signaling was increased between endothelial cells, fibroblasts, astrocytes, OLs, and microglia, and astrocytes (Extended Data Table 6-1). Endothelin regulates myelination capacity in OLs, as endothelin is upregulated after demyelination and directly inhibits OPC differentiation via astrocytes (Hammond et al., 2015). Additionally, we found that fractalkine (encoded by *Cx3c1*)-CX3CR1 signaling, a regulator of gliogenesis, was increased between several non-neuronal cell populations, including OLs, OPCs, fibroblasts, and astrocytes, to reactive microglia (Extended Data Table 6-1). A regulator of fractalkine expression and remyelination, TGF $\beta$ 1 signaling, was also enhanced following HX between endothelial cells, fibroblasts, and microglia. Canonical WNT signaling is important for TGF $\beta$ -mediated fibrosis (Akhmetshina et al., 2012), and we identified increased WNT signaling in deep layer cortical excitatory neurons (WNT4 with FZD4), as well as between vascular cells, deep layer excitatory neurons and astrocytes (WNT7A with FZD4). We observed a HX-induced increase in cytokine signaling (including IGF2-IGF1R, IGF2-IG2R, fractalkine-CX3CR1, TGFB1-TGFBR1, TGFB3-TGFBR1 ligand-receptor pairs) largely sourced by fibroblasts and other vascular cells, and targeting vascular cells and microglia (Figure 6E-F and Extended Data Table 6-1). Thus, vascular cells may represent an important source of inflammatory signaling leading to increased microglial activation after neonatal HX. Additionally, several homophilic (CDH5-CDH5, ESAM-ESAM, PECAM1-PECAM1) and heterophilic (FGF1/2-FGFR1/2R, BMP4/7-BMPR1A, VEGFA-FLT1) endothelial interactions involved in regulating vascular development and blood brain barrier permeability integrity were dysregulated in all

644 three regions of the brain (Figure 6A-F and Extended Data Table 6-1) (Argaw et al., 2012; Klimaschewski  
645 and Claus, 2021; Knox et al., 2022; Li et al., 2018). In addition, in the cortex, we found that HX induced  
646 an upregulation of *Sst* expression in interneurons and an upregulation of *Sstr2* expression in both  
647 interneurons and excitatory neurons (deep and superficial layers). Furthermore, LR analysis revealed  
648 increased SST-SSTR2 signaling from interneurons to other neurons following HX (Extended Data Table  
649 6-1), all of which could impact excitatory-inhibitory neuron balance.

650 Ephrin communication was commonly altered across the cortex, SVZ, and corpus callosum.  
651 Cortical excitatory neurons and interneurons in the HX brain showed an upregulation of receptors *Epha4*,  
652 *Epha6*, and *Epha7* and ligands *Efnb2* and *Efnb3* (Figure 5G and Extended Data Table 5-1). EFNA1  
653 signaling by cortical fibroblasts to OL-lineage cells and astrocytes was significantly upregulated post-HX  
654 (Extended Data Table 6-1). In the SVZ, there was widespread upregulation of ephrin genes; for example,  
655 *Epha4* and *Efnb2* were upregulated in all cell types following HX (Extended Data Table 5-1).  
656 Furthermore, all SVZ cells participated in ephrin signaling as sources and targets following HX. The OL-  
657 lineage in the corpus callosum also upregulated ephrin genes and showed increased ephrin signaling  
658 targeting all major Cell Types (Extended Data Table 6-1). EFNA1 interacts with EphA4 to inhibit OL  
659 process extension via ephexin1-RhoA-Rock-myosin 2 (Harboe et al., 2018). These HX-induced ephrin  
660 interactions may play an important role in guiding the migration and process extension of injury-  
661 responsive glial cells or new neurons.

662 Another important source of cell guidance signaling is the extracellular matrix. In particular,  
663 chondroitin sulfate proteoglycans (CSPGs) are extracellular matrix components known regulate cell  
664 migration, synapse formation and maturation, and inflammation in the developing brain (Dyck and Karimi-  
665 Abdolrezaee, 2015; Siebert et al., 2014). However, the upregulation of CSPGs following brain injury has  
666 been shown to block migration of neuroblasts and inhibit regeneration (Luo et al., 2022; Siebert et al.,  
667 2014). We found that OL-lineage cells and astrocytes in the cortex and corpus callosum, cortical  
668 excitatory neurons, cortical interneurons, and all SVZ cell types showed an upregulation of some CSPG  
669 genes such as *Vcan*, *Ncan*, *Bcan*, and *Tnr* (Figure 5G and Extended Data Table 5-1). To examine  
670 whether the increase in CSPG gene expression correlated with an increase in protein levels, we

671 performed immunofluorescence staining for NCAN in the P21 brain. We found that the average positive  
672 fluorescence intensity of NCAN staining over area was significantly higher across the HX cortex  
673 compared to NX (Figure 5H-I). Furthermore, the significant increase in NCAN fluorescence intensity was  
674 true across the superficial, middle, and deep cortical layers (Figure 5J). These results indicate an  
675 increase in neural guidance cues in the extracellular matrix that could affect the appropriate migration  
676 and integration of new cells in the HX brain.

677

678 **Neonatal HX is associated with changes in region-specific cell states**

679 Finally, we asked whether microglia, astrocyte, and OL-lineage cell state is dictated by spatial  
680 context by comparing gene expression patterns between the SVZ, corpus callosum, and cortex.  
681 Differential gene expression analysis revealed notable differences in cell state associated gene  
682 expression across different anatomical regions in the NX brain. OL-lineage cells in different regions  
683 showed different levels of gene expression for OL differentiation and maturation related genes. OPCs in  
684 the SVZ (Figure 7A-B) and corpus callosum (Figure 7D-E) had higher levels of many oligodendrogenesis  
685 genes including *Olig2*, *Gpr17*, *Itpr2*, and *Fyn* compared to both superficial and deep layer cortical OPCs.  
686 Following HX, these genes were upregulated in SVZ OPCs while only some (i.e., *Gpr17*) were  
687 upregulated in corpus callosum OPCs (Figure 5K and Extended Data Table 5-1). To characterize the  
688 overall differentiation and maturation state of OL-lineage cells, we used several established genes  
689 (Floriddia et al., 2020; Marques et al., 2016; Takeuchi et al., 2020) to calculate scores for OL  
690 differentiation priming (“OL genesis”), and OL maturation. We found that OPCs in the SVZ and corpus  
691 callosum had a higher OL genesis score than cortical OPCs (Figure 7F). Similarly, newly formed OLs in  
692 the corpus callosum had a higher OL genesis score than in the cortex (Figure 7G). Following HX, there  
693 was a trending but statistically not significant increase in the OL genesis scores among OPCs in the SVZ  
694 and corpus callosum, as well as in newly formed OLs in the corpus callosum (Figure 7F-G). The OL  
695 maturation score was higher in the corpus callosum than the superficial and deep cortical layers for OL  
696 lineage cells altogether (Figure 7H) and specifically in immature (Figure 7I) and mature OLs (Figure 7J).  
697 This score also showed a trending but not significant increase in upper cortical OLs following HX (Figure

698 7H-J). Overall, these results suggest regional differences in the maturation dynamics between corpus  
699 callosum and cortical OLs. However, the weak effect of HX on oligodendrogenic potential and maturation  
700 suggests that myelination impairments associated with DWMI may have less to do with OL dysfunction  
701 and more with the influence of their cellular environment.

702 In the both NX and HX brains, all astrocytes in the corpus callosum had significantly higher  
703 expression of *Gfap* than astrocytes in the cortex, with Astro-react also exhibiting higher levels of reactive  
704 markers *Ggta1* and *Serpina3n* in the corpus callosum (Figure 7K-M). Following HX, all astrocytes in the  
705 cortex, but not corpus callosum upregulated *Gfap* (Figure 5L). We then calculated astrocyte reactivity  
706 scores from established reactive astrocyte genes (Liddelow et al., 2017; Matusova et al., 2023; Zamanian  
707 et al., 2012) and found that astrocytes in the NX corpus callosum exhibited a significantly higher state of  
708 reactivity compared to those in the cortex. This heightened reactivity was not altered by HX treatment.  
709 Within the cortex, astrocytes in the superficial layers showed a slightly elevated reactivity score over  
710 those in the deep layers (Figure 7N-P). Astro-hom, on the other hand, had higher *Sparc* expression in the  
711 cortex than in the corpus callosum, with deep layer astrocytes expressing more *Sparc* than superficial  
712 ones, a trend maintained post-HX (Figure 7K-M). Since *Sparc* encodes a secreted protein that negatively  
713 regulates synaptogenesis (Kucukdereli et al., 2011), this emphasizes the specialized function of cortical  
714 astrocytes in synapse formation and neural homeostasis.

715 Differential gene expression analysis revealed that microglia in both the NX and HX SVZ and  
716 corpus callosum exhibited a significantly lower expression of both *Tmem119* and *Trem2* compared to  
717 microglia in the superficial cortex and deep cortex (Figure 7Q-T). SVZ microglia showed the same trend  
718 of lower expression of both *Tmem119* and *Trem2* when compared to the corpus callosum (Figure 7Q).  
719 This trend is unexpected because it is widely acknowledged that *Tmem119* has higher expression in  
720 homeostatic microglia while *Trem2* is higher in reactive microglia (Boche and Gordon, 2022). However,  
721 recent work showing that *Tmem119* gene expression levels and spatial distribution in the brain are  
722 incongruent with protein levels following traumatic brain injury challenge the use of transcriptomic  
723 *Tmem119* as a marker for homeostatic microglia (Mercurio et al., 2022). Therefore, to better characterize  
724 the reactivity state of microglia across different regions, we calculated reactivity scores using multiple

725 genes shown previously to be specific to or enriched in reactive microglia at the transcriptomic level (see  
726 *Methods*) (Paolicelli et al., 2022; Wahane et al., 2021). We observed a lower reactivity score in corpus  
727 callosum microglia, specifically Micro-react, compared to superficial cortex microglia (Figure 7U-W). HX  
728 exposure reduced the reactivity score of corpus callosum microglia significantly, pushing microglia  
729 reactivity in the corpus callosum to be significantly lower than both upper and deep cortex microglia. In  
730 addition, only microglia in the SVZ exhibited a significant change in state related genes following HX  
731 exposure, including an upregulation of homeostatic microglia-associated *Tmem119* and reactive marker  
732 *Lgals3* (Figure 5M).

733

#### 734 **DISCUSSION**

735 Advances in the care of very low birthweight preterm infants have markedly improved survival.  
736 However, despite these advances, survivors of preterm birth continue to have high propensity for  
737 developmental delay and disability. Chronic HX exposure resulting from an underdeveloped respiratory  
738 system leads to cerebral WMI, a major cause of neurodevelopmental disorders in preterm infants,  
739 including cerebral palsy. However, the underlying cellular mechanisms that govern the brain's response  
740 to HX and recovery from WMI remain poorly understood. Here, we employed high-resolution spatial  
741 transcriptomics as a discovery platform to map cell type- and region-specific transcriptional signatures  
742 during recovery from neonatal HX. At baseline (NX condition), we identified several brain region-specific  
743 cell states, including spatially restricted populations of glia and vascular cells that play a key role in  
744 modulating the signaling environment and may regulate developmental processes such as neurogenesis  
745 and gliogenesis, cell migration, synapse formation, and inflammation. We found that during the reparative  
746 phase following neonatal HX exposure, there were changes in regional cell type composition, neurogenic  
747 and gliogenic transcriptional programs, and local cellular architecture, which are likely the result of  
748 extensive changes in regional signaling networks. Thus, our results support a model of niche cell states  
749 and signaling networks that are region- and stimulus-dependent.

750 First, we demonstrate that at baseline, OPCs in the neurogenic niche and white matter have a  
751 transcriptomic profile that is more proliferative and more primed for differentiation than in the cortex. In

752 response to HX, OPCs within the neurogenic niche further upregulate proliferation-associated genes and  
753 genes encoding ligands that modulate OL formation and myelination. We found that OPCs upregulated  
754 BMP ligand genes such as *Bmp4* which, in the context of demyelinating injury, has been shown to be  
755 produced by injury-activated OPCs and inhibit the differentiation of OPCs to OLs (Ulanska-Poutanen et  
756 al., 2018). We also observed upregulation of *Cx3c1*, which encodes fractalkine, from several glial cell  
757 types including OL-lineage cells to reactive microglia. Fractalkine has an established pro-regenerative  
758 role in remyelination, particularly via OPCs and microglia (de Almeida et al., 2023; Ridderstad Wollberg  
759 et al., 2014). Interestingly, previous work has shown that environmental enrichment both enhances  
760 recovery from neonatal diffuse WMI and increases fractalkine levels. Importantly, TGF $\beta$  is known to  
761 regulate fractalkine expression, and we identified increased TGF $\beta$ 1 signaling among glial and vascular  
762 cell types, which likely acts as an upstream regulator of tissue remodeling after HX. While OPCs in the  
763 white matter became more abundant, newly formed OLs became less abundant, suggesting  
764 differentiation arrest, specifically in the transition from OPCs to newly formed OLs.

765 Further, we found that developing and mature OLs from the cortex and corpus callosum exhibited  
766 different cell states and responded differently to HX. At baseline, white matter OLs overall were more  
767 mature than cortical OLs (exhibiting higher OL maturation scores), and these levels did not change  
768 significantly following HX. Analysis of inter-lineage cell-cell communication revealed alterations in GAS6-  
769 TAM, EDN1-EDNRB, and fractalkine-CX3CR1 networks in the cortex that may play a direct role in  
770 promoting OPC differentiation and altering OL myelination capacity in the context of neonatal HX. In  
771 addition, we identify significant changes in the spatial organization of homeostatic astrocytes. Previous  
772 studies have shown that astrocyte-OL interactions are crucial in facilitating OPC differentiation into  
773 mature myelin-forming OL via a process orchestrated through the Nrf2 pathway (Molina-Gonzalez et al.,  
774 2023).

775 Importantly, we identified widespread changes in extracellular matrix components, including  
776 CSPGs, after HX. CSPGs contribute to the formation of perineuronal nets (PNNs) during postnatal  
777 development and play a role in the closure of the critical window of plasticity (Fawcett et al., 2019;  
778 Hensch, 2005). We observed that in most cell types in the cortex and corpus callosum, neonatal HX was

779 associated with increased expression of genes important for cell migration and projection guidance  
780 including ephrins and CSPGs. These signals may play an important role in coordinating the migration of  
781 injury-responsive cells such as immune cells and astrocytes, as well as migrating upper-layer excitatory  
782 neurons. Interestingly, we did find that the abundance and local organization of upper-layer excitatory  
783 neurons was disrupted by HX. However, it is unclear whether the upregulation of guidance cues such as  
784 CSPGs would help or hinder appropriate cell migration. Depletion of CSPGs in the adult brain by  
785 enzymatic degradation or genetic inhibition has been shown to promote plasticity (Lensjø et al., 2017;  
786 Reichelt et al., 2019; Willis et al., 2022). CSPGs can also act as potent inhibitors of myelination, axon  
787 guidance and regeneration, and other injury repair processes. Further work is needed to determine the  
788 clinical relevance of CSPGs in myelin recovery after neonatal WMI.

789 While most studies on neonatal WMI have focused on OL-lineage cells, our study underscores  
790 the complex and region-specific multicellular signaling that may support gliogenesis but also ultimately  
791 lead to impaired functional connectivity. Specifically, we found that endothelial cells, fibroblasts, and  
792 pericytes were major sources of signaling molecules, and that their phenotype changed dramatically  
793 following HX in a region-specific manner. Our findings imply that crosstalk signaling from vasculature-  
794 associated cells may be crucial for activating angiogenesis and forming adhesive interactions that  
795 maintain blood-brain barrier integrity and modulate permeability after HX exposure. Additionally, vascular  
796 cells may represent an important source of inflammatory ligands that promote microglial reactivity after  
797 neonatal HX. We also found that corpus callosum microglia may be less reactive than cortical microglia  
798 under NX and HX conditions, which contrasts with previous research in adult rodents and humans, that  
799 suggest that white matter microglia are more reactive to injury than gray matter microglia (Batchelor et  
800 al., 2008; van der Poel et al., 2019). As these earlier studies primarily involved adult and aged rodents,  
801 our findings reflect a different, developmental microglia state. Specifically, the heightened cortical  
802 microglial reactivity observed in our study may relate to their role in synapse refinement during brain  
803 development following HX exposure, although this requires further investigation.

804 An important strength of the present study is the use of MERFISH, which enables single cell-  
805 resolution spatial transcriptomics. Previous work on neonatal HX has focused largely on the corpus

806 callosum, but paracrine and non-cell autonomous mechanisms of recovery after neonatal brain injury are  
807 poorly understood. The present analysis spans most major anatomical brain regions and highlights  
808 regional variability in the vulnerability and response to injury. Nonetheless, there are several limitations to  
809 the present study. Firstly, the mouse model of chronic neonatal HX does not introduce inflammatory  
810 stimuli, which are often an important component of the encephalopathy of prematurity. Additionally, the  
811 sub-lethal chronic HX model employed does not fully replicate the intermittent hypoxic events  
812 experienced by many premature infants. Notably, the pattern of WMI in preterm infants has become less  
813 severe in the last two decades, and thus, cerebral dysmaturation may also be contributing to  
814 neurodevelopmental delays and impairments (Schneider and Miller, 2019). From a methodologic  
815 perspective, MERFISH requires segmentation of cell boundaries to assign transcripts to individual cells.  
816 We employed a machine learning algorithm and extensive manual curation, including stringent doublet  
817 elimination, to mitigate limitations of cell boundary identification. However, precise cell boundary  
818 identification remains an ongoing challenge for *in situ* spatial transcriptomics, and mis-segmentation may  
819 introduce false cell type assignment of gene expression. While our analysis was limited to a single time  
820 point, the objective of the study was to identify pathways critical for recovery and repair after neonatal  
821 HX. Finally, commercial MERFISH methods are presently limited to a finite number of genes, so  
822 additional changes at the level of the whole transcriptome were not captured.

823 Despite these limitations, this work presents an extensive spatially informed landscape of gene  
824 expression changes in an established mouse model of neonatal brain injury. We developed and  
825 employed a new approach to map physical cellular interactions using imaging-based spatial  
826 transcriptomics, which can be extended to other developmental and disease contexts. Our whole-brain  
827 analysis is a foundational resource for developmental WMI and for regenerative cellular communication.

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1122 **LEGENDS**

1123 **Figure 1: Multiplexed error-robust fluorescent *in situ* hybridization (MERFISH) sequencing**  
1124 **identifies all major cell types and anatomical regions of the postnatal murine brain.** (A) Schematic  
1125 representation of the HX paradigm, tissue harvesting, tissue processing, quality control, and downstream  
1126 data analysis approach applied to the MERFISH dataset. Tissue was harvested and processed for  
1127 postnatal day 21 (P21) HX and NX mice ( $n = 3$  male mice per condition). The MERFISH probe set used  
1128 in this study targeted a curated panel of genes listed in Extended Data Table 1-1. MERFISH-derived  
1129 spatial map displaying the (B) major anatomical regions outlined during sample processing steps, and  
1130 (C) a select set of genes used to identify and outline the anatomical regions utilized in downstream data  
1131 analysis. Areas of the brain are colored according to their anatomical region or major identifying gene.

1132 **Figure 2: Cell type classification and spatial distribution in the P21 mouse cortex.** Profiling of non-  
1133 neuronal (A-B) and neuronal (C-D) cell types in the cortex for a total of 668,947 cells. Transcriptomic  
1134 profiling for corpus callosum and subventricular zone (SVZ) cells is shown in Figure 3, and profiling of  
1135 septum, caudate putamen (CP), anterior commissure (ACo), and septal white matter tracts (SWM) cells  
1136 is shown in Extended Data Figure 2-1. Quality control metrics for each replicate are shown in Extended  
1137 Data Figure 2-2. (A) Violin plots showing gene expression patterns of non-neuronal Cell Subtypes.  
1138 UMAP visualization of (B) non-neuronal cells colored by Cell Subtype as in (A), and (C) neuronal cells  
1139 colored by Cell Subtype as in (D). UMAP plots are generated from combined replicates across NX and  
1140 HX conditions. Each dot represents a single cell, and cells are grouped with a solid line into major Cell  
1141 Types. Each major Cell Type group was subsetted and clustered independently to allow identification of  
1142 Cell Subtypes. UMAP visualizations of each Cell Type dataset, colored by Cell Subtype, are shown in  
1143 Extended Data Figure 2-3. (D) Violin plot showing gene expression patterns of neuronal Cell Subtypes.  
1144 (A, D) Violin plots show several key canonical marker genes used for cluster identification. The width of  
1145 the violin corresponds to the proportion of nuclei expressing the indicated gene, and the color of the violin  
1146 corresponds to the Cell Subtype. Abbreviations for cell types are as follows: Exc: excitatory neuron, Int:  
1147 interneuron, Exc-1,2,3: cortical layers I-III excitatory neurons, Exc-2,3: cortical layers II-III excitatory  
1148 neurons, Exc-2,3,4: cortical layers II-IV excitatory neurons, Exc-2,3,4,P: cortical layers II-IV excitatory

1149 neurons and piriform neurons, Exc-5: cortical layer V excitatory neurons, Exc-5,6: cortical layers V-VI  
1150 excitatory neurons, Exc-6b,P2,3: cortical layer VIb excitatory neurons and piriform neurons, Exc-6b,SP:  
1151 cortical layer VI excitatory neurons and subplate neurons, Piri: piriform neurons, SP: subplate neurons,  
1152 Vasc: vascular cell, OL: oligodendrocyte-lineage cell, Astro: astrocyte, Micro: microglia, OL-immat:  
1153 immature oligodendrocyte, OL-mat: mature oligodendrocyte, OL-new: newly-formed oligodendrocyte,  
1154 OPC: oligodendrocyte precursor cell, Astro-hom: homeostatic astrocyte, Astro-react: reactive astrocyte,  
1155 Micro-hom: homeostatic microglia, Micro-react: reactive microglia, Endo: endothelial cell, Fibro:  
1156 fibroblast, Peri: pericyte. Spatial plots displaying the distribution of (**E**) OL-lineage cells, (**F**) astrocytes,  
1157 (**G**) microglia, (**H**) vascular cells, (**I**) interneurons, and (**J**) excitatory neurons. Spatial plots are colored by  
1158 Cell Subtype, dotted lines demarcate the cortex, and labels include deep part of cortex, “d”, superficial  
1159 part of cortex, “s”, and meninges, “m”. Bar plots displaying the proportion of (**K**) neuronal, (**L**) OL-lineage,  
1160 and (**M**) non-neuronal Cell Subtypes in the cortex of HX versus NX mice. The x-axis displays all major  
1161 Cell Types and Cell Subtypes profiled through MERFISH. Data obtained from  $n = 3$  male biological  
1162 replicates per condition. Bars represent the average values for each condition, and dots represent the  
1163 average values for each mouse per condition. Significance is determined using the two-tailed Student’s t-  
1164 test. \*p-value < 0.05; \*\*p-value < 0.01. Comparisons not labeled with asterisks are not significant. Error  
1165 bars represent the average  $\pm 1$  standard deviation. Each bar is labeled by Cell Subtype as previously  
1166 defined.

1167 **Figure 3: Cell type classification and spatial distribution in the P21 mouse SVZ and corpus**  
1168 **callosum reveals arrested OL differentiation in the corpus callosum following neonatal hypoxia.**  
1169 (**A**) UMAP visualization of all corpus callosum cells, totaling 8,708 cells. UMAP plots are generated from  
1170 combined replicates across NX and HX conditions. Quality control metrics for each replicate are shown in  
1171 Extended Data Figure 2-2. Each dot represents a single cell, and cells are grouped with a solid line into  
1172 major Cell Types as follows: Astro: astrocyte, Micro: microglia, OL: oligodendrocyte, Vasc: vascular.  
1173 Each major Cell Type group was subsetted and clustered independently to allow identification of Cell  
1174 Subtypes. UMAP visualizations of each Cell Type dataset, colored by Cell SubType, are shown in  
1175 Extended Data Figure 3-1. (**B**) Violin plot showing gene expression patterns of Cell Subtypes identified in

1176 the corpus callosum with several key canonical marker genes used for cluster identification. The width of  
1177 the violin corresponds to the proportion of cells expressing the indicated gene, and the color of the violin  
1178 corresponds to the cell subtype. Each column is labeled by Cell Subtype as previously defined. **(C')**  
1179 Spatial plot displaying the distribution of Cell Types in the CC. **(C")** Zoomed view of the panel delineated  
1180 in C'. **(D)** UMAP visualization of all SVZ cells, totaling 10,754 cells. UMAP plot is generated from  
1181 combined replicates across NX and HX conditions. Quality control metrics for each replicate are shown in  
1182 Extended Data Figure 2-2. Each cluster is colored by cell type and are labeled by cell type, with all NSCs  
1183 labeled together and all neuroblasts labeled together, as follows: Epen: ependymal cell, TAP: transit  
1184 amplifying progenitor, NB: neuroblast, NB-OB: olfactory bulb neuroblast, NSC: neural stem cell, NSC  
1185 (dors): dorsal neural stem cell, NSC (sept): septal neural stem cell, NSC (vent): ventral neural stem cell.  
1186 **(E)** Violin plot showing gene expression patterns of Cell Subtypes identified in the SVZ with several key  
1187 canonical marker genes used for cluster identification. The width of the violin corresponds to the  
1188 proportion of cells expressing the indicated gene, and the color of the violin corresponds to the cell  
1189 subtype. Each column is labeled by Cell Subtype as previously defined. Bar plots displaying the  
1190 proportion of **(F)** Cell Subtypes **(G)** OL-lineage Cell Subtypes of HX versus NX mice. **(H)** Bar plot  
1191 displaying the proportion of Cell Subtypes in the SVZ of HX versus NX mice. The x-axis displays all major  
1192 Cell Subtypes profiled through MERFISH. Data obtained from  $n = 3$  male biological replicates per  
1193 condition. Bars represent the average values for each condition, and dots represent the average values  
1194 for each mouse per condition. Error bars represent the average  $\pm 1$  standard deviation. Each bar is  
1195 labeled by cell subtype as previously defined. **(I)** Spatial plot displaying the distribution of Cell Subtypes  
1196 in the SVZ. For (C) and (I), the label "d" denotes dorsal, "v" denotes ventral, and "s" denotes septal.

1197 **Figure 4: Neonatal hypoxia alters local spatial proximity between select Cell Type pairs across**  
1198 **brain regions.** Differential proximities between cell type pairs (heatmaps) in the **(A)** cortex, **(B)** corpus  
1199 callosum, and **(C)** SVZ. For cortex and corpus callosum, Cell Subtype classification was used. Positive  
1200 scores (purple) indicate an increased proportion of the surrounding cell type (columns, x-axis) in  
1201 proximity of the center cell type (rows, y-axis) in HX relative to NX, whereas negative scores (green)  
1202 indicate a decrease. Grey indicates not enough non-zero data was present for the respective cell type

pair. Significant (FDR < 0.05) relationships are denoted with an asterisk. Exemplar spatial plots (right panels) indicate the distribution of select center and surround cell types between NX (top) and HX (bottom) in (D) cortex, (E) corpus callosum, and (F) SVZ. The outer circles in the spatial plots correspond to the radius used to calculate the differential proximities in (A-C) and have been normalized to reflect the median cellular distances per sample. Violin plots (left panels) show the counts of the surrounding cell type in proximity to every central cell across the sample corresponding to the spatial plot (not just the sample area shown). P-values for t-tests are shown.

**Figure 5: Differential gene expression analysis finds transcriptionally distinct cellular subpopulations in the HX brain. (A-C)** Strip plots displaying DEGs between P21 HX and NX mice. Each dot represents a DEG: colored dots represent significant genes (FDR < 0.05) per cell type, gray dots represent non-significant genes (FDR > 0.05). The x-axis displays all major cell types across the (A) cortex, (B) corpus callosum, and (C) SVZ regions profiled through MERFISH analysis. Data obtained from  $n = 3$  biological replicates per condition. **(D-F)** UpSet plots displaying the number of unique and shared DEGs across cell types in the (D) cortex, (E) corpus callosum, and (F) SVZ. Unique genes are colored based on cell type, and genes shared between two or three cell types are indicated by black dots connected by lines according to shared origins. The horizontal histogram indicates the number of significant DEGs for each cell type, and the vertical barplots show the number of significant DEGs (FDR < 0.05) specific to one, two, or three cell types. **(G)** Differential gene expression comparison of HX and NX in each region (cortex, corpus callosum, and SVZ) for signaling genes across Cell Types. **(H)** Representative images of NCAN immunofluorescence stained P21 NX and HX cortices from coronal slices. The cortex of each slice was manually segmented into three approximately equidistant regions encompassing the superficial (supr.) cortical layers, middle cortical layers, and deep cortical layers. Dashed lines demarcate the corpus callosum, “CC”. **(I-J)** Average positive fluorescence intensity of NCAN across the area of the (I) entire cortex and (J) each of the three segmented regions in (H). **(K-L)** Differential gene expression comparison of HX and NX in each region (cortex, corpus callosum, and SVZ) for (K) OL state genes across all OL-lineage cells (from Cell Type) and Cell Subtypes within the OL-lineage (L) astrocyte reactivity genes across all astrocytes (Astro from Cell Type) and Cell Subtypes

1230 within astrocytes, and **(M)** microglia reactivity genes across all microglia (Micro from Cell Type) and Cell  
1231 Subtypes within microglia. Genes in **(K)** are grouped and labeled according to the signaling pathway or  
1232 function that they participate in. Cortex and corpus callosum data in (A, B, D, E, G) display Cell Type  
1233 information, and in (K, L) display both Cell Type and Cell Subtype information. Only significant genes are  
1234 shown. Colors represent average  $\log_2(FC)$  as per legend. Differential gene expression results comparing  
1235 signaling genes from one anatomical region to another within the NX brain are shown in Extended Data  
1236 Figure 5-1. Full differential gene expression results, including genes not shown here, are shown in  
1237 Extended Data Table 5-1.

1238 **Figure 6: Cell subtypes exhibit discrete cell-cell signaling networks in the brain of mice exposed**  
1239 **to neonatal hypoxia.** Chord diagrams of predicted intra-lineage cell-cell communication pathways that  
1240 are upregulated in the **(A)** SVZ, **(B)** corpus callosum, and **(C)** cortex of HX versus NX mice. Chord  
1241 diagrams of predicted inter-lineage cell-cell communication pathways that are upregulated in the **(D)**  
1242 SVZ, **(E)** corpus callosum, and **(F)** cortex of HX versus NX mice. Cell Subtype identity of the ligand is  
1243 indicated in the outermost edge of the diagram, while the Cell Subtype identity of the receptor is indicated  
1244 by the internal ring. Encoding gene symbols are used to represent predicted interactions of their protein  
1245 products. Colored arrows indicate the specific ligand-receptor (LR) pairs and are colored according to the  
1246 outgoing ligand signal. For all chord diagrams, only significant ligand and receptor interactions are plotted  
1247 ( $p < 0.05$ ). Full results are shown in Extended Data Table 6-1.

1248 **Figure 7: Cell state changes of OL-lineage cells, astrocytes, and microglia across anatomical**  
1249 **regions and following neonatal hypoxia exposure.** Dotplots displaying differential gene expression  
1250 results of OL-state (OL genesis and OL maturation) genes comparing all OL-lineage cells (Cell Type) and  
1251 Cell Subtypes within NX and HX between **(A)** SVZ and deep cortex, **(B)** SVZ and upper cortex, **(C)** upper  
1252 and deep cortex, **(D)** corpus callosum (CC in all panels) and deep cortex, and **(E)** corpus callosum and  
1253 upper cortex. Violin-boxplots showing OL genesis state score in **(F)** newly-formed OLs and **(G)** OPCs,  
1254 and OL maturation score of **(H)** all OLs, **(I)** immature OLs, and **(J)** mature OLs, split and colored by  
1255 condition across the SVZ, corpus callosum, and cortex. Dotplots displaying differential gene expression  
1256 results of astrocyte reactivity genes comparing all astrocyte Cell Types and Cell Subtypes within NX and

1257 HX between (**K**) corpus callosum and deep cortex, (**L**) corpus callosum and upper cortex, (**M**) upper and  
1258 deep cortex. Violin-boxplots showing astrocyte reactivity score of (**N**) all astrocytes, (**O**) homeostatic  
1259 astrocytes, and (**P**) reactive astrocytes, split and colored by condition, across the SVZ, corpus callosum,  
1260 and cortex dotplots displaying differential gene expression results of microglia reactivity genes comparing  
1261 all microglia Cell Types and Cell Subtypes within NX and HX between (**Q**) SVZ and corpus callosum,  
1262 SVZ and deep cortex, SVZ and upper cortex, (**R**) corpus callosum and deep cortex, (**S**) corpus callosum  
1263 and upper cortex, (**T**) upper cortex and deep cortex. Violin-boxplots showing microglia reactivity score of  
1264 (**U**) all microglia, (**V**) homeostatic microglia, and (**W**) reactive microglia, split and colored by condition,  
1265 across the SVZ, corpus callosum, and cortex. For all dotplots, only significant genes are shown  
1266 (FDR < 0.05) and dot color represents average  $\log_2(FC)$  as per the associated legend. Results for all  
1267 dotplots are also shown in Extended Data Table 5-1. For all violin-boxplots, the width of the violin plot  
1268 represents the proportion of cells expressing that value of the score. Each dot represents the average  
1269 score for each replicate, the bold central line of the boxplot represents the median score for the condition,  
1270 and the limits of the box represent the interquartile range. Significance is determined using the two-tailed  
1271 Student's t-test. \*p-value < 0.05; \*\*p-value < 0.01. Asterisks denoting p-value are colored according to  
1272 the comparison they refer to (ie. turquoise denotes comparisons of different regions within NX, purple  
1273 denotes comparisons of different regions with HX, and black denotes comparisons between HX and NX  
1274 within the same region).

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