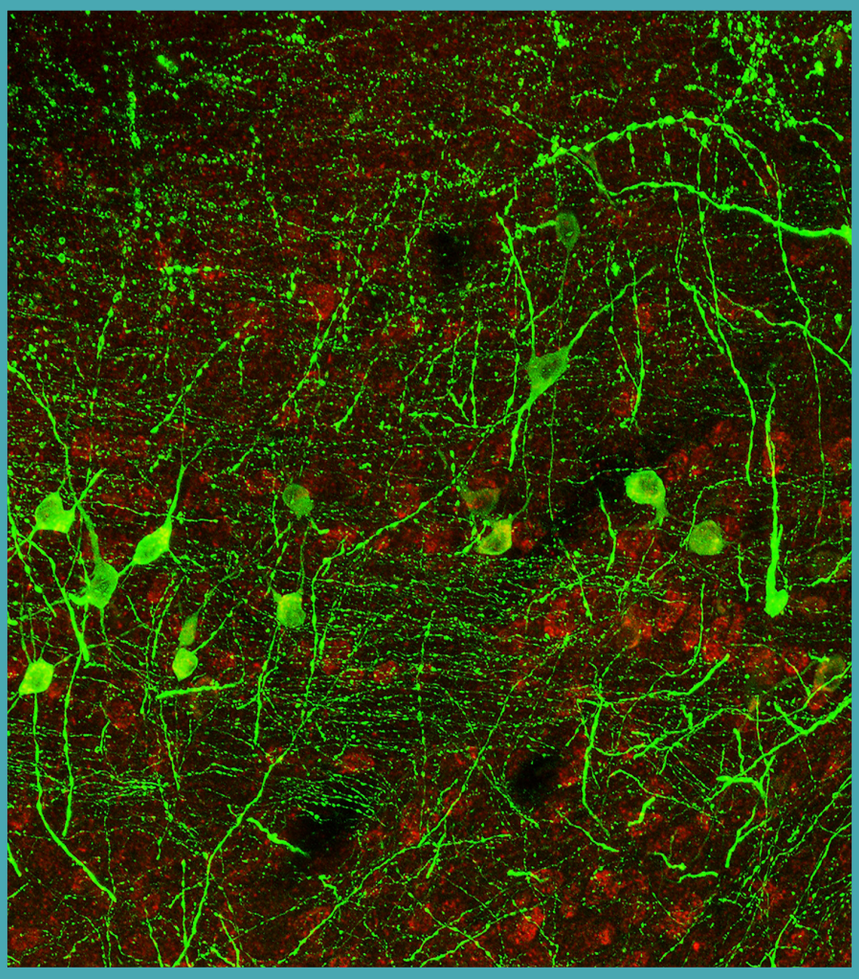
Neural markers guide

to help you progress faster



progress happens together

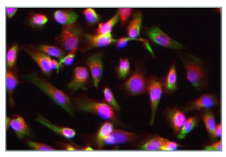
abcam

Contents

The markers shown in the guide are suggestions based on commonly used markers in published literature. There is often overlap in markers between different cell types, therefore we advise combining multiple markers and observing ultrastructural features where possible.

Neuroepithelial cells

Neuroepithelial (NE) cells are symmetrically dividing cells that form the neural plate and neural tube during embryonic development. They exhibit typical epithelial features such as tight junctions and are highly polarized along their apical-basal axis.



Nestin

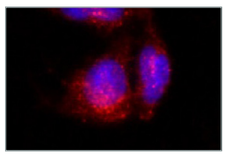
An intermediate filament protein expressed in NE cells. Its expression persists in radial glia until astrocyte development. Primary antibodies, conjugated antibodies, ELISA kits and proteins are available for Nestin.

Neural progenitor cells derived from human iPSCs stained red with anti-Nestin (ab105389).

SOX2

A transcription factor and the earliest marker of the neural plate. It is expressed in proliferating cells and those that acquire glial fates, but down-regulated in post-mitotic neurons. Primary antibodies, conjugated antibodies, ELISA kits, and cell lines are available for SOX2.

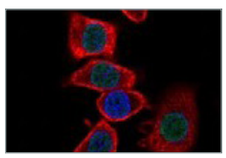
Leucoraja erinacea embryo stained with anti-SOX2 (ab92494).



Notch1

A transmembrane receptor that regulates the formation, migration, and differentiation of neural crest cells. Primary antibodies, conjugated antibodies, ELISA kits, and cell lines are available for Notch1.

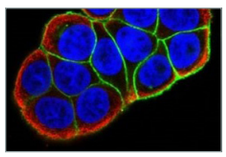
HeLa cell line stained red with anti-Notch1 (ab52627).



HES1 and HES3

Transcription factors that maintain the symmetrical cell division of NE cells. When NE cells become radial glia HES3 is down-regulated and HES5 is up-regulated. Primary antibodies, proteins and cell lines are available for HES1.

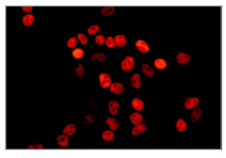
Human neuroblastoma epithelial cells stained green with anti-HES1 (ab108937).



E-cadherin and Occludin

Cell-cell junction proteins that are lost after neural tube closure, prior to neurogenesis. Primary antibodies, conjugated antibodies, proteins and ELISA kits are available for E-Cadherin. Primary antibodies and are available for Occludin.

Human pluripotent stem cells stained green with anti-E-Cadherin (ab40772).



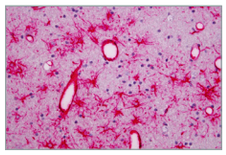
SOX10

A transcription factor present in migrating neural crest cells. Primary antibodies, conjugated antibodies, proteins and cell lines are available for SOX10.

A375 cells stained with anti-SOX10 (ab155279).

Radial glia

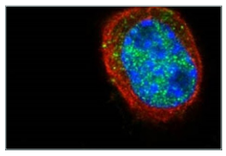
During neurogenesis, neuroepithelial (NE) cells transform into radial glia. Epithelial features such as tight junctions are downregulated in favor of adherens junctions. Glial hallmarks begin to emerge, including astrocyte markers and morphological features such as glycogen granules.



Vimentin and Nestin

Intermediate filament proteins whose expression persists until astrocyte development. Nestin is also found in NE cells, whilst Vimentin occurs during the epithelial-to-mesenchymal transition (EMT) of NE cells to radial glia. Primary antibodies, conjugated antibodies, proteins, ELISA kits and cell lines are available for Vimentin. Primary antibodies, proteins and ELISA kits are available for Nestin.

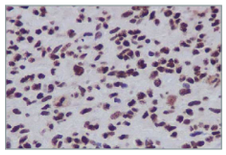
Rhesus monkey brain tissue sections stained with anti-Vimentin (ab92547).



PAX6

A transcription factor that promotes neurogenesis. Primary antibodies, conjugated antibodies and cell lines are available for PAX6.

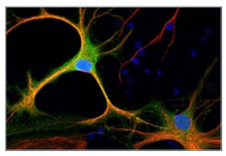
Mouse neuroblastoma cells stained green with anti-PAX6 (ab195045).



HES1 and HES5

Transcription factors that regulate the maintenance of radial glia. Primary antibodies, conjugated antibodies, proteins and cell lines are available for HES1. Primary antibodies are available for HES5.

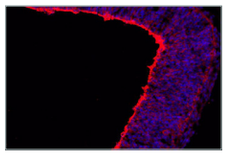
Human glioblastoma tissue labelled with anti-HES5 (ab194111).



Astrocytic markers: GFAP, GLAST, and BLBP

These astrocytic markers emerge as NE cells become radial glia. Primary antibodies, conjugated antibodies and ELISA kits are available for GFAP, GLAST and BLBP.

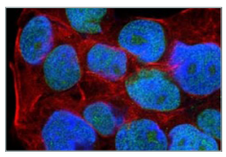
Mouse primary glial cells stained green with anti-BLBP (ab279649).



Adhesion and extracellular matrix molecules: TN-C and N-Cadherin

Upregulation of adhesion and extracellular matrix proteins accompanies the transformation of NE cells into radial glia. Primary antibodies, conjugated antibodies, proteins, ELISA kits and cell lines are available for TN-C and N-Cadherin.

Mouse embryonic coronal cortical section stained red with anti-N -Cadherin (ab76011).



SOX2

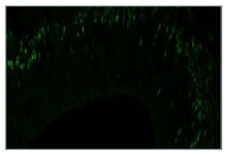
Transcription factor which is the earliest marker of the neural plate. SOX2 is expressed in proliferating cells and those that acquire glial fates, but down-regulated in post-mitotic neurons. Primary antibodies, conjugated antibodies, ELISA kits and cell lines are available for SOX2 .

Human embryonic carcinoma epithelial cells stained green with anti-SOX2 (ab93689).

Immature neurons and intermediate progenitors

Radial glia divide asymmetrically to produce one radial glia cell and one intermediate progenitor cell (IPC). IPCs differentiate into post-mitotic immature neurons, which migrate to their final destination in the nervous system and integrate into the neuronal network.

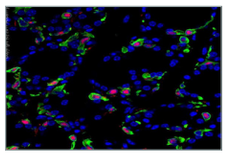
Intermediate progenitors



TBR2

A transcription factor whose expression marks the transition from radial glia to intermediate progenitors. Primary antibodies, conjugated antibodies, proteins and cell lines are available for TBR2.

Frozen rat E14.5 cerebrum tissue stained green with anti-TBR2 (ab216870).

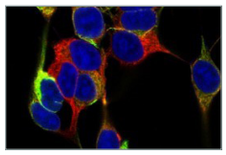


MASH1 (Ascl1)

A transcription factor essential for neural differentiation, which can also label active neural stem cells. Primary antibodies and proteins are available for MASH1.

Mouse thyroid tissue stained red with anti-MASH1 (ab211327).

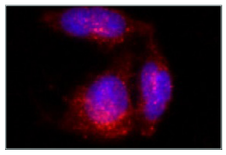
Immature neurons



Doublecortin

Doublecortin is a microtubule-associated phosphoprotein that promotes neurite extension and cell migration.Primary antibodies, conjugated antibodies, ELISA kits and proteins are available for Doublecortin.

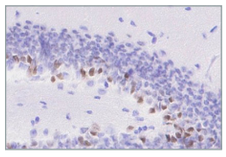
Human neurobastoma cell line from bone marrow stained green with anti-Doublecortin (ab207175).



Beta III tubulin

Beta III tubulin is a class of neuron-specific tubulin. Primary antibodies, conjugated antibodies, ELISA kits, proteins and cell lines are available for Beta III tubulin.

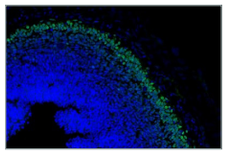
NGF-differentiated PC-12 cells stained red with anti-beta III Tubulin (ab52623).



NeuroD1

A transcription factor that promotes neuronal development. Primary antibodies and proteins are available for NeuroD1.

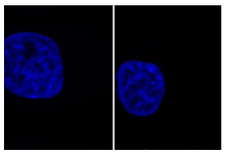
Mouse hippocampus tissue stained with anti-NeuroD1 (ab213725).



TBR1

A transcription factor whose expression marks the transition from intermediate progenitors to post-mitotic neurons. Primary antibodies are available for TBR1.

Rat E14 cerebral cortex stained green with anti-TBR1 (ab183032).



Stathmin 1

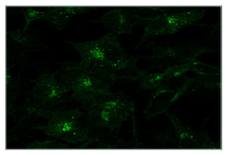
A cytoplasmic phosphoprotein involved in cytoskeletal regulation. Primary antibodies, conjugated antibodies, ELISA kits and proteins are available for Stathmin 1.

HeLa cells stained green with anti-Stathmin 1 (ab52630).

Oligodendrocytes and oligodendrocyte precursor cells

Oligodendrocytes are responsible for the production of myelin, which insulates the axons of neurons within the central nervous system. Their function is equivalent to that of Schwann cells in the peripheral nervous system.

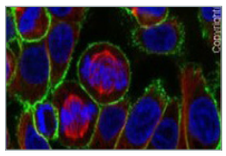
Oligodendrocyte precursor cells



PDGFR alpha

A cell surface tyrosine kinase receptor and a marker of oligodendrocyte precursor cells. Primary antibodies, conjugated antibodies, ELISA kits, proteins and cell lines are available for PDGFR alpha.

Replace legend with "SH-SY5Y cells stained green with anti-PDGFR alpha (ab203491).

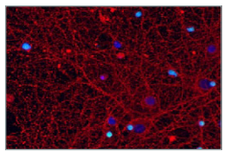


NG2

A membrane chondroitin sulfate proteoglycan (CSPG) expressed by oligodendrocyte precursor cells. Primary antibodies, conjugated antibodies, ELISA kits, proteins and cell lines are available for NG2.

Human malignant epithelial cell line stained green with anti-NG2 (ab255811).

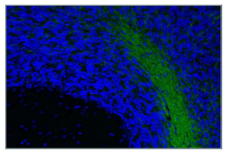
Oligodendrocytes



Olig2

Transcription factor necessary for oligodendrocyte development. Antibodies are available to Olig2. Primary antibodies, conjugated antibodies, proteins and cell lines are available for Olig2.

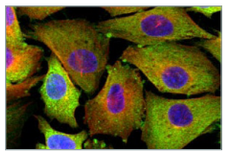
E18 mouse hippocampal brain cell culture stained green with anti-Olig2 (ab109186).



Oligodendrocyte specific protein (OSP) and myelin oligodendrocyte glycoprotein (MOG)

Proteins found on the surface of oligodendrocytes. Primary antibodies, conjugated antibodies and ELISA kits are available for MOG. Primary antibodies and proteins are available for OSP.

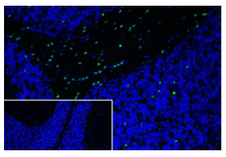
Cerebellum tissue stained green with anti-Myelin oligodendrocyte glycoprotein (ab233549).



Myelin basic protein (MBP)

A structural component of myelin, expressed exclusively by myelinating glia. Primary antibodies, conjugated antibodies, proteins and ELISA kits are available for MBP.

Human neuroblastoma cell line stained green with anti-Myelin basic protein (ab209328).



SOX10

Transcription factor that directs neural stem cells towards the glial lineage. Should be used in combination with other markers to identify oligodendrocytes. Primary antibodies, conjugated antibodies, cell lines and proteins are available for SOX10.

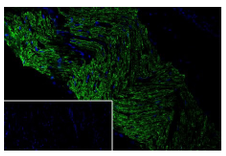
Mouse cerebellum tissue sections stained green with anti-SOX10 (ab227680).

Schwann cells and Schwann cell precursors

Schwann cells are the myelin-producing cells of the peripheral nervous system where they form the myelin sheath around axons. Their function is equivalent to that of oligodendrocytes in the central nervous system.

Schwann cell markers throughout development

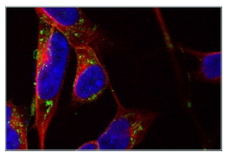
Schwann cell stage	Suggested markers					
Schwann cell precursor	SOX10	GAP43	BLBP	MPZ	Dhh	P75NTR
Myelinating Schwann cell	SOX10	S100	EGR2	MBP	MPZ	
Non myelinating Schwann cell	SOX10	GAP43	S100B	NCAM1	P75NTR	



Myelin protein zero (MPZ)

A structural component of the myelin sheath. Primary antibodies, conjugated antibodies, proteins and cell lines are available for MPZ.

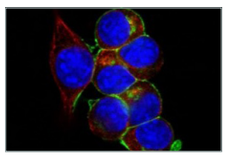
Rat sciatic nerves labeled with anti-Myelin Protein Zero (ab183868).



NCAM1

A glycoprotein involved in cell adhesion, expressed by non-myelinating Schwann cells. Primary antibodies, conjugated antibodies, proteins, ELISA kits and cell lines are available for NCAM1.

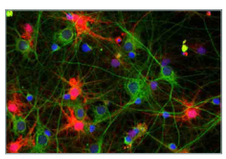
Human neuroblastoma epithelial cell stained green with anti-NCAM1 (ab75813).



GAP43

A cytoplasmic protein expressed by non-myelinating glia. Primary antibodies, conjugated antibodies, ELISA kits, proteins and cell lines are available for GAP43.

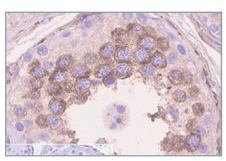
Mouse neuroblastoma call line stained green with anti-GAP43 (ab75810).



S100B

Homodimeric protein that is often found in cells derived from the neural crest. Primary antibodies, conjugated antibodies, ELISA kits, proteins and cell lines are available for S100B.

E18 rat hippocampal glia stained in red with anti-S100 beta (ab52642).



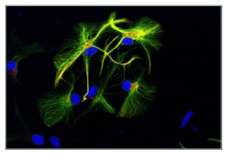
Dhh

Intercellular signal essential for a variety of patterning events during development. Primary antibodies, proteins and cell lines are available for Dhh.

Human testis tissue labelled with anti-Dhh (ab270453).

Astrocytes

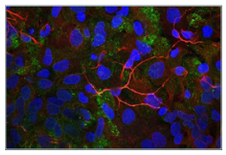
Astrocytes are the star-shaped glial cells and serve a wide variety of functions in the central nervous system, which are vital for brain development, physiology and pathology.



GFAP

An intermediate filament and major component of the astrocyte cytoskeleton. Primary antibodies, conjugated antibodies, protiens and ELISA kits are available for GFAP.

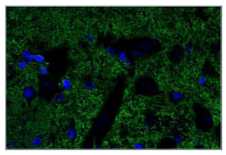
Mouse primary glia stained green with anti-GFAP (ab68428).



EAAT1 (GLAST)

An astrocyte-specific glutamate transporter. Primary antibodies and proteins are available for EAAT1.

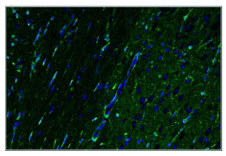
Rat primary glia stained green with anti-EAAT1 (ab181036).



EAAT2 (GLT-1)

An astrocyte-specific glutamate transporter. Primary antibodies and proteins are available for EAAT2

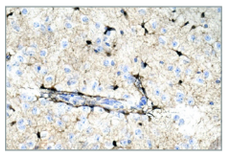
Mouse striatum tissue section stained green with anti-EAAT2 (ab205248).



Glutamine synthetase

An enzyme involved in the metabolism of nitrogen. In the brain it is primarily found in astrocytes. Primary antibodies, ELISA kits, proteins and cell lines are available for glutamine synethetase.

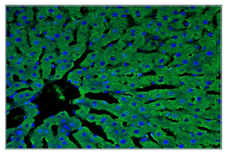
Mouse cerebrum tissue section stained green with anti-Glutamine synthetase (ab176562).



S100B

A calcium binding protein, also found in oligodendrocyte precursor cells (OPCs). Double labeling with NG2 will distinguish the OPCs from the astrocytes. Primary antibodies, conjugated antibodies, and proteins are available for S100 beta.

Mouse brain tissue sections stained with anti-S100 beta (ab52642).



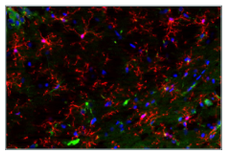
ALDH1L1

An enzyme that catalyzes the conversion of 10-formyltetrahydrofolate, NADP+ and water to tetrahydrofolate, NADPH and CO2. Primary antibodies are available for ALDH1L1.

Rat liver tissue section stained green with anti-ALDH1L1 (ab177463).

Microglia

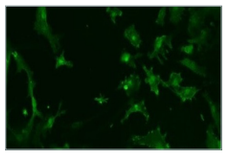
Microglia are the macrophages of the brain and spinal cord and act as an immune defense in the central nervous system. Due to the shared lineage of microglia and macrophages, many markers are common to both cell types, therefore combinations of markers are usually used to identify them.



CD11b and CD45

A combination of CD11b and CD45 labeling can distinguish microglia from macrophages: Resting microglia are $CD11b^{+}$, $CD45^{low}$, whereas macrophages are $CD11b^{+}$, $CD45^{high.}$ Primary antibodies, conjugated antibodies, proteins, ELISA kits and cell lines are available for CD11b. Primary antibodies, conjugated antibodies, proteins and ELISA kits are available for CD45.

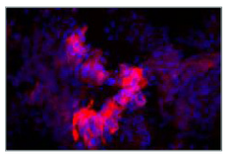
Rat brain tissue sections stained with anti-CD11b/c (red) (ab1211).



Iba1

A calcium-binding protein upregulated after cerebral ischemia. This is marker is particularly useful in IHC/ICC experiments. Primary antibodies, conjugated antibodies, proteins and cell lines are available for IBA1.

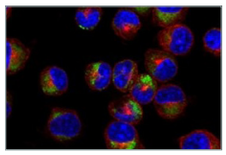
Mouse microglia cells stained green with anti-Iba1 (ab178846).



F4/80

A 160 KDa glycoprotein found on murine resting microglia. Primary antibodies, conjugated antibodies, and cell lines are available for F4/80.

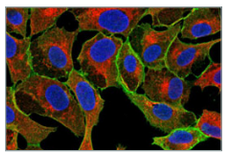
Mouse microglia stained red with anti-F4/80 (ab16911).



CD68

A lysosomal protein highly expressed by macrophages and activated microglia, but in low levels by resting microglia. Primary antibodies, conjugated antibodies, ELISA kits, proteins and cell lines are available for CD68.

J774A.1 cells stained green with anti-CD68 (ab283654).



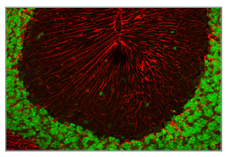
CD40

A cell surface molecule expressed by activated microglia necessary for antigen presentation. Primary antibodies, conjugated antibodies, ELISA kits, proteins and cell lines are available for CD40.

U20S cells stained green with anti-CD40 (ab224639).

Mature neurons

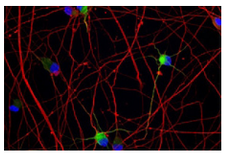
Mature neurons are terminally differentiated and are no longer able to divide. Their purpose is to receive, process, and transfer information in the central and peripheral nervous systems.



NeuN

An RNA binding protein that is highly specific for post-mitotic neurons. Primary antibodies and conjugated antibodies are available for NeuN.

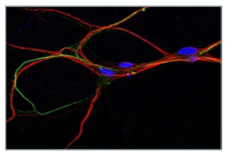
Mouse cerebellum section stained green with anti-NeuN (ab177487).



MAP2

A neuron-specific protein that promotes assembly and stability of the microtubule network. Primary antibodies, conjugated antibodies, proteins, ELISA kits and cell lines are available for MAP2.

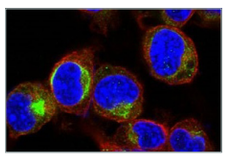
Human iPSC-derived glutamatergic neurons (ab259259) stained green with anti-MAP2 (ab183830).



160 kDa Neurofilament medium

Major intermediate filament found in neurons. Primary antibodies, ELISA kits and cell lines are available for 160kDa neurofilament medium.

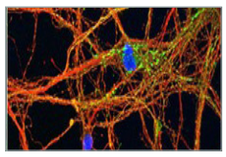
Mouse primary neuros stained green using anti-160 kDa neurofilament medium (ab254348).



200 kDa Neurofilament heavy

Major intermediate filament found in neurons. Primary antibodies and ELISA kits are available for 200kDa neurofilament heavy.

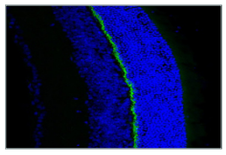
Mouse neuroblastoma cell line stained green using anti-Neurofilament heavy polypeptide (ab207176).



Synaptophysin

Synaptic vesicle protein that regulates vesicle endocytosis in neurons. Primary antibodies, conjugated antibodies, proteins and cell lines are available for synaptophysin.

Primary neurons stained green with anti-Synaptophysin (ab32127).



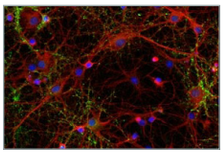
PSD95

Synaptic protein that associates with receptors and the cytoskeleton. Primary antibodies, proteins and cell lines are available for PSD95.

Mouse retina section stained green with anti-PSD95 (ab238135).

Glutamatergic neurons

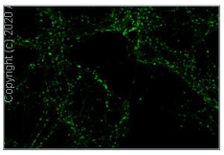
Glutamatergic neurons produce glutamate, which is one of the most common excitatory neurotransmitters in the central nervous system.



vGluT1

A glutamate transporter that transports cytoplasmic glutamate into vesicles. Primary antibodies, conjugated antibodies and proteins are available for vGluT1.

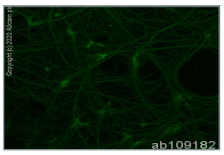
Primary hippocampal rat neurons stained green with anti-vGluT1(ab227805).



vGluT2

A glutamate transporter that transports cytoplasmic glutamate into vesicles. Primary antibodies are available for vGluT2.

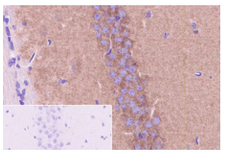
Mouse midbrain neurons stained green with anti-vGluT2 (ab216463).



NMDAR1

An essential subunit of all NMDA receptors. Primary antibodies, conjugated antibodies, proteins and ELISA kits are available for NMDAR1.

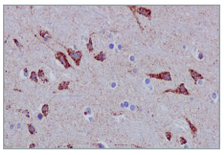
Mouse primary neurons stained green with anti-NMDAR1 (ab109182).



NMDAR2B

Another NMDA receptor subunit. This subunit forms the glutamate binding site on the NMDA receptors. Primary antibodies, conjugated antibodies and proteins are available for NMDAR2B.

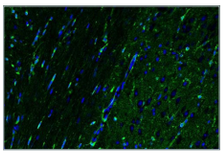
Mouse hippocampus section stained with anti-NMDAR2B (ab254356).



Glutaminase

An enzyme catalyzing the deamination of glutamine into glutamate. Primary antibodies, conjugated antibodies, cell lines and proteins are available for Glutaminase.

Human cerebral cortex tissue labeled with anti-Glutaminase (ab156876).



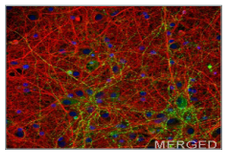
Glutamine synthetase

An enzyme catalyzing the ATP-dependent amidation of glutamate to form glutamine. It is primarily expressed in astrocytes but expression levels rise in neurons in neurodenegerative diseases. Primary antibodies, conjugated antibodies, ELISA kits, proteins and cell lines are available for Glutamine synthetase.

Mouse cerebrum tissue stained with anti-Glutamine synthetase (ab176562).

GABAergic neurons

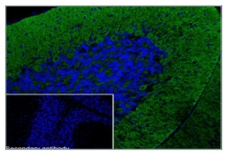
GABAergic neurons generate gamma aminobutyric acid (GABA), one of the two inhibitory neurotransmitters in the central nervous system.



GABA transporter 1 (GAT1)

A transporter on the cell membrane that moves GABA into the cell, removing it from the synaptic cleft. Primary antibodies are available for GABA transporter 1.

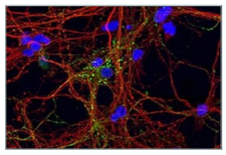
Mouse brain tissue section stained green with anti-GABA transporter 1 (ab259971).



$GABA_B$ receptor 1 and 2

$GABA_B$ receptors are metabotropic transmembrane receptors for GABA that are linked via G-proteins to potassium channels. $GABA_B$ receptor 1 and $GABA_B$ receptor 2 assemble as heterodimers in neuronal membranes.

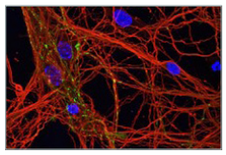
Mouse cerebellum stained green with anti-GABAB receptor 1 (ab238130).



GAD65

The 65 kDa isomorph of glutamate decarboxylase that catalyzes the formation of GABA from glutamate. Primary antibodies, conjugated antibodies, proteins and ELISA kits are available for GAD65.

Mouse primary neurons stained green with anti-GAD65 (ab239372).



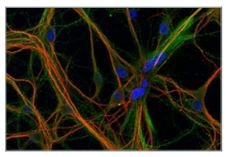
GAD67

The 67 kDa isomorph of glutamate decarboxylase. Unlike GAD65, which is also expressed in the pancreas, GAD67 is CNS-specific. Primary antibodies, conjugated antibodies, ELISA kits and proteins are available for GAD67.

Mouse brain section of neurons stained green with anti-GAD67 (ab213508).

Dopaminergic neurons

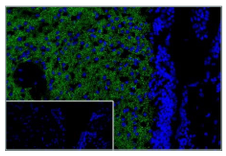
Dopaminergic neurons produce dopamine, a neurotransmitter with roles in neurological functions such as mood and reward. Progressive loss of dopaminergic neurons is the cause of many of the motor symptoms associated with Parkinson's disease



Tyrosine hydroxylase (TH)

An enzyme that converts L-tyrosine to L-3,4-dihydroxyphelylalanine (L-DOPA), which is a dopamine precursor. Primary antibodies, conjugated antibodies, ELISA kits and proteins are available for TH.

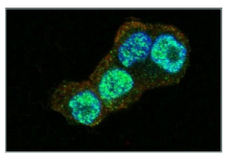
Mouse midbrain section stained green with anti-Tyrosine hydroxylase (ab75875).



Dopamine transporter (DAT)

A transmembrane transporter that controls the re-uptake of extracellular dopamine into presynaptic neurons. Primary antibodies, conjugated antibodies and proteins are are available for DAT.

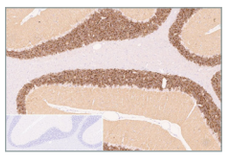
Mouse coronal brain section stained green with anti-Dopamine transporter (ab184451).



FOXA2

A transcriptional activator that regulates specification and differentiation of dopaminergic neurons. Primary antibodies, conjugated antibodies, ELISA kits and cell lines are available for FOXA2.

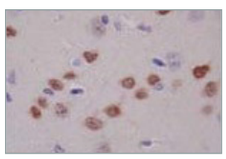
HT-29 cells stained green with anti-FOXA2 (ab108422).



GIRK2

A G-protein regulated potassium channel expressed within certain dopaminergic neurons of the substantia nigra. Primary antibodies are available for GIRK2.

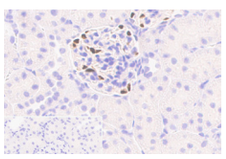
Rat cerebellum tissue section stained with anti-GIRK2 (ab259909).



Nurr1

A transcription factor that induces TH expression and subsequently dopaminergic neuron differentiation. Primary antibodies and proteins are are available for Nurr1.

Rat cerebral neurons stained with anti-Nurr1 (ab41917).



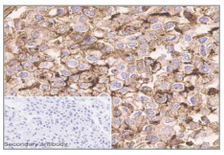
LMX1B

A transcription factor involved in a number of processes during dopaminergic neuron development. Primary antibodies and proteins are available for LMX1B.

Rat Kidney tissue stained with anti-LMX1B (ab259926).

Serotonergic neurons

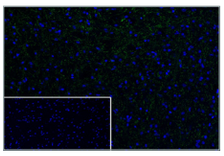
Serotonergic neurons synthesize the neurotransmitter serotonin (5-HT), which is found in the gastrointestinal tract, blood platelets, and the central nervous system.



Tryptophan hydroxylase (TPH)

An enzyme involved in serotonin synthesis. There are two isoforms of tryptophan hydroxylase (TPH1 and TPH2) with TPH2 predominantly found in the brain. Primary antibodies, conjugated antibodies and proteins are available for TPH.

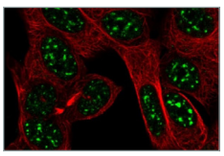
Human bladder carcinoma tissue section labeled with anti-TPH (ab52954).



Serotonin transporter

A transmembrane protein responsible for the re-uptake of 5-HT from the synaptic cleft into the presynaptic neuron. Primary antibodies and proteins are available for serotonin transporter.

Human cerebral cortex stained with anti-Serotonin transporter (ab254358).



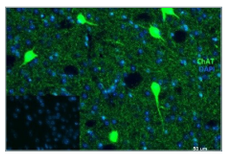
Pet1

A transcription factor that drives the transcription of genes essential for the metabolism as well as re-uptake of Serotonin. Primary antibodies and proteins are available for Pet1.

Human neuroblastoma cell line stained using anti-Pet1 (ab221724).

Cholinergic neurons

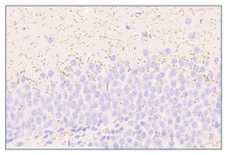
Cholinergic neurons use the neurotransmitter acetylcholine. Their progressive loss is one of the hallmarks of neurodegenerative diseases with cognitive deficits such as Alzheimer's disease.



Choline acetyltransferase (ChAT)

An enzyme that catalyzes the synthesis of acetylcholine. Primary antibodies and conjugated antibodies are available for ChAT.

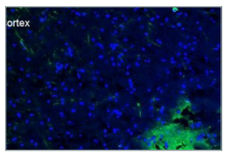
Mouse cerebral cortex section stained with anti-Choline acetyltransferase (ab178850).



Vesicular acetylcholine transporter (VAChT)

A transporter that uses a proton gradient established by the vacuolar ATPase to transport acetylcholine into secretory vesicles. Primary antibodies are available for VAChT.

Mouse cerebrum stained with anti-Vesicular acetylcholine transporter (ab271111).



Acetylcholinesterase

An enzyme that catalyzes the breakdown of acetylcholine into acetate and choline. Primary antibodies, proteins, ELISA kits and cell lines are available for acetylcholinesterase.

Rat sagittal section stained green with anti-Acetylcholinesterase (ab183591).

References and further reading

Neuroepithelial cells

Bylund, M., Andersson, E., Novitch, B. G. & Muhr, J. Vertebrate neurogenesis is counteracted by Sox1-3 activity. *Nat Neurosci* **6,** 1162–1168 (2003).

Jessen, K. R. & Mirsky, R. The origin and development of glial cells in peripheral nerves. *Nat. Rev. Neurosci.* **6,** 671–82 (2005).

Kageyama, R., Ohtsuka, T. & Kobayashi, T. Roles of Hes genes in neural development. *Development Growth and Differentiation* **50,** (2008).

Kriegstein, A. R. & Götz, M. Radial glia diversity: A matter of cell fate. *Glia* **43,** 37–43 (2003).

Noisa, P., Lund, C., Kanduri, K., Lund, R. & La, H. Notch signaling regulates the differentiation of neural crest from human pluripotent stem cells. *J. Cell Sci.* **127,** 2083–2094 (2014).

Papanayotou, C. *et al.* A mechanism regulating the onset of Sox2 expression in the embryonic neural plate. *Plos Biol* **6,** e2 (2008).

Radial glia

Bylund, M., Andersson, E., Novitch, B. G. & Muhr, J. Vertebrate neurogenesis is counteracted by Sox1-3 activity. *Nat Neurosci* **6,** 1162–1168 (2003).

Heins, N. *et al.* Glial cells generate neurons: the role of the transcription factor Pax6. *Nat. Neurosci.* **5,** 308–315 (2002).

Kageyama, R., Ohtsuka, T. & Kobayashi, T. Roles of Hes genes in neural development. *Development Growth and Differentiation* **50,** (2008).

Kriegstein, A. & Alvarez-Buylla, A. The glial nature of embryonic and adult neural stem cells. *Annu. Rev. Neurosci.* **32,** 149–84 (2009).

Kriegstein, A. R. & Götz, M. Radial glia diversity: A matter of cell fate. *Glia* **43,** 37–43 (2003).

Kriegstein, A. & Alvarez-Buylla, A. The glial nature of embryonic and adult neural stem cells. *Annu. Rev. Neurosci.* **32,** 149–84 (2009).

Lamouille, S., Xu, J. & Derynck, R. Molecular mechanisms of epithelial-mesenchymal transition. *Nat. Rev. Mol. Cell Biol.* **15,** 178–96 (2014).

Papanayotou, C. *et al.* A mechanism regulating the onset of Sox2 expression in the embryonic neural plate. *Plos Biol* **6,** e2 (2008).

Immature neurons and intermediate progenitors

Atweh, C. The Role of Stathmin in the Regulation of the Cell Cycle. *J.Cell.Biochem* **93,** (2004).

Englund, C. *et al.* Pax6, Tbr2, and Tbr1 Are Expressed Sequentially by Radial Glia, Intermediate Progenitor Cells, and post-mitotic Neurons in Developing Neocortex. *J. Neurosci.* **25,** 247–251 (2005).

Katsetos, C. D. *et al.* Class III beta-tubulin isotype (beta III) in the adrenal medulla: I. Localization in the developing human adrenal medulla. *Anat. Rec.* **250,** 335–43 (1998).

Kim, E. J., Ables, J. L., Dickel, L. K., Eisch, A. J. & Johnson, J. E. Ascl1 (Mash1) Defines Cells with Long-Term Neurogenic Potential in Subgranular and Subventricular Zones in Adult Mouse Brain. (2011).

Kwak, M. *et al.* Effects of Neonatal Hypoxic-Ischemic Injury and Hypothermic Neuroprotection on Neural Progenitor Cells in the Mouse Hippocampus. *Dev. Neurosci.* **37,** 428–439 (2015).

Martí-Mengual, U., Varea, E., Crespo, C., Blasco-Ibáñez, J. M. & Nacher, J. Cells expressing markers of immature neurons in the amygdala of adult humans. *Eur. J. Neurosci.* **37,** 10–22 (2013).

Menezes, J. R. & Luskin, M. B. Expression of neuron-specific tubulin defines a novel population in the proliferative layers of the developing telencephalon. *J. Neurosci.* **14,** 5399–5416 (1994).

Pollen, A. A. *et al.* Molecular Identity of Human Outer Radial Glia during Cortical Development. *Cell* **163,** 55–67 (2015).

Shin, J. *et al.* Single-Cell RNA-Seq with Waterfall Reveals Molecular Cascades underlying Adult Neurogenesis. *Cell Stem Cell* **17,** 360–372 (2015).

Oligodendrocytes and oligodendrocyte precursor cells

Barbarese, E. *et al.* Expression and localization of myelin basic protein in oligodendrocytes and transfected fibroblasts. *J. Neurochem.* **51,** 1737–45 (1988).

Dyer, C. A., Hickey, W. F. & Geisert, E. E. Myelin/oligodendrocyte-specific protein: a novel surface membrane protein that associates with microtubules. *J. Neurosci. Res.* **28,** 607–13 (1991).

Marques, S. *et al.* Oligodendrocyte heterogeneity in the mouse juvenile and adult central nervous system. *Science* **352,** 1326–9 (2016).

Mei, F. *et al.* Stage-specific deletion of Olig2 conveys opposing functions on differentiation and maturation of oligodendrocytes. *J. Neurosci.* **33,** 8454–62 (2013).

Pozniak, C. D. *et al.* Sox10 directs neural stem cells toward the oligodendrocyte lineage by decreasing Suppressor of Fused expression. *Proc. Natl. Acad. Sci. U. S. A.* **107,** 21795–800 (2010).

Scolding, N. J. *et al.* Myelin-oligodendrocyte glycoprotein (MOG) is a surface marker of oligodendrocyte maturation. *J. Neuroimmunol.* **22,** 169–176 (1989).

Zhou, Q., Choi, G. & Anderson, D. J. The bHLH transcription factor Olig2 Promotes oligodendrocyte differentiation in collaboration with Nkx2.2. *Neuron* **31,** 791–807 (2001).

Schwann cells and Schwann cell precursors

Jessen, K. R. & Mirsky, R. The origin and development of glial cells in peripheral nerves. *Nat. Rev. Neurosci.* **6,** 671–82 (2005).

Jessen, K. R., Mirsky, R. & Lloyd, A. C. Schwann Cells: Development and Role in Nerve Repair. *Cold Spring Harb. Perspect. Biol.* **7,** a020487 (2015).

Kuhlbrodt, K., Herbarth, B., Sock, E., Hermans-Borgmeyer, I. & Wegner, M. Sox10, a novel transcriptional modulator in glial cells. *J. Neurosci.* **18,** 237–250 (1998).

Liu, Z. *et al.* Specific marker expression and cell state of Schwann cells during culture in vitro. *PLoS One* **10,** e0123278 (2015).

Astrocytes

Cahoy, J. D. *et al.* A transcriptome database for astrocytes, neurons, and oligodendrocytes: a new resource for understanding brain development and function. *J. Neurosci.* **28,** 264–78 (2008).

Dimou, L. & Götz, M. Glial Cells as Progenitors and Stem Cells: New Roles in the Healthy and Diseased Brain. *Physiol. Rev.* **94,** 709–737 (2014).

Kriegstein, A. R. & Götz, M. Radial glia diversity: A matter of cell fate. *Glia* **43,** 37–43 (2003).

Microglia

Becher, B. & Antel, J. P. Comparison of phenotypic and functional properties of immediately ex vivo and cultured human adult microglia. *Glia* **18,** 1–10 (1996).

Ford, A. L., Goodsall, A. L., Hickey, W. F. & Sedgwick, J. D. Normal adult ramified microglia separated from other central nervous system macrophages by flow cytometric sorting. Phenotypic differences defined and direct ex vivo antigen presentation to myelin basic protein-reactive CD4+ T cells compared. *J. Immunol.* **154,** 4309–21 (1995).

Imai, Y., Ibata, I., Ito, D., Ohsawa, K. & Kohsaka, S. A novel gene iba1 in the major histocompatibility complex class III region encoding an EF hand protein expressed in a monocytic lineage. *Biochem. Biophys. Res. Commun.* **224,** 855–62 (1996).

Ito, D., Tanaka, K., Suzuki, S., Dembo, T. & Fukuuchi, Y. Enhanced Expression of Iba1, Ionized Calcium-Binding Adapter Molecule 1, After Transient Focal Cerebral Ischemia In Rat Brain. *Stroke* **32,** 1208–1215 (2001).

Patel, A. R., Ritzel, R., McCullough, L. D. & Liu, F. Microglia and ischemic stroke: A double-edged sword. *International Journal of Physiology, Pathophysiology and Pharmacology* **5,** 73–90 (2013).

Ponomarev, E. D., Shriver, L. P. & Dittel, B. N. CD40 Expression by Microglial Cells Is Required for Their Completion of a Two-Step Activation Process during Central Nervous System Autoimmune Inflammation. *J. Immunol.* **176,** 1402–1410 (2006).

Mature neurons

El-Husseini, A. E. *et al.* PSD-95 involvement in maturation of excitatory synapses. *Science* **290,** 1364–8 (2000).

Kwon, S. E. & Chapman, E. R. Synaptophysin regulates the kinetics of synaptic vesicle endocytosis in central neurons. *Neuron* **70,** 847–54 (2011).

Mullen, R. J., Buck, C. R. & Smith, A. M. NeuN, a neuronal specific nuclear protein in vertebrates. *Development* **116,** 201–211 (1992).

Soltani, M. H. *et al.* Microtubule-associated protein 2, a marker of neuronal differentiation, induces mitotic defects, inhibits growth of melanoma cells, and predicts metastatic potential of cutaneous melanoma. *Am. J. Pathol.* **166,** 1841–1850 (2005).

Trojanowski, J. Q., Walkenstein, N. & Lee, V. M. Expression of neurofilament subunits in neurons of the central and peripheral nervous system: an immunohistochemical study with monoclonal antibodies. *J. Neurosci.* **6,** 650–660 (1986).

Yuan, a., Rao, M. V., Veeranna & Nixon, R. a. Neurofilaments at a glance. *J. Cell Sci.* **125,** 3257–3263 (2012).

Glutamatergic neurons

Baude, A., Strube, C., Tell, F. & Kessler, J.-P. Glutamatergic neurotransmission in the nucleus tractus solitarii: structural and functional characteristics. *J. Chem. Neuroanat.* **38,** 145–53 (2009).

Fernandes, S. P., Dringen, R., Lawen, A. & Robinson, S. R. Neurones express glutamine synthetase when deprived of glutamine or interaction with astrocytes. *J. Neurochem.* **114,** 1527–36 (2010).

Wang, T. & Miller, K. E. Characterization of glutamatergic neurons in the rat atrial intrinsic cardiac ganglia that project to the cardiac ventricular wall. *Neuroscience* **329,** 134–150 (2016).

GABAergic neurons

Bettler, B., Kaupmann, K., Mosbacher, J. & Gassmann, M. Molecular structure and physiological functions of GABA(B) receptors. *Physiol. Rev.* **84,** 835–67 (2004).

Bráz, J. M. *et al.* Forebrain GABAergic Neuron Precursors Integrate into Adult Spinal Cord and Reduce Injury-Induced Neuropathic Pain. *Neuron* **74,** 663–675 (2012).

Volk, D. W., Sampson, A. R., Zhang, Y., Edelson, J. R. & Lewis, D. A. Cortical GABA markers identify a molecular subtype of psychotic and bipolar disorders. *Psychol. Med.* 1–12 (2016).

Zhou, Y. & Danbolt, N. C. GABA and Glutamate Transporters in Brain. *Front. Endocrinol. (Lausanne).* **4,** 165 (2013).

Dopaminergic neurons

Hall, F. S. *et al.* Decreased vesicular monoamine transporter 2 (VMAT2) and dopamine transporter (DAT) function in knockout mice affects aging of dopaminergic systems. *Neuropharmacology* **76 Pt A,** 146–55 (2014).

Hartfield, E. M. *et al.* Physiological characterisation of human iPS-derived dopaminergic neurons. *PLoS One* **9,** (2014).

Jankovic, J., Chen, S. & Le, W. D. The role of Nurr1 in the development of dopaminergic neurons and Parkinson's disease. *Prog. Neurobiol.* **77,** 128–138 (2005).

Nakatani, T., Kumai, M., Mizuhara, E., Minaki, Y. & Ono, Y. Lmx1a and Lmx1b cooperate with Foxa2 to coordinate the specification of dopaminergic neurons and control of floor plate cell differentiation in the developing mesencephalon. *Dev. Biol.* **339,** 101–113 (2010).

Reyes, S. *et al.* GIRK2 expression in dopamine neurons of the substantia nigra and ventral tegmental area. *J. Comp. Neurol.* **520,** 2591–607 (2012).

Serotonergic neurons

Hendricks, T. J. *et al.* Pet-1 ETS gene plays a critical role in 5-HT neuron development and is required for normal anxiety-like and aggressive behavior. *Neuron* **37,** 233–247 (2003).

Kittler, K., Lau, T. & Schloss, P. Antagonists and substrates differentially regulate serotonin transporter cell surface expression in serotonergic neurons. *Eur. J. Pharmacol.* **629,** 63–67 (2010).

Liu, C. *et al.* Pet-1 is required across different stages of life to regulate serotonergic function. *Nat. Neurosci.* **13,** 1190–1198 (2010).

Cholinergic neurons

Sarter, M. & Parikh, V. Choline transporters, cholinergic transmission and cognition. *Nature* **6,** 48–56 (2005).

Notes

Notes

Neural lineage markers at a glance

progress happens together
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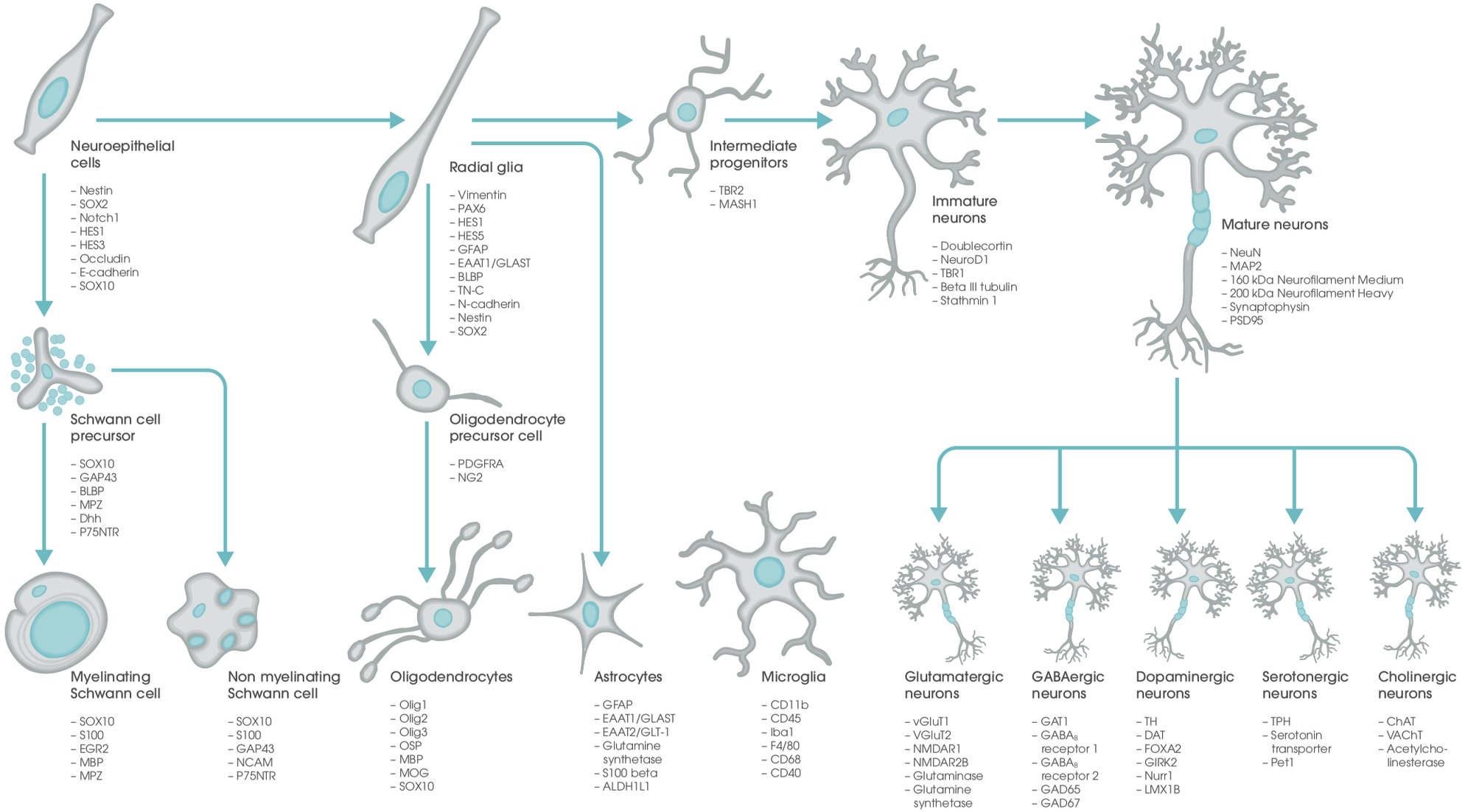

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